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Life cycle assessment of solar-powered green ammonia in Lebanon versus imported grey ammonia: firming options, grid-share thresholds and resource trade-offs

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Abstract **Original Research Article**

Green ammonia is widely presented as a low-carbon substitute for fossil-based fertiliser, but most life cycle assessments assume a steady supply of renewable electricity that a solar-powered plant does not have. This study asks whether ammonia produced in Lebanon from solar power can outperform the grey ammonia that the country effectively imports, mainly from Egypt as urea, once the intermittency of solar supply is modelled explicitly. A cradle-to-gate attributional life cycle assessment following ISO 14040/44 was built for 1 kg of anhydrous ammonia delivered to the Bekaa valley. Grey ammonia from Egyptian natural-gas steam reforming, including upstream gas emissions and shipping, was compared with electrolytic ammonia supplied by Bekaa photovoltaics under five configurations: grid only, PV with grid backup, PV with hydrogen storage and winter grid top-up, islanded PV with batteries, and islanded PV with hydrogen storage and a flexible Haber–Bosch loop. Solar supply was simulated hour by hour on representative days, and equipment was sized for each configuration. Climate change, water consumption and scarcity, and mineral resource depletion were assessed, with scenario, sensitivity and 10,000-run Monte Carlo analyses. Grey ammonia emitted 2.78 kg CO2e/kg NH3 (90% interval 2.34–3.17). The islanded configurations emitted 0.28 (hydrogen storage) and 0.47 (batteries) kg CO2e/kg NH3, and the hybrid with winter grid top-up 0.94, all lower than grey in every Monte Carlo run. In contrast, PV with grid backup emitted 3.82 and grid-only electrolysis 6.58 kg CO2e/kg NH3, because Lebanese electricity, 60% of it from diesel generators, carries 0.626 kg CO2e/kWh. Green ammonia breaks even with grey at a grid share of about 40% (90% interval 30–59%), whereas PV without storage cannot reduce the grid share below about 51%. The climate gain comes at the cost of 12–23 times higher mineral depletion, driven by silver in PV modules and copper in batteries, and 2.5–3.7 times higher water consumption. Storage, not solar capacity, therefore decides whether Lebanese green ammonia is low-carbon, and support schemes should require islanded operation or verified hourly matching.

Keywords: green ammonia; Haber–Bosch; solar photovoltaics; hydrogen storage; life cycle assessment; Lebanon.

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1. Introduction

Ammonia is the starting point of almost all synthetic nitrogen fertiliser, and its production by steam methane reforming (SMR) and the Haber–Bosch process is one of the largest single sources of industrial CO2, at about 1% of global energy-related emissions (IEA, 2021a). Replacing fossil hydrogen with hydrogen from water electrolysis powered by renewable electricity, so-called green ammonia, removes the direct process emissions. Life cycle assessments consistently find large reductions when the electricity is renewable and the plant runs steadily (Al-Ghussain et al., 2025; Lee et al., 2022; Mayer et al., 2023; Stafford et al., 2025). A study for neighbouring Jordan, for example, reported 0.1–0.5 kg CO2e/kg NH3 for PV- and wind-based green ammonia, against about 1.8 kg CO2e/kg NH3 for grey ammonia (Al-Ghussain et al., 2025).

These results rest on an assumption that is easy to overlook. The Haber–Bosch loop is designed for continuous operation and tolerates only limited turndown, whereas solar power is available for only part of each day and varies by season. A real solar-powered plant must therefore oversize its PV field and electrolysers and add hydrogen storage, batteries or a grid connection. Techno-economic studies have shown that this firming dominates plant design and cost (Tully et al., 2025; Wang et al., 2023), but its life-cycle consequences are rarely quantified. When the firming electricity comes from a carbon-intensive grid, it can cancel the benefit entirely.

Lebanon makes this question concrete. The country produces no ammonia; its nitrogen fertiliser arrives mainly as urea, about three-quarters of it from Egypt in 2023 (World Bank, n.d.), where gas-based plants emit roughly 1.6–2.5 t CO2 per tonne of ammonia directly (Ricardo, 2023). At the same time, Lebanon has some of the best solar resources in the Eastern Mediterranean, particularly in the Bekaa valley, and had more than 1 GW of PV installed by the end of 2023, most of it added since 2021, supplying about 15% of its electricity (El Hajj and Abou Moussa, 2025; MEW and LCEC, 2025). Its grid, however, is among the most carbon-intensive in the region: private diesel generators supplied 47% of electricity in 2022 (MEW and LCEC, 2025), and in Beirut they now run most of the day, with documented effects on air quality (Al Hallak et al., 2024). A green-ammonia plant in the Bekaa that relies on the grid at night could therefore emit more than the imported product it is meant to replace.

This study asks whether, and under which supply configurations, ammonia produced from Lebanese solar power can outperform imported grey ammonia. It makes three contributions. First, it builds a cradle-to-gate LCA in which the solar resource is simulated hourly and the PV field, electrolyser, batteries and hydrogen storage are sized for each configuration, so that intermittency is represented in the inventory rather than assumed away. Second, it derives the grid-share threshold at which green ammonia loses its climate advantage under Lebanese electricity, and shows why solar power without storage cannot meet it. Third, it quantifies the resource trade-offs of the low-carbon configurations, water consumption and scarcity and mineral depletion, which matter in a water-stressed, import-dependent country. Section 2 reviews the literature and identifies the research gap; Section 3 describes the LCA model; Section 4 presents and discusses the results; Section 5 concludes.

2. Literature review and research gap

Peer-reviewed studies published from 2022 to 2026 were identified in Scopus, Web of Science and the OpenAlex index using combinations of "green ammonia", "Haber–Bosch", "electrolytic hydrogen", "life cycle assessment", "flexible operation", "hydrogen storage", "critical materials" and "water consumption", and supplemented by Lebanese and regional energy-sector reports. Four strands are relevant.

2.1 Life cycle assessments of grey and green ammonia

Comparative LCAs agree on the direction of the result. Lee et al. (2022) compared the techno-economic performance and life-cycle greenhouse-gas emissions of a wide range of ammonia pathways, from conventional SMR to carbon capture, nuclear

and renewable routes. Oni et al. (2022) compared SMR with thermal decomposition of methane. Mayer et al. (2023) combined techno-economic analysis with a full LCA of blue and green ammonia, showing that low natural-gas leakage is a precondition for blue ammonia and that advances in photovoltaics could further reduce the impacts of PV-based green ammonia. Regional studies have followed. In Jordan, Al-Ghussain et al. (2025) reported 0.1–0.5 kg CO2e/kg NH3 for PV- and wind-based green ammonia, against about 1.8 for grey. For a coastal South African facility, Stafford et al. (2025) reported 0.79 kg CO2e/kg NH3 for the full system including energy-supply infrastructure, falling to 0.28 with co-product credits, with electrolysis contributing 68% of impacts. Gado (2024) assessed solar and wind hydrogen and ammonia at three Egyptian sites. Further studies examined low-pressure Haber–Bosch (Song et al., 2025), ammonia and methane from green hydrogen and CO2 (Kadam and Yadav, 2024), the long-term climate vulnerability of green-ammonia economics across Köppen–Geiger zones (Rai and Oh, 2026), PV-thermal-powered synthesis (Wang et al., 2026) and renewable urea production from alkaline electrolysis (Kim et al., 2023). Almost all of these studies, however, model the plant as if it received steady electricity or represent firming only in cost terms.

2.2 Life cycle assessments of electrolytic hydrogen

Because hydrogen accounts for most of the energy in green ammonia, the electrolysis literature is directly relevant. Reviews report climate impacts from about 0.5 to about 30 kg CO2e/kg H2 depending on electricity source, and agree that electricity supply dominates impacts while electrolyser manufacture is minor (Ajeeb et al., 2024; Shaya and Glöser-Chahoud, 2024). Prospective LCAs project further reductions for PEM electrolysis through learning (Koj et al., 2025). Zaki et al. (2025) found that embodied impacts of liquid alkaline electrolysers are below 10% of life-cycle impacts and that system electricity use ranges from about 49 to 64 kWh/kg H2 depending on design. Gan et al. (2024) showed that the embodied emissions of the power plants supplying electrolysers must be included for a fair comparison. Other studies addressed PEM electrolysis coupled with desalination in Saudi Arabia (Vázquez-Sánchez et al., 2025), grid-based electrolysis in South Korea (Kim and Kim, 2024) and onshore and offshore wind hydrogen (Zhang et al., 2023). A consistent message is that grid-connected electrolysis is only low-carbon on low-carbon grids.

