The economics of global green ammonia trade – "Shipping Australian wind and sunshine to Germany"

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Motivation and reserach question

Motivation

- The production and transport **of green hydrogen carriers** is getting increasing attention.
- **Global hydrogen trade** allows:
  - ➢ Import-dependent countries with limited potential for renewable energies, to replace fossil fuel imports
  - ➢ Export opportunities are opening up for many countries with high potentials for renewable energy.
- We focus on **green ammonia** production and long-distance transportation, which is likely to be attractive for early global green energy transition.

Motivation

- Today ammonia is mainly produced from **fossil gas** worldwide (72 %) and from **coal** in China (26 %).
- In 2019, global ammonia production emitted about **0.45 Gt** carbon dioxide (CO_2).
- **Ammonia demand** prediction **by 2050** (Net zero emission scenarios in 2050, IEA 2021) :
  - **25 %** increase in global ammonia demand for existing users
  - Green ammonia as an energy carrier: additional demand in **the range of twice** of global ammonia demand today
- Transition to **ammonia production with green hydrogen** (green ammonia) will contribute to a significant **emission reduction** in a timely manner.

Research Gap

- A wide range of techno-economic assessments for green and blue ammonia

Hijikata, T. (2002) , Ishimoto et al. (2020), Runge et al. (2020) DNV GL (2018),Stiller et al. (2008), Wijayanta et al. (2019), Zhang et al. (2020) Armijo, J., & Philibert, C. (2020) , Li et al. (2020), Nayak-Luke and Bañares-Alcántara (2020),.....

- Often simplified models are used, which do not allow:
  - ➢ to represent the dynamic operational management associated with the volatile renewable generation.
  - ➢ to model the synergies between different technologies.
- Very few studies are concerned with the entire value chain
  (ammonia decomposition to green hydrogen)

Main question of research

At which levelized cost could green ammonia (and green hydrogen) be imported from Australia to Germany by 2030?

Research framework

Current global ammonia maket and trade

The challenges and opportunities that arise from transformation of current ammonia value chain to green ammonia as global energy carrier

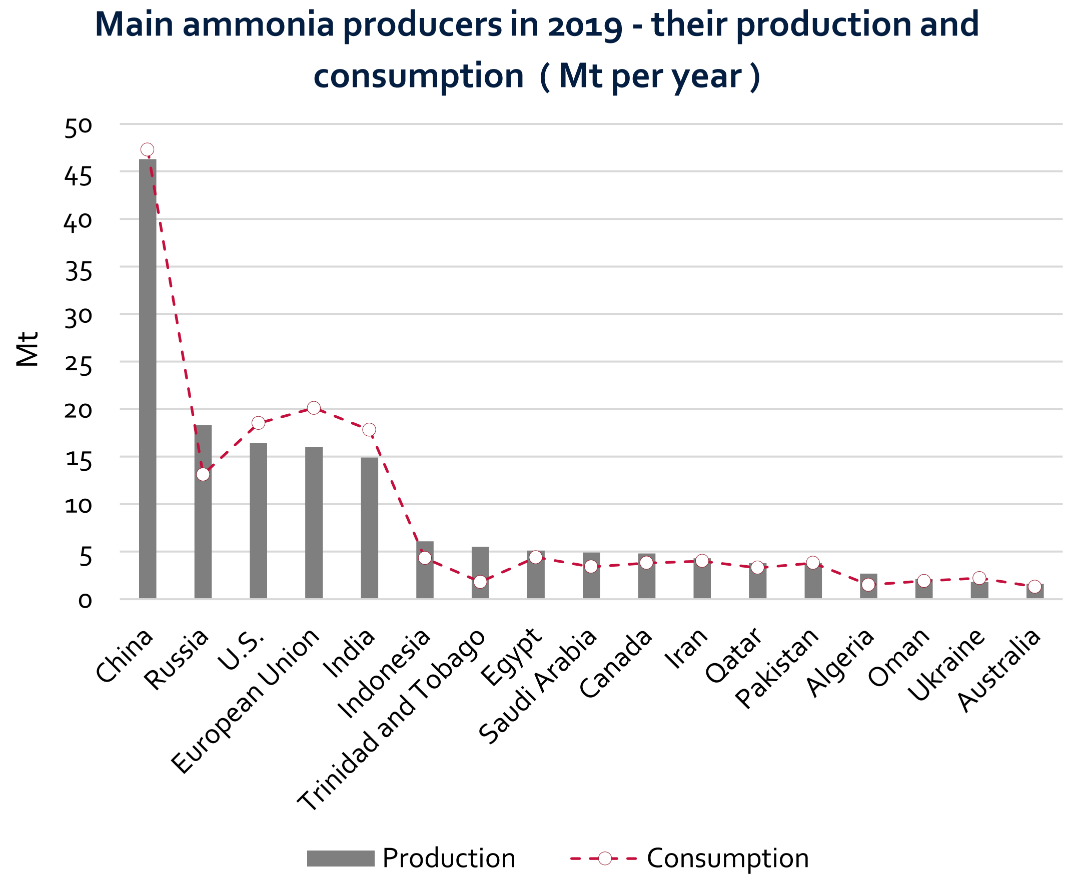
A comprehensive techno-economic model for green ammonia value chain

