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The digital layer of Green Hydrogen

GREEN AMMONIA

Key Technical Challenges to Profitable Production

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GREEN AMMONIA -

a versatile energy carrier

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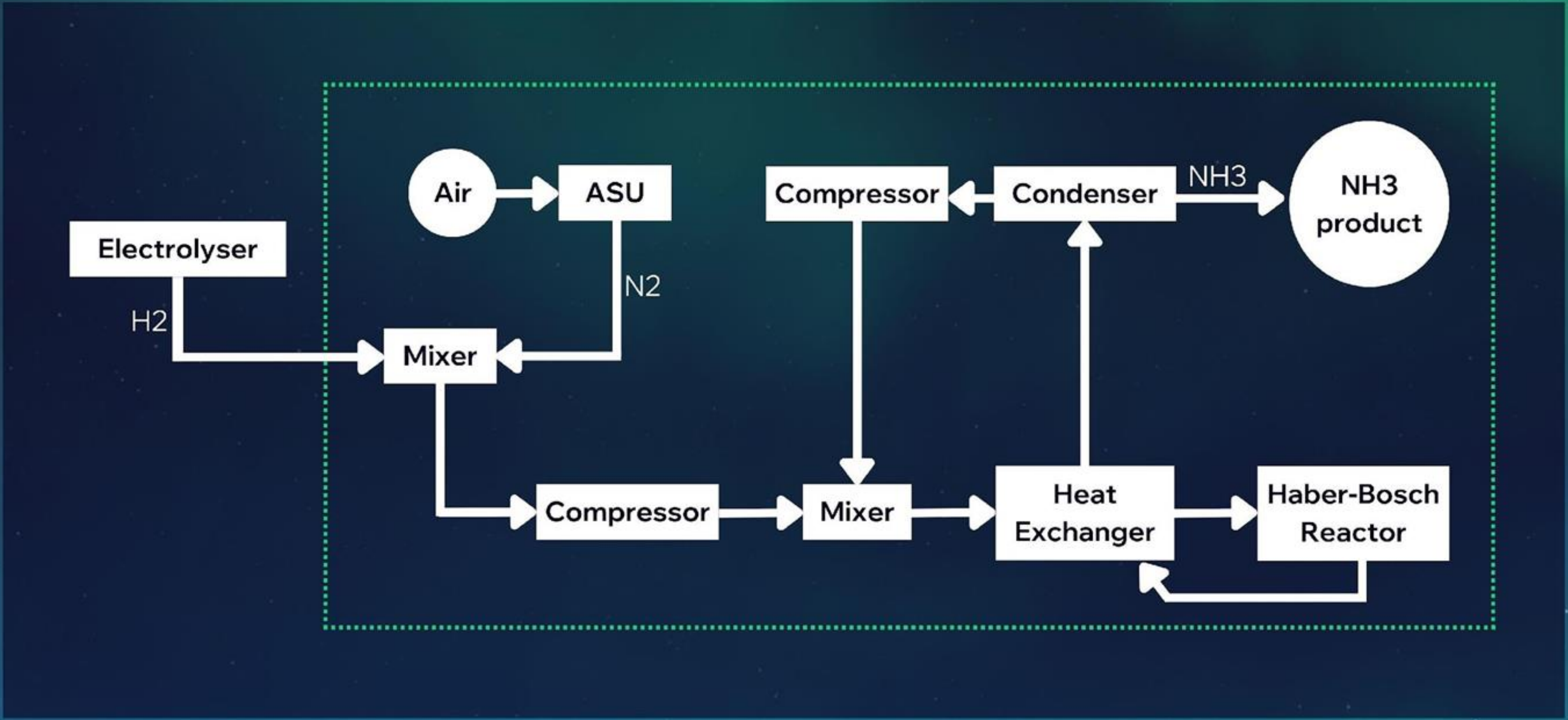
Electrified
Haber-Bosch