2.3 Intermittency and flexible operation

A separate, mostly techno-economic literature addresses how renewable intermittency is absorbed. Wang et al. (2023) optimised renewable generation for off-grid green ammonia considering Haber–Bosch flexibility. Tully et al. (2025) showed that allowing the synthesis loop to turn down to 60% reduced the required hydrogen storage by 84% in an off-grid case. Other studies examined flexible multi-generation systems (Wen and Aziz, 2022), sizing and pricing of grid-connected power-to-ammonia under limited synthesis flexibility (Yu et al., 2024), multi-stable flexible operation strategies (Zhou et al., 2024) and the effect of process design on the levelised cost of flexible green ammonia (Pistolesi et al., 2025). Pistolesi et al. (2025) treated about 60% as a realistic minimum load for the synthesis unit, found that solar-only designs need more than 100 MWh of storage, and capped grid electricity at 10% for the product to qualify as green. These studies establish that storage and flexibility, not generation alone, determine whether a renewable plant can run, but they rarely translate the resulting equipment and grid imports into life-cycle emissions.

2.4 Resource trade-offs

Low-carbon ammonia shifts burdens towards materials and water. Xun et al. (2025) assessed the supply sustainability of eight critical materials for electrolysers and fuel cells, identifying resource-depletion pressure and substitutability as the main concerns for alkaline electrolysers, which rely on nickel, and supply-disruption risk for PEM electrolysers, which rely on platinum and iridium. PV modules depend on silver, whose use per watt varies several-fold between cell technologies (Zhang

et al., 2021), and stationary LFP batteries carry about 91 kg CO2e per kWh of storage (Lin et al., 2024). Electrolysis consumes water stoichiometrically, about 9 kg per kg H2, plus purification losses and cooling; reviews of water use in electrolytic hydrogen production (Santos Sánchez et al., 2026) and system designs that weigh energy, water, emissions and cost (González Palencia et al., 2022) show that cooling choices can multiply total consumption. These trade-offs are especially relevant where water is scarce.

2.5 The Lebanese context

Lebanese energy reports document a carbon-intensive and fragmented electricity supply dominated by private diesel generation (MEW and LCEC, 2025), rapid growth of distributed PV (El Hajj and Abou Moussa, 2025) and the air-quality burden of the generator fleet (Al Hallak et al., 2024). No study has assessed hydrogen or ammonia production in Lebanon, and none has asked whether the country's solar resource could displace its imported nitrogen fertiliser at lower life-cycle emissions.

2.6 Research gap

Table 1 summarises how the reviewed strands cover the questions addressed in this study.

Table 1. Coverage of the reviewed literature (2022–2026) against the questions addressed in this study.

Literature strand	Refs.	Green vs grey LCA	Intermittency modelled hour by hour	Firming equipment in the inventory	Grid-share threshold	Water and minerals
Ammonia LCA	(Al-Ghussain et al., 2025; Gado, 2024; Kadam and Yadav, 2024; Kim et al., 2023; Lee et al., 2022; Mayer et al., 2023; Oni et al., 2022; Rai and Oh, 2026; Song et al., 2025; Stafford et al., 2025; Wang et al., 2026)	Yes	Rarely	Rarely	No	Some studies
Electrolytic hydrogen LCA	(Ajeeb et al., 2024; Gan et al., 2024; Kim and Kim, 2024; Koj et al., 2025; Shaya and Glöser-Chahoud, 2024; Vázquez-Sánchez et al., 2025; Zaki et al., 2025; Zhang et al., 2023)	No (hydrogen)	No	No	Implicit, via grid mix	Some studies
Flexibility and storage design	(Pistolesi et al., 2025; Tully et al., 2025; Wang et al., 2023; Wen and Aziz, 2022; Yu et al., 2024; Zhou et al., 2024)	No	Yes	Cost only	Cost-based caps (Pistolesi et al., 2025)	No
Resource studies	(González Palencia et al., 2022; Lin et al., 2024; Santos Sánchez et al., 2026; Xun et al., 2025; Zhang et al.,	No	No	No	No	Yes

Literature strand	Refs.	Green vs grey LCA	Intermittency modelled hour by hour	Firming equipment in the inventory	Grid-share threshold	Water and minerals
	2021)					
Lebanese energy reports	(Al Hallak et al., 2024; El Hajj and Abou Moussa, 2025; MEW and LCEC, 2025)	No	No	No	No	No
This study	—	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Three gaps follow. First, life-cycle comparisons of green and grey ammonia have not represented solar intermittency and the equipment needed to absorb it, so their results correspond to an idealised, steadily supplied plant. Second, no study has expressed the role of grid backup as a life-cycle threshold, that is, the share of grid electricity at which green ammonia stops being lower-carbon than the product it replaces. Third, there is no assessment for Lebanon or for any electricity system dominated by diesel generation, where the threshold is expected to be most restrictive. This study addresses all three and adds water and mineral indicators to show what the low-carbon configurations trade away.

3 Life cycle assessment

3.1 Goal, scope and functional unit

The goal is to determine whether ammonia produced in Lebanon from solar power has lower life-cycle greenhouse-gas emissions than imported grey ammonia, under which supply configurations, and with what consequences for water and mineral resources. The intended audience is Lebanese energy and agriculture policymakers, prospective investors in green hydrogen and ammonia in the Eastern Mediterranean, and LCA practitioners. The study follows ISO 14040/14044 (ISO, 2006a, 2006b) and is attributional.

The **functional unit** is 1 kg of anhydrous ammonia (NH3) delivered to an agricultural distribution point in the Bekaa valley. Ammonia is used as the reference product because it is the nitrogen carrier common to all downstream fertilisers; conversion to urea or other products, field application and field N2O emissions are identical for both routes and are excluded. The boundary is cradle-to-gate plus delivery. It includes natural-gas extraction and supply, ammonia synthesis and transport for the grey route, and PV, electrolyser, battery and hydrogen-storage manufacture, grid electricity and water supply for the green route. The Haber–Bosch and air-separation plant hardware, catalysts and plant land occupation are excluded for both routes. No credit is given for co-produced oxygen. Climate change is assessed as GWP100 (kg CO2e).

3.2 Grey route: imported Egyptian ammonia

Grey ammonia is modelled as produced by SMR in Egypt, the dominant origin of Lebanon's nitrogen fertiliser (World Bank, n.d.), shipped about 460 km from Damietta to Beirut and trucked 60 km to the Bekaa (Table 2). Direct CO2 is computed from natural-gas use with the IPCC default of 56.1 kg CO2 per GJ (IPCC, 2006). Gas use is set at 40 GJ/t NH3, between the 28–33 GJ/t of best-available technology and the roughly 44 GJ/t implied by the 2.48 t CO2/t direct emissions reported for an Egyptian ammonia–nitric acid plant (Ricardo, 2023). Upstream emissions of gas production, processing and

transmission are 12 g CO2e/MJ, the global average used by the IEA, which also notes a more than five-fold variation between supply sources (IEA, 2025). Purchased electricity follows the Egyptian case study (Ricardo, 2023). Process water and mineral depletion for the grey route are taken from an openLCA model of the same route characterised with the EF 3.1 method.

Table 2. Grey-route inventory and parameters, per kg NH3 delivered to the Bekaa.

Item	Value (range)	Result (kg CO2e)	Source
Natural gas, feed + fuel	40 MJ (30.5–44)	—	(Ricardo, 2023)
Direct CO2, reforming and firing	0.0561 kg CO2/MJ	2.244	(IPCC, 2006)
Upstream gas supply	12 g CO2e/MJ (6–25)	0.480	(IEA, 2025)
Purchased electricity	0.041 kg CO2e (0.02–0.08)	0.041	(Ricardo, 2023)
Shipping (460 km) and trucking (60 km)	0.015 (0.010–0.025) and 0.154 kg CO2e/t·km	0.016	(DESNZ, 2024); assumption
Total climate change		**2.781**	
Water consumption	2.3 L (1.5–5.0)	—	openLCA, EF 3.1
Mineral depletion	3.08×10^{-7} kg Sb-eq	—	openLCA, EF 3.1

3.3 Green route: process and supply configurations

The green plant produces hydrogen in alkaline electrolysers and nitrogen in an air-separation unit, and synthesises ammonia in a Haber–Bosch loop. Stoichiometry requires 0.1776 kg H2 and 0.8224 kg N2 per kg NH3. Electrolyser system consumption is 55 kWh/kg H2 (49–64; Tully et al., 2025; Zaki et al., 2025), and the air-separation unit and synthesis loop require 0.73 kWh/kg NH3 (0.5–1.0), derived from the 10.5 kWh/kg NH3 total reported by Tully et al. (2025). The total load is therefore 10.50 kWh/kg NH3. Hydrogen sent to storage is compressed to about 200 bar at 2.0 kWh/kg H2 (1–3; assumption).

