Regional life cycle assessment of green hydrogen export from Chile: wind-methanol vs. solar-ammonia pathways

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Abstract:

Green hydrogen (GH_2) export from Chile is typically evaluated through techno-economic lenses, while environmental assessments remain limited to production-gate boundaries and climate change alone. This paper presents a cradle-to-destination-port life cycle assessment (LCA) of four GH_2 export pathways from two real Chilean projects: wind-powered e-methanol at HIF Cabo Negro (Magallanes, 384 MW, 57% capacity factor) and solar-powered green ammonia at the Volta/MAE project (Mejillones, 600 MW). Four pathway variants are evaluated: biogenic and direct air capture (DAC) CO_2 sourcing for methanol, and mixed versus full seawater reverse osmosis (SWRO) water supply for ammonia, across three destination ports: Rotterdam, Los Angeles, and Kobe-Kansai. Six midpoint impact categories from the Environmental Footprint 3.1 (EF 3.1) method are assessed: climate change, particulate matter, water use, land use, fossil resource use, and minerals and metals. Site-specific renewable electricity characterization factors are derived for both sites, replacing outdated national-average inventory data. All four green pathways achieve climate intensities 2.7 to 6.2 times below grey hydrogen (9.50 kg CO_2-eq/kg H_2-eq). MEJ solar ammonia reaches 1.66 kg CO_2-eq/kg H_2-eq delivered to Rotterdam, approaching the blue hydrogen benchmark of 2.20 kg CO_2-eq/kg H_2-eq even after full international shipping. No single pathway dominates across all six impact categories: MAG biogenic methanol shows a particulate matter burden ten times higher than other pathways, traced to forest residue combustion in the CO_2 supply chain, while MEJ ammonia carries the highest land use score driven by the photovoltaic (PV) supply chain. Maritime shipping contributes between 11% and 48% of total climate footprint depending on route and carrier, a supply chain stage systematically absent from production-gate assessments and directly relevant to emerging import certification frameworks in Europe, the United States, and Japan.

Keywords:

Chile; E-methanol; Environmental Footprint; Green ammonia; Green hydrogen; Life cycle assessment

1. Introduction

Green hydrogen (GH_2) and its derivative carriers are widely recognized as key vectors for decarbonizing hard-to-abate sectors including maritime transport, industrial chemistry, and long-distance energy trade. Large-scale GH_2 trade will depend on cryogenic or chemically bound carriers such as ammonia and methanol transported by sea, adding a supply-chain stage that most existing environmental assessments omit [1,2].

Research on GH_2 export remains disproportionately focused on economic metrics, notably the levelized cost of hydrogen (LCOH) [3], rather than comprehensive multi-impact LCA. Studies that report environmental impacts frequently stop at the production gate [4–6], rely on national-average electricity inventories [6–8], or restrict assessment to climate change alone [9,10]. Ecoinvent datasets prior to version 3.9 characterize PV and wind manufacturing inputs from the early 2010s [11], and PEM electrolyzer studies such as [12] rely on stack designs that predate current commercial performance. These gaps are particularly consequential for Chilean pathways, where site capacity factors deviate substantially from national averages.

Chile occupies an exceptional position in the emerging GH_2 export landscape, underpinned by Patagonian wind in Magallanes with capacity factors exceeding 57% [13], and Atacama solar radiation above 2,500 kWh/m²/year [14], consistent with the National Green Hydrogen Strategy [15] targeting top-three global exporter status by 2040. The HIF Cabo Negro project produces e-methanol from wind-powered electrolysis

[16] while the Volta/MAE project in Mejillones is developing large-scale green ammonia with seawater desalination and municipal wastewater reuse [17]. Key specifications of both projects are summarized in Table 1. The environmental profile of these projects against a full cradle-to-destination-port boundary has not previously been reported.

Table 1. *Selected GH2 Chilean projects' specifications.*

Parameter	Cabo Negro, Magallanes [16]	Mejillones, Antofagasta [17]	Unit
Location (lat., long.)	-52.94, -70.81	-23.11, -70.43	-
Concession Owner	HIF	Mejillones Ammonia Energy (MAE)	-
Phase of the Project	Industrial Plant	Industrial Plant (2 phases)	-
Type of plant	On-shore wind-based e-methanol plant	Solar PV–based green ammonia plant	-
Turbines Manufacturer/Model	Siemens-Gamesa SG 6.0-145	-	-
Total Installed Capacity	384	600	MW
Capacity Factor	0.57	Not reported	-
Source of Water	Sea Water Desalination Plant	Wastewater reuse (85%) + desalination (15%)	-
Electrolyzer Capacity	287	~700	MW
GH2 Production	27830	-	tons/year
e-Methanol Production	175,000	-	tons/year
Ammonia production		600,000	tons/year
CO_2 Avoided	215,000	-	tons/year
Investment	1.3 bn	2.5 bn	USD

Water availability is a cross-cutting constraint. Carreño [18] estimates that full GH_2 sector deployment in Antofagasta would require approximately 43 million m³/year of process water by 2030, making SWRO infrastructure a prerequisite at scale. In Magallanes, 100% SWRO is already the operational baseline given the absence of nearby urban wastewater networks. Four pathway variants are modelled to reflect these conditions, as described in Table 2: two wind-powered methanol variants in Magallanes differing in CO_2 source (biogenic versus DAC), and two solar-powered ammonia variants in Mejillones differing in water supply strategy (mixed SWRO/MWWR versus 100% SWRO sensitivity).

Table 2. *Pathway variants modelled.*

Pathway ID	Site	Renewable	Carrier	CO_2/N_2 source	Water supply
1. MAG-Biogenic	Magallanes (53°S)	Wind 384 MW, 57% CF	Methanol	Biogenic CO_2 (forest biomass flue gas)	100% SWRO
2. MAG-DAC	Magallanes (53°S)	Wind 384 MW, 57% CF	Methanol	Direct air capture (DAC) CO_2	100% SWRO
3. MEJ-NH_3	Mejillones (23°S)	Solar PV 600 MW, >2,500 kWh/m²/yr	Ammonia	N_2 from air (HB + ASU)	15% SWRO + 85% MWWR
3b. MEJ-NH_3 SWRO	Mejillones (23°S)	Solar PV 600 MW	Ammonia	N_2 from air (HB + ASU)	100% SWRO — sensitivity (Q1)

MAG = Magallanes; MEJ = Mejillones; CF = capacity factor; HB = Haber-Bosch; ASU = Air Separation Unit; SWRO = Seawater Reverse Osmosis; MWWR = Municipal Wastewater Reuse.

