

# Optimal design of a green ammonia export supply chain from Saudi Arabia under demand, price and route uncertainty: a two-stage stochastic programming approach

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## Research Article

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**Posted Date:** October 12th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-11134508/v1>

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**Additional Declarations:** No competing interests reported.

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# Optimal design of a green ammonia export supply chain from Saudi Arabia under demand, price and route uncertainty: a two-stage stochastic programming approach

## Abstract

Saudi Arabia plans to export green ammonia to Europe and East Asia, but its 2030 demand, its delivered price and the availability of the Suez route are all uncertain. This paper presents a two-stage stochastic mixed-integer linear program that selects export sites on the Red Sea and Arabian Gulf coasts, sizes the solar, wind, electrolyzer and ammonia synthesis capacity at each, and decides production and shipping to Rotterdam, Japan and Korea in 50 scenarios of demand, price and route state. Renewable supply uses linear supply blocks checked against the NEOM Green Hydrogen project, and all data sources are public. The risk-neutral solution opens NEOM only, with 1.80 Mt/yr of ammonia capacity fed by 4.4 GW of PV, 2.9 GW of wind and 3.6 GW of electrolysis, and an expected annual profit of 160 million USD. The design sized on expected demand and price builds 3.17 Mt/yr at NEOM and Yanbu and has an expected loss of 140 million USD per year, so the value of the stochastic solution is 301 million USD per year; the expected value of perfect information is 199 million USD per year. Gulf sites are not selected because their production cost is about 130 USD/t higher than at NEOM. A strongly risk-averse investor does not invest without price support, while a delivered price floor of 750 USD/t keeps the investment at every level of risk aversion. Expected profit is most sensitive to the price level, the cost of capital and the electrolyzer cost.

**Keywords:** green ammonia; hydrogen export; supply chain design; two-stage stochastic programming; conditional value-at-risk; Saudi Arabia

## 1. Introduction

Saudi Arabia has one of the best combined solar and wind resources in the world and a long coastline on two seas, which makes it a candidate exporter of green hydrogen. Because hydrogen is costly to ship as a liquid, most export plans use ammonia as the carrier. The NEOM Green Hydrogen Company (NGHC) project, a joint venture of ACWA Power, Air Products and NEOM, is building more than 2 GW of electrolysis fed by up to 4 GW of solar and wind to produce up to 1.2 Mt/yr of ammonia, at an investment of 8.4 billion USD (thyssenkrupp 2021; NGHC 2023, 2026). Other coastal industrial cities, such as Yanbu and Jubail, are also candidate export locations.

Whether such projects pay depends on three things that are not known when the investment is made. The first is how much green ammonia the import markets will take. The REPowerEU plan foresees 10 Mt/yr of hydrogen imports into the European Union by 2030, but independent estimates of imports in 2030 range from 0.7 to 8.7 Mt/yr of hydrogen (Transport & Environment 2024; Rikabi 2024). Japan aims to use 3 Mt/yr of fuel ammonia by 2030 (Kumagai 2021) and has awarded contracts for difference for about 0.8 Mt/yr of low-carbon ammonia (Wood Mackenzie 2026). Korea awarded one clean-power contract in 2024, implying about 0.4 Mt/yr of ammonia, and then canceled its 2025 auction (Rumley 2025; Argus Media 2025). The second is the delivered price. Platts assessed the delivered cost of renewable ammonia at 820 to 930 USD/t in 2025 (Burgess et al. 2025), the first H2Global auction cleared at a net product price of 811 EUR/t (Hintco 2024), and model studies place the 2030 European import price near 141 EUR/MWh, about 730 EUR/t (Genge and Müsgens 2025). The third is the shipping route. Attacks on shipping in the Red Sea cut Suez Canal traffic by more than half in 2024 and

forced Europe-bound cargo around the Cape of Good Hope (UNCTAD 2024a, b), and traffic was still about 60 percent below normal in January 2026 (Schuler 2026). The conflict with Iran that began at the end of February 2026 then cut ship transits through the Strait of Hormuz by more than 90 percent (UNCTAD 2026) and sharply reduced Gulf oil exports for several months, and attacks near Bab el-Mandeb reduced Saudi oil exports from the Red Sea port of Yanbu in August 2026 (EIA 2026).

Most published supply chain studies of hydrogen or ammonia export from the Middle East are deterministic: they compute a levelized cost for a given site and route and vary the inputs one at a time. A few studies apply stochastic programming to hydrogen or ammonia supply chains, but they treat demand, price or renewable supply, and none of them considers the export chain from Saudi Arabia with its two coasts and the risk of route disruption. This paper fills that gap. Its contributions are as follows. First, it formulates a two-stage stochastic mixed-integer linear program (MILP) in which site selection and capacity are first-stage decisions and production, market allocation and routing are second-stage decisions, with demand, price and route availability as joint uncertainties. Second, it builds the input data set from public sources and states every assumption, so the model can be reproduced and updated. Third, it quantifies the value of the stochastic solution and the expected value of perfect information for this export chain, and shows how risk aversion and price support change the investment decision. The model is small enough to solve with open-source software in under a second, which makes it usable for scenario studies by industry and government.

## 2. Literature review

Techno-economic studies of green hydrogen and ammonia production in Saudi Arabia agree on the cost range but differ in scope. Alhadhrami et al. (2024) modeled hydrogen production in Saudi Arabia and Germany and found a levelized cost of hydrogen of 2.34 to 3.08 USD/kg in Saudi Arabia for 2030 and beyond, with alkaline electrolysis. Florez et al. (2024) optimized islanded ammonia production at three coastal sites and reported 383 USD/t of ammonia by 2030, with shipping to Europe or Asia adding less than 40 USD/t. Sadiq et al. (2025) compared NEOM and Duqm at 300 to 1200 t/d and found 556 to 680 USD/t. Vazquez-Sanchez et al. (2026) compared Duba, Yanbu and Jubail by hydrogen cost using a mixed-integer model of the renewable and electrolyzer system. These studies fix the site or the market and do not treat uncertainty beyond one-at-a-time sensitivity.

Shipping cost studies give the second building block. The landed-cost study of KBR (2022) for the Clean Air Task Force estimated a freight cost of 210 USD per tonne of hydrogen for ammonia shipped from Saudi Arabia to Rotterdam, about 37 USD per tonne of ammonia. Seo et al. (2024) computed 32.5 USD/t of ammonia from Dammam to Ulsan with an 84,000 m<sup>3</sup> carrier burning fuel oil. Egerer et al. (2023) found transport and storage costs of 11.1 EUR/MWh, about 58 EUR/t, from Australia to Germany. The IEA (2023) assumptions annex gives ship size, speed, boil-off and fuel use for a reference ammonia carrier. None of these studies includes canal closure or war-risk premiums, although both changed shipping costs from 2024 to 2026 (UNCTAD 2024a; Schuler 2026).

Stochastic programming has been applied to hydrogen supply chains in several forms. Ochoa Bique et al. (2023) built a multistage stochastic MILP for a hydrogen network with three demand branches per stage weighted 0.3, 0.4 and 0.3. Mitrai et al. (2024) used a two-stage stochastic MILP for renewable ammonia in Minnesota with ten price scenarios drawn from the historical price distribution, and later extended it to a multistage model (Mitrai et al. 2026). Efthymiadou et al. (2025) solved a two-stage stochastic MILP for the hydrogen infrastructure of Great Britain with 1125 scenarios reduced to 25. Ma

et al. (2025) combined baseline, conservative and optimistic scenarios with clustering of wind and solar output for a hydrogen chain in China. These works show that two-stage models with a few demand and price levels are common and solvable, but none addresses an export chain with route uncertainty. The value of the stochastic solution and the expected value of perfect information (Birge and Louveaux 2011), and the conditional value-at-risk (Rockafellar and Uryasev 2000), are the accepted measures of the benefit of a stochastic model and of the effect of risk aversion, and are used here.