- The levelized cost of green ammonia and green hydrogen
- Optimal capacities and investment levels for the components of value chain

Case study

Ammonia market today

Global ammonia production and consumption

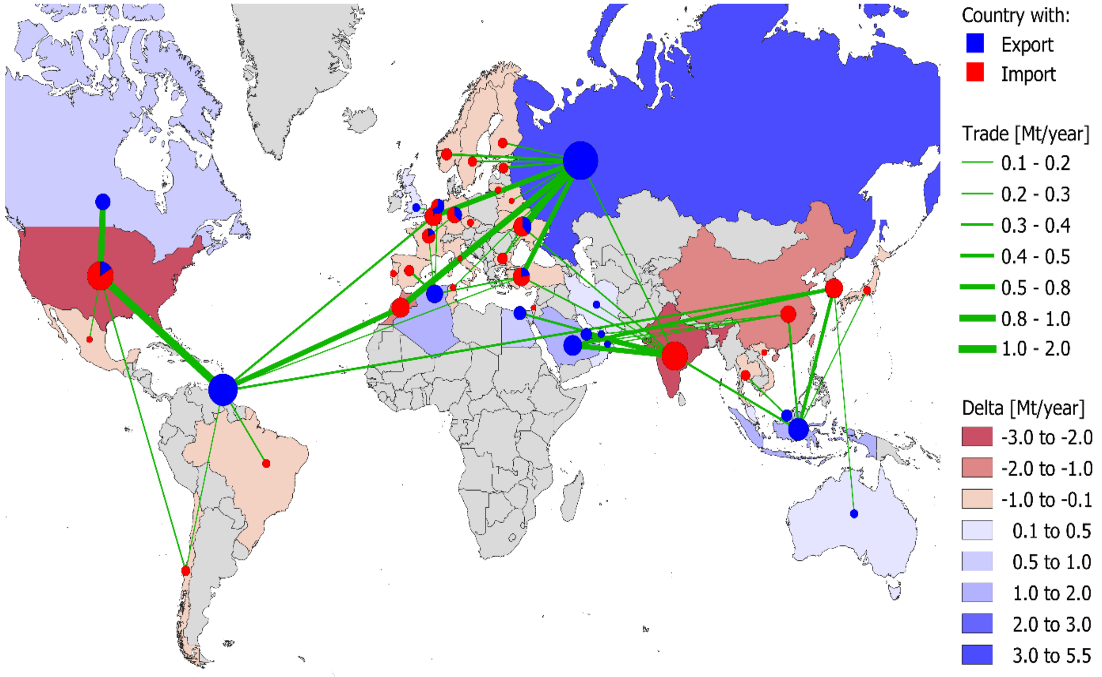


Scource: (UGSG 2022, IFA 2022)

- In 2019, global ammonia production was approx. 180 Mt.
- Global production is concentrated in certain countries.
  - High population density
  - Low fossil fuel prices
- Largest consumers produce most of their ammonia demand locally.