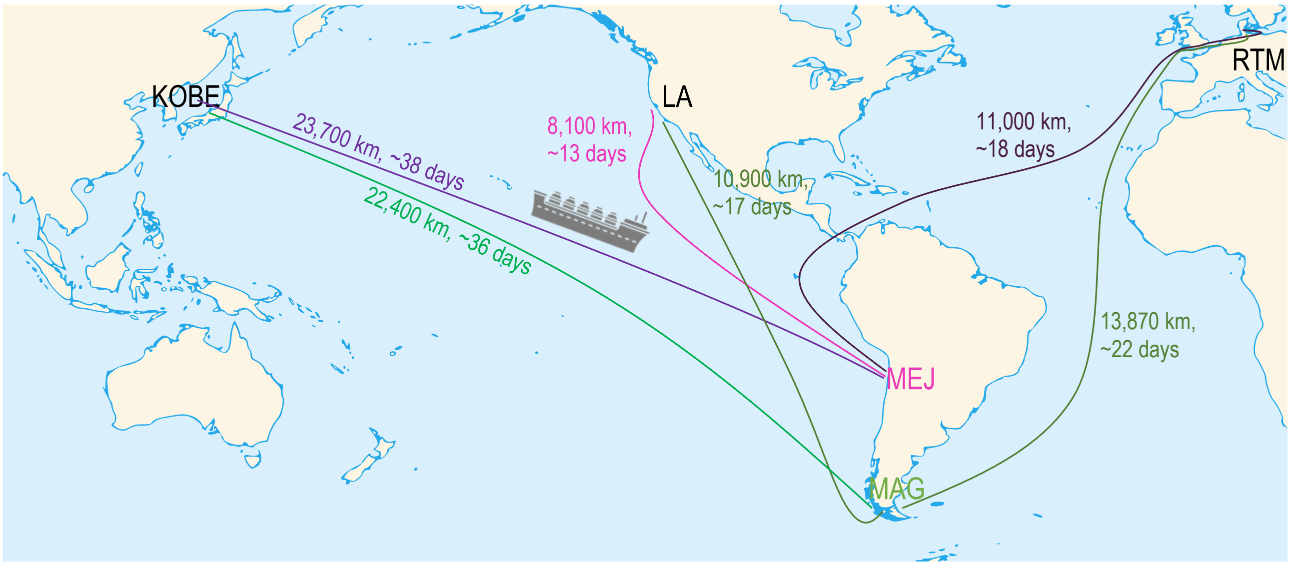

Figure 1. *Shipping routes and distances from Chilean production sites to destination ports [19]. MAG = Magallanes (Cabo Negro); MEJ = Mejillones; RTM = Rotterdam; LA = Los Angeles; KOBE = Kobe-Kansai.*

Emerging import regulations in Europe [20], the United States [21], and Japan [22] are creating regulatory demand for full lifecycle intensity certification including maritime shipping. As shown in Figure 1, destination ports span three major import markets: Rotterdam, Los Angeles, and Kobe-Kansai, with the longest route covering 23,703 km. Shipping can contribute 11–48% of total carbon footprint depending on route and carrier (see Section 3), a term systematically absent from production-gate assessments.

Against this background, this paper makes three contributions to the literature. First, it provides the first multi-impact LCA of two real Chilean GH_2 export projects under industrial development, moving beyond generic country-level models. Second, it replaces national-average ecoinvent proxies with site-specific electricity characterization, materially affecting all downstream results. Third, it integrates maritime shipping across three destination markets and six EF 3.1 impact categories, enabling compliance-relevant assessment against emerging EU, US, and Japanese certification thresholds.

All calculations are performed in Brightway2 [23] with ecoinvent 3.10 [11]updated via Premise [24] to a 2020 base year. Section 2 describes the methodology, Section 3 presents results and discussion, and Section 4 states conclusions and future work directions.

2. Methodology

2.1. Life Cycle Assessment Framework

Environmental impacts were assessed following an attributional, process-based life cycle assessment (LCA) in accordance with ISO 14040/44 [25]. The LCA quantifies inputs and outputs between the technosphere and the environment along the full supply chain, from renewable electricity generation and hydrogen production in Chile through carrier synthesis, maritime shipping, and delivery to the destination port. System modelling and impact calculations were performed in Brightway2 [23] using background datasets from ecoinvent 3.10 cut-off system model [11].

2.2. Goal, Scope and Functional Unit

This study quantifies and compares the life cycle environmental impacts of two Chilean GH_2 export pathways, wind-powered e-methanol from Magallanes and solar-powered ammonia from Mejillones, delivered to Rotterdam (EU), Los Angeles (US), and Kobe-Kansai (Japan). The system boundary is cradle-to-destination-port, encompassing renewable electricity generation, water provision, electrolysis, CO_2 or N_2 supply, carrier synthesis, and maritime shipping; end-use conversion is excluded as carrier- and market-dependent and outside the scope of Chilean exporters' compliance obligations.

The primary functional unit is 1 kg of hydrogen equivalent (kg H_2-eq) delivered to the destination port. A secondary functional unit of 1 kWh of site-specific renewable electricity is used internally to characterise the electricity generation stage and propagate site-specific impacts into the foreground model (Section 2.3).

2.3. System Boundaries

The study adopts a cradle-to-destination-port system boundary. Included stages are: (i) full life cycle of the renewable electricity generation asset, covering manufacturing, installation, operation and maintenance, and end-of-life, for the Siemens Gamesa SG 6.0-145 wind farm in Magallanes (384 MW) and utility-scale monocrystalline silicon PV in Mejillones (600 MW); (ii) process water supply via SWRO desalination, municipal wastewater reuse (MWWR, treated as a zero-burden secondary resource per ISO 14044 §4.3.4), or a mixed scenario as per project documentation; (iii) PEM electrolysis; (iv) carrier synthesis, either methanol via CO_2 hydrogenation and distillation, or ammonia via Haber-Bosch with integrated air separation; and (v) maritime shipping from the origin port to the destination port.

Explicitly excluded are downstream carrier reconversion, end-use combustion, onshore distribution beyond the arrival port, and decommissioning of processing facilities. These exclusions are consistent with the scope relevant to Chilean exporters under current GH_2 certification frameworks [20,22,26] and with the production-to-port boundary adopted in comparable export LCA studies [7,8,27]

2.4. Impact Assessment Method and Environmental Indicators

Life cycle impact assessment (LCIA) was carried out using the Environmental Footprint 3.1 (EF 3.1) no long-term characterization method [28], recommended by the European Commission for product environmental footprints and directly relevant to EU RED III compliance. Six midpoint impact categories were assessed, selected to cover the main environmental trade-offs identified in the literature for hydrogen export systems:

- Climate change (kg CO_2eq): primary regulatory metric for GH_2 certification
- Particulate matter (disease incidence): relevant to biomass CO_2 supply chains
- Water use (m^3 world-equivalent, AWARE): critical for water-stressed Chilean regions
- Land use (Pt, soil quality index): relevant to solar PV footprint
- Fossil resource use (MJ): to capture DAC energy burden
- Minerals and metals (kg Sb-eq): to capture electrolyser and turbine material demand

Results are reported at midpoint level; no single-score aggregation is applied, since the study objective is to identify trade-offs across impact categories rather than to declare a single winner.

