

Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate

Annex I

Hydrogen Conditioning Pathway – Liquid Hydrogen as carrier

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Annex I (informative)

Hydrogen Conditioning Pathway – Liquid Hydrogen as carrier

I.1 Process description and overview

Sections I.1.1 and I.1.2 provide a description and an overview for liquid hydrogen as carrier.

I.1.1 Description

Hydrogen is liquefied to enable its delivery and/or storage at a higher density than feasible in gaseous form. Liquid hydrogen is delivered to end uses in cryogenic liquid tanker trucks or ships. Each kilogram of hydrogen typically requires about 10-15 kWh of electricity to liquefy, consumed mainly by compressors.^{1,2} Many different pathways to improve the efficiency of conventional liquefaction have been proposed or explored in R&D projects to date, including the use of mixed refrigerants (MR) instead of liquid nitrogen for precooling, utilization of liquefied natural gas at regasification terminals, or helium or neon for liquefaction; closer integration of nitrogen liquefaction and hydrogen liquefaction plants; the use of higher efficiency compressors; power generation during hydrogen expansion (e.g., through use of turbo expanders); and novel alternatives to mechanical cycles, such as the use of magnetocaloric materials.^{1,2,3,4,5} section I.1.2 describes the steps in conventional hydrogen liquefaction and a corresponding recommended approach to emissions analysis. The approach described also applies to any method of hydrogen liquefaction that accepts pure hydrogen gas (99%) as a feedstock, utilizes pre-cooling gases, and uses only electricity as the external energy source.

Key steps within the hydrogen liquefaction and delivery supply chain are described in Figure I.1. The guidance in Section **Erreur ! Source du renvoi introuvable.** describes the mechanism to characterize the combined emissions of Modules 2 and 3. The emissions associated with Module 1 should be calculated per the Annexes A to G associated with the production of hydrogen.” For liquid hydrogen transport emissions, refer to section 4.3.2.6.

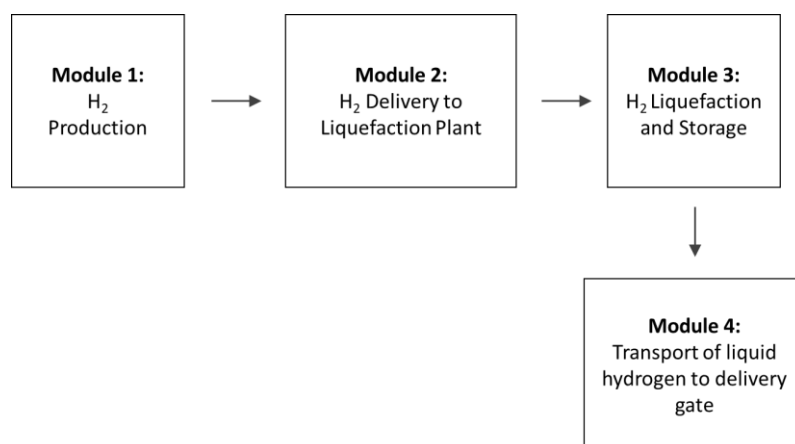


Figure I.1 — Modules for Life Cycle Analysis of Hydrogen Liquefaction

¹ <https://doi.org/10.1016/j.ijhydene.2010.02.109>

² <https://doi.org/10.1016/j.ijhydene.2020.09.188>

³ <https://www.mdpi.com/1996-1073/14/18/5917>

⁴ <https://doi.org/10.1016/j.ijhydene.2017.03.167>

⁵ <https://link.springer.com/article/10.1007/s11708-019-0657-4>

The reporting metric for life cycle analysis of Modules 1-4 is kgCO₂e/kgH₂. The current guidance recommends that the functional unit (kg H₂) reflect the mass of liquid hydrogen delivered to the end user at the end of Module 4. This unit implicitly accounts for hydrogen boil-off during the liquefaction process, bulk storage, and hydrogen delivery. Consequently, within the reporting metric, emissions will only be leveled only over the hydrogen the end user ultimately receives.

As an exception if it is necessary to report an emission for each module depending on the purpose, such as comparing processes or measuring the effects of improving processes it should be leveled by the mass of liquefied hydrogen at the end of each module.

I.1.2 Overview

Some hydrogen liquefaction plants are co-located with hydrogen production facilities, so delivery of the hydrogen from a production facility to the liquefaction plant (Module 2 of Figure I.1 —) is not required. If gaseous hydrogen is delivered between a production plant and a liquefaction plant that are not co-located, pipelines are the delivery mode most likely to be utilized. If pipeline delivery is used, emissions associated with compressors within the pipeline infrastructure must be accounted for.

