Cooperación Público-Privada entre Soventix y GIZ en el marco del proyecto apoyado por H2Uppp:

¨SolarNH3-Pool Chile: Conceptos para el desarrollo de un parque industrial sostenible de hidrógeno/amoníaco verde en la región de Antofagasta (Chile)¨

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Powerful Returns

Este documento se ha realizado en el marco del Programa Internacional de Fomento del Hidrógeno (H2Uppp) del Ministerio Federal de Economía y Protección del Clima (BMWK) de Alemania que promueve proyectos y el desarrollo del mercado del hidrógeno verde en determinados países en desarrollo y emergentes como parte de la Estrategia Nacional del Hidrógeno.

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First Climate

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Green Ammonia and Hydrogen Production in Chile

WP1 & WP2 Results: Estimated Carbon Footprint and Emissions Reductions of Green Ammonia

Version 2.0

June 27th, 2023

Climate Strategies | Compensation Neutralization | Climate Protection Projects | Green Energy | my.FirstClimate.com

Agenda

- Project Background & Objective
- WP1 & 2 System Boundaries
- Solar PV Plant
- Seawater Desalination Plant
- Electrolysis Plant & Hydrogen Transport
- Ammonia Production & Transport
- Ammonia Transport
- Results

Project Background & Objectives

Background and Project Objectives

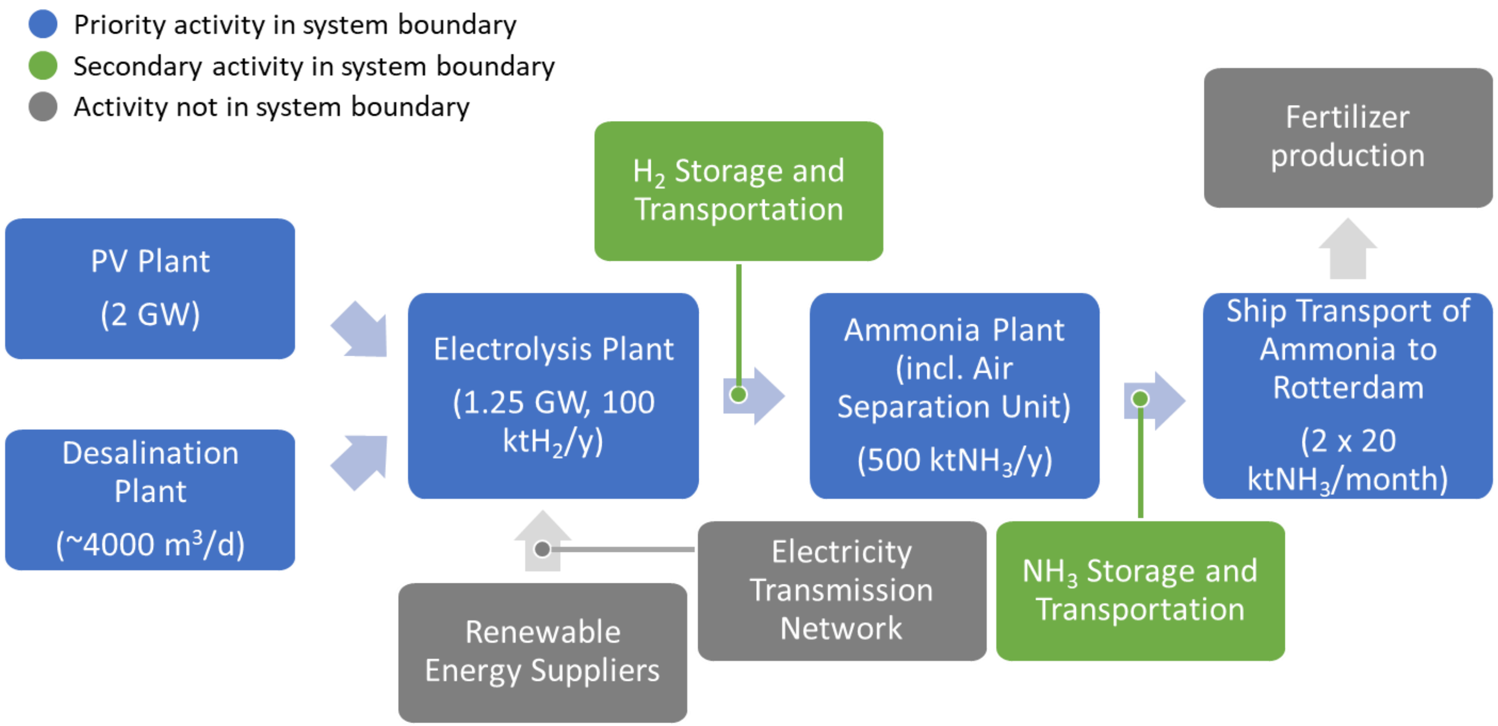
Objectives:

- **WP1: Estimation** of the project's carbon footprint (green ammonia facility, which operates on green hydrogen, solar PV and a desalination facility).

- **WP2: Estimation** of the emission reductions compared to conventional (grey) ammonia production

WP1 & WP2:
System Boundaries

GHG-Accounting – System Boundaries (1 of 2)



Activities in reporting boundary:

- Renewable electricity generation and water desalination
- Electrolysis
- Hydrogen storage and transportation in Chile
- Ammonia production and storage
- Ammonia shipments to EU

Project Methodology – WP1

WP1 : Estimated Carbon Footprint

- To estimate the carbon footprint of green ammonia production (tCO_2e/tNH_3), each individual activity in the system boundary was analyzed
- Based on the details of the project and its value chain, literature on installations of similar type/scale were analyzed, their life cycle stages compared, and life cycle greenhouse gas emissions assessed for comparison with the project.
- GHG emissions for the individual installations of solar PV (cradle-to-grave) and desalination (cradle-to-gate) are derived from various sources with similar characteristics as the project.
- GHG emissions for hydrogen production (cradle-to-gate) are derived by studying a hypothetical plant based in western Australia with a similar set-up of solar PV, desalination and electrolysis facility.
- Similarly, green ammonia production using the Haber Bosch process and nitrogen production are assessed based on literature presenting a hypothetical plant to determine the GHG emissions (cradle-to-gate) released per ton of produced green ammonia.
- Using the cradle-to-gate GHG emissions from all the feasible technologies reviewed, a range of estimates for GHG emissions for the project are determined.