2.5. Site-Specific Electricity Characterization

Renewable electricity generation is the dominant contributor to life cycle impacts in electrolysis-based green hydrogen: for a PEM system operating at 43–50 kWh/kg H_2, the carbon intensity of the input electricity propagates almost linearly into the total climate change impact of the pathway [29]. The exceptional renewable resource quality at both Chilean project sites: Patagonian wind in Magallanes (capacity factor 57%) and Atacama solar radiation in Mejillones (global horizontal irradiance ~2,500 kWh/m²/year), is precisely why these locations were selected for development, and it is the primary justification for replacing national-average ecoinvent datasets with site-specific characterization factors. The Chilean national-average datasets in ecoinvent 3.10 assume capacity factors of 35% for wind and 20% for solar PV [11], both of which substantially underestimate the performance of the project sites and would inflate lifecycle impacts by 15–47% depending on the pathway (see Section 3).

Solar PV, Mejillones. A 1 MW reference plant was modelled using the ecoinvent 3.10 dataset, which captures the embodied impacts of monocrystalline silicon modules, mounting structure, inverter, and balance-of-system electronics. The national-average ecoinvent carbon intensity for this dataset is 0.080 kg CO_2eq/kWh (updated from a 2012 inventory baseline [11]). To obtain a site-specific yield, the plant was simulated in the System Advisor Model (SAM, [30] using a generic 360 W monocrystalline module (Jinko Solar, 19.16% efficiency) under Mejillones irradiance data [31]. The simulation returns an annual electricity yield of 2,947.855 kWh/kW, which, integrated over a 30-year lifespan with 0.5%/year degradation, gives a lifetime-average yield used to reweight the ecoinvent embodied impact per kWh.

Wind, Magallanes. For the Siemens Gamesa SG 6.0-145 turbine deployed in the HIF Global project, no turbine-specific EPD was available at the time of this study. The closest available EPD within the Siemens Gamesa onshore product range (for the SG 6.6-155) was used as a proxy, representative of a European onshore context. Both turbines belong to the same direct-drive platform and share comparable nacelle architecture and material composition per MW of rated capacity; the proxy is considered conservative given that the SG 6.6-155 has a larger rotor and higher specific yield, which would slightly underestimate the embodied impact per kWh of the SG 6.0-145 at equal capacity factor. [32]. The ecoinvent 3.10 was used as the structural proxy for all non-climate impact categories. A capacity factor correction was applied: the embodied manufacturing carbon per kWh scales inversely with full-load hours, thus the EPD climate change value was adjusted from 45.8% to the Magallanes project capacity factor of 57% using the ratio of lifetime energy outputs. This corrected climate change value was then used as a scaling factor to proportionally adjust all six EF 3.1 impact categories, yielding a consistent site-specific characterization vector for Magallanes wind electricity.

2.6. Water Supply Modelling

Process water for PEM electrolysis must meet ASTM D1193 Type I/II purity standards (electrical resistivity >1 MΩ·cm), requiring a three-stage supply system: raw water intake (seawater via SWRO or municipal wastewater effluent via MWWR), electrodeionization (EDI) pre-treatment, and mixed-bed ion exchange polishing, consuming approximately 15% of intake volume.

Two demand scenarios are modelled. The baseline (10 L/kg H_2) represents near-stoichiometric direct electrolysis demand and is used as the primary foreground parameter. For Magallanes, 100% SWRO is assumed given the absence of accessible urban wastewater infrastructure at Cabo Negro; for Mejillones, a mixed supply of 85% MWWR and 15% SWRO is applied as assumption. The full-system sensitivity scenario (35 L/kg H_2) follows [18] and accounts for all demand components: electrolysis (11 L/kg H_2), water-cooled electrolyser cooling (22 L/kg H_2), and EDI pre-treatment losses (2 L/kg H_2). At a SWRO recovery rate of 42% [33], this requires 83.3 L of seawater intake and generates 48.3 L of brine discharge per kg H_2 produced; the associated SWRO inventory is parameterized following [34].

Municipal wastewater reuse is modelled with zero environmental burden in both scenarios, consistent with ISO 14044 §4.3.4: the wastewater treatment process occurs independently of the GH_2 system, and the treated effluent is treated as a secondary resource output of the urban sanitation system with no allocated upstream impacts.

2.7. Computational LCA Framework: Brightway2 and Premise

The life cycle model was implemented in Brightway2 [23], an open-source Python-based LCA framework that allows full programmatic control over foreground activity construction, background database queries, and LCIA calculations.

The background life cycle inventory database used is ecoinvent 3.10 cut-off [11], accessed via Brightway2's bw2io import routines. For the two electricity datasets for Magallanes wind and Mejillones solar PV, the ecoinvent national-average Chilean datasets were not used directly as final inputs; instead, they served as structural proxies whose impact vectors were rescaled by site-specific correction factors. All other background processes (electrolyzer components, chemical production, shipping fuels, water treatment) use ecoinvent 3.10 without modification.

To account for the expected evolution of background supply chains over the operational horizon of the projects, the Premise library [24] was used to generate a prospective version of the ecoinvent database. Premise systematically updates electricity mixes, fuel production chains, and industrial process emissions in ecoinvent according to Integrated Assessment Model (IAM) outputs, enabling the generation of prospective background databases consistent with decarbonisation scenarios such as IEA Net Zero by 2050. In this study, Premise was used to prepare a 2020-aligned base version of ecoinvent 3.10 as the primary background database; full prospective sensitivity analysis against a 2040-horizon scenario is identified as a priority direction for future work (Section 4).

The foreground model builds 13 activities covering electricity generation, water provision (including SWRO), electrolysis, CO_2 supply (biogenic and DAC), nitrogen supply (Haber–Bosch ASU proxy), methanol and ammonia synthesis, and maritime shipping for three destination ports. Impact results are computed for six EF 3.1 no-LT midpoint categories across 12 delivered pathways (three destinations x two CO_2 strategies for Magallanes, plus two water scenarios for Mejillones), totaling 144 individual LCIA calculations per database version.

All foreground parameters, proxy choices, and uncertainty flags are documented in Table A.1 (Appendix A). Results are reported first for the site-specific renewable electricity characterisation, which conditions all downstream impacts, and then for the full cradle-to-destination-port pathways across six EF 3.1 impact categories, three destination markets, and four pathway variants.

3. Results and discussion

3.1. Site-specific electricity characterization

The site-specific electricity results confirm that both Chilean project sites offer among the lowest renewable electricity carbon intensities reported in the literature for their respective technologies (5.84 g CO_2eq/kWh for Magallanes wind and 21.6 g CO_2eq/kWh for Mejillones solar PV) driven by exceptional capacity factors and, in the solar case, by modern high-efficiency modules under Atacama irradiance conditions. These values sit well below the national-average ecoinvent baselines (9.6 and 80 g CO_2eq/kWh respectively) and at the lower end of comparable ground-mounted and onshore wind LCA studies (Table 3). This gap is not trivial: replacing the site-specific factors with the national-average proxies would increase the total pathway climate change result by 15–47% depending on the carrier, confirming that electricity characterization is the primary methodological sensitivity in electrolysis-based GH_2 LCA.