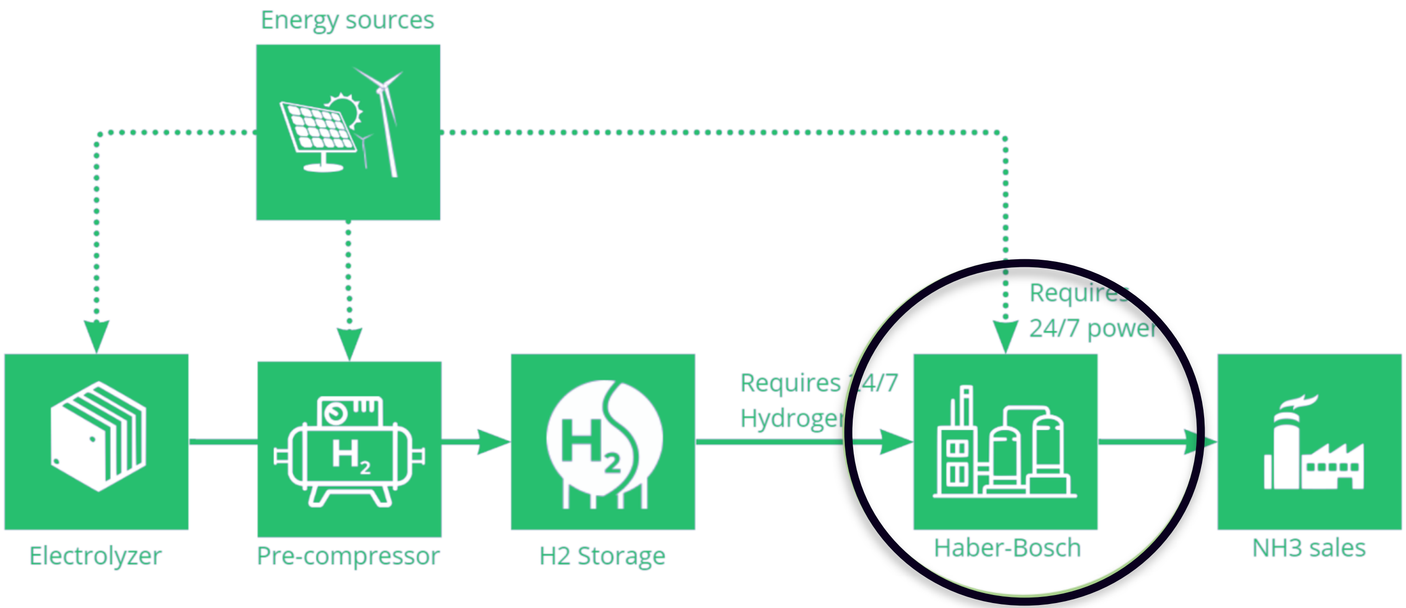
The dominant technology for green ammonia production

- Hydrogen from electrolyzers (not SMR)
- Compressors are fully electric
- Limited ability to ramp up and down.
- Minimum production rate is ~60% of nominal

Electrified Haber-Bosch



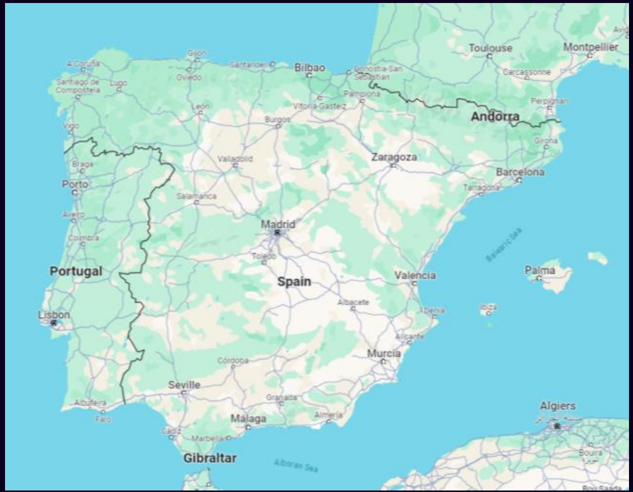
Green ammonia projects face the challenges of intermittent energy



Renewable energy sources → Variable energy → Variable hydrogen production

Simulated with
SOUTHERN LIGHTS

CASE STUDY:
Green ammonia in Iberia



- Located in South of Spain
- Good solar power conditions

Starting assumptions:

- 480 MW Solar
- 336 MW Electrolyzer
- Hydrogen production: 1.6 ton/h = 14 kt/y

Ammonia target:

- Min 8 ton/h (= 192 ton/d = 70kton/y)

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Ammonia prices in Europe:

Grey ammonia: ~0.45 EUR/kg

Green ammonia: 0.8-1.5 EUR/kg

2030 green ammonia: 0.48 EUR/kg

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CASE STUDY:
Green ammonia in Iberia

Simulated with SOUTHERN LIGHTS

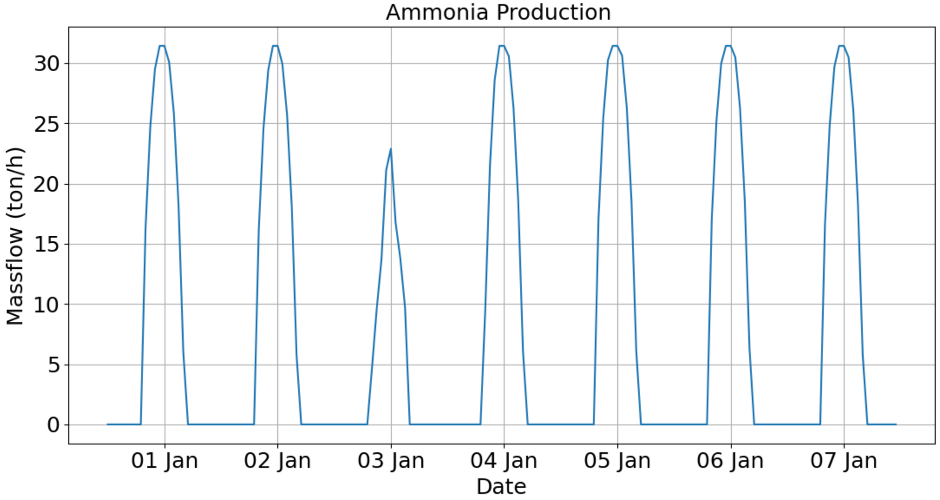
Project assumptions

- Island-mode operations from solar power
- Solar input from a 480 MW park
- Electrolyzer of 336 MW. Capex price: 900+150 EUR/kW
- Compressor for 1 bar → 200 bar Hydrogen

- Hydrogen storage capex: 1000 EUR/kg
- Ammonia production capex: 3000 EUR/(kg/h)

“ The Naïve scenario”

What if there were no operational restrictions in ammonia production?