### 3. Problem description and model

#### 3.1 System boundary

The system covers five coastal sites, three import markets and the sea routes between them (Table 1). NEOM, Yanbu and Rabigh are on the Red Sea; Jubail and Ras Al-Khair are on the Arabian Gulf. Each site can host PV, onshore wind, alkaline electrolysis, hydrogen buffer storage, an air separation unit with a Haber-Bosch loop, refrigerated ammonia storage and an export jetty. Ammonia is shipped in 84,000 m<sup>3</sup> carriers to Rotterdam, to Japan (Yokohama) and to Korea (Ulsan). Red Sea ports reach Rotterdam through the Suez Canal or, when the canal is not available, around the Cape of Good Hope; they reach East Asia through Bab el-Mandeb and the Strait of Malacca. Gulf ports reach Rotterdam through Hormuz, Bab el-Mandeb and Suez or around the Cape, and East Asia through Hormuz and Malacca. Desalinated water is costed at 0.413 USD/m<sup>3</sup>, the levelized water cost of the Jubail 3A plant (Knott 2020). Downstream cracking to hydrogen is outside the boundary; the product is sold as ammonia at the import terminal. The planning year is 2030 and all costs are in real 2024 USD.

Table 1. Candidate sites, resource and route data.

| Site         | Coast   | PV capacity factor | Wind capacity factor | Jetty and site cost (M USD) | Distance to Rotterdam via Suez / Cape (nm) | Distance to Japan / Korea (nm) |
|--------------|---------|--------------------|----------------------|-----------------------------|--------------------------------------------|--------------------------------|
| NEOM         | Red Sea | 0.279              | 0.37                 | 140                         | 3588 / 11365                               | 7712 / 7350                    |
| Yanbu        | Red Sea | 0.274              | 0.33                 | 140                         | 3891 / 11177                               | 7524 / 7163                    |
| Rabigh       | Red Sea | 0.264              | 0.22                 | 240                         | 4008 / 10977                               | 7324 / 6963                    |
| Jubail       | Gulf    | 0.251              | 0.25                 | 140                         | 6527 / 11310                               | 6702 / 6340                    |
| Ras Al-Khair | Gulf    | 0.254              | 0.25                 | 140                         | 6618 / 11401                               | 6793 / 6432                    |

PV capacity factors are the fixed-tilt values from the Global Solar Atlas (Solargis and World Bank 2026) scaled by 1.25 for single-axis tracking and bifacial modules, which are standard in Saudi utility projects. Wind capacity factors come from site studies at NEOM (Alfawzan et al. 2020), Yanbu (Ramli and Bouchekara 2025) and Jubail (Baseer et al. 2015); the Rabigh value reflects the low wind speed measured there (Shuja et al. 2025), and Ras Al-Khair uses Jubail as a proxy. Jetty cost follows the IEA port archetypes (IEA 2025): 90 million USD for a naturally sheltered jetty port and 190 million USD for an open coastal jetty port with a breakwater, which is used for Rabigh. Each site also carries 50 million USD of site development, which gives 140 million USD for four sites and 240 million USD for Rabigh. Sea distances were computed with the searoute package (Halili 2026) on the Eurostat SeaRoute maritime network (Eurostat 2022), with the Suez passage closed for the Cape route. These are network-based approximations; they agree within 3 percent with published routed distances for Jeddah to Rotterdam and Yokohama (Breezada 2026) and for Dammam to Ulsan (Seo et al. 2024).

#### 3.2 Two-stage stochastic formulation

Sets are sites  $i \in I$ , markets  $m \in M$ , routes  $r \in R(i,m)$ , supply blocks  $k \in K$  and scenarios  $s \in S$  with probability  $p_s$ . First-stage variables are the site opening binary  $y_i$ , the electrolyzer capacity in each supply block  $B_{ik}$  (MW), the PV, wind and electrolyzer capacities  $P_i^{PV}$ ,  $P_i^W$  and  $P_i^{EL}$  (MW), and the ammonia capacity  $C_i$  (t/yr). Second-stage variables are the tonnes  $x_{imrs}$  delivered from site  $i$  to market  $m$  by route  $r$  in scenario  $s$ . The objective maximizes expected annual profit:

$$\max \sum_s p_s \left[ \sum_{i,m,r} \left( \pi_{ms} - c_{imrs}^{ship} - \frac{c^{var}}{\delta_{imr}} \right) x_{imrs} \right] - F \quad (1)$$

where  $\pi_{ms}$  is the delivered price,  $c_{imrs}^{ship}$  the shipping cost per tonne delivered,  $c^{var}$  the variable production cost per tonne produced,  $\delta_{imr}$  the fraction of the loaded cargo that arrives after boil-off, and  $F$  the annual fixed cost:

$$F = \sum_i \left[ a f_i y_i + a_{PV} P_i^{PV} + a_W P_i^W + a_{EL} P_i^{EL} + (a_{HB} + a_{ST} + a_{H2}) C_i \right] \quad (2)$$

in which  $a$  is the capital recovery factor for the cost of capital and plant life,  $f_i$  the site fixed cost, and  $a_{PV}$ ,  $a_W$ ,  $a_{EL}$ ,  $a_{HB}$ ,  $a_{ST}$  and  $a_{H2}$  the annualized capital and fixed operating cost per unit of PV, wind, electrolyzer, Haber-Bosch, ammonia storage and hydrogen buffer capacity. The first-stage constraints are:

$$C_i \leq C_i^{max} y_i \quad \forall i \quad (3)$$

$$P_i^{EL} = \sum_k B_{ik}, \quad P_i^{PV} = \sum_k \rho_k^{PV} B_{ik}, \quad P_i^W = \sum_k \rho_k^W B_{ik} \quad \forall i \quad (4)$$

$$e_{EL} C_i \leq 8760 \sum_k u_{ik} B_{ik} \quad \forall i \quad (5)$$

Constraint (3) limits capacity at an open site. Constraint (4) sizes the renewable plant from the electrolyzer blocks with the fixed ratios  $\rho_k^{PV}$  and  $\rho_k^W$ . Constraint (5) requires that the electricity for the hydrogen needed by the ammonia capacity,  $e_{EL}$  MWh per tonne, fits within the full-load hours the blocks can deliver, where  $u_{ik}$  is the achievable utilization of block  $k$  at site  $i$ . The second-stage constraints are:

$$\sum_{m,r} \frac{x_{imrs}}{\delta_{imr}} \leq C_i \quad \forall i, s \quad (6)$$

$$\sum_{i,r} x_{imrs} \leq D_{ms} \quad \forall m, s \quad (7)$$

$$x_{imrs} = 0 \quad \forall (i, m, r, s) \text{ with route } r \text{ not available in scenario } s \quad (8)$$

Constraint (6) keeps production within capacity, (7) keeps sales within the scenario demand  $D_{ms}$ , and (8) closes the Suez route in disrupted scenarios. All variables except  $y_i$  are non-negative and continuous. The model has 5 binary variables, 35 first-stage continuous variables and 1000 second-stage variables for 50 scenarios.