Table 3. *Site-specific electricity characterization climate change factors, values in gCO_2eq/kWh.*

Electricity source	This study (site-specific)	Ecoinvent CL national avg.	Literature range
Magallanes wind (57% CF)	5.84	~9.6 (35% CF)	4–23.7 [35,36] (onshore wind)
Mejillones solar PV (SAM)	21.6	~80 (2012 baseline)	41.8-64.2 [[37–39] (utility PV)

3.2. Multi-criteria life cycle results

Figure 2 presents the full multi-criteria results for all four pathway variants delivered to Rotterdam, expressed across the six EF 3.1 impact categories on independent scales. No single pathway dominates all categories simultaneously, which is the central finding of this study. The key observations across categories and destinations are:

- **Climate change**: MEJ solar ammonia is the lowest-carbon pathway (1.66 kg CO_2-eq/kg H_2-eq to Rotterdam), approaching the blue hydrogen benchmark (2.20 kg CO_2-eq) even after including full international shipping. MAG biogenic methanol (3.21 kg CO_2-eq) is the best methanol variant. MAG DAC methanol (5.25 kg CO_2-eq) is the worst green pathway but still 1.8× below grey hydrogen (9.50 kg CO_2-eq). All four variants clear the grey hydrogen benchmark by a factor of 2.7–6.2 regardless of destination.
- **Route sensitivity**: Shipping distance matters but does not alter pathway rankings. The Kobe-Kansai route adds 0.58 kg CO_2-eq (+35%) to MEJ ammonia and 0.37 kg CO_2-eq (+11%) to MAG methanol relative to Rotterdam, reflecting the longer Pacific crossing and the lower energy density of ammonia as a carrier.
- **Particulate matter**: MAG biogenic methanol shows a PM burden approximately 10× higher than all other pathways, traced to forest residue combustion in the biogenic CO_2 supply chain. This is a genuine physical result, not a modelling artefact, and represents a conservative upper bound — alternative biogenic CO_2 sources such as ethanol fermentation or biogas upgrading would reduce PM by 2–10x× (Section 3.3).
- **Water use**: MEJ ammonia (0.72 m³ deprivation/kg H_2-eq) and MAG DAC methanol (0.58 m³) show comparable water use. MAG biogenic methanol is the most allocation-sensitive result in the dataset: applying ISO 14044 §4.3.4 zero-burden treatment to biomass cultivation water reduces this indicator from 2.32 to 0.13 m³ — a 17-fold difference that underlines the importance of transparent allocation reporting for biomass-based pathways.
- **Land use**: MEJ ammonia (124.8 Pt) is 19–36x higher than both methanol pathways (3.5–6.4 Pt), driven entirely by the PV supply chain of the 600 MW solar field. The 100% SWRO sensitivity scenario adds less than 0.2 Pt, confirming that water infrastructure has a negligible contribution to land use.
- **Fossil resource use**: MAG DAC methanol (86.9 MJ/kg H_2-eq) is the clear outlier, driven by the energy intensity of direct air capture. MEJ ammonia (20.4 MJ) and MAG biogenic methanol (44.0 MJ) perform significantly better. If DAC were powered entirely by co-located Magallanes wind, its fossil resource score would decrease substantially.
- **Minerals and metals**: All pathways show similar and relatively low scores (4.2–10 kg Sb-eq/kg H_2-eq), reflecting electrolyzer and turbine material demand. No pathway is strongly differentiated on this indicator.

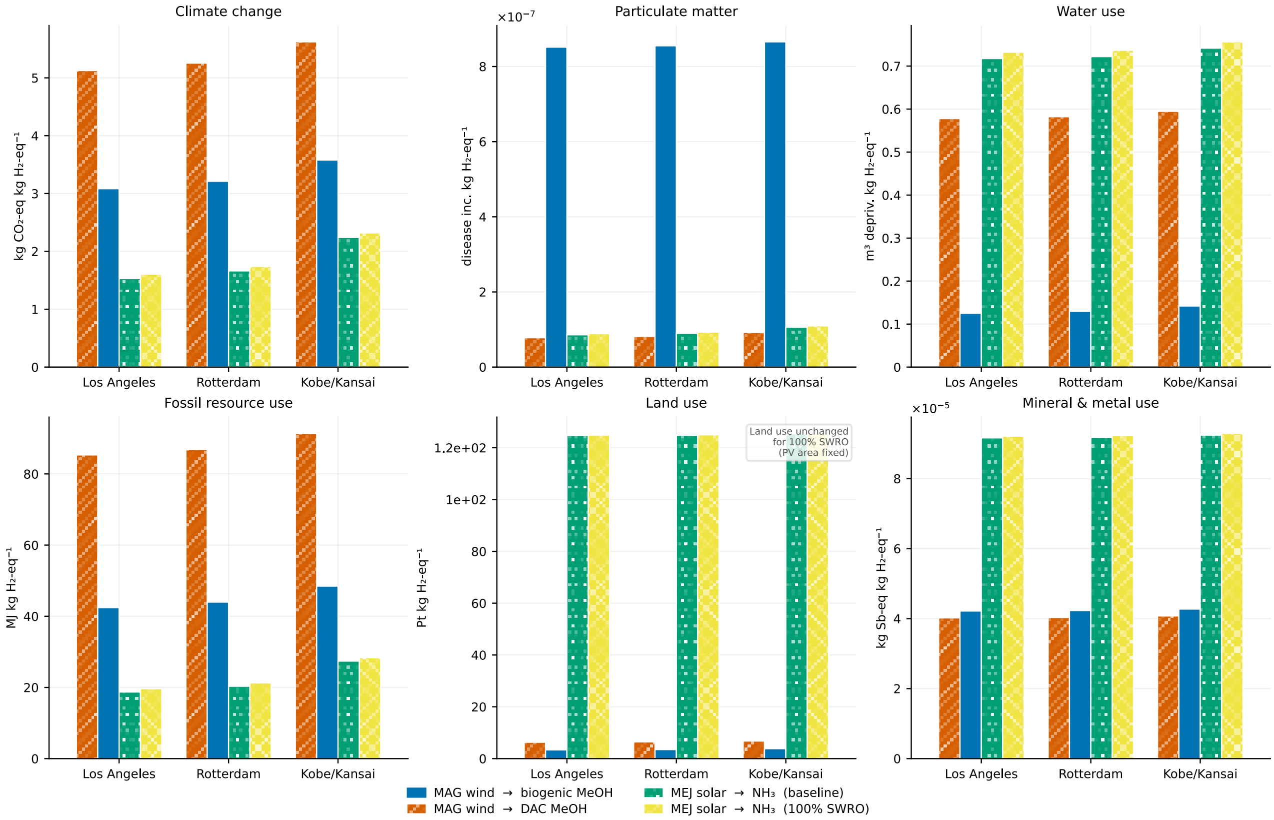

Figure 2. Life cycle impact results for four pathway variants delivered to Rotterdam across six EF 3.1 impact categories. Independent y-axis scales per panel.