WP2 : Estimated Emission Reductions

- In order to determine the GHG emissions of grey ammonia production using steam methane reforming, ammonia production in different countries around the world is assessed based on literature review and their life cycle stages are compared.
- Using the same life cycle boundary of cradle-to-gate, the GHG footprint for grey ammonia is determined as an average of ammonia production facilities in Europe and compared to the estimated footprint of green ammonia

Solar PV Plant

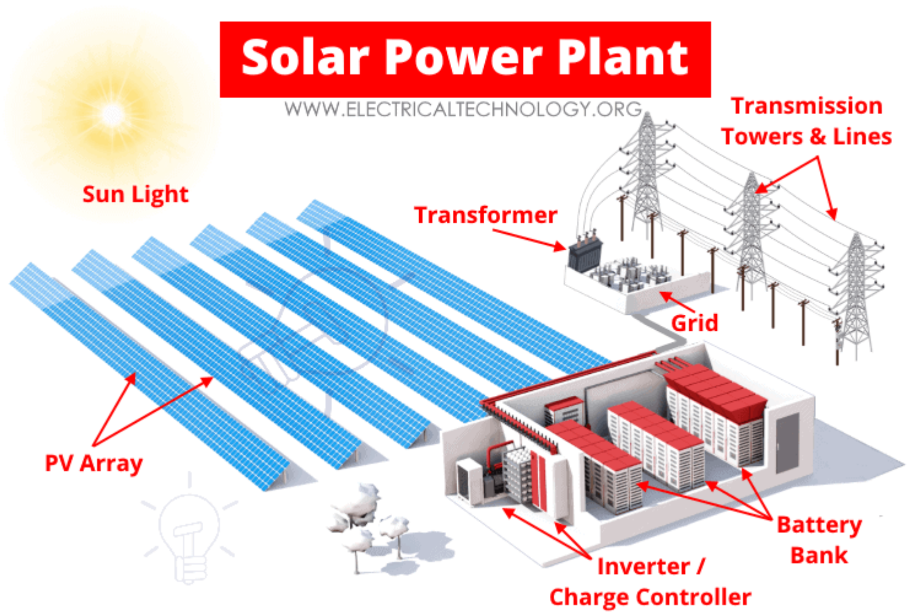
Typical Solar PV Plant : Overview of Emission Sources

Construction Phase

- Scope 1 and 2 emissions (fuel use in construction machinery, vehicles of company, other direct emissions through construction processes & electricity use in the construction phase)
- Purchase of panels (polycrystalline / monocrystalline panels), inverters (string inverters / microinverters), racking/mounting, transformer, batteries, wires and other equipment for construction
- Upstream transport of purchased material to site (fuel usage in transport, distance travelled & weight of goods)
- Waste generated in construction (plastic, paper, electronic waste etc.) and travel and commuting emissions to site

Operational Phase

- Periodic inspection and electrical testing
- Checks for damage and replacement
- Removal of surface degradation
- Battery bank, replacement every 5 - 15 years
- Solar panel replacement every 20-25 years
- Inverter replacement every 10- 15 years



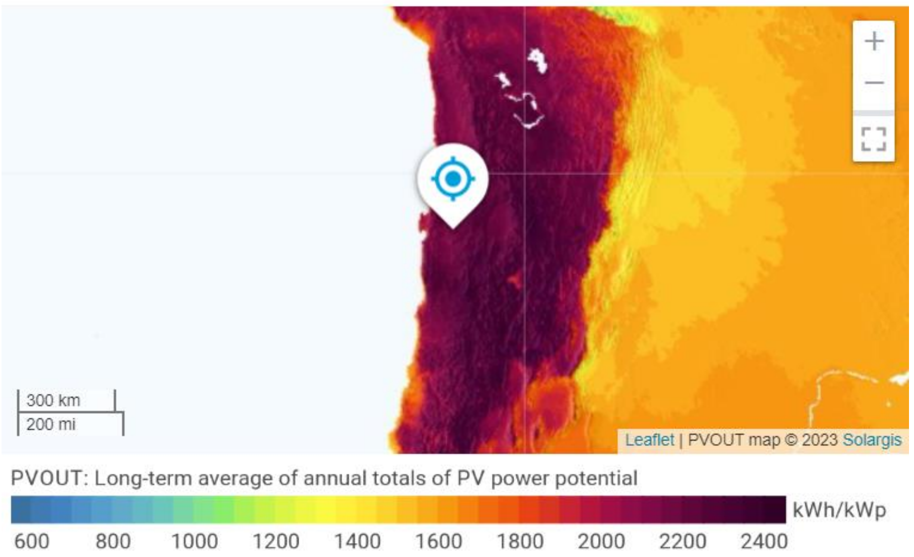
Solar PV plant (Mejillones) - Context

- A preliminary assessment of a site located approx. 80-100 km away from Mejillones is conducted to review the project parameters (direct normal irradiation of 3375 kWh/m2)
- As per client specification, a slightly higher direct normal irradiation (DNI) of **3500 kWh/m²** is assumed.
- Greenhouse gas emissions (cradle-to-grave) from different ground mounted Solar PV technologies are assessed to derive an average **GHG emissions per kWh** of produced electricity.
- An electrical line of 100 km is planned between the solar PV plant in the mountains and the electrolysis plant located near Mejillones. The GHG emission contribution of electrical lines has been ignored for the final calculation of the footprint.

Life Cycle Stages	Upstream Processes	Operational Processes	Downstream Processes
Photovoltaics (PV)  ~40 g CO_2eq/kWh	• Raw Materials Extraction • Materials Production • Module Manufacture • System/Plant Component Manufacture • Installation/Plant Construction	• Power Generation • System/Plant Operation and Maintenance	• System/Plant Decommissioning • Disposal

Source : National renewable energy laboratory(https://www.nrel.gov/docs/fy13osti/56487.pdf)

PVOUT map



Factor	Acronym	Value	Unit
Direct normal Irradiation	DNI	3375.1	kWh/m²
Global horizontal Irradiation	GHI	2614.8	kWh/m²
Diffuse horizontal Irradiation	DIF	458.7	kWh/m²
Global tilted Irradiation at optimum angle	Optimum	2829.0	kWh/m²
Air temperature	TEMP	17.6	°C
Optimum tilt of PV modules	OPTA	24.0	°
Terrain elevation	ELE	1610.0	m

Source : Global solar atlas

Solar PV plant (Mejillones) – Estimated Emissions

PV Technology	Average gCO_2eq/kWh	Lifecycle stages	Applicable PV plant capacity
Poly Si - ground mounted	64.0	Cradle to grave	Global Average, Average Irradiation of 2100 kWh/m2/year
CdTe, Ground Mounted	22.0	Cradle to grave	Global Average, Average Irradiation of 2100 kWh/m2/year
CIGS, Ground Mounted	20.9	Cradle to grave	Global Average, Average Irradiation of 2100 kWh/m2/year
PV systems, crystalline silicon (c-Si) and thin film (TF)	40.0	Cradle to grave	Average Irradiation between 1700-2400 kWh/m2/year and System lifetime of 30 years
single crystalline, monocrystalline, silicon	90.0	Cradle to grid	photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted - Chile

Direct normal irradiation (kWh/m2)	Source	$kgCO_2e/kWh$	Life Cycle Stages	Comments
2100	Average Cradle to grave irradiation values referring to the sources above	**0.037**	Cradle to grave	Average cradle-to-grave GHG emissions per kWh generated by solar PV (excluding the single crystalline, monocrystalline silicon case due to different life cycle stages)
3500	Soventix	**0.022**	Cradle to grave	With higher irradiation, the electricity output increases. For simplification, it is assumed the GHG emissions of the system do not vary with irradiation, and hence, the cradle-to-gate emissions for 3500 kWh/m2 can be extrapolated.