### 3.3 Renewable supply blocks

An annual model cannot follow the hourly match between variable renewables and the electrolyzer. The usual remedies are hourly dispatch, which makes the stochastic problem large, or a fixed utilization factor, which ignores the renewable mix. This paper uses an intermediate approach. The electrolyzer at

each site is divided into three supply blocks, PV-only, wind-only and hybrid, each with a fixed renewable-to-electrolyzer sizing ratio and a curtailment fraction (Table 2). The achievable utilization of a block is then given by the energy balance:

$$u_{ik} = (\rho_k^{PV} CF_i^{PV} + \rho_k^W CF_i^W)(1 - \gamma_k) \frac{e_{EL}}{e_{EL} + e_{HB}} \quad (9)$$

where  $CF$  are the site capacity factors,  $\gamma_k$  the curtailment fraction and  $e_{HB}$  the electricity for synthesis and air separation per tonne. The hybrid block was checked against the NGHC design: with 1.2 MW of PV and 0.8 MW of wind per MW of electrolyzer and 8 percent curtailment, it gives a utilization of 0.545 at NEOM and 0.49 Mt of ammonia per GW of electrolyzer, with a renewable-to-electrolyzer ratio of 2.0. NGHC plans up to 1.2 Mt/yr of ammonia from more than 2 GW of electrolysis fed by 2.2 GW of PV and 1.6 GW of wind (thyssenkrupp 2021; NGHC 2026), which is up to about 0.6 Mt per GW and a ratio of up to 1.9. The PV-only block carries a higher curtailment fraction because a single resource with a diurnal profile cannot be matched as well. The curtailment fractions are assumed, and hybrid-block values of 4 and 12 percent are also tested. The optimizer chooses the block mix at each site, so the renewable mix is a decision, not an input.

Table 2. Supply blocks and achievable electrolyzer utilization.

| Block     | PV per MW electrolyzer | Wind per MW electrolyzer | Curtailment | NEOM  | Yanbu | Rabigh | Jubail | Ras Al-Khair |
|-----------|------------------------|--------------------------|-------------|-------|-------|--------|--------|--------------|
| PV only   | 1.5                    | 0                        | 0.18        | 0.322 | 0.316 | 0.305  | 0.290  | 0.293        |
| Wind only | 0                      | 1.2                      | 0.10        | 0.375 | 0.335 | 0.223  | 0.253  | 0.253        |
| Hybrid    | 1.2                    | 0.8                      | 0.08        | 0.545 | 0.512 | 0.426  | 0.433  | 0.436        |

### 3.4 Shipping cost

The cost per tonne delivered on each arc is built from a round-trip voyage of an 84,000 m3 carrier loading 56,000 t of ammonia at 0.682 t/m3 and 98 percent fill (Seo et al. 2024; Engineering ToolBox 2005). Sea days are twice the distance divided by 15 knots, close to the 14.8-knot fleet average of BW LPG (n.d.); two port days are added for loading and discharge (Seo et al. 2024). The voyage cost is the sum of the time charter, bunker fuel at 45 t/day, close to the about 42 t/day reported by BW LPG (n.d.), at an assumed long-run price of 600 USD/t, port fees of 50,000 USD per call, Suez tolls of 380,000 USD for the laden transit and 85 percent of that for the ballast transit, derived from the 2024 canal tariff (Suez Canal Authority 2024), and, in the disrupted state, a war-risk premium of 0.5 percent of an assumed 125 million USD hull value per Bab el-Mandeb transit. The charter rate of 45,000 USD/day lies between the 43,700 USD/day at which BW LPG fixed part of its 2026 time-charter days and its fourth-quarter 2025 earnings of 50,300 USD/day (BW LPG 2026); spot fixtures above 58,000 USD/day in early 2026 (Dorian LPG 2026) are covered by the charter rates of 30,000 to 90,000 USD/day that are also tested. The war-risk premium lies between the 0.7 to 1 percent seen in early 2024 (UNCTAD 2024a) and the 0.2 percent of late 2025 (Schuler 2026). Boil-off of 0.03 percent per day on the laden leg reduces the delivered tonnes; this is slightly above the 0.02 percent per day of the IEA reference carrier (IEA 2023). In the disrupted state, Red Sea ports pay the premium on every voyage, because cargo to East Asia and cargo to Europe around the Cape both pass Bab el-Mandeb; Gulf ports pay it only on the Suez route, which is closed in that state, so they carry no premium.

### 3.5 Scenarios

Three uncertain quantities are combined. Demand is the addressable demand for Saudi green ammonia in each market, obtained from import demand, the share expected to arrive as ammonia and an assumed Saudi market share. For Rotterdam, the three anchors are 0.7, 3.5 and 8.7 Mt/yr of hydrogen, with 40 percent of it arriving as ammonia and a 25 percent Saudi share. The low and high anchors are import estimates for 2030 (Transport & Environment 2024; Rikabi 2024); the middle anchor is the total EU hydrogen need in the Agora pathway cited by Transport & Environment (2024), used here as a central import level, and is close to the 2.6 Mt/yr that the same study expects could be exported to the EU from planned projects. For Japan the anchors are 0.8, 1.8 and 3.0 Mt/yr of ammonia: the contracted volume (Wood Mackenzie 2026), an assumed middle level and the 2030 fuel ammonia target (Kumagai 2021), with a 30 percent share. For Korea they are 0.4, 1.0 and 2.5 Mt/yr: the volume implied by the 2024 award (Rumley 2025) and two assumed higher levels, with a 30 percent share. Two intermediate levels are placed at the midpoints, giving five levels with probabilities 0.1, 0.2, 0.4, 0.2 and 0.1 (Table 3), a discrete set similar to those used by Ochoa Bique et al. (2023) and Efthymiadou et al. (2025). Price has five levels with the same probabilities. The Rotterdam levels of 650 to 1050 USD/t cover the model import price of Genge and Müsgens (2025), the Platts assessment of Middle East ammonia delivered to north-west Europe (Burgess et al. 2025) and the H2Global net price (Hintco 2024). Japan levels are 50 USD/t and Korea levels 60 to 70 USD/t below Rotterdam, in line with the Platts finding that the Middle East to Far East route is the cheapest delivered route (Burgess et al. 2025) and with the Korean fuel cost limit of about 700 USD/t implied by the 2024 auction (Rumley 2025). Route state is normal with probability 0.75 or disrupted with probability 0.25. This is an assumed long-run frequency over the plant life; the Red Sea disruption began in late 2023 and traffic was still well below normal in early 2026 (Schuler 2026), and probabilities of 0 and 0.5 are also tested. The three quantities are treated as independent, which gives the 50 scenarios listed in Table S5.