The plant has a nominal output of 1 kg NH3/h. Because all quantities scale linearly, results per kg are independent of plant size. Five supply configurations were modelled (Table 3).

Table 3. Green-ammonia supply configurations.

Code	Configuration	Operation	Sizing rule
G0	Grid only	Constant load, all electricity from the grid	—
G1	PV + grid backup	Constant load; PV used when available,	Annual PV generation = annual

Code	Configuration	Operation	Sizing rule
		grid otherwise, PV surplus curtailed	demand (ratio r = 1; r varied 0–3)
G2	PV + H2 storage + grid top-up	Electrolyser follows PV; H2 buffer feeds a constant synthesis loop; grid covers winter shortfall	PV sized for annual balance
G3	Islanded PV + battery	Constant load; LFP battery stores daytime surplus for the night	Smallest PV field that meets demand in every month (bisection)
G4	Islanded PV + H2 storage, flexible synthesis	Electrolyser follows PV; synthesis output varies by month between 60% and 100% of nominal	PV sized so that the darkest month runs at 60%

In G2 and G4 the air-separation unit and synthesis loop run continuously, so their night-time electricity is supplied from a small battery. The 60% minimum synthesis load follows recent design studies (Pistolesi et al., 2025; Tully et al., 2025).

3.4 Solar resource and hourly simulation

The Bekaa solar resource is represented by monthly in-plane irradiation at 20° tilt, from 3.98 kWh/m²/day in December to 8.17 in June (Hajj Shehadeh, 2015). For each month, the daily irradiation is distributed over the daylight hours of a representative day with a sine profile, using a day length computed from solar declination at 33.85° N. With a performance ratio of 0.80, the modelled yield is 1,877 kWh/kWp per year. This is higher than the 1,450–1,510 kWh/kWp average reported for installed Lebanese systems, many of which are rooftop and partly shaded (El Hajj and Abou Moussa, 2025), so scenario S7 tests an observed yield of about 1,480 kWh/kWp.

For each configuration and month, the 24 hourly PV outputs are compared with the load. The model records direct PV use, battery charge and discharge (round-trip efficiency 0.90), hydrogen sent to and drawn from storage, grid imports and curtailment. Battery capacity is set by the largest night-time deficit at 90% depth of discharge, and hydrogen storage by the largest daily volume consumed outside PV hours. Electrolyser capacity in G2 and G4 equals the peak PV output. The approach captures daily and seasonal variation but not multi-day cloudy periods (Section 4.11).

3.5 Equipment inventory

Table 4. Green-route equipment and electricity parameters.

Parameter	Value (range)	Source
PV module embodied GHG, Chinese production	810 (600–1,100) kg CO2e/kWp	(Reichel et al., 2022)
PV balance of system (mounting, inverter, cabling)	150 (100–250) kg CO2e/kWp	Assumption
PV lifetime; degradation	30 years; 0.5%/yr	Assumption

Parameter	Value (range)	Source
Resulting PV emission factor	18.3 g CO2e/kWh	Calculated
Electrolyser embodied GHG, incl. stack replacement	250 (120–500) kg CO2e/kW; 20 years	Assumption, consistent with embodied impacts below 10% of total (Zaki et al., 2025)
LFP battery embodied GHG	90.8 (60–120) kg CO2e/kWh; 15 years	(Lin et al., 2024)
Hydrogen storage, Type I steel vessels	60 (40–100) kg steel per kg H2 at 2.0 kg CO2e/kg steel; 30 years	Assumption
Lebanese grid electricity	0.626 (0.364–0.80) kg CO2e/kWh	(Ember, 2024; UNFCCC, 2022); Section 3.6

3.6 Grid electricity

The Lebanese grid factor of 0.626 kg CO2e/kWh weights the national generation intensity of 0.364 kg CO2e/kWh (Ember, 2024) at 40% and a diesel-generator factor of 0.80 kg CO2e/kWh, the CDM default for generator units above 200 kW (UNFCCC, 2022) at 60%, consistent with the generator share reported in the national renewable energy plan (MEW and LCEC, 2025). The same factor is used in the authors' companion assessments of Lebanese systems, so results are comparable across them. Scenarios S4 and S5 test EDL-only supply (0.364) and a 2030+ grid with a large renewable share (0.30).

3.7 Water and mineral indicators

Water consumption comprises stoichiometric water (8.94 kg per kg H2), purification reject at 75% recovery (70–90%), evaporative cooling (7 L per kg H2, 0–15; assumption, zero for dry cooling) and the water embodied in electricity (PV 0.2 L/kWh and grid 0.5 L/kWh; assumptions). Water scarcity is computed with AWARE characterisation factors (Boulay et al., 2018; Seitfudem et al., 2025): 98.4 m^3 world-eq/m^3 for non-agricultural use in Egypt, and a provisional 60 (30–100) for Lebanon pending the official country value. Mineral depletion uses CML abiotic depletion potentials based on ultimate reserves (van Oers et al., 2002), in kg Sb-eq/kg: silver 1.18, copper 1.37×10^{-3}, nickel 6.53×10^{-5}, lithium 1.15×10^{-5}, iron 5.24×10^{-8}. These are applied to the dominant metals in each component:

- PV: 12 g Ag/kWp (8–15.5; Zhang et al., 2021) and 3.6 kg Cu/kWp (2.5–5.0), consistent with about 68 t Cu/TWh (World Nuclear Association, 2024).
- Alkaline electrolysers: 1.0 kg Ni/kW (0.8–1.5; IEA, 2021b).
- LFP batteries: 0.5 kg Cu/kWh (0.3–0.8; assumption) and 0.10 kg Li/kWh (from LiFePO4 stoichiometry).
- Hydrogen storage vessels: steel.

For the grey route, the mineral result of the openLCA model characterised with EF 3.1 is used.

3.8 Scenarios, sensitivity and uncertainty

Table 5. Scenarios.

Scenario	Change from base
S1 Base	Values in Tables 2–4
S2 Best-practice grey	Gas 30.5 GJ/t, upstream 6 g CO2e/MJ
S3 High-intensity grey	Gas 44 GJ/t, upstream 25 g CO2e/MJ
S4 EDL grid only	Grid 0.364 kg CO2e/kWh
S5 2030+ grid	Grid 0.30 kg CO2e/kWh
S6 Advanced technology	Electrolyser 49 kWh/kg H2 and 120 kg CO2e/kW; PV modules 600 kg CO2e/kWp
S7 Observed PV yield	Performance ratio reduced so that yield is about 1,480 kWh/kWp

One-at-a-time sensitivity moved each uncertain parameter to its minimum and maximum. Uncertainty was propagated by Monte Carlo simulation with 10,000 paired runs and triangular distributions (Tables 2 and 4): each run used the same parameter draw for all routes, and equipment was re-sized in every run. The break-even grid share g* was derived for a constant-load plant without storage:

$$g^* = (GWP_{grey} - GWP_{electrolyser} - e \cdot EF_{PV}) / [e \cdot (EF_{grid} - EF_{PV})] \quad (1)$$

where e is the total electricity demand per kg NH3 and EF_PV and EF_grid are the emission factors of PV and grid electricity.

3.9 Implementation and verification

The model was implemented in Python and independently in a spreadsheet with live formulas for the 288-hour solar profile, both routes and all five configurations. For the battery configuration, the PV size found by bisection in Python is entered in the spreadsheet, and a live energy-balance check confirms that the worst month is just met. The two implementations agree to within 2×10^{-9} (relative) on every base-case quantity.

4. Results and discussion

4.1 Climate change: grey ammonia and the five green configurations

Imported grey ammonia emits 2.78 kg CO2e per kg NH3 delivered to the Bekaa (Table 6). Direct CO2 from reforming and firing contributes 2.24 kg (81%), upstream gas supply 0.48 kg (17%), purchased electricity 0.04 kg and shipping and trucking 0.02 kg. The result lies within the 1.6–2.5 t CO2/t direct emissions reported for Egyptian plants (Ricardo, 2023) once upstream emissions are added.