0.037 $kgCO_2e/kWh$

Average cradle-to-grave GHG emissions per kWh generated by solar PV at DNI of approx. 2100 kWh/m2 (excluding the single crystalline, monocrystalline silicon case due to different life cycle stages)

0.022 $kgCO_2e/kWh$

Estimated (FC calculation) cradle-to-grave GHG emissions per kWh generated by solar PV at DNI of 3500 kWh/m2

Seawater Desalination Plant

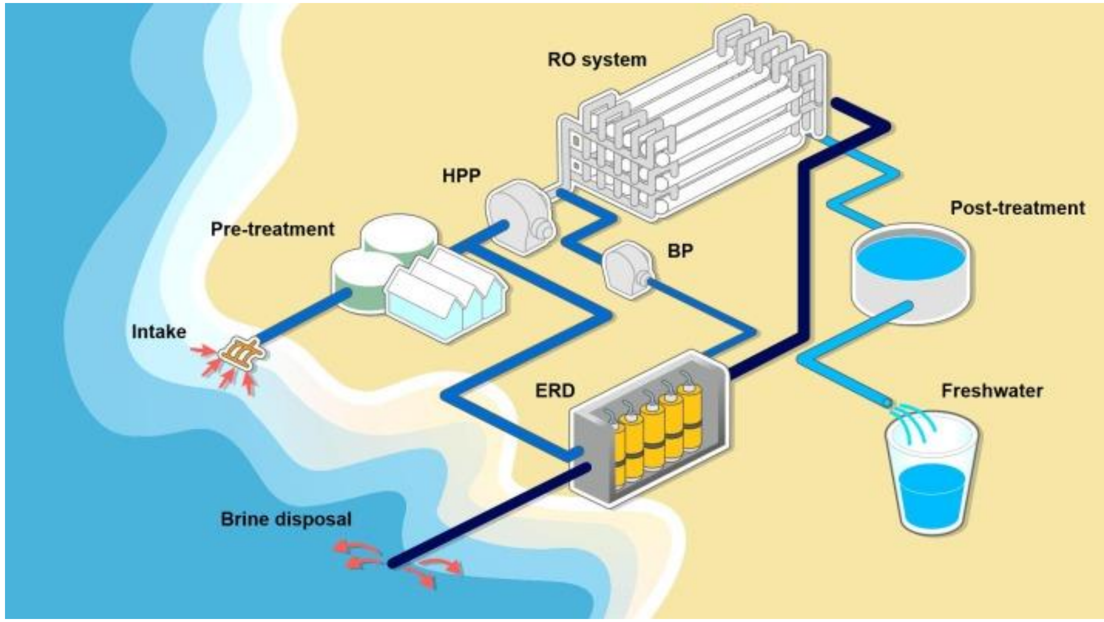
Desalination Plant : Overview of Emission Sources

Construction Phase

- Energy and fuel usage in construction and purchase of goods for the construction of the following systems
- Intake system (located offshore) and intake pump station (located at the treatment plant) and an intake pipeline (connecting the two)
- Pre-treatment system (multimedia filters, cartridge filters)
- Treatment system (reverse osmosis membranes , pumps, electricity)
- Post treatment system and disposal systems (tanks, pipes, booster pumps etc.)
- Upstream transport of purchased material to site (fuel usage in transport, distance travelled & weight of goods)
- Waste generated in construction (plastic, paper, electronic waste etc.) and travel and commuting emissions to site

Operational Phase

- Energy usage in plant
- Maintenance and technical systems check
- Filter and membrane replacement
- Technological replacements
- Personnel



Source : https://www.sciencedirect.com/science/article/abs/pii/S030626191931339X

Seawater Desalination plant (Mejillones) – Estimated emissions

- **Cradle-to-gate** emissions from desalination using different technologies and electricity sources are assessed
- Average GHG emissions per kg of produced desalinated water for a facility that runs on 100% renewable electricity is derived

0.00061 $kgCO_2e/kg\ H_2O$

GHG emissions per kg of H_2O produced by seawater desalination using renewable electricity

Life cycle GHG emissions of different desalination plants			
Technology	**Desalination GHG emissions Value**	**Units**	**LCA Stages**
Seawater Reverse Osmosis desalination, Grid Electricity AU	1.34	$kgCO_2e/m3\ H_2O$	Construction till operation (cradle-to-gate)
Seawater electrodialysis desalination, (100% non renewable electricity)	2.46	$kgCO_2e/m3\ H_2O$	Water production and delivery (approximately cradle-to-gate, detailed life cycle in the calculation sheet**)
Seawater Desalination Electrodialysis (100% renewable electricity)	0.61*	$kgCO_2e/m3\ H_2O$	Water production and delivery (approximately cradle-to-gate, detailed life cycle in the calculation sheet**)
Seawater Reverse Osmosis desalination (Average Grid Electricity Mix)	3.55	$kgCO_2e/m3\ H_2O$	Study considers different life cycle stages.
Brackish water Reverse Osmosis desalination (Average Grid Electricity Mix)	1.45	$kgCO_2e/m3\ H_2O$	Study considers different life cycle stages.