Global ammonia trade flows

Global ammonia trade flows and balances larger 0.1 Mt per year in 2019



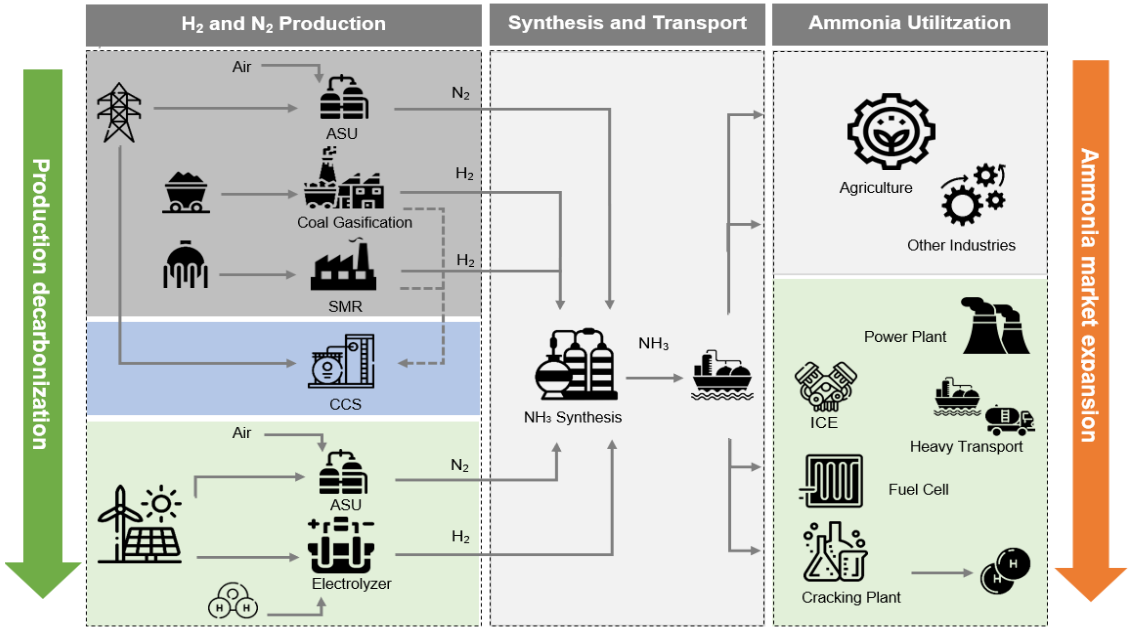
Scource: (CEPII 2022)

- 20.6 Mt (12 %) of global production is traded between countries.
- Large exporters are mostly gas producing countries.
- The European Union is one on the large ammonia importer.
- Large scale maritime transport of ammonia

Scource: (CEPII 2022, IEA 2021)

Green ammonia versus conventional ammonia production

Evolution of green ammonia versus conventional/gray ammonia



SMR- steam methane reforming, ATR- auto-thermal reforming, CCS- carbon capture and storage, ASU- Air separation unit, ICE- Internal combustion engines; Blue ammonia can be produced through SMR and CCS or alternatively via ATR with CCS, *Images: Flaticon.com*

Upstream transition :

- From gray to green hydrogen:
  - Renewable energies
  - Water electrolysis for green hydrogen (H_2)
- Ammonia synthesis could take place in existing plants
- Transport will use the existing infrastrcture

Downstream transition :

- Transition could allow ammonia to gain a foothold in several new sectors.

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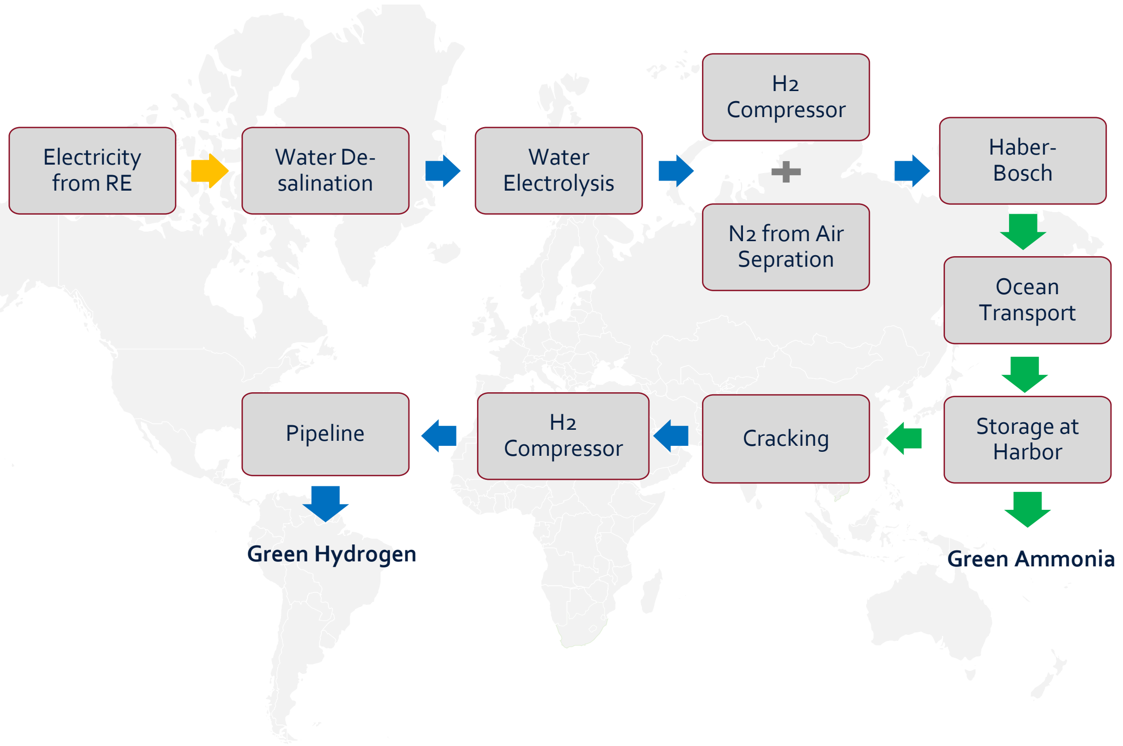
Techno-economic analysis of green ammonia-Optimization model