“ The Naïve scenario”

- No restriction on ramp-rates in ammonia production
- Full flexibility: Production allowed to go from 0% to 100%
- Off-takers accept a fluctuating output

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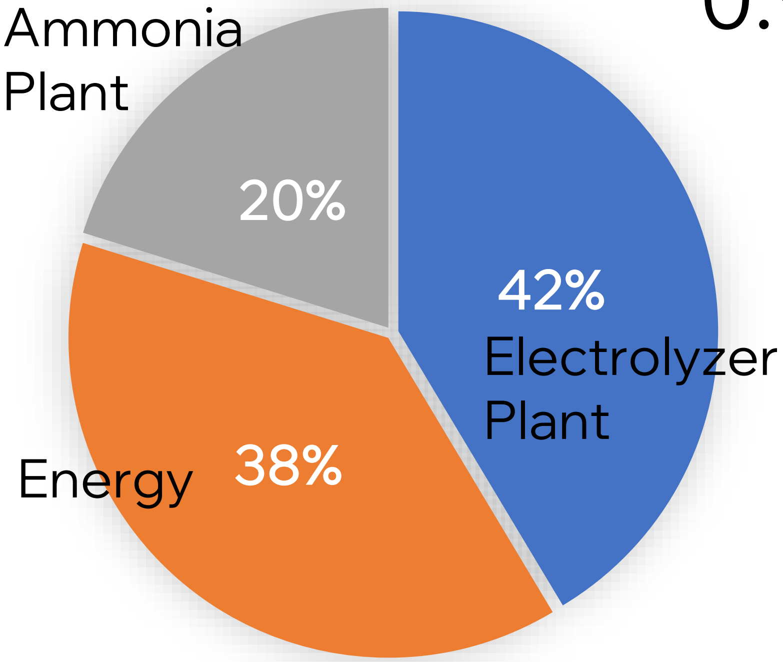
Levelized Cost of Ammonia

0.96 €/kg



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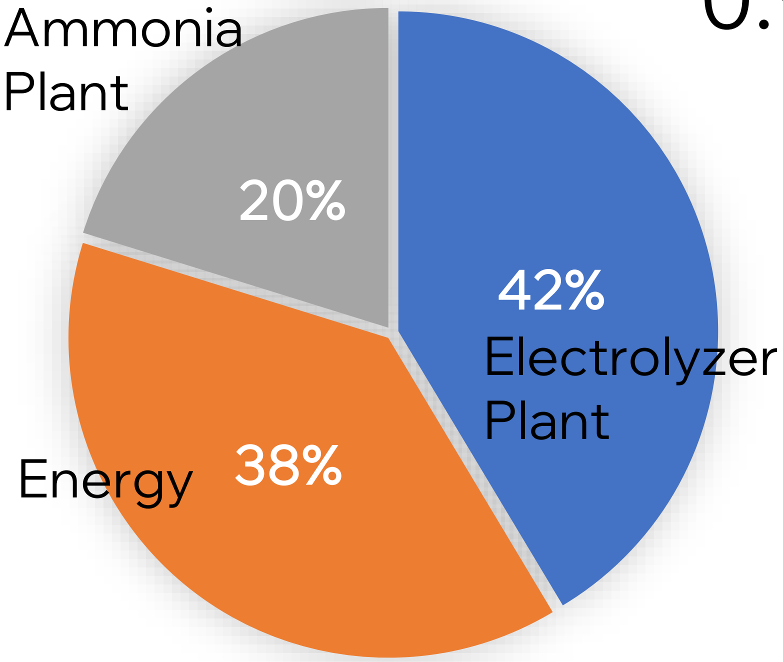

"The Naïve scenario"

- No restriction on ramp-rates ammonia production
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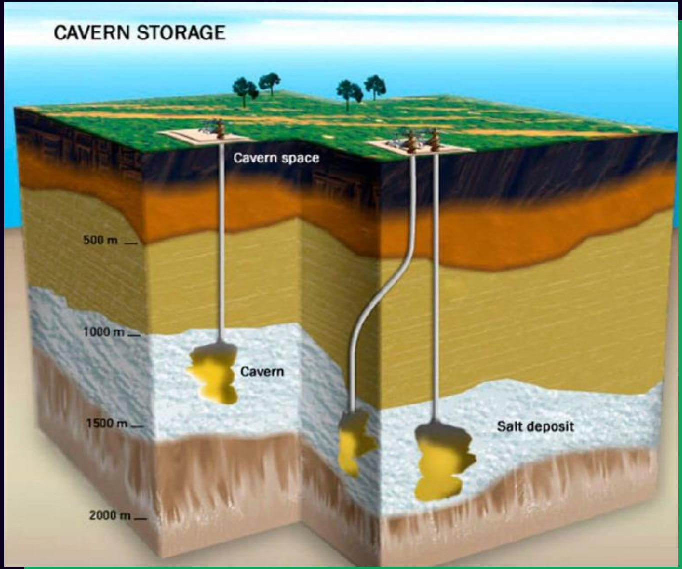
Ammonia production requires storage