Table 3. Demand and price scenario levels.

| Level    | Probability | Rotterdam demand (Mt/yr) | Japan demand (Mt/yr) | Korea demand (Mt/yr) | Rotterdam price (USD/t) | Japan price (USD/t) | Korea price (USD/t) |
|----------|-------------|--------------------------|----------------------|----------------------|-------------------------|---------------------|---------------------|
| Low      | 0.1         | 0.40                     | 0.24                 | 0.12                 | 650                     | 600                 | 590                 |
| Low-mid  | 0.2         | 1.19                     | 0.39                 | 0.21                 | 750                     | 700                 | 685                 |
| Mid      | 0.4         | 1.98                     | 0.54                 | 0.30                 | 850                     | 800                 | 780                 |
| Mid-high | 0.2         | 3.46                     | 0.72                 | 0.53                 | 950                     | 900                 | 880                 |
| High     | 0.1         | 4.93                     | 0.90                 | 0.75                 | 1050                    | 1000                | 980                 |

### 3.6 Cost data

Table 4 lists the technology and financial inputs; the full notation is given in Table S1 and the complete input set with sources in Table S2 of the Supplementary material. Capital costs for 2030 for PV, wind and alkaline electrolysis are taken from the KAPSARC model of Saudi hydrogen production (Alhadhrami et al. 2024). The electrolyzer value of 700 USD/kW lies within the IEA 2030 range for Chinese systems (450 to 900 USD/kW) and well below the global average of 1400 to 1820 USD/kW (IEA 2025); values from 450 to 1400 USD/kW are also tested. Ammonia synthesis with air separation costs 770 USD per tonne per year of capacity (Kriegsmann et al. 2025), a 2023 estimate that lies inside the IEA 2030 range of 560 to 980 USD per tonne per year (IEA 2025). Electrolyzer efficiency and

operating cost fractions follow the IEA annex (IEA 2025). Ammonia storage is sized for 15 days of production (Kriegsmann et al. 2025) at 800 USD/t of capacity, inside the installed range of 560 to 1060 USD/t (Cao et al. 2025). The hydrogen buffer is costed at an assumed 100 USD per tonne per year of ammonia capacity, which adds about 12 USD/t; this is below the 35 to 150 USD/t that IRENA (2022) gives for intermediate hydrogen storage, so higher values are also tested. The cost of capital is 8 percent real over 25 years, the value used in a recent Yanbu renewable hydrogen hub study (Alturki 2026). It lies between the 6 percent (best case) and 10 percent (average case) that IRENA (2020) uses; both values are tested, together with 5 percent.

Table 4. Technology and financial inputs, 2030 basis.

| Item                                | Value                          | Unit                         | Source                                      |
|-------------------------------------|--------------------------------|------------------------------|---------------------------------------------|
| PV capital cost                     | 555                            | USD/kW                       | Alhadhrami et al. (2024)                    |
| PV fixed O&M                        | 10                             | USD/kW/yr                    | assumed                                     |
| Wind capital cost                   | 992                            | USD/kW                       | Alhadhrami et al. (2024)                    |
| Wind fixed O&M                      | 30                             | USD/kW/yr                    | assumed                                     |
| Electrolyzer capital cost           | 700                            | USD/kW                       | Alhadhrami et al. (2024); IEA (2025)        |
| Electrolyzer fixed O&M              | 3                              | % of capital/yr              | IEA (2025)                                  |
| Electrolyzer electricity use        | 52.1                           | kWh/kg H <sub>2</sub>        | IEA (2025)                                  |
| Haber-Bosch and ASU capital cost    | 770                            | USD per t/yr                 | Kriegsmann et al. (2025)                    |
| Haber-Bosch and ASU fixed O&M       | 2.9                            | % of capital/yr              | IEA (2025)                                  |
| Haber-Bosch and ASU electricity use | 0.6                            | MWh/t NH <sub>3</sub>        | IEA (2025)                                  |
| Balance of plant electricity factor | 1.05                           | -                            | assumed                                     |
| Ammonia storage                     | 15 days at 800                 | USD/t capacity               | Kriegsmann et al. (2025); Cao et al. (2025) |
| Hydrogen buffer                     | 100                            | USD per t/yr NH <sub>3</sub> | assumed                                     |
| Water use and price                 | 9 L/kg H <sub>2</sub> at 0.413 | USD/m <sup>3</sup>           | stoichiometric; Knott (2020)                |
| Other variable cost                 | 5                              | USD/t NH <sub>3</sub>        | assumed                                     |
| Cost of capital, plant life         | 8, 25                          | % real, years                | Alturki (2026); IRENA (2020)                |
| Site capacity limit                 | 2.0                            | Mt/yr                        | assumed                                     |

### 3.7 Solution and evaluation

The model is written in Pyomo (Bynum et al. 2021) and solved with the HiGHS solver (Huangfu and Hall 2018) to a relative gap of  $10^{-6}$ ; each instance solves in well under one second on a laptop. The stochastic solution, called the recourse problem (RP), is compared with three reference problems (Birge and Louveaux 2011). The wait-and-see problem (WS) solves each scenario with full knowledge and takes the probability-weighted average; the difference WS minus RP is the expected value of perfect information (EVPI). The expected-value problem (EV) replaces demand and price by their means and the shipping cost of each arc by its probability-weighted value over the two route states, with the Cape cost used for the Suez route in the disrupted state; fixing its first-stage decisions and evaluating them

over all scenarios gives the expected result of the expected-value solution (EEV), and RP minus EEV is the value of the stochastic solution (VSS). Risk aversion is introduced by replacing the objective with a weighted sum of the expected profit and the conditional value-at-risk at the 90 percent level,  $CVaR_{0.9}$ , which is the expected profit in the worst 10 percent of outcomes (Rockafellar and Uryasev 2000):

$$\max (1 - \lambda)E[\Pi] + \lambda \left( \eta - \frac{1}{1 - \alpha} \sum_s p_s z_s \right), \quad z_s \geq \eta - \Pi_s, \quad z_s \geq 0 \quad (10)$$

where  $\Pi_s$  is the profit in scenario  $s$ ,  $\eta$  an auxiliary variable equal at the optimum to the value-at-risk,  $\alpha = 0.9$  and  $\lambda$  the risk-aversion weight from 0 (risk neutral) to 1. The same problem is also solved with a delivered price floor, under which the price in every scenario is the larger of the scenario price and the floor, to represent contract-for-difference support of the kind used by H2Global (Hintco 2024) and the Japanese price-gap scheme (Wood Mackenzie 2026). Each risk-averse design is then evaluated with its first-stage decisions fixed and the risk-neutral objective, so that the reported expected profit uses the best recourse in every scenario. Mass and energy balances, the cost build-up and the stochastic programming identities were checked for the base solution (Supplementary material, Section S8).

## 4. Results

### 4.1 Site cost comparison

Fig. 1(a) shows the gate cost of ammonia at each site at full utilization of a 1 Mt/yr plant with the best supply block, and Table S3 gives every combination of site and block. NEOM is the cheapest at 654 USD/t, Yanbu follows at 688 USD/t, and the three remaining sites are close together at 785 to 790 USD/t. The ranking is set by the wind resource. At NEOM and Yanbu the hybrid block reaches an electrolyzer utilization of 0.51 to 0.55, so the electrolyzer and synthesis capital is spread over more tonnes. At Rabigh the wind capacity factor of 0.22 makes the PV-only block the best choice at a utilization of 0.30, and the electrolyzer share of the gate cost rises from 175 USD/t at NEOM to 313 USD/t. At Jubail and Ras Al-Khair the hybrid block is chosen but reaches only 0.43 to 0.44. The gate cost at NEOM lies within the 556 to 680 USD/t reported by Sadiq et al. (2025) for NEOM and Duqm, and the implied hydrogen cost of about 2.9 USD/kg is within the 2.34 to 3.08 USD/kg of Alhadhrami et al. (2024). The 480 USD/t that IRENA and AEA (2022) expect by 2030 at the best sites and the 383 USD/t of Florez et al. (2024) are lower; at a cost of capital of 5 percent, the gate cost at NEOM in this model falls to 531 USD/t.