Value chain of green ammonia and green hydrogen

Optimization model



Model

- Linear optimization model

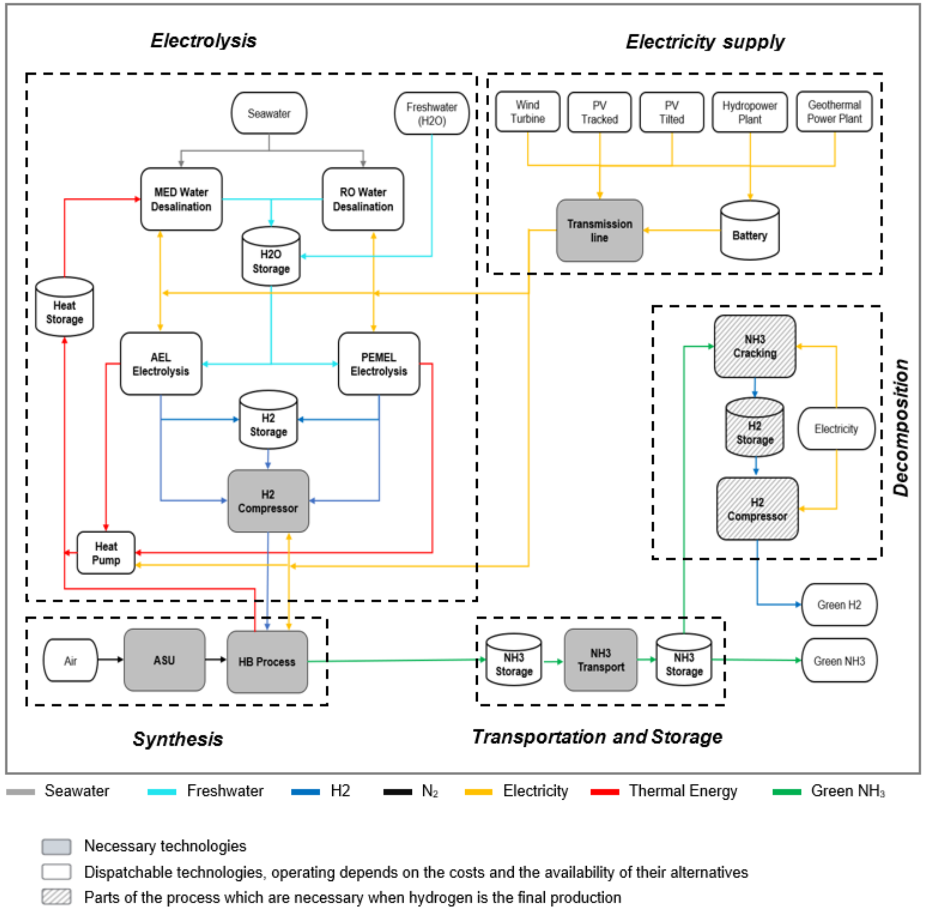
Parameters

- Hourly renewable potentials
- Cost assumption (investments and operational costs)
- Technical assumptions
- Green ammonia and green hydrogen demand