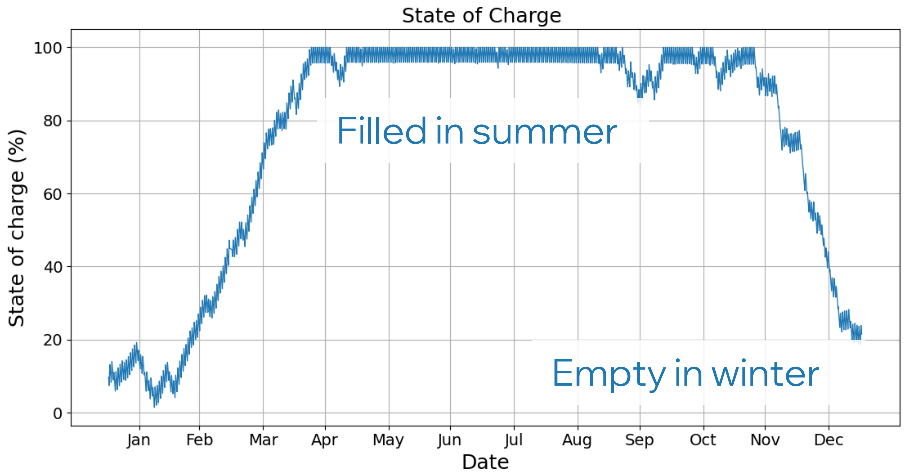
…when operating from variable energy and hydrogen supply

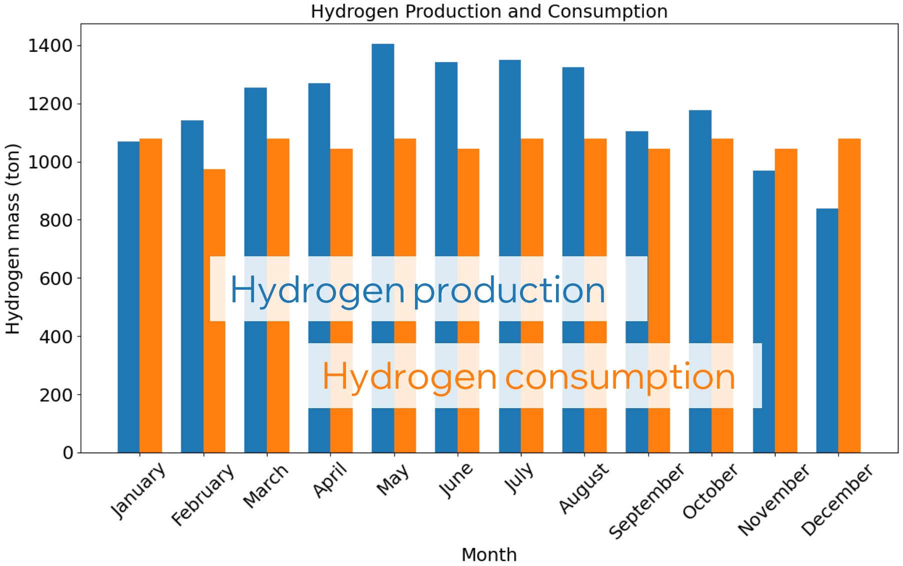


Ammonia production requires storage

Goal: Achieve 24/7 hydrogen supply for ammonia production

Hydrogen storage of **450 tons** H2





→ Hydrogen storage needs to be huge to achieve 24/7 supply on a ***seasonal basis***.

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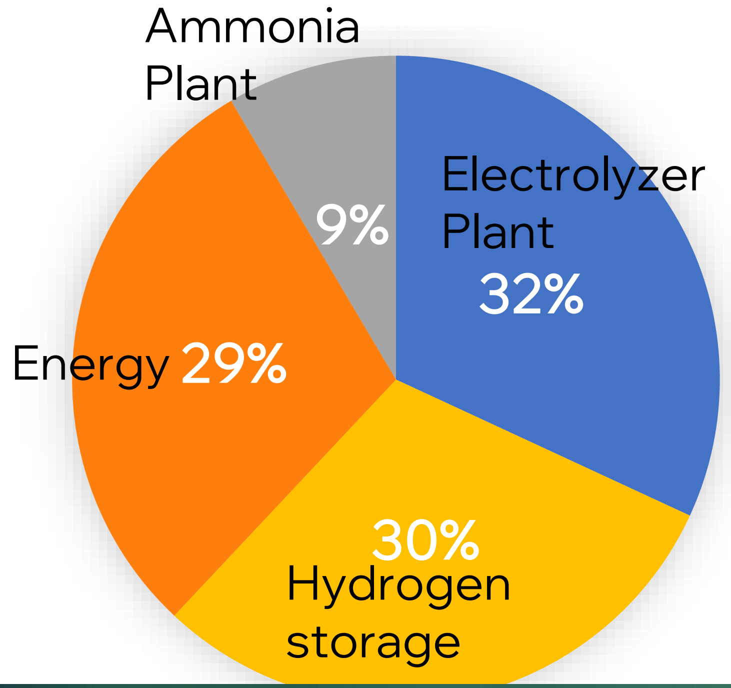
“Seasonal storage scenario”