Table 6. Climate change by route and contributor, kg CO2e per kg NH3 (S1).

Contributor	Grey	G0	G1	G2	G3	G4
Direct process CO2	2.244	—	—	—	—	—
Natural gas upstream	0.480	—	—	—	—	—
Grid electricity	0.041	6.570	3.615	0.683	—	—
PV electricity (embodied)	—	—	0.192	0.196	0.332	0.215
Electrolyser	—	0.014	0.014	0.056	0.014	0.061
Battery	—	—	—	0.008	0.121	0.008
Hydrogen storage	—	—	—	0.001	—	0.001
Transport	0.016	—	—	—	—	—
Total	**2.781**	**6.584**	**3.821**	**0.944**	**0.466**	**0.284**
Change vs grey	—	+137%	+37%	−66%	−83%	−90%

The green configurations split into two groups. The three with storage are far below grey: the islanded plant with hydrogen storage and flexible synthesis (G4) emits 0.28 kg CO2e/kg NH3, the islanded plant with batteries (G3) 0.47, and the hybrid with winter grid top-up (G2) 0.94. The two without storage are above grey. Grid-only electrolysis (G0) emits 6.58 kg, more than twice the grey value, because the 10.5 kWh of electricity needed per kg NH3 carries Lebanon's 0.626 kg CO2e/kWh. PV with grid backup (G1) emits 3.82 kg, 37% more than grey, because a constant-load plant can draw only 45% of its electricity directly from PV even when the PV field generates as much electricity as the plant uses over a year; the rest is drawn from the grid at night.

Figure 1 generalises this result. For a constant-load plant without storage, emissions rise linearly with the grid share (Eq. 1), and green ammonia equals grey at a grid share of g* = 40%. Adding more PV to configuration G1 does not help: with a PV field three times the annual demand, the grid share falls only to 51%, and emissions stay at about 3.8–4.0 kg CO2e/kg NH3 because the additional panels are mostly curtailed. Without storage, the 40% threshold is out of reach. Hydrogen or battery storage moves the plant into the low-carbon region by shifting solar electricity, or the hydrogen made from it, into the night.

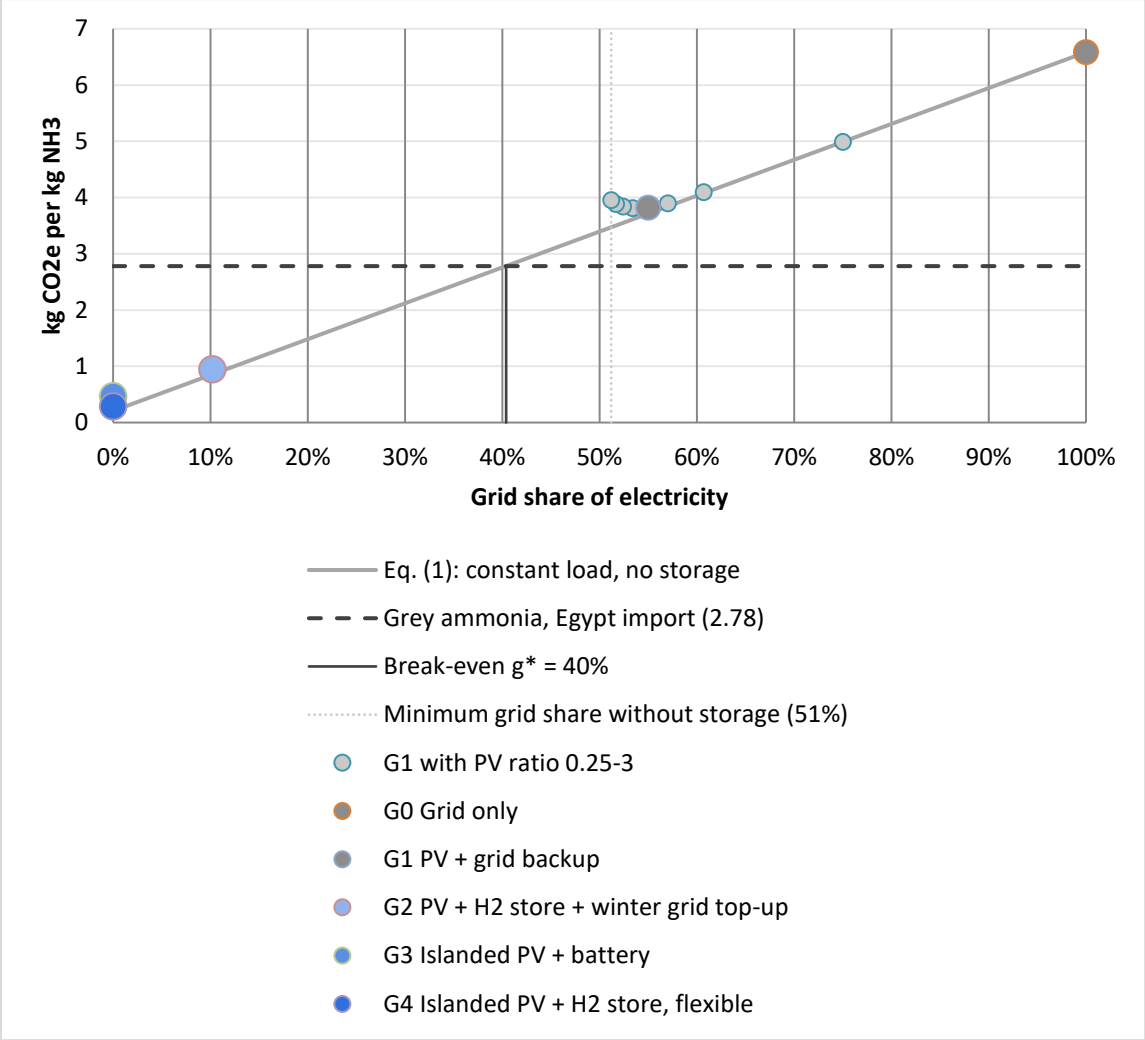


Figure 1. Climate change impact of green ammonia (kg CO_2e/kg NH_3) against the share of electricity drawn from the Lebanese grid, compared with imported grey ammonia from Egypt (2.78 kg CO_2e/kg NH_3, dashed line). The solid line is Eq. (1), without curtailment: a constant-load plant with no storage. Along it, emissions rise from 0.21 kg CO_2e/kg NH_3 on PV alone to 6.58 kg on the grid alone, and they equal grey ammonia at a grid share of g* = 40%. The small grey circles show configuration G1 with PV fields from 0.25 to 3 times the annual demand. Even the largest field brings the grid share down only to 51% (dotted line), so G1 stays at 3.8–4.0 kg CO_2e/kg NH_3. The large markers are the five configurations: G0 grid-only (6.58), G1 PV and grid without storage (3.82), G2 PV with hydrogen storage and winter grid top-up (0.94), G3 islanded PV with batteries (0.47) and G4 islanded PV with hydrogen storage and flexible synthesis (0.28). Blue markers are configurations with storage and grey markers are configurations without storage. Source: this study's calculations, base scenario S1.

4.2 Equipment sizing and seasonal operation

Table 7 shows the equipment each configuration needs per 1 kg NH3/h of nominal capacity. The configurations that work, G2–G4, differ mainly in how they handle the night and the winter.

Table 7. Equipment sizing and operation per 1 kg NH3/h nominal capacity (S1).

Quantity	G0	G1	G2	G3	G4
PV field (kWp)	—	49.0	50.0	84.6	48.6
Electrolyser (kW)	9.8	9.8	39.0	9.8	37.9
Electrolyser capacity factor	1.00	1.00	0.25	1.00	0.23
Battery (kWh)	—	—	11.4	174.5	9.7
Hydrogen storage (kg H2)	—	—	2.5	—	2.1
Grid share of electricity	100%	55%	10%	0%	0%
PV curtailed	—	55%	10%	42%	9%
Annual output (share of nominal)	100%	100%	100%	100%	89%

The battery-based plant (G3) must carry the full 10.5 kW load through nights of up to 14 hours. It therefore needs 175 kWh of batteries and a PV field sized for December, of which 42% is curtailed over the year. The battery contributes 0.12 kg CO2e/kg NH3 and the oversized PV field 0.33 kg (Table 6). The hydrogen-buffered plants (G2, G4) let the electrolyser follow the sun. They need an electrolyser four times larger, running at a capacity factor of only 23–25%, but they store hydrogen rather than electricity, and the hydrogen buffer of 2–2.5 kg contributes almost nothing to emissions.