*assumed 1m3 = 1000 kg at standard atmospheric pressure

Electrolysis Plant & Hydrogen Transport

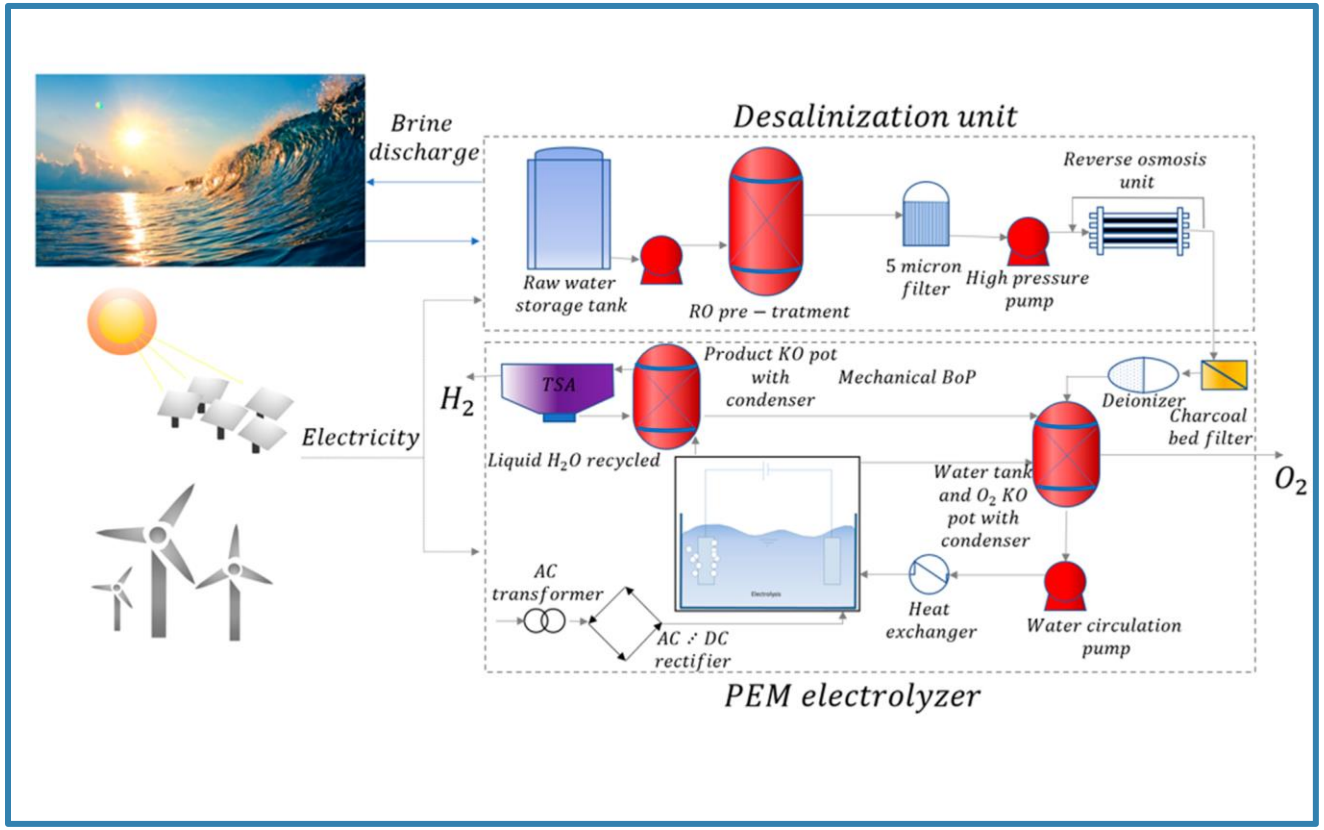
Electrolysis Plant – Overview of Emission Sources

Construction Phase

- Scope 1 and 2 emissions from the construction of electrolysis plant
- Energy usage
- Emissions from the purchased goods (industrial scale electrolysers, water tanks, pipes etc.)
- Transport of materials
- Waste generated in construction

Operation Phase

- Operation and maintenance of plant
- Energy usage in operation
- Service and personnel



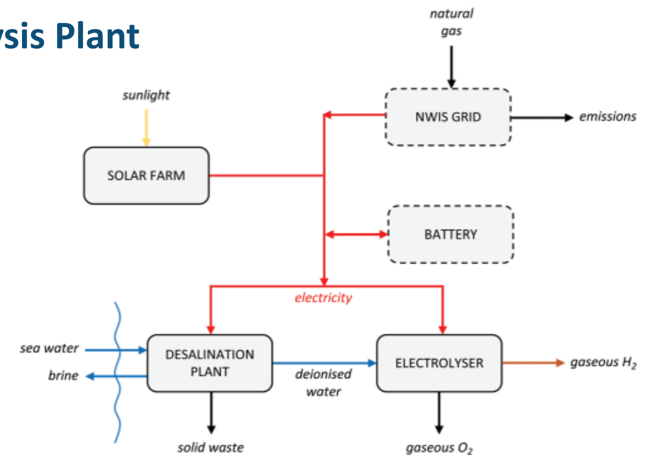
Electrolysis plant (Mejillones) – Estimate Emissions

- To determine the emissions from an electrolysis plant, a hypothetical green hydrogen facility using solar pv and desalination plant for its operation is used
- Life cycle stages are assessed to derive cradle-to-gate GHG emissions from different underlying processes in producing green hydrogen.
- Estimated **GHG emissions per kg of** H_2 **produced** by using seawater desalination and solar PV are obtained:

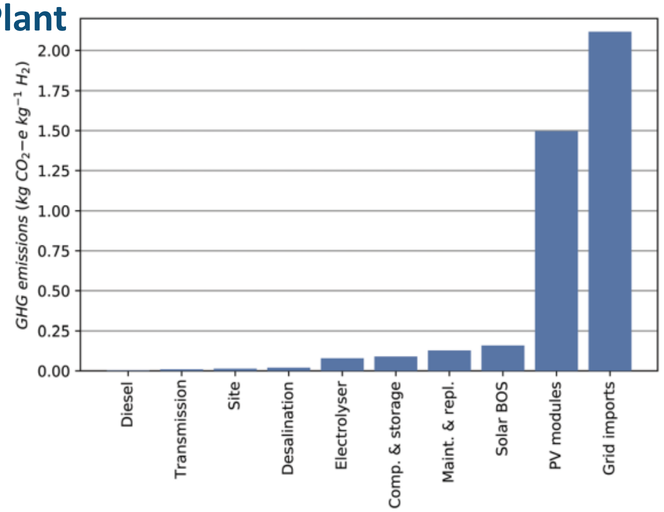
4.22 kgCO$_2$e/kg H_2

- Hydrogen is produced during the availability of sunlight, however, as ammonia production requires a continuous supply of hydrogen, storage of hydrogen is required by the project to ensure continuous supply to the ammonia plant during night hours. The energy consumed for the storage is assumed to be sourced from renewable sources and GHG emissions are ignored for the scope of this study
- The transport of hydrogen has also been ignored due to the fact that the hydrogen transport takes place directly with a pipeline from electrolysis plant to ammonia plant that is 300 meters away.