Fig. 1(b) shows the shipping cost per tonne delivered, and Table S4 lists every arc. In the normal state, NEOM to Rotterdam via Suez costs 42 USD/t, of which the canal tolls are 13 USD/t, and Jubail to Rotterdam costs 63 USD/t. To Japan the order reverses: 59 USD/t from NEOM and 52 USD/t from Jubail. The NEOM to Rotterdam value is close to the 37 USD/t of KBR (2022) for Saudi Arabia to Rotterdam and below the 49 to 67 USD/t for Chile to Germany over about 13,000 km (Souissi 2024). Jubail to Korea costs 49 USD/t, above the 32.5 USD/t that Seo et al. (2024) computed for Dammam to Ulsan with a carrier of the same size. In the disrupted state the Cape route to Rotterdam costs 108 USD/t from NEOM and 85 USD/t from Jubail, and the war-risk premium raises the NEOM to Japan cost to 81 USD/t. The largest shipping difference between any two sites for the same market is about 30 USD/t, for East Asian cargo in the disrupted state, which is far below the 130 USD/t production cost gap between NEOM and the Gulf sites.

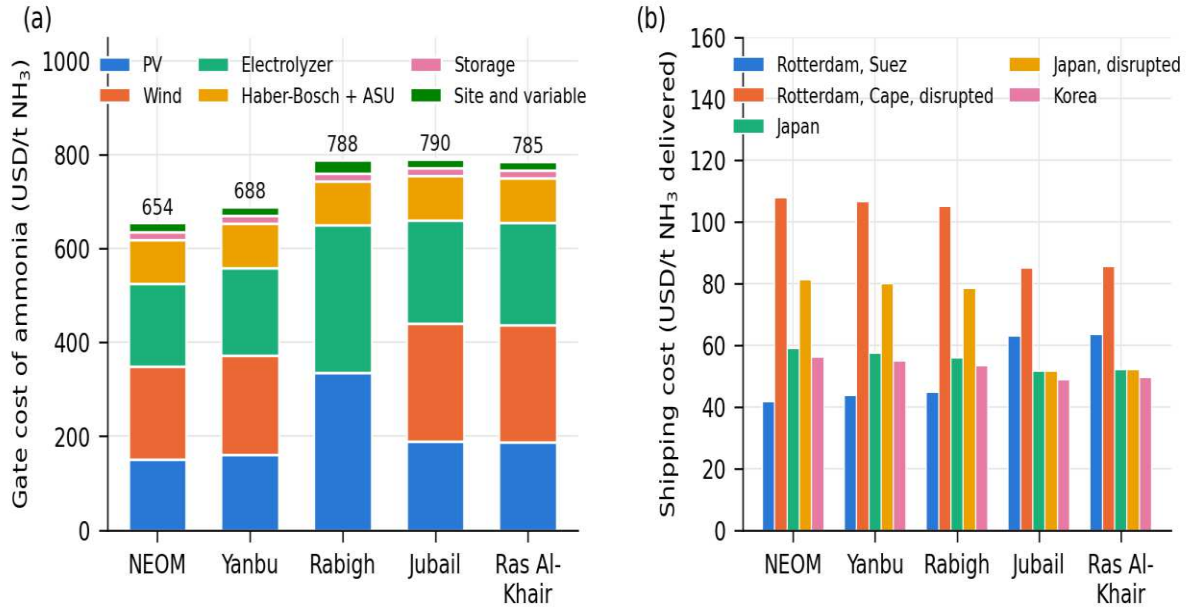


Fig. 1. Gate cost by site and component (a) and shipping cost by site, market and route state (b).

#### 4.2 Stochastic design

Table 5 gives the first-stage decisions of the stochastic solution and of the expected-value solution. The stochastic solution opens NEOM only, with 1.80 Mt/yr of ammonia capacity fed by a hybrid block of 3.64 GW of electrolysis, 4.36 GW of PV and 2.91 GW of wind. The investment is 9.6 billion USD, of which 2.4 billion is PV, 2.9 billion wind, 2.5 billion electrolyzers, 1.4 billion synthesis and air separation, and 0.4 billion storage, site and jetty. The annualized fixed cost is 1155 million USD, and the expected annual profit is 160 million USD. The capacity of 1.80 Mt/yr of production matches the low-mid demand level of 1.79 Mt/yr of deliveries, which is met or exceeded with probability 0.9. The model does not build for the mid level of 2.82 Mt/yr because the extra capacity would be used with probability 0.7 and the probability-weighted margin does not cover its annual capital cost of about 640 USD per tonne of capacity. Deliveries equal 42 percent of capacity in the low-demand scenarios; in all other scenarios the plant runs at full capacity.

The expected-value solution opens NEOM at its 2.0 Mt/yr limit and Yanbu at 1.17 Mt/yr, a total of 3.17 Mt/yr, which serves the mean demand of 3.16 Mt/yr. Evaluated over the 50 scenarios, its expected profit is minus 140 million USD, because much of the capacity is idle in the low and low-mid demand scenarios, which have a combined probability of 0.3, while its fixed cost is paid in full.

Table 5. First-stage decisions of the stochastic (RP) and expected-value (EV) solutions.

| Case | Site  | Ammonia capacity (Mt/yr) | PV (MW) | Wind (MW) | Electrolyzer (MW) | Gate cost (USD/t) |
|------|-------|--------------------------|---------|-----------|-------------------|-------------------|
| RP   | NEOM  | 1.80                     | 4364    | 2909      | 3636              | 648               |
| EV   | NEOM  | 2.00                     | 4856    | 3237      | 4046              | 648               |
| EV   | Yanbu | 1.17                     | 3034    | 2023      | 2528              | 686               |

#### 4.3 Value of the stochastic solution and of perfect information

Fig. 2 shows the cumulative distribution of annual profit over the 50 scenarios for the stochastic solution, the expected-value solution and the wait-and-see solutions, and Table 6 gives the summary

measures; the profit in each scenario is listed in Table S6. The stochastic solution loses money with a probability of 0.235, with a worst case of minus 757 million USD when demand and price are both low and the route is disrupted, and earns up to 641 million USD. The expected-value solution loses money with a probability of 0.505 and has a worst case of minus 1684 million USD. The value of the stochastic solution is 301 million USD per year, 1.9 times the expected profit of the stochastic solution itself. The wait-and-see bound is 359 million USD, so the expected value of perfect information is 199 million USD per year. With perfect information the design changes with the scenario: nothing is built when the price is low or when a low-mid price coincides with a disrupted route, NEOM alone is built at low or low-mid demand, NEOM and Yanbu at mid demand with a mid or higher price, and three or four sites, including Rabigh, Jubail or Ras Al-Khair, at mid-high or high demand and price. The EVPI is the most an exporter should pay for firm information on demand, price and route state; long-term offtake contracts provide much of this information for demand and price, and the NGHC project has an exclusive 30-year offtake agreement with Air Products (NGHC 2023), which removes most of this uncertainty for that project.