The main difference between G2 and G4 is seasonal (Figure 2). The Bekaa PV field produces about twice as much per day in June as in December. G4 sizes PV so that December still supports 60% output and lets the synthesis loop run at 60–91% from November to March. This keeps curtailment at 9% and avoids grid electricity entirely, at the cost of an 11% lower annual output from the same plant. G2 instead holds output at 100% and imports winter electricity from the grid. Its 10% grid share contributes 0.68 kg CO2e/kg NH3, which explains why G2 emits more than three times as much as G4.

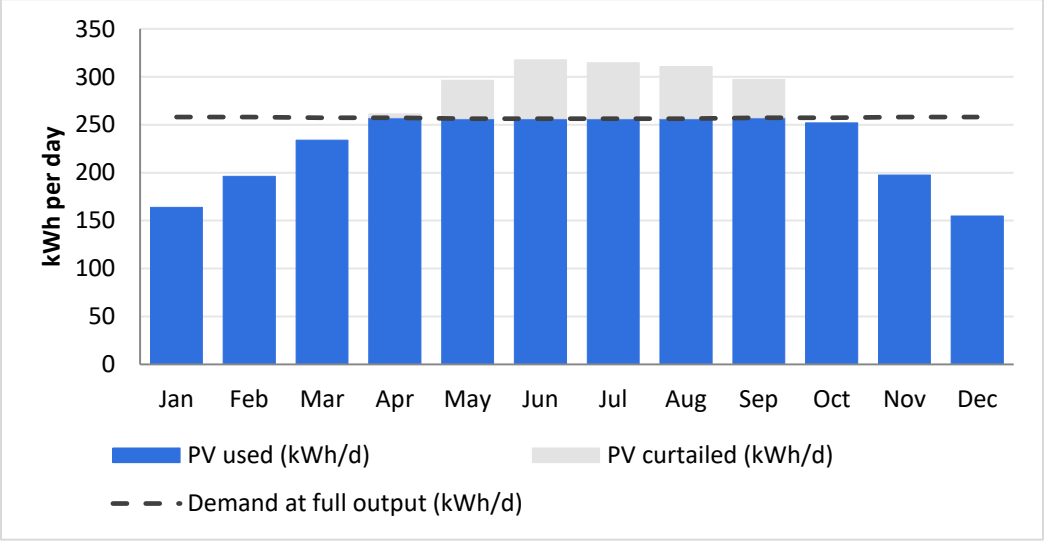


Figure 2. Monthly energy balance of the islanded PV and hydrogen-buffered configuration (G4) for a plant with 1 kg NH_3/h nominal capacity, in kWh per day. Blue bars are the PV electricity used and light bars are curtailed PV. The dashed line is the electricity demand at full output. From November to March, the synthesis loop runs at 60–91% of nominal output to follow the PV supply, instead of storing hydrogen for months. This keeps annual curtailment at 9% and means no grid electricity is needed. Source: this study's calculations, configuration G4, base scenario S1.

4.3 Scenarios, sensitivity and uncertainty

Table 8 reports climate change under each scenario. The ranking of the storage-based configurations is unchanged in every scenario, and all three stay well below grey ammonia. The grey benchmark itself spans 1.95 kg CO2e/kg NH3 (best-practice plant and low-leakage gas, S2) to 3.63 (high-intensity plant and high-leakage gas, S3). Even against best-practice grey, G4 is 85% lower and G2 52% lower. The break-even grid share moves with the grey benchmark, from 27% (S2) to 54% (S3), and with the grid factor, to 71% on EDL-only supply (S4) and 87% on a 2030+ grid of 0.30 kg CO2e/kWh (S5). In S5, PV with grid backup (G1) finally falls below grey, at 1.94 kg CO2e/kg NH3. With the observed average Lebanese PV yield of about 1,480 kWh/kWp (S7), emissions of the solar configurations rise by 1–20% but the conclusions do not change.

Table 8. Climate change by scenario, kg CO2e per kg NH3, and break-even grid share g*.

Scenario	Grey	G0	G1	G2	G3	G4	g*
S1 Base	2.78	6.58	3.82	0.94	0.47	0.28	40%
S2 Best-practice grey	1.95	6.58	3.82	0.94	0.47	0.28	27%
S3 High-intensity grey	3.63	6.58	3.82	0.94	0.47	0.28	54%
S4 EDL grid only (0.364)	2.78	3.83	2.31	0.66	0.47	0.28	71%
S5 2030+ grid (0.30)	2.78	3.16	1.94	0.59	0.47	0.28	87%
S6 Advanced technology	2.78	5.91	3.39	0.79	0.35	0.19	46%
S7 Observed PV yield	2.78	6.58	3.87	1.00	0.56	0.34	40%

One-at-a-time sensitivity shows different drivers for each route. Grey ammonia is driven by natural-gas intensity (2.13–3.05 kg CO2e/kg NH3 over 30.5–44 GJ/t) and upstream gas emissions (2.54–3.30 over 6–25 g CO2e/MJ). For the islanded configurations, the embodied carbon of PV modules is the largest driver (G4: 0.24–0.35; G3: 0.39–0.57), followed by electrolyser electricity use, electrolyser embodied carbon (G4) and battery embodied carbon (G3). For G2 the grid factor dominates (0.66–1.13).

The Monte Carlo results (Table 9) confirm the split between configurations with and without storage. G2, G3 and G4 were lower than grey in all 10,000 paired runs. PV with grid backup was lower in only 6% of runs, and grid-only electrolysis in none. The break-even grid share has a 90% interval of 30–59%, so even its upper bound is close to the 51% minimum that PV without storage can achieve.

Table 9. Monte Carlo results (10,000 paired runs), climate change in kg CO2e per kg NH3.

Route	P5	P50	P95	Probability lower than grey
Grey (Egypt import)	2.34	2.75	3.17	—
G0 Grid only	4.65	6.42	8.04	0%
G1 PV + grid backup	2.76	3.75	4.65	6%
G2 PV + H2 store + winter grid	0.75	0.95	1.14	100%
G3 Islanded PV + battery	0.41	0.49	0.58	100%
G4 Islanded PV + H2 store, flexible	0.25	0.31	0.37	100%
Break-even grid share g*	30%	41%	59%	—

4.4 Resource trade-offs: water and minerals

The climate benefit of the storage-based configurations comes with higher water and mineral use (Figure 3). Water consumption is 5.7–7.0 L per kg NH3, compared with 2.3 L for grey. Of this, 2.1 L is stoichiometric and purification water, 1.2 L is evaporative cooling, and the rest is water embodied in PV and grid electricity. Weighted by AWARE factors, the green configurations score 1.5–1.9 times the grey value. This ratio is smaller than the volume ratio because Egyptian water, which grey ammonia consumes, is close to the maximum scarcity factor (98.4). The ratio depends on the provisional Lebanese factor of 60. The Monte Carlo medians (0.39–0.48 m³ world-eq for G2–G4 against 0.28 for grey) indicate that the green configurations very likely carry a higher water-scarcity burden.

Mineral depletion rises 12–23-fold, from 3.1×10^{-7} kg Sb-eq for grey to $3.7–7.1 \times 10^{-6}$ for G2–G4. In G2 and G4 about 73% of this comes from silver in the PV modules and about 25% from copper in modules and cabling. G3 has the highest value mainly because its PV field is 74% larger, with the copper in 175 kWh of batteries adding a further 13%. Nickel in the alkaline electrolysers contributes less than 1%, because its depletion potential is low, although supply-sustainability concerns for nickel remain (Xun et al., 2025).