Levelized Cost of Ammonia

1.36 €/kg



- Realistic restriction on ramp-rates and flexibility
- Hydrogen storage of 450 tons = 13 days of production
- Ammonia production capacity is reduced → higher load factor
- Under-utilized storage most of the year

→ Hydrogen storage costs are too high, if no cheap underground storage is available.

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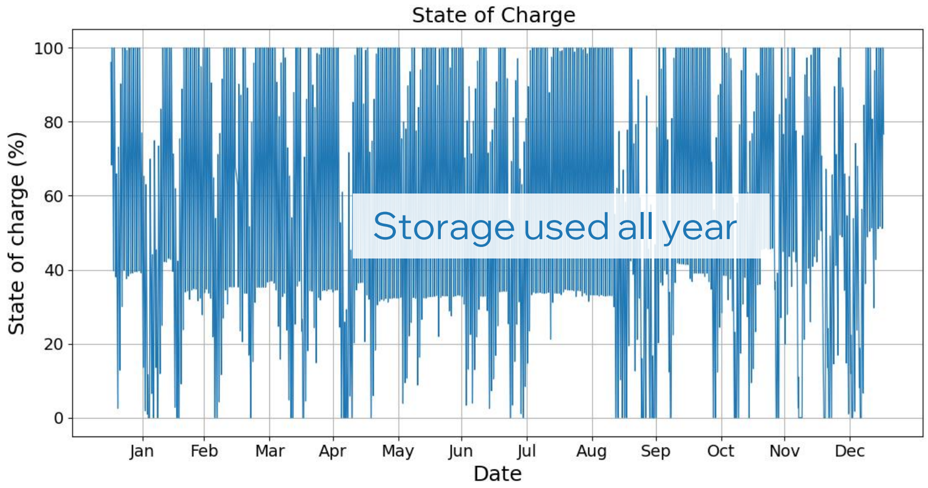
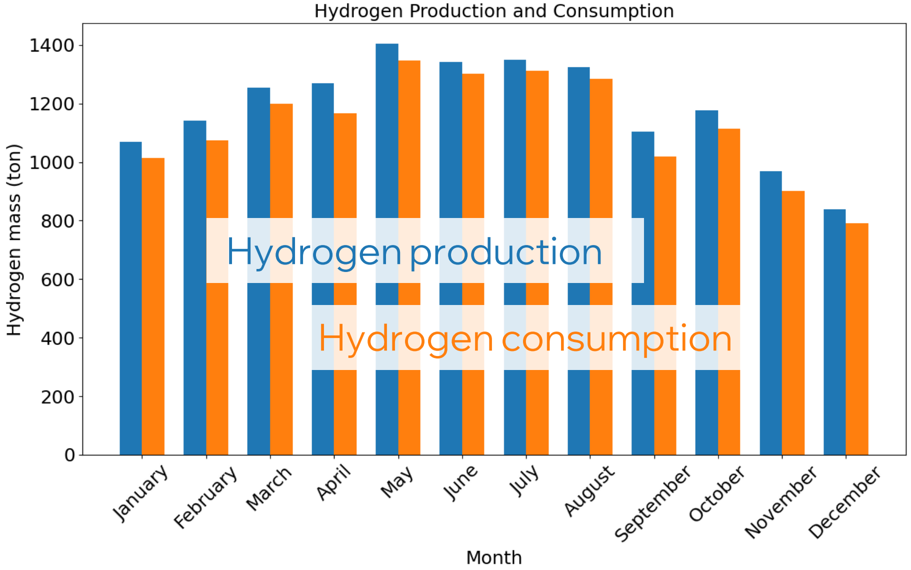
Seasonally adapted Ammonia production

Goal: Achieve 24/7 hydrogen supply with less storage

Hydrogen storage of **35 tons** H2





→ Hydrogen storage can be reduced when adapting ammonia production with the seasons.