Decision variables

- Levelized costs of final product (green ammonia & green hydrogen)
- Maximum capacity of each technology across the value chain

Cost minimization model

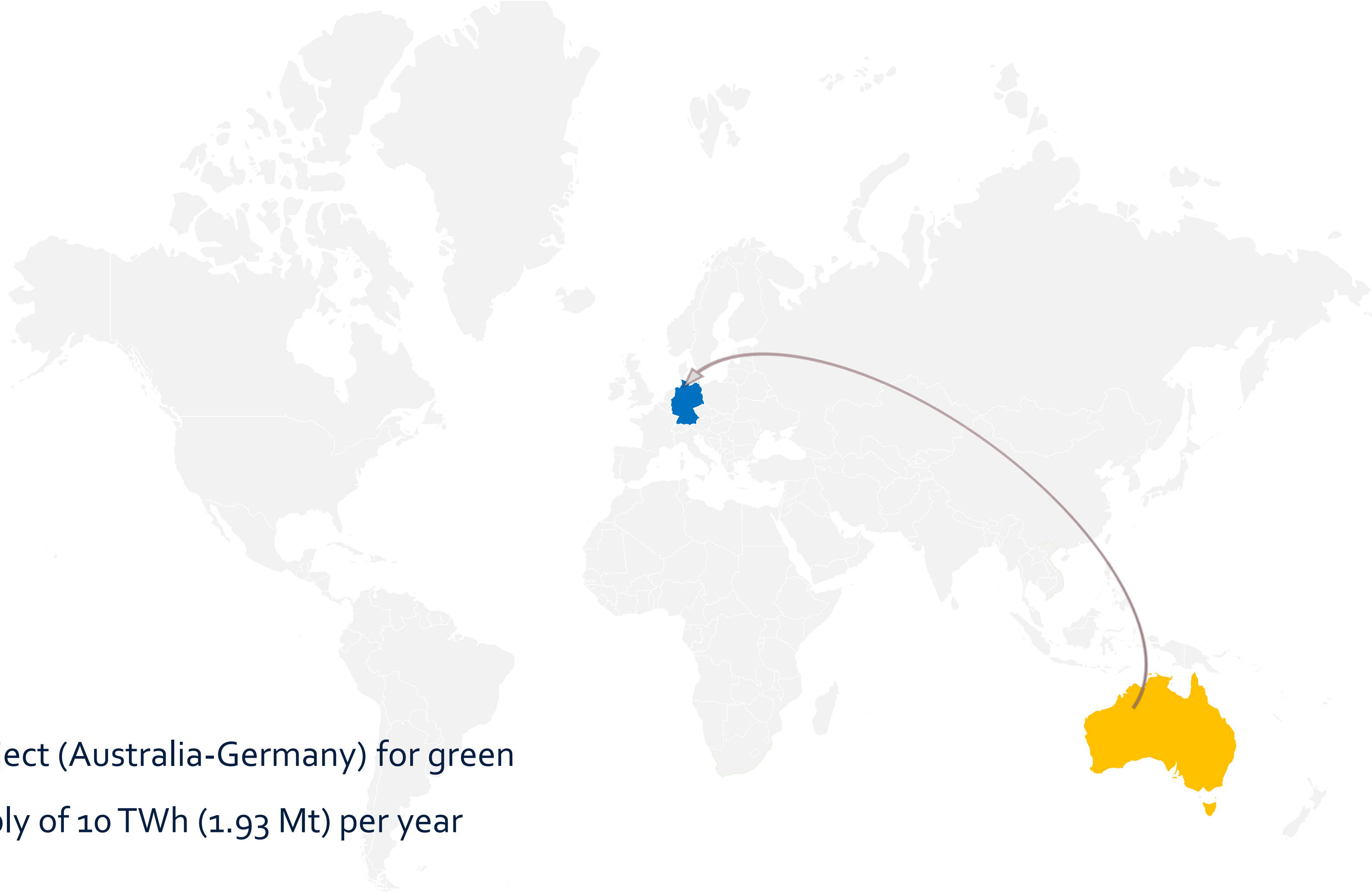


- The **objective** is to minimize the sum of annual total cost of the whole value chain.