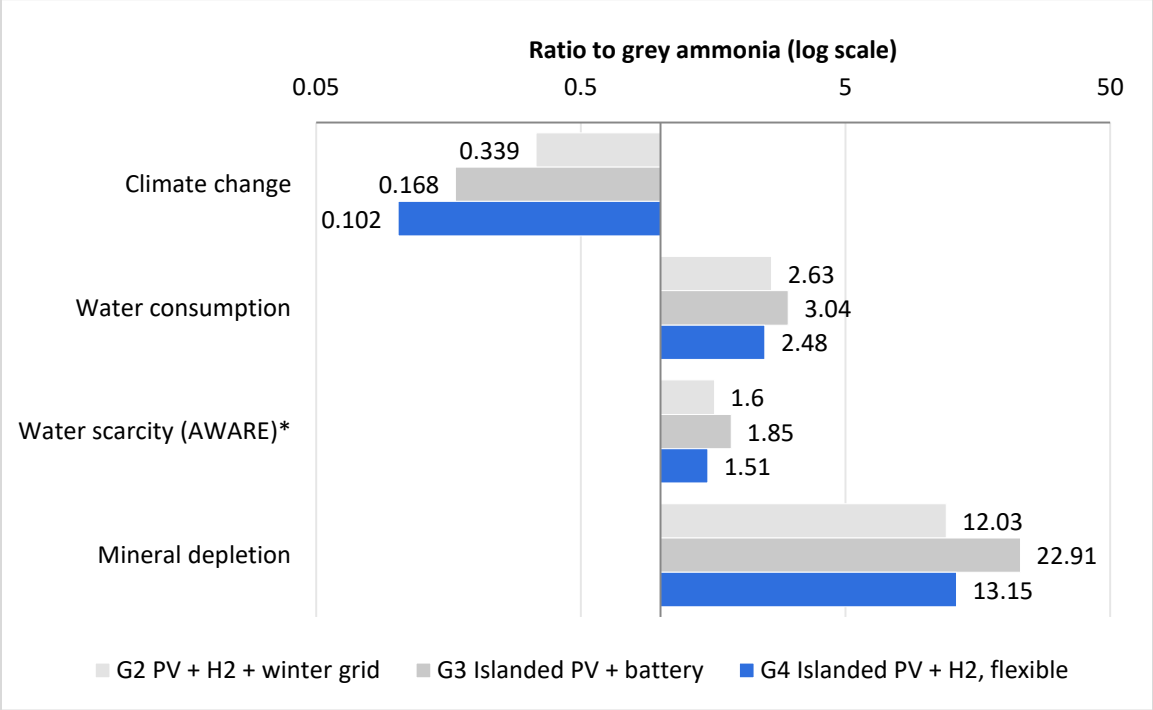


Figure 3. Environmental profile of the three storage-based green ammonia configurations (G2–G4), shown as ratios to imported grey ammonia (grey = 1, log scale). Green ammonia cuts climate change impact by 66–90%. The costs are 2.5–3.0 times more water consumption, 1.5–1.9 times higher AWARE-weighted water scarcity, and 12–23 times higher mineral resource depletion, mainly from silver and copper in PV modules. G2: PV with hydrogen storage and winter grid top-up. G3: islanded PV with battery storage. G4: islanded PV with hydrogen storage and flexible synthesis. Source: this study's calculations, base scenario S1. The water scarcity result uses a provisional AWARE characterisation factor for Lebanon (60) and 98.4 for Egypt.

4.5 Comparison with the literature

Grey ammonia: The grey result of 2.78 kg CO2e/kg NH3 is higher than the roughly 1.8 kg often quoted for gas-based ammonia (Al-Ghussain et al., 2025) and the 1.6–2.5 t CO2/t direct emissions of Egyptian plants (Ricardo, 2023). The difference is upstream gas supply (0.48 kg), which direct-emission benchmarks omit, and a gas intensity representative of Egyptian rather than best-available plants. The best-practice case (S2, 1.95) matches the lower literature values. This confirms the point made by Mayer et al. (2023) and Lee et al. (2022) that gas-supply emissions are a material part of the fossil benchmark.

Green ammonia: The islanded results of 0.28–0.47 kg CO2e/kg NH3 fall within the 0.1–0.5 range reported for PV and wind in Jordan (Al-Ghussain et al., 2025) and below the 0.79 reported for a South African facility that includes the energy-supply infrastructure and synthesis plant (Stafford et al., 2025). The comparison with Stafford et al. (2025) is approximate because the present study excludes Haber–Bosch and air-separation hardware. The grid-only result corresponds to about 34 kg CO2e per kg of hydrogen, above the upper end of the 0.5–30 kg range in recent reviews of electrolytic hydrogen (Ajeeb et al., 2024; Shaya and Glöser-Chahoud, 2024), because Lebanon's diesel-heavy grid is more carbon-intensive than almost any grid in those reviews.

Embodied infrastructure: Electrolyser

manufacture contributes 21% of G4 emissions, more than the below-10% share reported by Zaki et al. (2025). The reason is the electrolyser's capacity factor of 23% when it follows the sun, which spreads the same embodied carbon over less hydrogen. This supports the argument by Gan et al. (2024) that the embodied emissions of the supply system must be counted when electrolysis is coupled to variable renewables.

Flexibility: The finding that a flexible synthesis loop removes the need for seasonal storage, at the cost of about 11% of annual output, agrees with techno-economic studies that identify flexibility as the main lever for reducing storage (Pistolesi et al., 2025; Tully et al., 2025; Wang et al., 2023; Zhou et al., 2024). Pistolesi et al. (2025) capped grid electricity at 10% for their product to count as green. The present results show that, on a grid of 0.626 kg CO2e/kWh, a 10% share already adds 0.68 kg CO2e/kg NH3. The cap is well below the 40% break-even, but it is not a negligible penalty.

4.6 Drivers of impacts and trade-offs

Three drivers determine the result.

1. **The grid share of electricity.** This is the dominant driver for any configuration that touches the grid, and it is bounded below by about 51% for a constant-load plant without storage.
2. **The embodied carbon of PV electricity.** At 18 g CO2e/kWh, this is the dominant contribution in the islanded configurations. It scales with module manufacturing emissions and inversely with yield.
3. **For grey ammonia, natural-gas intensity and supply-chain methane.** Together these set a benchmark that varies by a factor of almost two.

The trade-offs are the following.

- **Minerals and water.** Discussed in Section 4.4: 12–23 times more mineral depletion and 2.5–3 times more water consumption.
- **Land:** At an indicative ground-mounted density of 33 MW/km² (IRENA, 2020), the G4 configuration needs about 0.19 km² of PV per thousand tonnes of annual ammonia output. A plant meeting a substantial share of Lebanese nitrogen demand would therefore occupy several square kilometres of the Bekaa, where land is also agricultural.
- **Output and capital use:** The flexible G4 plant produces 11% less than its nominal capacity, and its electrolysers run at a 23% capacity factor. Both raise the cost per tonne, which this study does not assess.
- **Product form:** Lebanon imports nitrogen mainly as urea, whose synthesis requires CO2. Grey plants obtain this CO2 from reforming, whereas a green plant would need a separate CO2 source or would have to supply ammonium-based fertilisers instead. The functional unit of ammonia deliberately avoids this downstream question, but it affects how readily green ammonia could replace current imports.

4.7 Improvement opportunities

The sensitivity and scenario results identify the main levers:

1. **Avoid grid electricity, or require it to be time-matched to low-carbon supply.** This is the single largest lever. Islanded operation (G3, G4) or a strict cap on grid imports, ideally combined with dedicated renewable supply for the residual load, keeps the plant in the low-carbon region of Figure 1.
2. **Prefer hydrogen buffering and synthesis flexibility to batteries.** G4 emits 39% less than G3, uses a PV field 43% smaller and curtails 9% rather than 42% of its PV output.
3. **Use lower-carbon PV and more efficient electrolysers.** Advanced technology (S6) lowers G4 to 0.19 kg CO2e/kg NH3.
4. **Reduce silver use.** Silver dominates mineral depletion. Moving to modules with lower

silver loading, or to copper metallisation, and recovering silver at end of life would address the largest trade-off.

5. **Use dry cooling and non-potable feedwater.** Removing evaporative cooling would cut water consumption by about 1.2 L/kg NH3. Using treated wastewater or desalinated brackish water as electrolyser feed, as assessed in a companion study by the authors, would reduce competition with irrigation.
6. **Add wind where available.** A complementary wind resource, for example in northern Lebanon, would reduce the seasonal mismatch and the need to turn down in winter. This option was not modelled.

4.8 Policy and industry implications

For Lebanese policymakers, the main implication is that green ammonia support should be conditional on how a plant is supplied, not only on its use of electrolysis. A plant that draws more than about 40% of its electricity from the current grid, which in practice means any constant-load plant without storage, would increase emissions relative to imported fertiliser. Certification or support schemes should therefore require islanded operation, hourly matching of grid imports with additional renewable supply, or a grid-share cap well below the break-even. The 10% cap proposed in the literature (Pistolesi et al., 2025) would be a defensible choice. As the grid decarbonises under the national renewable energy plan (MEW and LCEC, 2025), the break-even rises (71% on EDL-only supply, 87% at 0.30 kg CO2e/kWh), so grid-connected designs become viable later. Their emissions are locked in by the grid's present carbon intensity, however, not its future one.