Hypothetical Electrolysis Plant



Electrolysis Plant

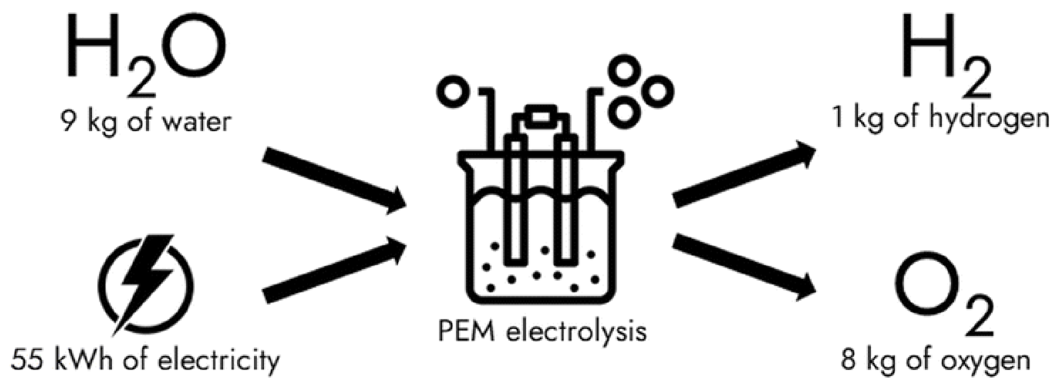


Source : https://doi.org/10.1039/D1EE01288F

Electrolysis plant (Mejillones) – Estimate Emissions

- As comparison, a bottom-up estimate of the GHG emissions per kg of H_2 are also derived from the results of the solar PV plant and the desalination plant.
- Using the mass/energy balance relationship at right, the comparison estimated GHG emissions per kg of H_2 produced by using seawater desalination and solar PV are :

2.03 kgCO$_2$e/kg H_2



Source : Source : The many greenhouse gas footprints of green hydrogen - Sustainable Energy & Fuels (RSC Publishing)
DOI:10.1039/D2SE00444E

Ammonia Production & Transportation

Ammonia Production – Emission Sources

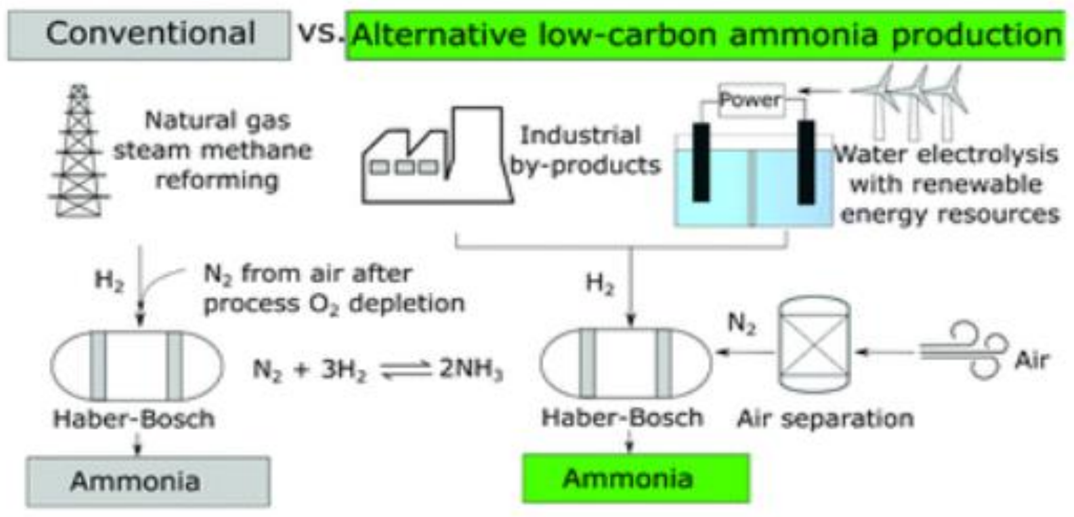
Construction Phase

- Scope 1 and 2 emissions
- Purchased goods (compressor, filters, separator etc.)
- Upstream transport of materials, waste in construction, travel emissions during construction phase.

Operational Phase

- Electricity and energy Usage
- Maintenance and equipment
- Hydrogen and nitrogen production and sourcing

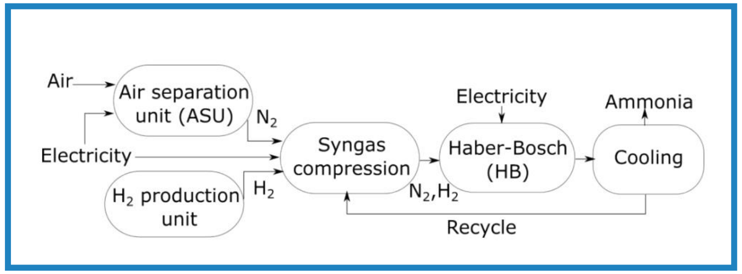
Green Ammonia Production Process



Green Ammonia Production (Mejillones) – Estimate Emissions

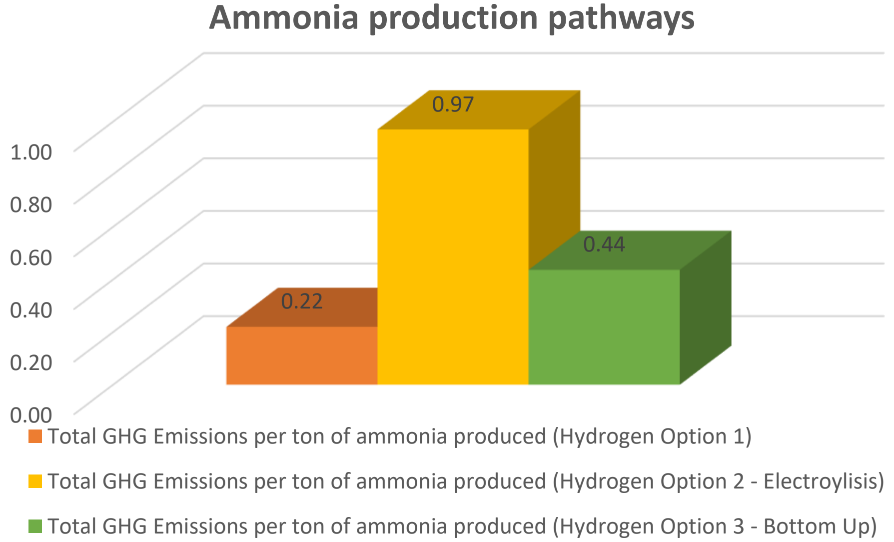
- A preliminary assessment of green ammonia production is conducted to assess the types of technologies and processes involved in this activity. A standard green ammonia production process involves the Haber Bosch process with N_2 and H_2 as inputs.
- Based upon literature review, a hypothetical facility was chosen for review and estimation of footprint due to its relative similarity to the project facility. The green ammonia plant is fed with hydrogen produced using low temperature electrolysis with renewable energy. The nitrogen is produced from cryogenic distillation. As a result, the estimated GHG emissions (cradle-to-gate) for green ammonia production via this pathway are obtained (Option 1)
- In addition, GHG emissions (cradle-to-gate) for green ammonia are computed from the two additional pathways to produce hydrogen using the hypothetical electrolysis facility (Option 2) and bottom-up electrolysis calculation factoring in irradiation of 3500 kWh/m2 (Option 3)