Hydrogen liquefaction may rely on the Claude cycle or similar mechanical pathways. While configurations of individual plants can vary, current commercialized scale liquefaction generally entails pre-cooling of the hydrogen gas below its inversion temperature⁶ with liquid nitrogen that is typically produced onsite, use of turbines and expanders to reduce pressure and temperature, and use of a Joule-Thomson throttling valve to further reduce temperature to 20 K to condense/liquefy hydrogen. Cold hydrogen flash gas is commonly recycled to precool inlet hydrogen streams throughout the process. Compressors pressurize the hydrogen before expansion, followed by heat rejection to facilitate a larger pressure and temperature drop. Additionally, catalytic converters are integrated throughout the liquefaction process to convert ortho isomers of hydrogen to para isomers, such that the liquid hydrogen supplied to a consumer is ultimately >95% para. The para isomer of hydrogen has a lower energy state than ortho at 20 K. As such, without catalytic conversion, ortho hydrogen will spontaneously convert to para over the course of days to weeks. The ortho-para conversion is exothermic and would result in boil-off losses of stored hydrogen if allowed to occur spontaneously in the absence of conversion. Catalysis of this conversion is incorporated into hydrogen liquefaction plants to mitigate subsequent boil-off losses once the hydrogen is liquefied and placed in storage or loaded for shipping.^{7,8}

Refrigerants used for pre-cooling in hydrogen liquefaction, such as liquid nitrogen, need to be either continuously re-cooled or liquefied or be continuously replaced with new batches of cold refrigerant. Both cases must account for the energy consumption and co-products associated with cooling the refrigerant. Co-products are more likely to be generated in open cycles, wherein the refrigerant is replaced rather than recycled throughout the process.

⁶ The inversion temperature of a gas at any pressure is the critical temperature above which the Joule-Thomson (J-T) coefficient is negative; i.e., the gas temperature increases as its pressure is decreased with iso-enthalpic expansion. Gases at temperature below their inversion point have positive J-T coefficient, i.e., the gas temperature decreases as its pressure is decreased with iso-enthalpic expansion.

⁷ Baker, C. R. (1975). Efficiency and Economics of Large Scale Hydrogen Liquefaction. SAE Transactions, 84, 3104–3113. <http://www.jstor.org/stable/44633641>

⁸ https://www.idealhy.eu/uploads/documents/IDEALHY_D1-1_Report_Tech_Overview_and_Barriers_web2.pdf