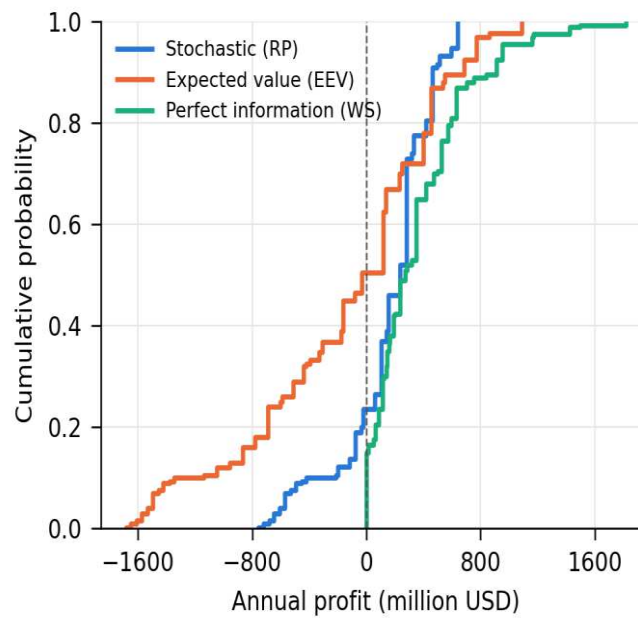


Fig. 2. Cumulative probability of annual profit for the RP, EEV and WS solutions.

Table 6. Stochastic programming measures, million USD per year.

| Measure                                         | Value  |
|-------------------------------------------------|--------|
| Stochastic solution (RP)                        | 160.4  |
| Wait-and-see (WS)                               | 359.2  |
| Expected-value problem (EV)                     | 346.8  |
| Expected result of the EV solution (EEV)        | -140.2 |
| Expected value of perfect information (WS - RP) | 198.8  |
| Value of the stochastic solution (RP - EEV)     | 300.6  |

#### 4.4 Risk aversion and price support

Fig. 3(a) shows the trade-off between expected profit and  $CVaR_{0.9}$  as the risk-aversion weight is varied, Fig. 3(b) the capacity chosen, and Table S8 all values. Without price support, the risk-neutral design

has a  $CVaR_{0.9}$  of minus 580 million USD. Raising  $\lambda$  to 0.1 cuts capacity to 1.20 Mt/yr and improves  $CVaR_{0.9}$  to minus 213 million USD at a cost of 33 million USD of expected profit. At  $\lambda = 0.4$  to 0.6 capacity falls to the low-demand level of 0.76 to 0.77 Mt/yr, with a  $CVaR_{0.9}$  of minus 55 million USD and an expected profit of 97 million USD. At  $\lambda = 0.7$  and above the model builds nothing, because every design that invests has a negative  $CVaR_{0.9}$  and the weighted objective falls below zero. A delivered price floor of 700 USD/t raises the risk-neutral expected profit by 10 million USD and keeps investment up to  $\lambda = 0.8$ . A floor of 750 USD/t makes  $CVaR_{0.9}$  positive for  $\lambda$  of 0.3 and above and keeps investment at every value of  $\lambda$ ; the worst scenario then loses about 6 million USD at 0.76 Mt/yr. The floor never changes the risk-neutral capacity of 1.80 Mt/yr, because it binds only in the low and low-mid price scenarios. Price support therefore matters for whether a risk-averse investor builds at all, not for how much a risk-neutral investor builds.

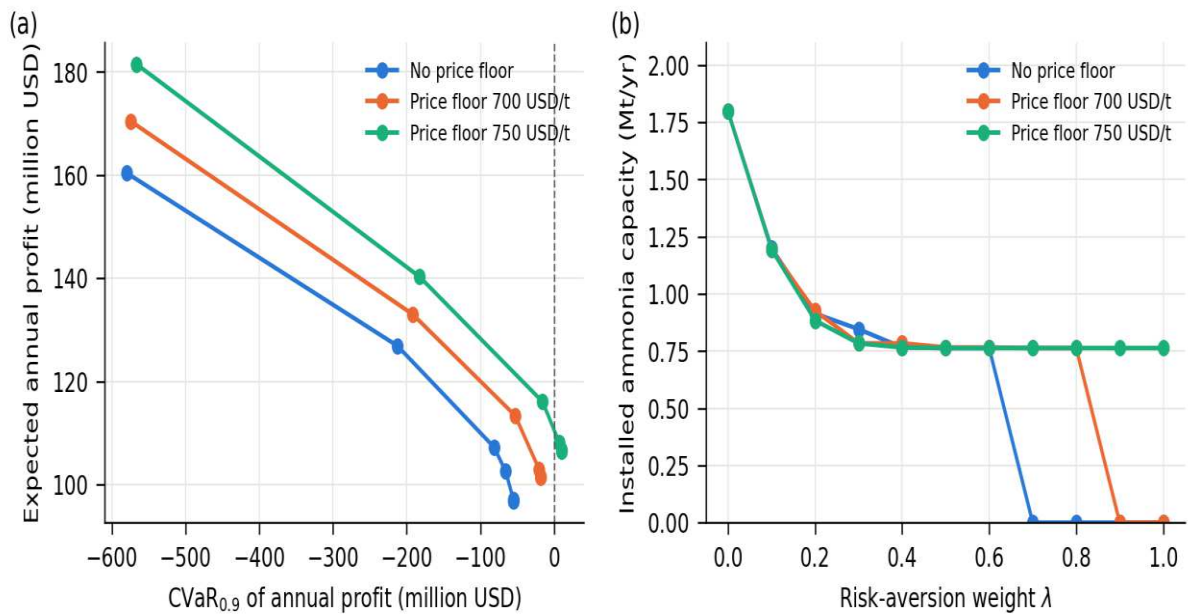


Fig. 3. Expected profit against CVaR (a) and capacity against risk-aversion weight (b).

#### 4.5 Market allocation and route disruption

Fig. 4 shows where the stochastic solution sends its ammonia at the mid price level for each demand level and route state. Rotterdam takes all output whenever demand allows, because its price is 50 USD/t above Japan and its shipping cost from NEOM is 17 USD/t lower. Japan and Korea are served only in the low and low-mid demand scenarios, where Rotterdam demand is below capacity. In the disrupted state, the model ships to Rotterdam around the Cape at 108 USD/t rather than moving cargo to Japan at 81 USD/t, because the price gap of 50 USD/t exceeds the 27 USD/t shipping difference; Asian cargo from the Red Sea also pays the war-risk premium, so disruption does not favor Asia. Disruption lowers the profit of each combination of demand and price by 35 to 130 million USD, 112 million USD on average, but leaves the allocation almost unchanged. The Gulf sites, which carry no war-risk premium in the disrupted state, are not opened in any risk-neutral, risk-averse or sensitivity case. They appear only in the wait-and-see solutions for mid-high and high demand, after NEOM and Yanbu reach their capacity limits, where Ras Al-Khair and Jubail compete with Rabigh, whose gate cost is almost the same.