Hypothetical Green Ammonia Plant



Source : https://pubs.rsc.org/en/content/articlelanding/2020/gc/d0gc02301a

GHG emissions from different green ammonia production pathways (cradle-to-gate) depending on the source of hydrogen (tCO_2e/tNH_3)



Green Ammonia Transport (Mejillones – Rotterdam) – Emission Sources

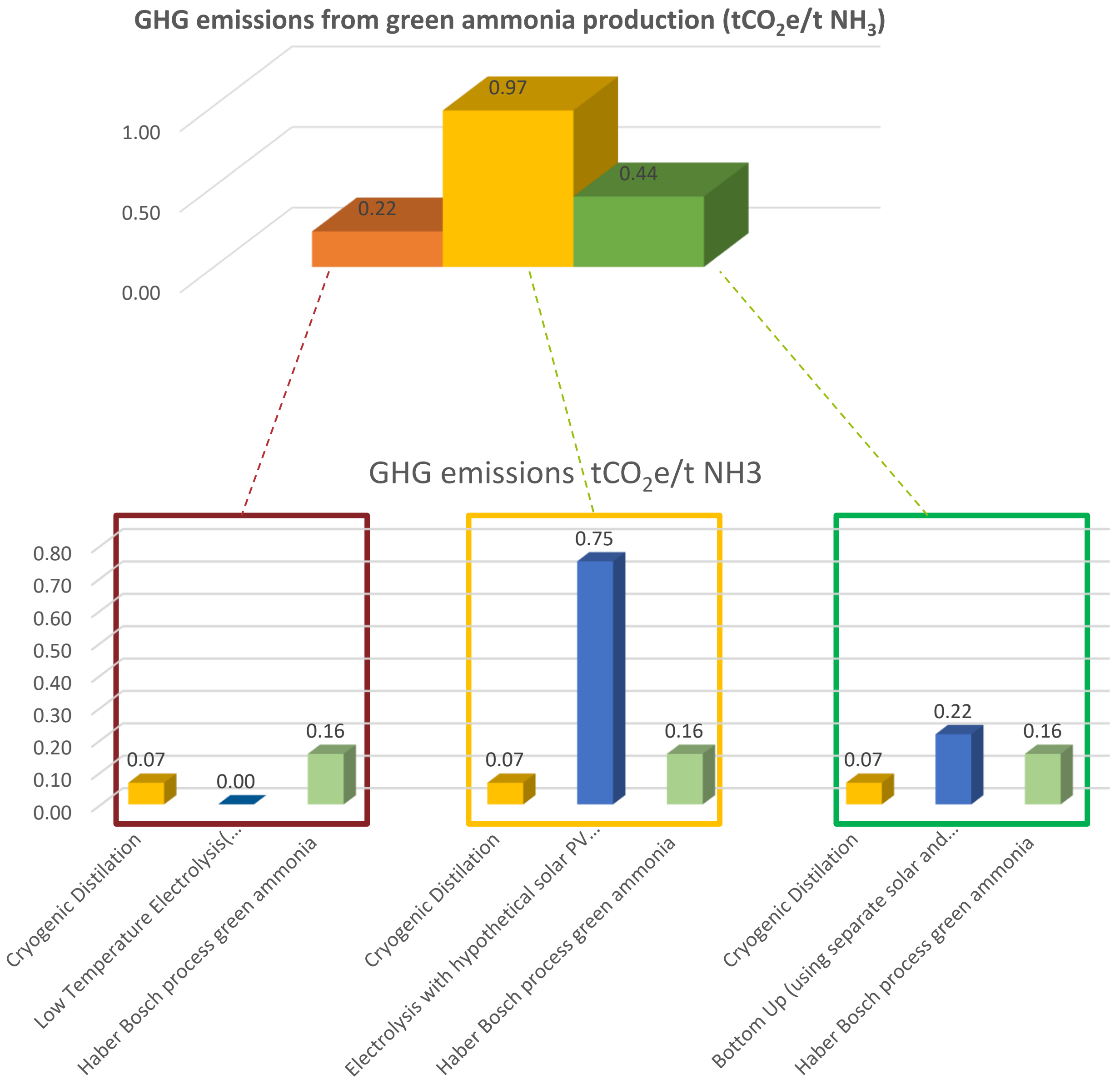
- Green ammonia produced at the project site is transported to the nearby port to be shipped to Rotterdam.
- The ammonia is assumed to be transported in LPG tankers over a shipping distance approx. 13’000 km till Rotterdam.
- Upon arrival at the Rotterdam port, the ammonia is then assumed to be transported via rail over 500 km to the fertilizer production facility in Germany (Ludwigshafen). The transport here is assumed to be primarily rail as this is considerable the most stable means of transport. Switching to river transport on the Rhine has minimal decreasing impact on transport emissions.
- All the emissions generated from the transport of ammonia from Chile to Europe are calculated as tons of GHG per ton of Green Ammonia produced:

$0.18\ tCO_2e\ /\ tNH_3$

Summary Results WP1

GHG Emissions of Green Ammonia

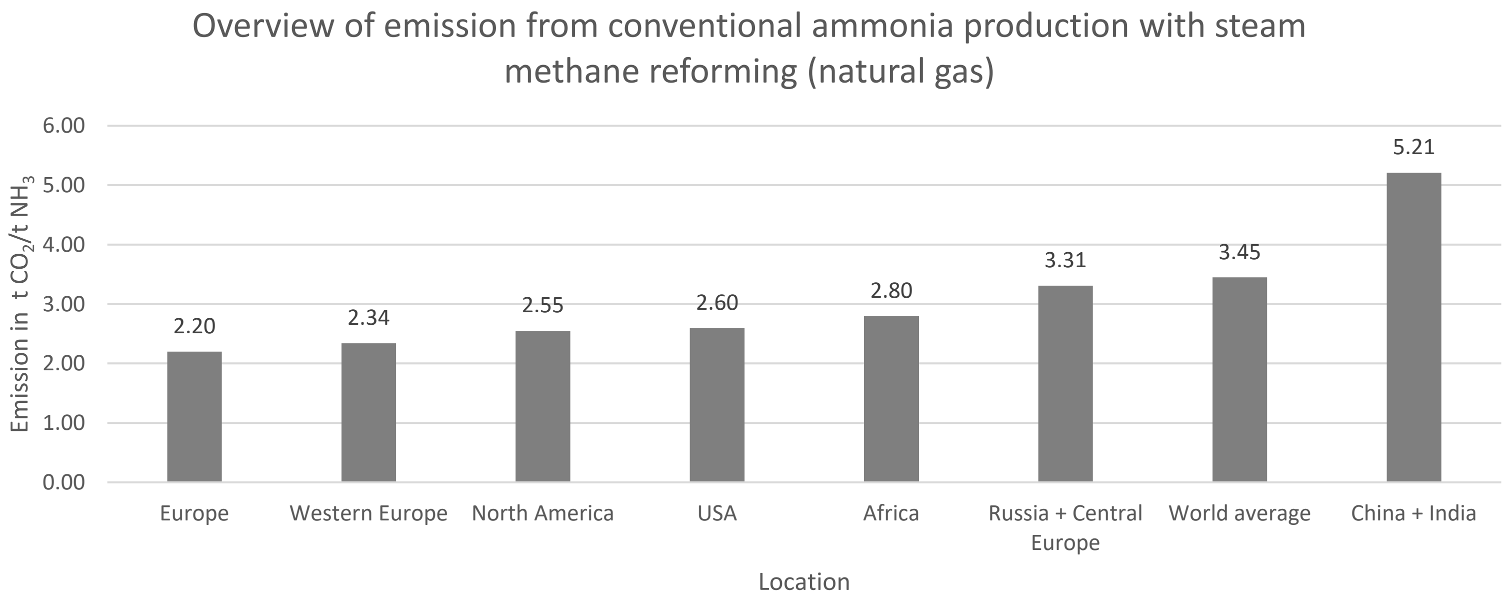
- The GHG footprint of green ammonia is determined using the cradle-to-gate GHG footprint of the corresponding H_2 used, N_2 used and the GHG footprint of the Haber Bosch process.
- N_2 is produced using the process of Cryogenic distillation and three H_2 production pathways are analyzed including low temperature electrolysis, H_2 produced from a hypothetical electrolysis plant and H_2 produced from a bottom-up approach using solar PV and desalination plant.
- The results and estimated range of **0.22-0.97 tCO_2e / tNH_3** for the value chain of the project.