The radar chart (Figure 3) four scenarios to capture the most meaningful contrasts: the two Magallanes variants isolate the effect of CO_2 sourcing (biogenic versus DAC), Mejillones ammonia to Rotterdam provides a cross-technology comparison, and Mejillones ammonia to Kobe-Kansai replaces the SWRO sensitivity, which differs by less than 5% across all categories, to reveal the penalty of the longest shipping distance in the study. The normalised profiles confirm no pathway is universally optimal: biogenic methanol scores well on climate and fossil resources but poorly on particulate matter, solar ammonia dominates on land use, and the Kobe-Kansai profile diverges from Rotterdam only on climate change, confirming that route choice affects carbon intensity but leaves the remaining impact categories unchanged.

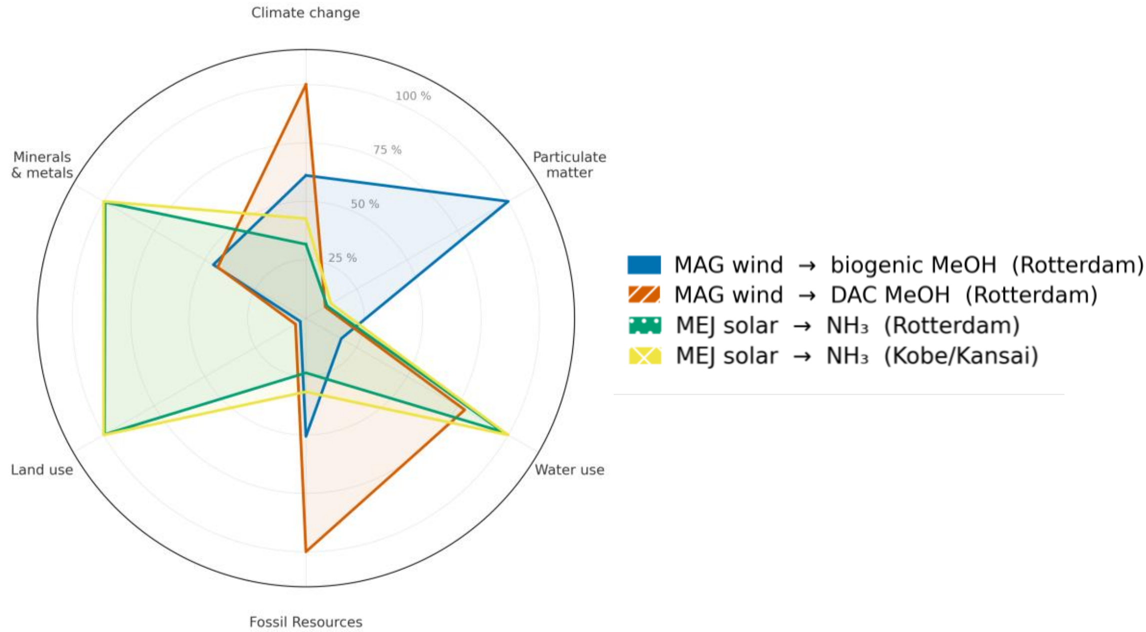

Figure 3. Normalized multi-criteria environmental profiles for four contrasting export scenarios (0 = best, 100 = worst performer per category). MAG-Bio = MAG biogenic methanol, Rotterdam; MAG-DAC = MAG DAC methanol, Rotterdam; MEJ-RTM = MEJ solar ammonia, Rotterdam; MEJ-KIX = MEJ solar ammonia, Kobe.

3.3. Climate change

Table 4 summarizes the climate change results for all pathway variants across three destination ports, with and without the N_2 sensitivity correction for ammonia. All green pathways achieve climate intensities between 2.7 and 6.2 times lower than grey hydrogen (9.50 kg CO_2-eq/kg H_2-eq). MAG biogenic methanol (3.21 kg CO_2-eq to Rotterdam) and MEJ solar ammonia (1.66 kg CO_2-eq to Rotterdam, or 1.86 with the N_2 correction) approach or fall below the blue hydrogen benchmark of 2.20 kg CO_2-eq/kg H_2-eq even after including full international shipping, while MAG DAC methanol (5.25 kg CO_2-eq) remains well below grey hydrogen but does not reach that benchmark, reflecting the energy burden of direct air capture at current performance levels. Route sensitivity is significant for ammonia but does not alter comparative rankings: the Kobe-Kansai route adds 0.58 kg CO_2-eq (+35%) relative to Rotterdam due to the 23,703 km Pacific crossing, whereas the penalty for MAG methanol variants is smaller (+0.37 kg CO_2-eq, +11%) given methanol's higher energy density, and Los Angeles is consistently the best-performing destination for all pathways.

Table 4. *Climate change results (kg CO_2-eq/kg H_2-eq delivered) by pathway and destination port. Grey and blue H_2 listed as benchmarks.*

Pathway	Los Angeles	Rotterdam	Kobe/Kansai	Rotterdam +N_2*
MAG-Biogenic MeOH	3.084	3.212	3.580	3.212
MAG-DAC MeOH	5.126	5.254	5.622	5.254
MEJ Solar NH_3 (baseline)	1.529	1.663	2.241	1.863
MEJ Solar NH_3 (100% SWRO)	1.607	1.741	2.319	1.941
Grey H_2 (SMR, no CCS)		9.500		—
Blue H_2 (SMR + 90% CCS)		2.200		—

*N_2/ASU sensitivity correction: +0.20 kg CO_2-eq/kg H_2-eq applied to NH_3 pathways only. Conservative lower bound without correction; upper bound with correction shown as "+N_2" column.

Figure 4 presents the stage-level breakdown for the Rotterdam route. The dominant driver differs by pathway.

- For MAG biogenic methanol, the CO_2 supply chain accounts for approximately 72% of total climate change impact, confirming that CO_2 sourcing strategy rather than renewable electricity quality is the primary design variable for methanol pathways.
- For MAG DAC methanol, DAC CO_2 supply reaches approximately 83%, a share that would decrease substantially if DAC were powered by co-located Magallanes wind under a prospective grid scenario.
- For MEJ solar ammonia, electricity dominates at approximately 69% with maritime shipping contributing 30%, making this pathway uniquely sensitive to electricity carbon intensity and uniquely well-positioned given the 5.84 g CO_2-eq/kWh Magallanes wind and 21.6 g CO_2-eq/kWh Mejillones PV factors derived in Section 2.5.

These profiles have direct implications for improvement priorities: methanol exporters gain more from reducing CO_2 supply chain impacts than from electrolyzer efficiency gains, while for ammonia exporters electricity carbon intensity and shipping distance are the two levers that matter most, both already optimized at the Mejillones site.