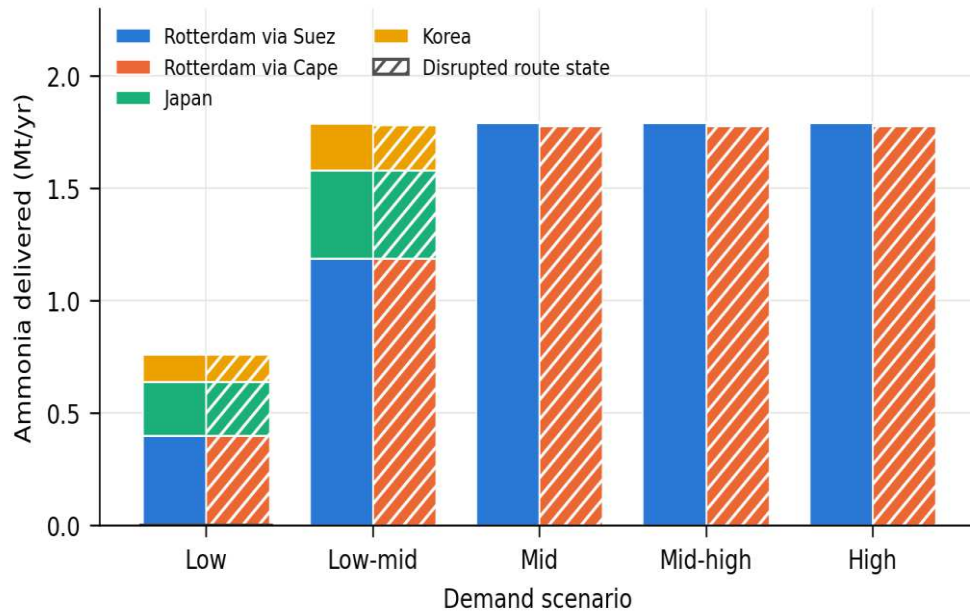


Fig. 4. Ammonia delivered by market and route in the stochastic solution, mid price level.

#### 4.6 Sensitivity analysis

Fig. 5 ranks the one-at-a-time sensitivities by their effect on expected profit, Fig. 6 shows how capacity responds to the three inputs that change it most, and Table 7 lists selected cases; all cases are given in Table S7. The price level has the largest effect: a 100 USD/t shift in all delivered prices changes expected profit by 140 to 169 million USD. The cost of capital is second: at 6 percent, expected profit is 309 million USD, and at 10 percent, 28 million USD. Electrolyzer capital cost is third: at 450 USD/kW, expected profit is 273 million USD; at 1000 USD/kW, 40 million USD; and at 1400 USD/kW, the lower end of the IEA global average for 2030, no investment is made. Wind capital cost matters more than PV capital cost because wind is the larger cost item at NEOM. The assumed curtailment of the hybrid block also matters: 4 percent raises expected profit to 200 million USD and 12 percent lowers it to 118 million USD, without changing the design. Shipping inputs have smaller effects: doubling the charter rate to 90,000 USD/day reduces expected profit by 46 million USD, the 2026 crisis bunker price of 925 USD/t reduces it by 14 million USD, and raising the disruption probability from 0 to 0.5 lowers it from 188 to 132 million USD. Capacity moves between a few discrete levels (Fig. 6). A cost of capital of 5 percent or a price shift of plus 150 USD/t raises capacity to about 2.0 Mt/yr, the NEOM site limit; a cost of capital of 10 percent, an electrolyzer cost of 1000 USD/kW or a price shift of minus 100 USD/t reduces it to the low-demand level of about 0.76 Mt/yr. Scaling all demand by 1.5 or 2 opens Yanbu in addition to NEOM, and a site limit of 1.5 Mt/yr caps the design at that value with an expected profit of 144 million USD. The hydrogen buffer cost is important: if the buffer adds 35 USD/t, the lower end of the IRENA (2022) range, expected profit falls to 120 million USD, and if it adds 150 USD/t, the upper end, no investment is made. If NEOM is not available, Yanbu is chosen at the same 1.80 Mt/yr with an expected profit of 98 million USD; if neither NEOM nor Yanbu is available, nothing is built at the base prices.

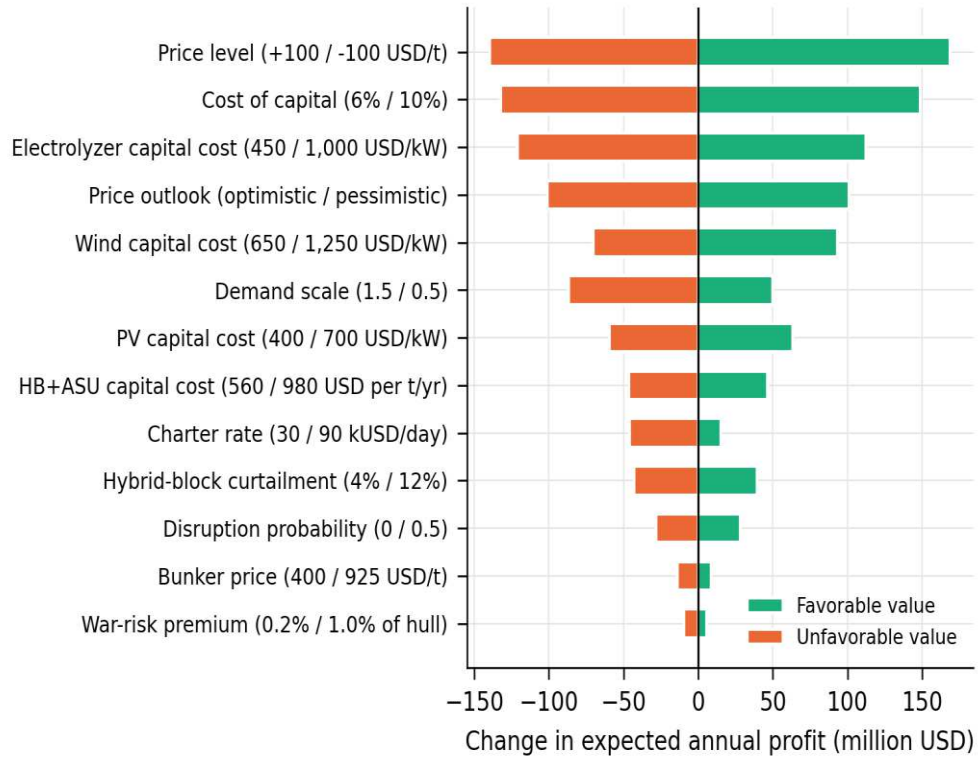


Fig. 5. Change in expected annual profit for one-at-a-time parameter variations.

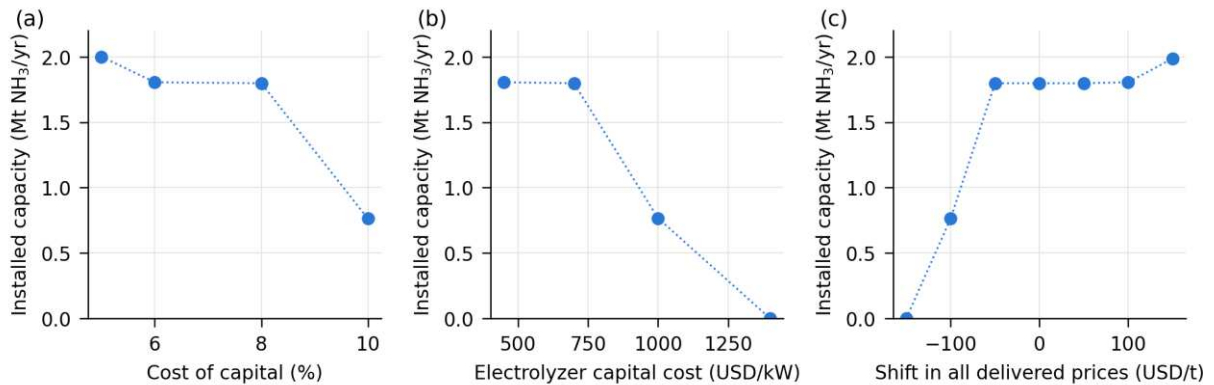


Fig. 6. Installed capacity against cost of capital (a), electrolyzer capital cost (b) and delivered price shift (c).