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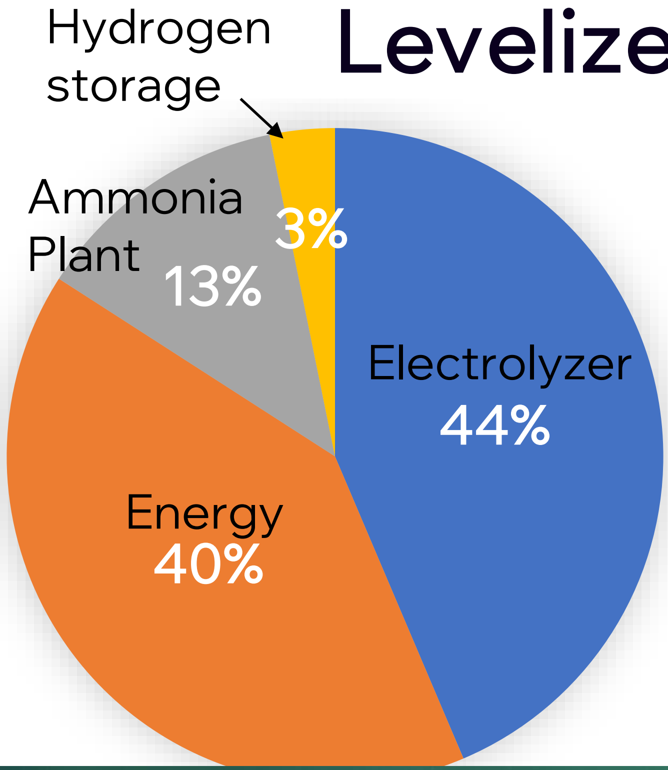
“Seasonally adapted scenario”

Levelized Cost of Ammonia

0.94 €/kg



- Realistic restriction on ramp-rates and flexibility
- Hydrogen storage of 35 tons = 1 day of production
- Storage is well utilized

→ Seasonal decrease in production reduced storage need and keeps production costs down.

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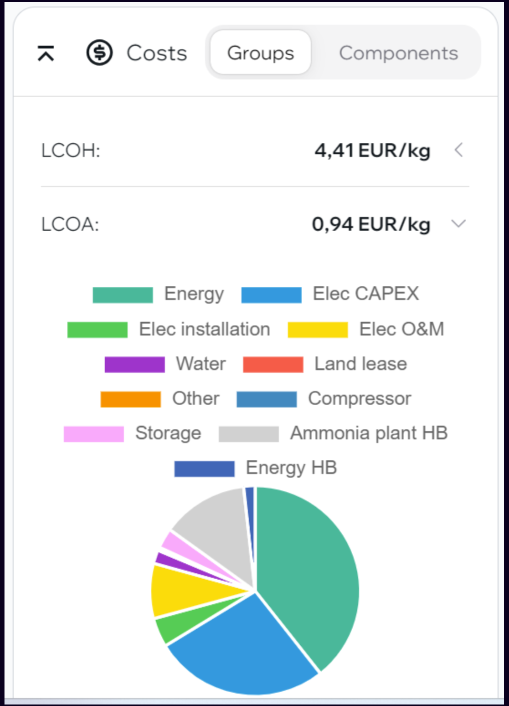
Green ammonia becomes more profitable when adapting to variable energy inputs

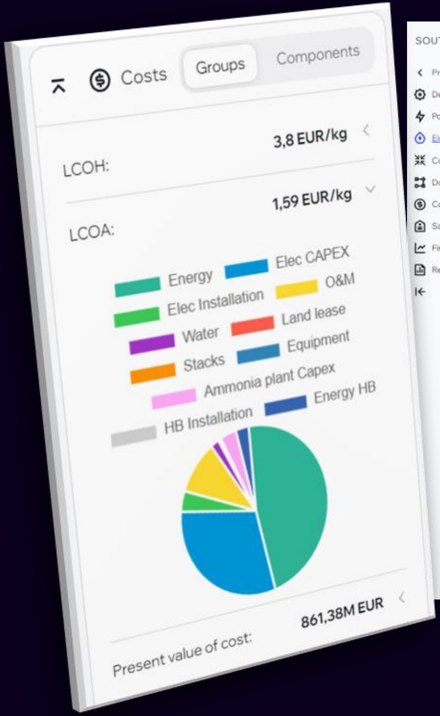
Scenario	Storage size	LCOA [EUR/kg]
"Naïve"	--	0.96
Seasonal storage	450t (13days)	1.36
Seasonally adapted	35t (1 day)	0.94

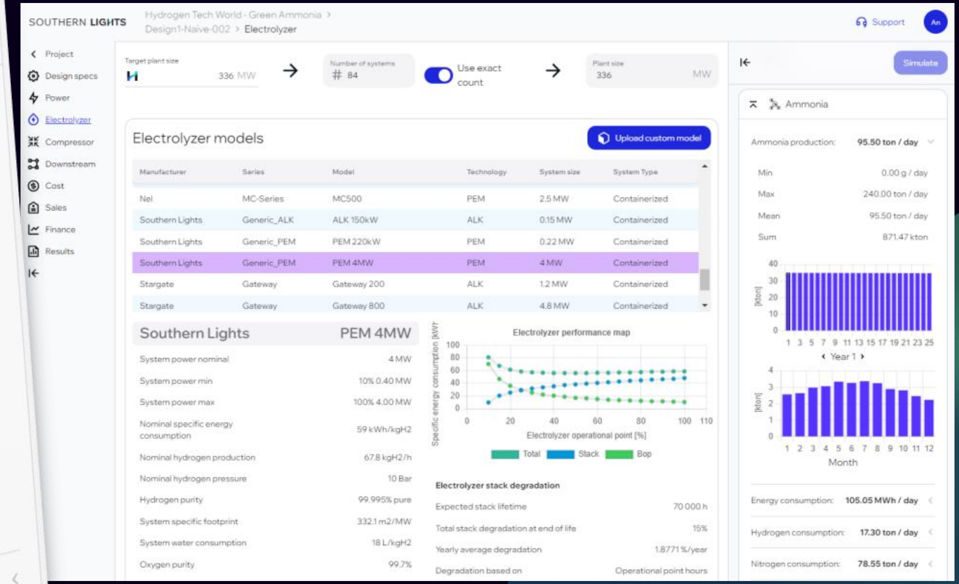


Research made by Southern Lights team:

Pierfrancesco Losi & Anton Frisk

Develop your Green Ammonia projects with SOUTHERN LIGHTS





Come talk to us at booth **B08**

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Develop your Green Ammonia projects with SOUTHERN LIGHTS

Get the full presentation and case study here!

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Sources and supporting material

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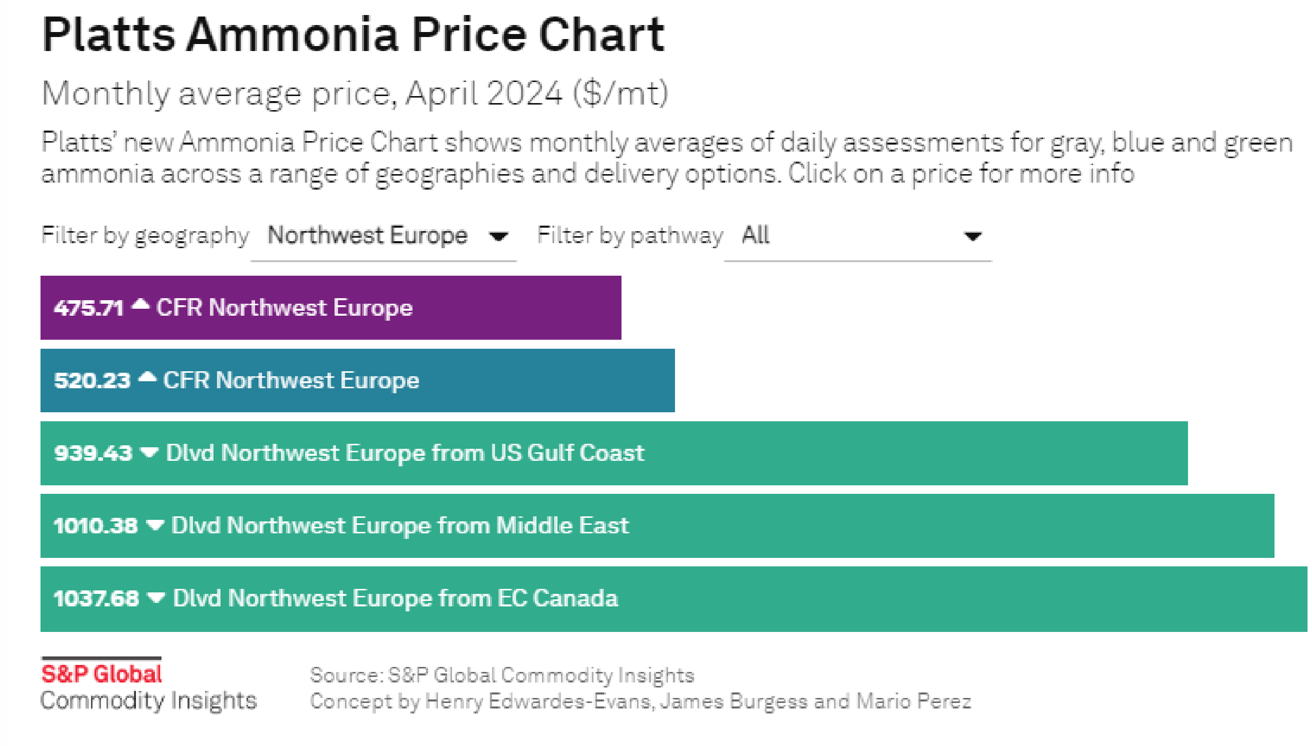
Ammonia production costs



Ammonia production costs

Cost of green ammonia

Though the current cost of green ammonia is very high compared to traditional ammonia. However, this cost is expected to decrease as the renewable energy cost decreases. The current Price of green ammonia is in the range of $ 700 – 1400 per tonne at sites with renewable resources like sun and wind. By 2030, it is expected to drop to $ 480 per tonne, and by 2050, to $ 310 per tonne. To make green ammonia competitive with traditional ammonia, a carbon price reduction of around $ 150 per tonne of CO_2 is needed. It is also estimated that, if the renewable electricity price is below $ 20 per megawatt-hour, green ammonia will be competitive with traditional ammonia.