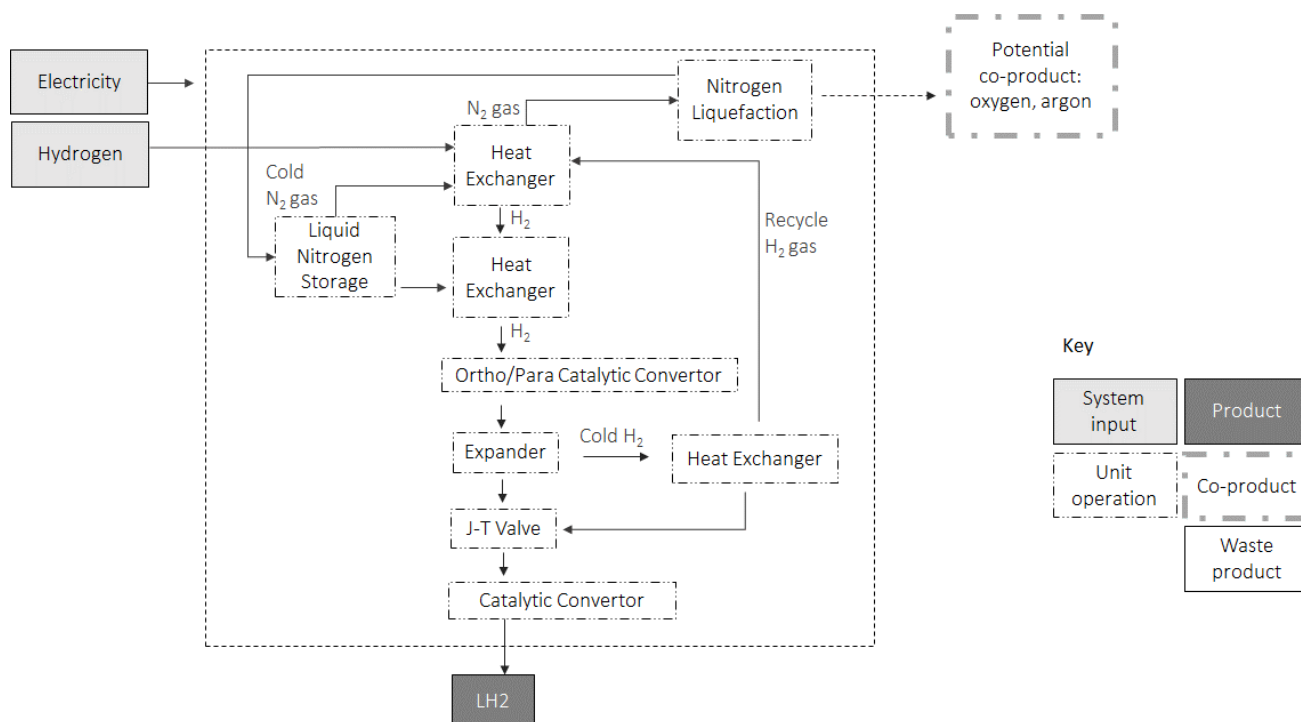


Figure I.1 — An example of configuration of conventional hydrogen liquefaction plants based on the Claude cycle

Compressors are not depicted in this figure but are incorporated throughout the plant to pressurize hydrogen before expansion and transfer hydrogen between components. Figure A.2 is adapted from [7].

I.2 Emission sources and inventory

Emissions that should be accounted for in the life cycle analysis of hydrogen liquefaction are described in Table I.1. Potential co-products associated with liquid nitrogen generation, in scenarios where the nitrogen supply is being replenished throughout the process rather than recycled, are described in Table I.2.

Table I.1 — Key Emission Sources in Hydrogen Liquefaction

| Process unit/stage | Key emissions sources | Secondary emissions sources |
|---|---|-----------------------------|
| Hydrogen delivery to a liquefaction plant | <ul style="list-style-type: none"> Electricity consumed or fuel burned in pipeline compressors | |
| Air Separation (using nitrogen pre-cooling) | <ul style="list-style-type: none"> Electricity for air compression | |
| Hydrogen liquefaction | <ul style="list-style-type: none"> Electricity consumed onsite to power cooling or liquefaction of refrigerant (e.g., nitrogen, mixed refrigerant, helium) and hydrogen liquefaction facility (e.g., for compression). | |

I.3 Emission Allocation

Table I.2 — provides information for emission allocation for liquid hydrogen as carrier.

Table I.2 — Potential Co-Products and Emissions Accounting Framework for Hydrogen Liquefaction

| Step | Potential Co-Products | Recommended Approach to Emissions Accounting |
|---|-----------------------|--|
| Air separation unit for nitrogen supply | Oxygen Argon | Use of allocation factors specified in database or by LCA. Regarding allocation for ASU, if it's inside the system boundary, use mass allocation. Or, if it is outside of the system boundary, it should be considered as an upstream emission factor. |

I.4 Information to be reported

Table I.3 — provides information to be reported for liquid hydrogen as carrier.

Table I.3 — Information to be reported for Hydrogen Liquefaction

| Category | Parameters to Report |
|------------------------|--|
| Facility details | Facility identity Facility location Facility capacity Commencement of facility operation |
| Product specification | Liquid hydrogen produced [kg] Liquid hydrogen temperature at the delivery gate [K] Hydrogen purity level at the delivery gate [%] Specification of contaminants |
| GHG emissions overview | Emissions intensity of liquefaction process [kgCO ₂ e/kgH ₂ *] (* at delivery gate or at consumption gate) |
| Batch details | Beginning and end of batch dates Batch quantity [kg] |
| Electricity | Location-based emissions accounting: <ul style="list-style-type: none"> - Quantity of purchased grid electricity [kWh] - Location based emission factor used [kgCO₂e/kWh] Market-based emissions accounting <ul style="list-style-type: none"> - Quantity of purchased grid electricity [kWh] - Quantity of contracted renewable electricity [kWh] and/or quantity of associated GOs or RECs - Type of GOs or RECs - Residual electricity - Residual mix emission factor [kgCO₂e/kWh] On-site electricity generation <ul style="list-style-type: none"> - Quantity of on-site generation [kWh] |

| | |
|----------|---|
| | <ul style="list-style-type: none">- Emission factor for on-site generation (as applicable) [kgCO₂e/kWh] |
| Hydrogen | Emissions intensity of hydrogen being utilized (calculated via guidance of this document) [kgCO ₂ e/kgH ₂] |