Table 7. Selected sensitivity cases: expected profit, capacity and sites opened.

| Case                      | Expected profit (M USD/yr) | Capacity (Mt/yr) | Sites |
|---------------------------|----------------------------|------------------|-------|
| Base                      | 160.4                      | 1.80             | NEOM  |
| Cost of capital 5 %       | 385.4                      | 2.00             | NEOM  |
| Cost of capital 6 %       | 309.2                      | 1.81             | NEOM  |
| Cost of capital 10 %      | 28.2                       | 0.76             | NEOM  |
| Electrolyzer 450 USD/kW   | 272.9                      | 1.81             | NEOM  |
| Electrolyzer 1000 USD/kW  | 39.6                       | 0.77             | NEOM  |
| Electrolyzer 1400 USD/kW  | 0.0                        | 0                | none  |
| Price shift +100 USD/t    | 329.2                      | 1.81             | NEOM  |
| Price shift -100 USD/t    | 20.9                       | 0.76             | NEOM  |
| Pessimistic price outlook | 59.4                       | 1.80             | NEOM  |

| Case                           | Expected profit (M USD/yr) | Capacity (Mt/yr) | Sites       |
|--------------------------------|----------------------------|------------------|-------------|
| Optimistic price outlook       | 261.5                      | 1.80             | NEOM        |
| Demand scale 1.5               | 210.2                      | 2.70             | NEOM, Yanbu |
| Demand scale 0.5               | 73.7                       | 0.90             | NEOM        |
| Disruption probability 0       | 188.4                      | 1.80             | NEOM        |
| Disruption probability 0.5     | 132.4                      | 1.80             | NEOM        |
| Charter rate 90,000 USD/day    | 114.4                      | 1.80             | NEOM        |
| Price floor 750 USD/t          | 181.5                      | 1.80             | NEOM        |
| Hybrid-block curtailment 4 %   | 199.7                      | 1.80             | NEOM        |
| Hybrid-block curtailment 12 %  | 117.6                      | 1.80             | NEOM        |
| Hydrogen buffer adds 35 USD/t  | 119.7                      | 1.80             | NEOM        |
| Hydrogen buffer adds 150 USD/t | 0.0                        | 0                | none        |
| Site limit 1.5 Mt/yr           | 144.0                      | 1.50             | NEOM        |
| NEOM excluded                  | 98.0                       | 1.80             | Yanbu       |
| NEOM and Yanbu excluded        | 0.0                        | 0                | none        |

## 5. Discussion

Three findings stand out. First, the choice of site is not sensitive to uncertainty. NEOM is the least-cost site in every scenario, every sensitivity case and every risk setting, and Yanbu is the second site whenever more than 2 Mt/yr is needed. The Gulf sites have shorter routes to East Asia and are not exposed to the Red Sea, but their production cost is about 130 USD/t higher because of the weaker wind resource, and no shipping or disruption effect in the model approaches that gap. The model also does not include a closure of the Strait of Hormuz, which would make the Gulf sites less attractive still. This supports locating the first Saudi export project at NEOM and suggests that Gulf export projects will depend on lower solar and wind costs or on local ammonia demand rather than on exports.

Second, the size of the investment is sensitive to uncertainty, and the direction is toward smaller plants. The stochastic solution is built for the demand level that is met with 90 percent probability rather than for the mean demand, and the expected-value design built for the mean loses money on average. The value of the stochastic solution, 301 million USD per year, exceeds the expected profit of the best design, which is a strong argument for using stochastic rather than deterministic models for export investments of this size. The expected value of perfect information, 199 million USD per year, gives a scale for the value of firm offtake contracts and is consistent with the choice of NGHHC to sign an exclusive 30-year offtake agreement before financial close (NGHC 2023).

Third, risk aversion and price support interact. A risk-neutral investor builds 1.80 Mt/yr with or without a price floor. A moderately risk-averse investor builds about 0.76 to 0.85 Mt/yr at base prices but accepts a CVaR of about minus 55 to minus 66 million USD, and a strongly risk-averse investor, with a weight of 0.7 or more on CVaR, builds nothing. With a floor of 750 USD/t, the CVaR becomes positive and investment continues at every level of risk aversion. Contract-for-difference schemes therefore change who invests rather than how much a given investor builds. The floor of 750 USD/t is below the 811 EUR/t net price of the first H2Global contract (Hintco 2024) and close to the 2030 import price in model studies (Genge and Müsgens 2025), so support at the levels already seen is enough to attract risk-averse capital to a NEOM-type project.

The model has limits that should be kept in mind. The supply blocks approximate hourly dispatch with fixed sizing ratios and assumed curtailment fractions checked against one project; an hourly model would let the optimizer choose the oversizing and storage and could find a different cost at each site, although the ranking of sites is set by the wind resource. For the same reason, the size of the hydrogen buffer that keeps the synthesis loop running is not modeled and its cost is assumed; at the upper end of the IRENA (2022) range the project is not profitable at base prices. The addressable demand depends on assumed Saudi market shares and on middle demand levels that are partly assumed, and the three uncertain quantities are treated as independent, although low demand and low price may be correlated; both can be changed in the scenario table. The route states cover the Red Sea only. A closure of the Strait of Hormuz, as in 2026 (UNCTAD 2026), is not modeled, and attacks near Bab el-Mandeb could stop Red Sea traffic to Asia rather than only raise its cost. Ships are chartered by the voyage and the model does not size a fleet, which ignores the option of owning ammonia-capable ships. The model is a single-period design for 2030 and does not account for phased expansion, which a multistage version could include. Finally, the sea distances are network-based approximations, and the wind capacity factor for the Gulf sites rests on a 2015 study at Jubail that is also used as a proxy for Ras Al-Khair.

## 6. Conclusions

A two-stage stochastic mixed-integer linear program was developed for the design of a green ammonia export supply chain from Saudi Arabia to Europe and East Asia under joint uncertainty in demand, delivered price and route availability, using public data and open-source software. The risk-neutral design opens NEOM only, with 1.80 Mt/yr of ammonia capacity, 4.4 GW of PV, 2.9 GW of wind and 3.6 GW of electrolysis, at a gate cost of 648 USD/t and an expected annual profit of 160 million USD. Sizing to expected demand and price instead would build 3.17 Mt/yr at NEOM and Yanbu and lose 140 million USD per year, so the value of the stochastic solution is 301 million USD per year; the expected value of perfect information is 199 million USD per year. The site choice does not change with uncertainty: NEOM is first and Yanbu second in every stochastic, risk-averse and sensitivity case, and the Gulf sites are not chosen in these cases because their production cost gap of about 130 USD/t exceeds any shipping advantage. Disruption of the Red Sea route reduces annual profit by 35 to 130 million USD when it occurs but does not change the design and leaves the market allocation almost unchanged. A strongly risk-averse investor does not invest without price support, while a delivered price floor of 750 USD/t makes the CVaR positive and keeps investment at every level of risk aversion. Expected profit is most sensitive to the delivered price, the cost of capital and electrolyzer capital cost, and the assumed hydrogen buffer cost and hybrid-block curtailment also have a large effect. Future work should replace the supply blocks with hourly dispatch at the selected sites, add correlation between demand and price and a Hormuz closure state, and extend the model to phased expansion from 2030 to 2040.

**Competing interests:** The author has no relevant financial or non-financial interests to disclose.

**Data availability:** All input values and their sources are listed in the Supplementary material. The model code (Python, Pyomo) and the result files are available from the corresponding author on reasonable request and will be deposited in a public repository on acceptance.

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