EXHIBIT 5: Future cost for green ammonia

Year	2020	2030	2040	2050
Low end ($/tonne)	720	475	380	310
High end ($/tonne)	1400	950	750	610

Note: Rounded to $ 5 per tonne.
Source: IRENA

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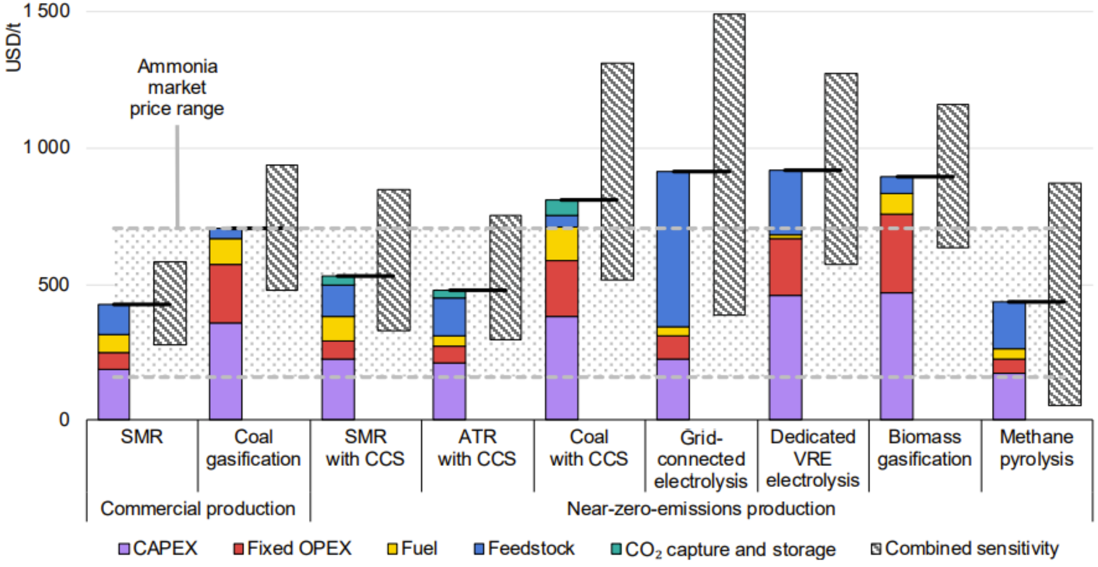
Ammonia production costs

https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

Figure 1.6 Simplified levelised cost of ammonia production for commercial and near-zero-emission production routes in 2020



IEA, 2021.

Notes: SMR = steam methane reforming; ATR = auto-thermal reforming; CCS = carbon capture and storage; VRE = variable renewable energy. The simplified levelised cost is calculated using a discount rate of 8% and a design life of 25 years for all equipment, with the exception of the electrolyser stack (11 years) and system (28 years). CAPEX includes core equipment costs, corresponding to the plant battery limit (including CO_2 capture equipment in the case of CCS-equipped routes, electrolysers in the case of electrolysis-based routes, and hydrogen storage in the case of the dedicated VRE electrolysis route), and includes engineering, procurement and construction costs, equating to 70% of core equipment costs. A 95% capacity factor is used for all equipment apart from the dedicated VRE electrolysis route, where a 50% capacity factor is used. The combined sensitivity includes the impact on the total levelised cost of varying the regional coefficient for CAPEX and fixed OPEX (a factor of 73-127% of the CAPEX cost estimated for the United States), energy cost variation for natural gas (USD 3-8.2/GJ), coal (USD 1.3-2.9/GJ), electricity (USD 4.5-30.2/GJ) and bioenergy (USD 2.2-4.4/GJ). The dedicated VRE electrolysis route uses a narrower electricity cost range (USD 2.8-11.1/GJ). Where relevant, the central values for the column series are calculated based on an output weighted average of the fuel prices faced across regions today. For the electrolysis routes, electrolyser cost = USD 1477/kW$_e$, electrolyser efficiency = 64% and feedstock refers to the electricity used for electrolysis. For CCS-equipped routes, the CO_2 capture rate is 90%, the CO_2 transport and storage costs vary by

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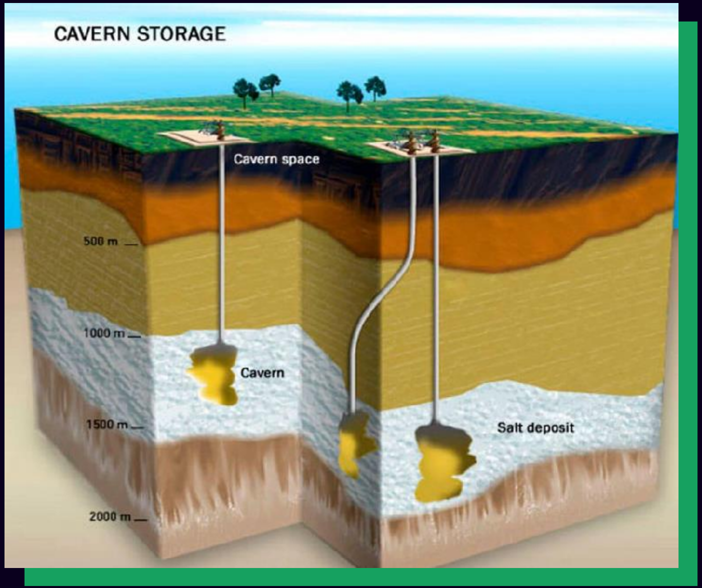

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