For investors and developers, the results favour hydrogen-buffered, flexible plants. They also show that water and mineral footprints should be reported alongside carbon. For Egyptian exporters of grey ammonia, the 0.48 kg CO2e/kg NH3 of upstream gas emissions is a reduction opportunity in its own right, and one that will matter as carbon border adjustments extend to fertilisers (Ricardo, 2023).

4.9 Limitations

The study has the following limitations.

- **Solar resource.** The resource is represented by one representative day per month. Multi-day cloudy periods, which would increase storage needs, are not captured. The modelled yield of 1,877 kWh/kWp exceeds the observed Lebanese average, tested in S7.
- **Plant scope.** The Haber–Bosch and air-separation hardware, catalysts and plant construction are excluded for both routes. This slightly favours the green route, whose plant may be sized above its average output.
- **Cost.** Cost is not assessed, although it is central to the feasibility of the low-capacity-factor configurations.
- **Water scarcity factor.** The Lebanese AWARE factor is provisional and must be replaced with the official value before the water-scarcity results are used.
- **Mineral method.** Mineral depletion for the green route is computed bottom-up for the dominant metals, whereas the grey value comes from the openLCA model characterised with EF 3.1. The two are therefore not fully consistent.
- **Grid accounting.** The grid factor is an attributional average. A marginal approach would probably assign diesel generation to additional loads, which would make grid-connected configurations worse.
- **Grey origin.** The grey route is modelled for Egyptian supply only. The urea question discussed in Section 4.6 is outside the functional unit.

These limitations affect the magnitude of individual results more than the main conclusion. Whether storage is used, and how much grid electricity a plant draws, decides the sign of the comparison.

5. Conclusions

This study compared imported Egyptian grey ammonia with ammonia made from Bekaa solar power under five supply configurations, with solar intermittency simulated hour by hour and the firming equipment included in the inventory. The main conclusions are:

1. **The firming strategy, not the solar resource, decides the result.** With storage, green ammonia emits 0.28–0.94 kg CO2e/kg NH3, 66–90% less than grey ammonia at 2.78. Without storage, it emits 3.82 (PV with grid backup) to 6.58 (grid only), 37–137% more.
2. **There is a clear grid-share threshold.** Under Lebanese electricity at 0.626 kg CO2e/kWh, green ammonia loses its climate advantage above a grid share of about 40% (90% interval 30–59%). A constant-load plant with PV but no storage cannot get below about 51%, however large its PV field.
3. **Hydrogen buffering with a flexible synthesis loop is the best design.** Turning the loop down to 60% in winter (G4) avoids grid electricity and seasonal storage, gives the lowest emissions (0.28 kg CO2e/kg NH3) and curtails only 9% of PV output, at the cost of 11% lower annual output. A battery-based islanded plant emits 64% more and curtails 42% of its PV output.
4. **The results are robust.** All three storage-based configurations were lower than grey in all 10,000 Monte Carlo runs and in every scenario, including against a best-practice grey benchmark of 1.95 kg CO2e/kg NH3.
5. **The low-carbon routes shift burdens to resources.** Mineral depletion rises 12–23-fold, driven by silver in PV modules, and water consumption 2.5–3-fold, with water scarcity about 1.5–1.9 times higher on provisional factors.

For Lebanon, the implication is that green-ammonia support should be tied to verified islanded operation or hourly-matched supply, and to a grid-share cap well below the break-even, such as 10%. It should not be given simply for using electrolysis. Future work should add cost, multi-day weather from a typical meteorological year, wind complementarity, the official AWARE factor for Lebanon, and the CO2 supply needed if green ammonia is to be converted to urea.

Declarations

Data availability. The calculation model (spreadsheet with live formulas and Python script) is available from the corresponding author on reasonable request. All input data are from the cited sources or are identified as assumptions.

References

1. Ajeeb, W., Costa Neto, R., Baptista, P. (2024). Life cycle assessment of green hydrogen production through electrolysis: a literature review. *Sustainable Energy Technologies and Assessments*, 69, 103923. https://doi.org/10.1016/j.seta.2024.103923
2. Al Hallak, M., Kurdieh, A.A., Yassine, A., El Hage, R., Saliba, N. (2024). When do science recommendations stop being effective? The case of the sprawl of diesel electricity generators in Beirut. *PLOS ONE*, 19, e0313341. https://doi.org/10.1371/journal.pone.0313341
3. Al-Ghussain, L., Alrbai, M., Al-Dahidi, S. (2025). Comprehensive techno-economic and life cycle greenhouse gases analysis of green ammonia production utilizing PV and wind energy: Jordan as a case study. *Renewable Energy*, 249, 123249. https://doi.org/10.1016/j.renene.2025.123249
4. Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., et al. (2018). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water

consumption based on available water remaining (AWARE). *International Journal of Life Cycle Assessment*, 23(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

5. DESNZ (2024). Greenhouse gas reporting: conversion factors 2024. UK Department for Energy Security and Net Zero, London.
6. El Hajj, M., Abou Moussa, H. (2025). *The 2023 Solar PV Status Report for Lebanon*. Lebanese Center for Energy Conservation, Beirut.
7. Ember (2024). Yearly electricity data: Lebanon (generation mix and carbon intensity, 2023). Ember, London.
8. Gado, M.G. (2024). Techno-economic-environmental assessment of green hydrogen and ammonia synthesis using solar and wind resources for three selected sites in Egypt. *e-Prime – Advances in Electrical Engineering, Electronics and Energy*, 10, 100780.
9. Gan, Y., Ng, C., Elgowainy, A., Marcinkoski, J. (2024). Considering embodied greenhouse emissions of nuclear and renewable power plants for electrolytic hydrogen and its use for synthetic ammonia, methanol, Fischer–Tropsch fuel production. *Environmental Science & Technology*, 58(42), 18654–18662. https://doi.org/10.1021/acs.est.3c06769
10. González Palencia, J.C., Itoi, Y., Araki, M. (2022). Design of a hydrogen production system considering energy consumption, water consumption, CO2 emissions and cost. *Energies*, 15, 7938. https://doi.org/10.3390/en15217938
11. Hajj Shehadeh, N. (2015). *Solar-Powered Pumping in Lebanon: A Comprehensive Guide on Solar Water Pumping Solutions*. UNDP-CEDRO, Beirut.
12. IEA (2021a). *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production*. International Energy Agency, Paris.
13. IEA (2021b). *The Role of Critical Minerals in Clean Energy Transitions*. International Energy Agency, Paris.
14. IEA (2025). *Assessing Emissions from LNG Supply and Abatement Options*. International Energy Agency, Paris, June 2025.
15. IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 2: Energy, Chapter 2 Stationary Combustion. IGES, Hayama.
16. IRENA (2020). *Renewable Energy Outlook: Lebanon*. International Renewable Energy Agency, Abu Dhabi.
17. ISO (2006a). *ISO 14040:2006/Amd 1:2020. Environmental management — Life cycle assessment — Principles and framework*. International Organization for Standardization, Geneva.
18. ISO (2006b). *ISO 14044:2006/Amd 1:2017/Amd 2:2020. Environmental management — Life cycle assessment — Requirements and guidelines*. International Organization for Standardization, Geneva.
19. Kadam, R.S., Yadav, G.D. (2024). Life cycle analysis of ammonia and methane production using green hydrogen and carbon dioxide. *Journal of Cleaner Production*, 449, 141620. https://doi.org/10.1016/j.jclepro.2024.141620
20. Kim, H., Choe, C., Lee, A., Lim, H. (2023). Application of green hydrogen with theoretical and empirical approaches of alkaline water electrolysis: life cycle-based techno economic and environmental assessments of renewable urea synthesis. *International Journal of Hydrogen Energy*, 48, 16148. https://doi.org/10.1016/j.ijhydene.2023.01.062
21. Kim, K.-M., Kim, D. (2024). Life cycle assessment of greenhouse gas emissions in hydrogen production via water electrolysis in South Korea. *Sustainability*, 16, 11010. https://doi.org/10.3390/su162411010

22. Koj, J.C., Zapp, P., Wieland, C.M., Görner, K., Kuckshinrichs, W. (2025). Green hydrogen production by PEM water electrolysis up to the year 2050: prospective life cycle assessment using learning curves. *Journal of Industrial Ecology*, 29, 145. https://doi.org/10.1111/jiec.13592

23. Lee, K., Liu, X., Vyawahare, P., Sun, P., Elgowainy, A., Wang, M. (2022). Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production. *Green Chemistry*, 24(12), 4830–4844. https://doi.org/10.1039/d2gc00843b

24. Lin, X., Meng, W., Yu, M., Yang, Z., Luo, Q., Rao, Z., Zhang, T., Cao, Y. (2024). Environmental impact analysis of lithium iron phosphate batteries for energy storage in China. *Frontiers in Energy Research*, 12, 1361720. https://doi.org/10.3389/fenrg.2024.1361720

25. Mayer, P., Ramírez, A., Pezzella, G., Winter, B., Sarathy, S.M., Gascón, J., Bardow, A. (2023). Blue and green ammonia production: a techno-economic and life cycle assessment perspective. *iScience*, 26, 107389. https://doi.org/10.1016/j.isci.2023.107389

26. MEW and LCEC (2025). *The National Renewable Energy Action Plan of Lebanon, 2025–2030* (lead author S. Mortada). Ministry of Energy and Water and Lebanese Center for Energy Conservation, Beirut, September 2025.