Summary Results WP2

GHG Emissions of Grey Ammonia Production

Conventional ammonia production takes place using the process of steam methane reforming, where methane is used to produce hydrogen and the hydrogen is utilized along with nitrogen to produce ammonia. The graph below lists the overview of GHG emissions for producing 1 ton of grey ammonia at locations around the world. The variability of GHG emissions is caused by the source of energy.



Location	GHG Emissions (tCO_2e/tNH_3)
Europe	2.20
Western Europe	2.34
North America	2.55
USA	2.60
Africa	2.80
Russia + Central Europe	3.31
World average	3.45
China + India	5.21

Europe average:

2.27 tCO_2e/tNH_3

Emission reductions (Grey vs. Green Ammonia)

Green ammonia produced with hydrogen from low temperature electrolysis with renewable energy can lead to up to **90%** reduction in GHG emissions compared to grey ammonia

Emission reductions (%)

Estimated footprint (grey ammonia) per t NH_3

2.27 tCO_2e/tNH_3

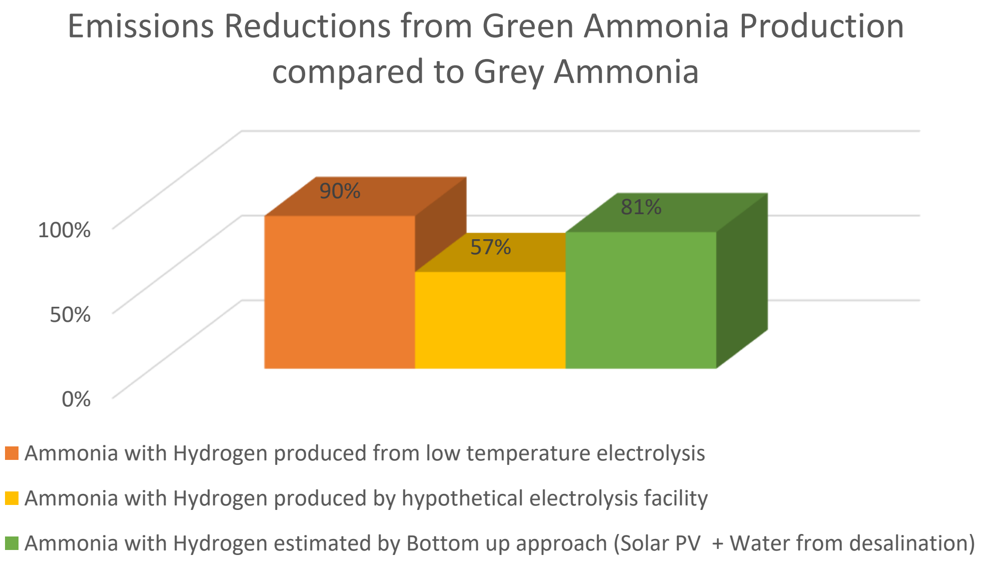
Estimation based on standard values in life-cycle databases

Estimated footprint (green ammonia) per t NH_3

Options 1-3

Estimation based on activities in system boundary

Emissions GHG reductions from green ammonia production compared to grey ammonia (%)		
Green ammonia with hydrogen produced from low temperature electrolysis (Option 1)	**Green ammonia with hydrogen produced by hypothetical electrolysis facility (Option 2)**	**Green ammonia estimated by bottom-up approach (hydrogen production by solar PV + desalination) factoring in DNI of 3500 kWh/m2 (Option 3)**
90%	**57%**	**81%**



Appendix

Comparison of emission reduction for fossil and non fossil based hydrogen production and desalination methods

Hydrogen Type	CO_2 footprint range	Units	Technology type
Grey	11.9	$kgCO_2e/ kgH_2$	Steam Methane Reforming
Green (produced from hypothetical facility above)	4.22	$kgCO_2e/ kgH_2$	Electrolysis using a PV and seawater reverse osmosis desalination plant
Green (Produced from bottom up analysis above)	1.22	$kgCO_2e/ kgH_2$	Bottom Up GHG calculations from GHG of Water(produced by seawater electrodialysis desalination- using renwable electricity) and Solar PV

65%

GHG reduction from **Grey** vs **Green hydrogen** produced from Hypothetical facility

90%

GHG reduction from **Grey vs Green hydrogen** produced from bottom-up analysis

Desalination technology type	GHG Footprint ($kgCO_2e/kgH_2O$)	
	Using basic fossil energy	Using Natural gas
Reverse Osmosis	0.005	
MSF (Multi-Stage Flash Distillation)	0.018	0.016
MED(Multi-Effect Distillation)	0.015	0.013

0.00061 $kgCO_2e/kg\ H_2O$

GHG emissions per kg of H2O produced by seawater electrodialysis desalination using renewable electricity

87%

GHG reduction from desalination with **Reverse Osmosis using fossil energy** vs **seawater electrodialysis desalination using renewable electricity**