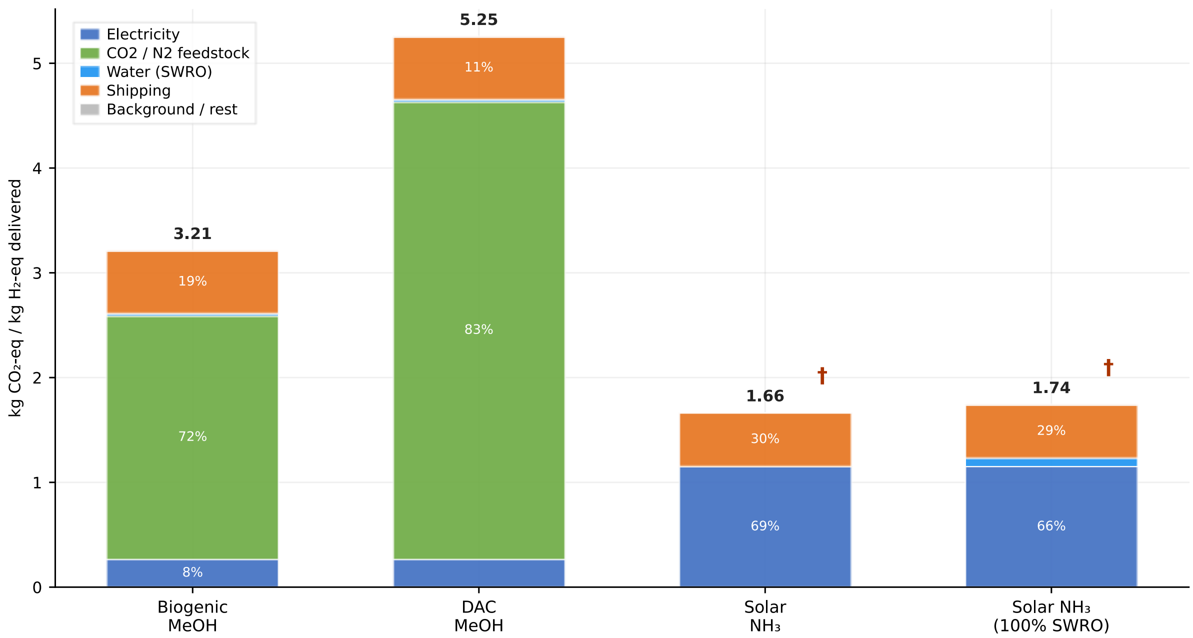

Figure 4. *Climate Change stage breakdown (kg CO_2-eq/kg H_2-eq delivered), Rotterdam route. Stacked bars by stage: electricity (dark blue), CO_2/N_2 feedstock (green), SWRO water (light blue), shipping (orange), background/rest (grey). The † indicates N_2/ASU sensitivity correction (+0.20 kg CO_2-eq).*

3.4. Water use

Figure 5 shows the underlying physical water inventory. Water use (AWARE, m³ world-equivalent deprivation per kg H_2-eq) is the most methodology-sensitive category in the study: for MAG biogenic methanol, applying ISO 14044 zero-burden allocation to biomass cultivation water reduces the indicator from 2.32 to

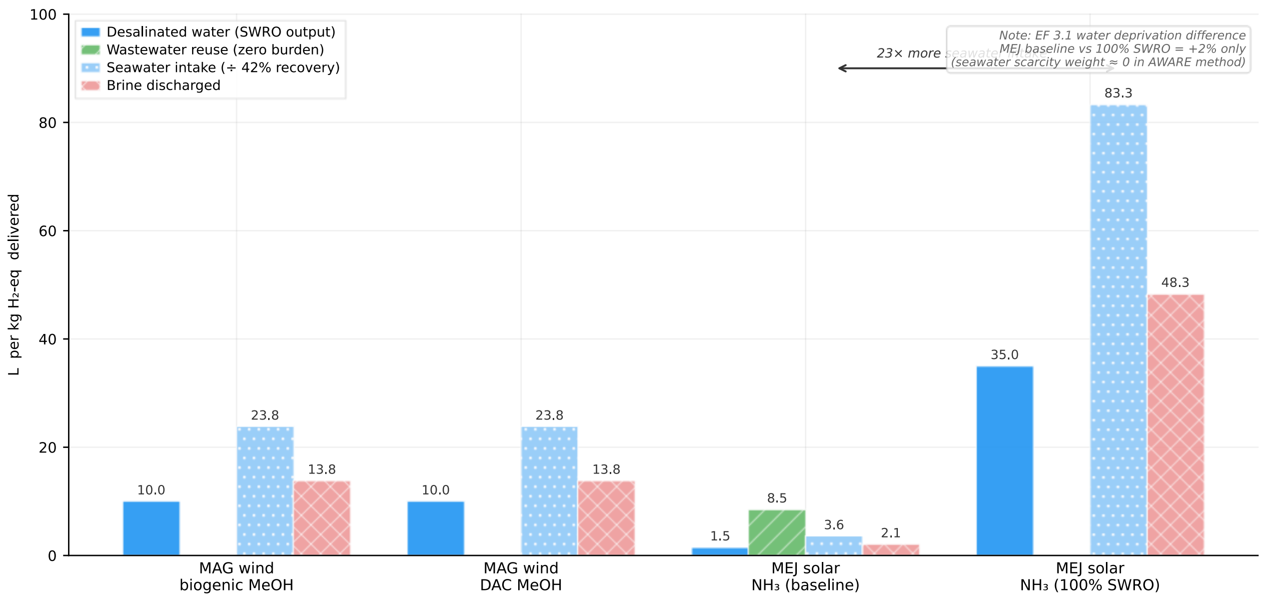

Figure 5. Physical water inventory per kg H_2-eq for the four pathway variants (Rotterdam route). Values shown for raw water intake, process consumption, and brine discharge. MAG scenarios assume 100% SWRO; MEJ baseline assumes 15% SWRO / 85% MWWR; MEJ 100% SWRO sensitivity assumes full desalination at 35 L/kg H_2 following [18].

0.13 m³/kg H_2-eq, a 17-fold difference that underlines the importance of transparent allocation reporting, while under zero-burden allocation MAG DAC methanol (0.58 m³) and MEJ solar ammonia baseline (0.72 m³) show comparable deprivation, both driven by SWRO demand. The 100% SWRO sensitivity for Mejillones increases water deprivation by less than 3% and adds only 0.08 kg CO_2-eq (<5%) to climate change, confirming that water supply strategy is an infrastructure and permitting decision rather than a significant environmental differentiator, though at full deployment process water requirements in Antofagasta could reach 43 Mm^3/year [18], making SWRO a regional planning prerequisite independent of its lifecycle score.

3.5. Particulate matter, fossil resource use and minerals

Particulate matter shows the sharpest contrast of all six categories and is driven almost entirely by the CO_2 supply chain: MAG biogenic methanol reaches 8.55 × 10^{-7} disease incidence/kg H_2-eq, approximately 10× higher than MAG DAC and MEJ ammonia (8.17 and 8.97 × 10^{-8} respectively), traced to forest residue combustion, with contribution analysis confirming that 85–90% of total PM originates in the biogenic CO_2 proxy process. This is nonetheless a conservative upper bound, as alternative feedstocks such as ethanol fermentation or biogas upgrading involve no combustion and would reduce PM by 2–10×, making CO_2 feedstock selection a dual climate-and-PM design decision. Fossil resource use is dominated by CO_2 sourcing strategy, with MAG DAC methanol (86.9 MJ) the clear outlier due to direct air capture energy intensity, while MEJ solar ammonia (20.4 MJ) benefits from the absence of a carbon capture step. Minerals and metals show the smallest differentiation across pathways (4.2–10 kg Sb-eq). These categories are reported at midpoint level using EF 3.1 factors; a natural extension would apply the Cumulative Energy Demand method [40,41], which disaggregates primary energy by source and enables direct comparison of energy return on investment across pathways.