27. Oni, A.O., Giwa, T., Font-Palma, C., Fadare, D.A. (2022). Comparative techno-economic and life cycle greenhouse gas assessment of ammonia production from thermal decomposition of methane and steam methane reforming technologies. *International Journal of Greenhouse Gas Control*, 123, 103819. https://doi.org/10.1016/j.ijggc.2022.103819

28. Pistolesi, C., Giaconia, A., Bassano, C., De Falco, M. (2025). Flexible green ammonia production: impact of process design on the levelized cost of ammonia. *Fuels*, 6, 39. https://doi.org/10.3390/fuels6020039

29. Rai, A., Oh, T.H. (2026). Long-term climate vulnerability of green ammonia economics: an integrated techno-economic and life cycle assessment across Köppen-Geiger zones. *Applied Energy*, 425, 128532. https://doi.org/10.1016/j.apenergy.2026.128532

30. Reichel, C., Müller, A., Friedrich, L., Herceg, S., Mittag, M., Neuhaus, D.H. (2022). CO2 emissions of silicon photovoltaic modules – impact of module design and production location. In *Proceedings of the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8)*, Milan, 26–30 September 2022. Fraunhofer ISE.

31. Ricardo (2023). *CBAM training case study – Nitrogen fertilizers, Egypt*. Ricardo plc for the European Bank for Reconstruction and Development, London, December 2023.

32. Santos Sánchez, A., Nonato, G.V., Silva, A.L., Nogueira, I.B.R., Rebello, C.M., Medeiros, D.L., et al. (2026). Water consumption in hydrogen production through electrolysis: overview, state-of-the-art, and future trends. *WIREs Energy and Environment*, 15. https://doi.org/10.1002/wene.70035

33. Seitfudem, G., Berger, M., Müller Schmied, H., Boulay, A.-M. (2025). The updated and improved method for water scarcity impact assessment in LCA, AWARE2.0. *Journal of Industrial Ecology*, 29(3), 891–907. https://doi.org/10.1111/jiec.70023

34. Shaya, N., Glöser-Chahoud, S. (2024). A review of life cycle assessment (LCA) studies for hydrogen production technologies through water electrolysis: recent advances. *Energies*, 17, 3968. https://doi.org/10.3390/en17163968

35. Song, G., Chen, Y., He, Y., Jia, Q., Wu, Q., Cui, X., Zhao, H. (2025). Techno-economic and life cycle greenhouse gas assessment of green ammonia produced by low-pressure Haber-Bosch process. *Energy Nexus*, 17, 100379. https://doi.org/10.1016/j.nexus.2025.100379

36. Stafford, W.H.L., Chaba, K.J., Russo, V., Goga, T., Roos, T.H., Sharp, M., Nahman, A. (2025). Life cycle assessment of green ammonia production at a coastal facility in South Africa. *Frontiers in Energy*, 19, 1072. https://doi.org/10.1007/s11708-025-1013-5

37. Tully, Z., King, J., Johnson, K. (2025). Hydrogen storage minimization under industrial flexibility constraints: a techno-economic analysis of off-grid green ammonia production. *International Journal of Hydrogen Energy*, 111, 12–21. https://doi.org/10.1016/j.ijhydene.2025.02.109

38. UNFCCC (2022). AMS-I.F.: Renewable electricity generation for captive use and mini-grid, version 05.0 (CDM-MP88-A08), default emission factors for diesel generator systems. UNFCCC CDM, Bonn.

39. van Oers, L., de Koning, A., Guinée, J.B., Huppes, G. (2002). *Abiotic Resource Depletion in LCA: Improving Characterisation Factors for Abiotic Resource Depletion as Recommended in the New Dutch LCA Handbook*. DWW report 2002.032. Road and Hydraulic Engineering Institute (Rijkswaterstaat), Delft.

40. Vázquez-Sánchez, H., Okeke, I.J., Singh, E., Baaqel, H., Saville, B.A., MacLean, H.L., Sarathy, S.M. (2025). A life cycle assessment of e-hydrogen production using proton-exchange membrane water electrolysis coupled with desalination in Saudi Arabia. *International Journal of Hydrogen Energy*, 139, 792. https://doi.org/10.1016/j.ijhydene.2025.05.154

41. Wang, C., Walsh, S.D.C., Longden, T., Palmer, G., Lutalo, I., Dargaville, R. (2023). Optimising renewable generation configurations of off-grid green ammonia production systems considering Haber-Bosch flexibility. *Energy Conversion and Management*, 280, 116790. https://doi.org/10.1016/j.enconman.2023.116790

42. Wang, X., Zhang, W., Yang, K., Guo, J., Li, Z., Zou, R., Chen, P., Zhang, C., Yi, Z. (2026). PVT-powered green ammonia synthesis system: coordinated multi-energy optimization and life cycle evaluation. *Applied Thermal Engineering*, 300, 131389. https://doi.org/10.1016/j.applthermaleng.2026.131389

43. Wen, D., Aziz, M. (2022). Flexible operation strategy of an integrated renewable multi-generation system for electricity, hydrogen, ammonia, and heating. *Energy Conversion and Management*, 253, 115166. https://doi.org/10.1016/j.enconman.2021.115166

44. World Bank (n.d.). World Integrated Trade Solution (WITS): Lebanon imports of urea (HS 310210) by partner, 2023. https://wits.worldbank.org (accessed 2026).

45. World Nuclear Association (2024). Mineral requirements for electricity generation (updated 3 December 2024; copper data from Bright New World). WNA, London.

46. Xun, D., Liu, M., Hao, H., Sun, X., Geng, Y., You, F., Dou, H., Li, H., Dong, Z. (2025). Sustainable supply of critical materials for water electrolysers and fuel cells. *Communications Earth & Environment*, 6. https://doi.org/10.1038/s43247-025-02621-6

47. Yu, Z., Lin, J., Liu, F., Li, J., Zhao, Y., Song, Y., Song, Y., Zhang, X. (2024). Optimal sizing and pricing of grid-connected renewable power to ammonia systems considering the limited flexibility of ammonia synthesis. *IEEE Transactions on Power Systems*, 39(2), 3631.

https://doi.org/10.1109/TPWRS.2023.3279130

48. Zaki, M.T., Smith, C., Badgett, A., Breunig, H.M. (2025). Liquid alkaline water electrolyzers: comparing performance across design, operation, and end-of-life scenarios. *Environmental Science & Technology*, 59(41), 21941–21956.
49. Zhang, J., Wang, Z., He, Y., Li, M., Wang, X., Wang, B., Zhu, Y., Cen, K. (2023). Comparison of onshore/offshore wind power hydrogen production through water electrolysis by life cycle assessment. *Sustainable Energy Technologies and Assessments*, 60, 103515. https://doi.org/10.1016/j.seta.2023.103515
50. Zhang, Y., Kim, M., Wang, L., Verlinden, P., Hallam, B. (2021). Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption. *Energy & Environmental Science*, 14(11), 5587–5610. https://doi.org/10.1039/D1EE01814K
51. Zhou, J., Zhang, Z., Zhang, R., Zhang, W., Xu, G., Wang, H. (2024). Optimal capacity and multi-stable flexible operation strategy of green ammonia systems: adapting to fluctuations in renewable energy. *Energy Conversion and Management*, 314, 118720. https://doi.org/10.1016/j.enconman.2024.118720