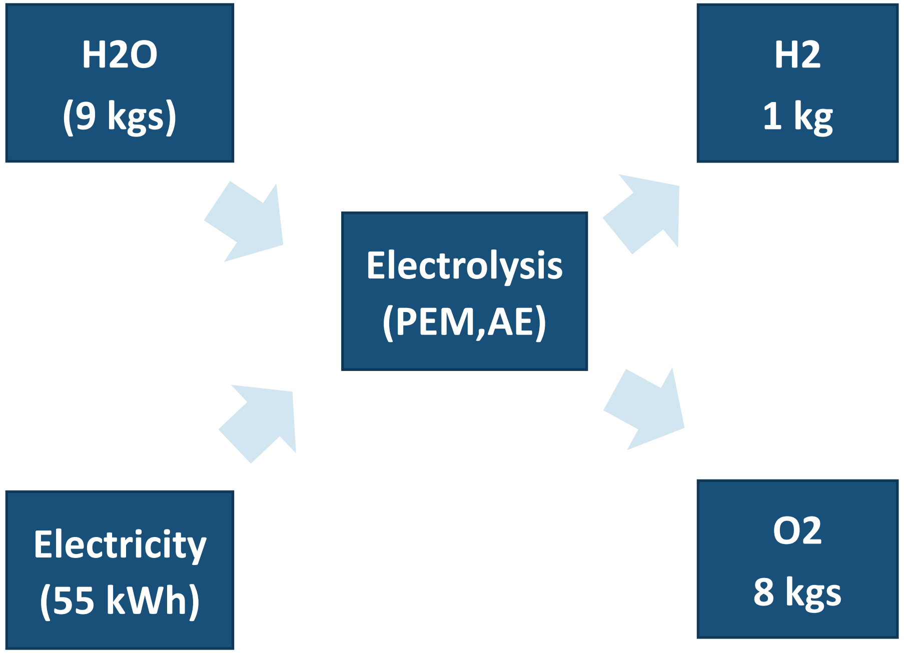
96%

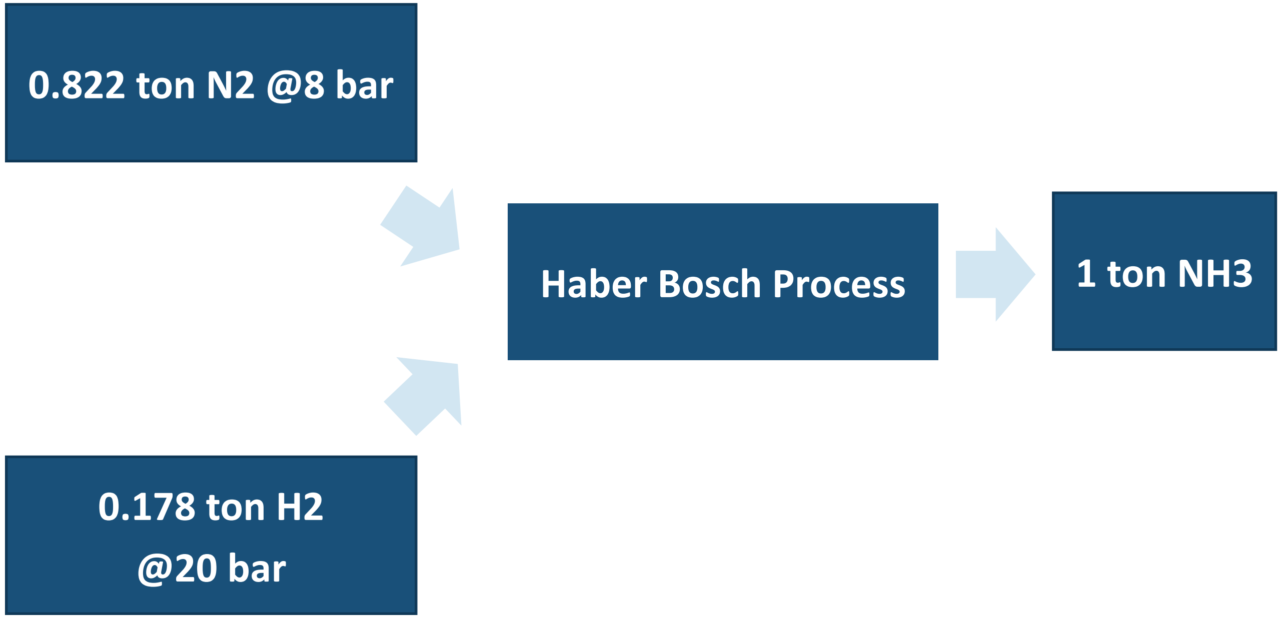
GHG reduction from desalination using **MSF (Multi stage flash) using natural gas** vs **seawater electrodialysis desalination using renewable electricity**

95%

GHG reduction from Desalination using **MED(Multi-Effect Distillation) using natural gas** vs **seawater electrodialysis desalination using renewable electricity**

Mass Balance





Source : The many greenhouse gas footprints of green hydrogen - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D2SE00444E

Source : Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products - Green Chemistry (RSC Publishing)

Range of Applicability (1/2)

Solar PV

- GHG emission values calculated in terms of $KgCO_2e$ /kWh
- Values calculated for ground mounted PV facilities
- Applicable PV technologies (Poly Si, CdTe, crystalline silicon (c-Si) and thin film (TF), CIGS)
- Life cycle stages considered are cradle to grave
- Direct normal irradiation of approx. 3500 kWh/m^2

Desalination Plant

- GHG emission values calculated in terms of $kgCO_2e/m^3$ H_2O and converted to $KgCO_2e/Kg$ H_2O assuming density of water to be 1000 kg H_2O / m^3 H_2O.
- Values calculated for a seawater desalination facility using electrodialysis technology operating on 100% renewable electricity.
- Life cycle stages considered are cradle to gate.
- Site location for the seawater desalination facility using electrodialysis technology is western Australia with close access to seawater.

Range of Applicability (2/2)

Electrolysis Plant

- GHG emission values calculated in terms of $KgCO_2e$ /kg H_2
- Values calculated for hydrogen produced from electrolysis using a PV facility of 1GW with a lifetime of 20yrs and seawater reverse osmosis desalination plant.
- The electrolyser technology taken into consideration is Alkaline electrolyser (AE).
- The hypothetical facility has a production output of 36 500 tonnes H_2 per year and includes a dedicated high voltage (275 kV AC) transmission line connecting the solar farm with the hydrogen production facility
- Life cycle stages considered are cradle-to-gate.

Ammonia Plant

- GHG emission values calculated in terms of tCO_2e/t NH_3
- The technology used is green ammonia production process which includes an air separation unit and a hydrogen production unit connected to the Haber Bosch loop to produce ammonia.
- The technologies considered for nitrogen production are cryogenic distillation and pressure swing adsorption.
- The life cycle stages considered are cradle to plant gate.
- The transport of ammonia takes place by a pipeline from production site to the port and then by ship to europe.

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