4. Conclusions

This paper presents the first multi-impact, cradle-to-destination-port LCA of two real Chilean GH_2 export projects under industrial development, addressing three gaps systematically identified in the literature: the production-gate boundary, reliance on national-average electricity inventories, and restriction of environmental reporting to climate change alone. Four pathway variants are evaluated against six EF 3.1 impact categories and three destination markets using site-specific renewable electricity characterization and a fully traceable Brightway2 foreground model.

The results confirm the fundamental climate case for Chilean GH_2 export: all pathways achieve climate intensities 2.7–6.2 times below grey hydrogen regardless of destination, and MEJ solar ammonia (1.66–1.86 kg CO_2-eq/kg H_2-eq to Rotterdam) approaches or falls below the blue hydrogen benchmark of 2.20 kg CO_2-eq/kg H_2-eq even after including full international shipping. However, no single pathway dominates across all six impact categories, and the multi-criteria profile reveals trade-offs invisible to climate-only assessments: solar ammonia minimizes climate change and fossil resource use but carries the highest land use score, while biogenic methanol is competitive on climate but exhibits a particulate matter burden 10 times higher than other pathways, traced to forest residue combustion in the CO_2 supply chain and sensitive to feedstock selection.

Two findings carry direct regulatory relevance. First, maritime shipping contributes between 11% and 48% of total carbon footprint depending on route and carrier, a supply chain stage systematically absent from production-gate assessments: for the Kobe-Kansai route, the total pathway climate change (2.24 kg CO_2-eq/kg H_2-eq) approaches the blue hydrogen benchmark, with direct implications for exporters seeking certification under EU RED III, IRA Section 45V, or Japan GIF MRV protocols. Second, site-specific electricity characterization is the most critical methodological choice in electrolysis-based GH_2 LCA: national-average proxies would overestimate pathway climate change by 15–47%, obscuring the genuine environmental advantage of both Chilean project sites and potentially misclassifying compliant pathways under emerging thresholds.

CO_2 sourcing strategy emerges as the primary design variable for methanol pathways, contributing 72–83% of total climate change and governing the climate-versus-PM trade-off, while for ammonia pathways electricity carbon intensity and shipping distance are the two dominant levers, both already optimized at the Mejillones site. Water supply strategy has a negligible effect on lifecycle scores, though desalination infrastructure remains a regional planning prerequisite at deployment scale in Antofagasta.

Future work should address four directions: Monte Carlo uncertainty propagation of proxy assumptions; extension with the Cumulative Energy Demand method to provide a net energy balance perspective relevant to hydrogen carriers as traded energy products; explicit mapping of results against the quantitative thresholds of EU RED III, IRA Section 45V, and Japan GIF MRV protocols; and situating these findings within Chile's National Green Hydrogen Strategy to identify which pathway variants are best positioned to meet both cost and multi-criteria environmental requirements as the country pursues top-three global exporter status by 2040.

Acknowledgement

A. Pino acknowledges financial support from ANID, FONDECYT Postdoctorado, Grant No. 3261308, and the DAAD ERA Fellowships Green Hydrogen (GH2) Programme.

References

[1] Energy Agency I. Global Hydrogen Review 2024. 2024.

[2] IRENA. GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL PART II TECHNOLOGY REVIEW OF HYDROGEN CARRIERS. 2022.

[3] Pozo D, Sauma E, Bolado-Lavín R. Levelized cost analysis for renewable ammonia production in Chile. Energy 2025;335. https://doi.org/10.1016/j.energy.2025.137554.

[4] Wilkinson J, Mays T, McManus M. Review and meta-analysis of recent life cycle assessments of hydrogen production. Cleaner Environmental Systems 2023;9. https://doi.org/10.1016/j.cesys.2023.100116.

[5] Thomas Adisan RPS, Manan ZA, Lim JS, Andiappan V, How BS, Alwi SRW. Benchmarking Hydrogen Life Cycle Assessments: A Review of Methodologies and Result. Chemical Engineering Transactions 2025;120:13–8. https://doi.org/10.3303/CET25120003.

[6] Kolb S, Müller J, Luna-Jaspe N, Karl J. Renewable hydrogen imports for the German energy transition – A comparative life cycle assessment. J Clean Prod 2022;373:133289. https://doi.org/10.1016/j.jclepro.2022.133289.

[7] Weidner T, Tulus V, Guillén-Gosálbez G. Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis. Int J Hydrogen Energy 2023;48:8310–27. https://doi.org/10.1016/j.ijhydene.2022.11.044.

[8] Hermesmann M, Tsiklios C, Müller TE. Environmental Assessment of Climate-friendly Hydrogen Supply Chains-A Trade-off between Capacity Utilization and Transport Distance? Energy Proceedings 2022.

[9] Al-Qahtani A, Parkinson B, Hellgardt K, Shah N, Guillen-Gosalbez G. Uncovering the true cost of hydrogen production routes using life cycle monetisation. Appl Energy 2021;281. https://doi.org/10.1016/j.apenergy.2020.115958.

[10] Magnaval G, Mouhoub M, Boulay AM, Margni M. Harmonizing the assessment of (green) hydrogen supply chain: a modular and parametrized life cycle assessment framework. Energy Environ Sci 2026. https://doi.org/10.1039/d5ee07747h.

[11] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I) overview and methodology. Int J Life Cycle Assess 2016;21:1218–30. https://doi.org/10.1007s11367-016-1087-8.

[12] Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Appl Energy 2019;237:862–72. https://doi.org/10.1016/j.apenergy.2019.01.001.

[13] Cacciuttolo C, Huertas A, Montoya B, Cano D. The Present and Future of Production of Green Hydrogen, Green Ammonia, and Green E-Fuels for the Decarbonization of the Planet from the Magallanes Region, Chile. Applied Sciences (Switzerland) 2025;15. https://doi.org/10.3390/app15116228.

[14] Escobar RA, Cortés C, Pino A, Pereira EB, Martins FR, Cardemil JM. Solar energy resource assessment in Chile: Satellite estimation and ground station measurements. Renew Energy 2014;71:324–32. https://doi.org/10.1016/j.renene.2014.05.013.

[15] Ministerio del Medio Ambiente (MMA). Green Hydrogen National Strategy (Estrategia nacional de hidrógeno verde). 2020.

[16] HIF Cabo Negro n.d. https://es.hifglobal.com/locations/cabonegro (accessed January 28, 2026).

[17] MAE | Mejillones Ammonia Energy n.d. https://mae-energy.com/ (accessed January 28, 2026).

[18] Carreño R. Disponibilidad del recurso hídrico en el desarrollo del hidrógeno verde y sus derivados en Chile. 2023.

[19] European Commission. Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing

a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin 2023.
[20] United States Congress. Inflation Reduction Act of 2022, Section 45V: Credit for Production of Clean Hydrogen. 2022.
[21] Ministry of Economy T, (METI) I, New Energy, (NEDO) ITDO. Green Innovation Fund: Hydrogen and Ammonia Supply Chain Projects. 2021.
[22] Mutel C. Brightway: An open source framework for Life Cycle Assessment. J Open Source Softw 2017;236. https://doi.org/10.21105/joss.00236.
[23] Sacchi R, Terlouw T, Siala K, Dirnaichner A, Bauer C, Cox B, et al. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renewable and Sustainable Energy Reviews 2022;160:112311. https://doi.org/10.1016/J.RSER.2022.112311.
[24] All in One at Sea. Port to Port Distance Calculator & Voyage Planner | All in One at Sea n.d. https://allinoneatsea.com/port-to-port (accessed May 28, 2026).
[25] International Organization for Standardization. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework, EN 2006.
[26] United States Congress. Inflation Reduction Act of 2022, Section 45V: Credit for Production of Clean Hydrogen. 2022.
[27] Kolb S, Müller J, Luna-Jaspe N, Karl J. Renewable hydrogen imports for the German energy transition – A comparative life cycle assessment. J Clean Prod 2022;373. https://doi.org/10.1016/j.jclepro.2022.133289.
[28] European Commission JRC. EF 3.1 — Environmental Footprint characterisation factors. Luxembourg: 2021.
[29] Kolahchian Tabrizi M, Famiglietti J, Bonalumi D, Campanari S. The Carbon Footprint of Hydrogen Produced with State-of-the-Art Photovoltaic Electricity Using Life-Cycle Assessment Methodology. Energies (Basel) 2023;16. https://doi.org/10.3390/en16135190.
[30] National Renewable Energy Laboratory. System Advisor Model Version 2025.4.16 (SAM) 2025.
[31] Explorador Solar (Solar Explorer) n.d. https://solar.minenergia.cl/exploracion (accessed May 29, 2026).
[32] Siemens Gamesa. EPD Electricity from a European onshore wind farm using SG 6.6-155 wind turbines. 2022.
[33] Jones E, Qadir M, van Vliet MTH, Smakhtin V, Kang S mu. The state of desalination and brine production: A global outlook. Science of The Total Environment 2019;657:1343–56. https://doi.org/10.1016/J.SCITOTENV.2018.12.076.
[34] Najjar E, Al-Hindi M, Massoud M, Saad W. Life Cycle Assessment of a seawater reverse osmosis plant powered by a hybrid energy system (fossil fuel and waste to energy). Energy Reports 2021;7:448–65. https://doi.org/10.1016/j.egyr.2021.07.106.
[35] Schreiber A, Marx J, Zapp P. Comparative life cycle assessment of electricity generation by different wind turbine types. J Clean Prod 2019;233:561–72. https://doi.org/10.1016/J.JCLEPRO.2019.06.058.
[36] Guezuraga B, Zauner R, Pölz W. Life cycle assessment of two different 2 MW class wind turbines. Renew Energy 2012;37:37–44. https://doi.org/10.1016/J.RENENE.2011.05.008.
[37] Wong JH, Royapoor M, Chan CW. Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems. Renewable and Sustainable Energy Reviews 2016;58:608–18. https://doi.org/10.1016/j.rser.2015.12.241.
[38] Fthenakis V, Betita R, Shields M, Vinje R, Blunden J. Life Cycle Analysis of High-Performance Monocrystalline Silicon Photovoltaic Systems: Energy Payback Times and Net Energy Production Value. 27th European Photovoltaic Solar Energy Conference and Exhibition, 2012.
[39] Kim B ju, Lee J yong, Kim K hwan, Hur T. Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. Solar Energy 2014;99:100–14. https://doi.org/10.1016/j.solener.2013.10.038.
[40] Frischknecht R, Komoto K, Doi T. Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology. Report IEA-PVPS T12-25:2023 2023.
[41] Burkhardt J, Patyk A, Tanguy P, Retzke C. Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply. Appl Energy 2016;181:54–64. https://doi.org/10.1016/j.apenergy.2016.07.104.

Appendix A

Table A.1 presents all primary foreground model parameters with their sources and uncertainty assessments. All parameters are traceable to project documentation, peer-reviewed literature, or industry standards, ensuring full reproducibility of the Brightway2 foreground model described in Section 2.7.

Parameter	Value	Unit	Source	Uncertainty
Electrolysis energy MAG	43.47	kWh/kg H_2	HIF/Haru Oni operational KPI 2023	Low — actual operating data
Electrolysis energy MEJ	50.0	kWh/kg H_2	IEA Global Hydrogen Review 2023, Table 2.2 (PEM central)	Moderate — IEA range 46-60
MeOH synthesis + distillation	0.50	kWh/kg MeOH	Ecoinvent LAM methanol synthesis proxy	Low
NH_3 synthesis (HB + ASU)	0.60	kWh/kg NH_3	IEA Ammonia Technology Roadmap 2021, Table A2	Low
Process water (baseline)	10.0	L/kg H_2	Near-stoichiometric: 9.0 L theoretical + process losses	Low
Process water (100% SWRO, Q1)	35.0	L/kg H_2	Carreño (2023) GIZ PtX Hub Chile: 11+22+2 L/kg H_2	Low — mass balance study
MEJ water mix (baseline)	15% SWRO + 85% MWWR	—	Volta/MAE Phase 1 water management plan	Moderate — pre-FID data
MAG water supply	100% SWRO	—	HIF/Haru Oni project docs (no MWWR near Cabo Negro)	Low
SWRO recovery factor	42%	kg desal./kg seawater	Jones et al. (2018) Chilean standard seawater	Low
N_2/ASU for HB	Not in Premise — zero (lower bound)	—	Proxy absent in ecoinvent 3.10 / Premise Base2020	HIGH — see Section 3, N_2 sensitivity
Biogenic CO_2 source	Forest residues + flue gas capture	—	HIF/Haru Oni sourcing; Magallanes forest sector	Moderate — feedstock varies
Shipping MeOH proxy	Liquid goods tanker	—	Ecoinvent GLO; Brynolf et al. (2014) J. Clean. Prod. 74	Low
Shipping NH_3 proxy	LNG tanker (cryogenic proxy)	—	Ecoinvent GLO — dedicated NH_3 tanker absent from DB	Moderate — ±15%
LHV H_2	120.1	MJ/kg	IUPAC thermodynamic standard	N/A
SWRO CO_2 intensity factor	2.33	g CO_2/kg water	Ecoinvent seawater ultrafiltration two-stage proxy	Low

MAG = Magallanes; MEJ = Mejillones; HB = Haber-Bosch; ASU = Air Separation Unit; SWRO = Seawater Reverse Osmosis; MWWR = Municipal Wastewater Reuse; CF = capacity factor.