- **Constraints** come either in the form of
  - Power production and consumption balances
  - Inter-temporal generation capacity and storage upper limits

Case study:
Green ammonia import from Australia to Germany

Case study- Green ammonia import from Australia to Germany

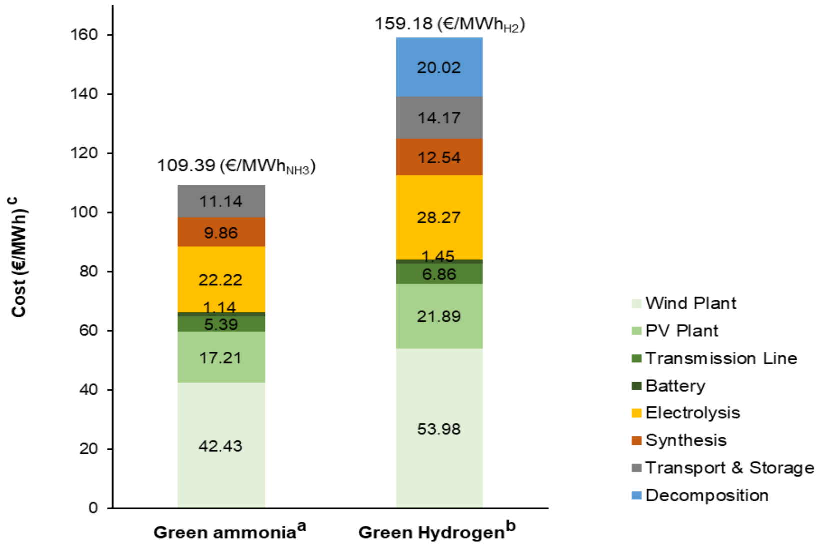


- A bilateral project (Australia-Germany) for green ammonia supply of 10 TWh (1.93 Mt) per year

Total levelized costs and cost components

Green ammonia and green hydrogen

Total levelized costs and cost components (€/MWh), based on cost-optimised hybrid RE power plants in Australia and transport to Germany for the year 2030

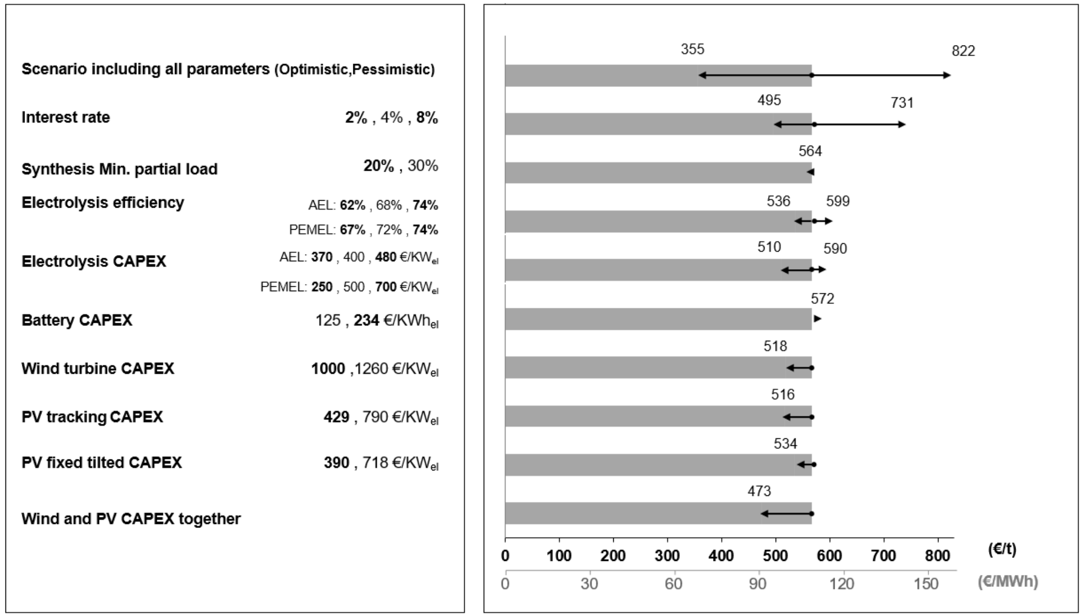


a- Cost components (€/MWh_{NH_3}) for green ammonia imported from Australia at the German harbor. b- Cost components (€/MWh_{H_2}) for green hydrogen at the German harbor, reconverted from Australian green ammonia. c- All cost assumptions and technological key parameters used in this study, have been summarized in Table A-1 in the Appendix A.

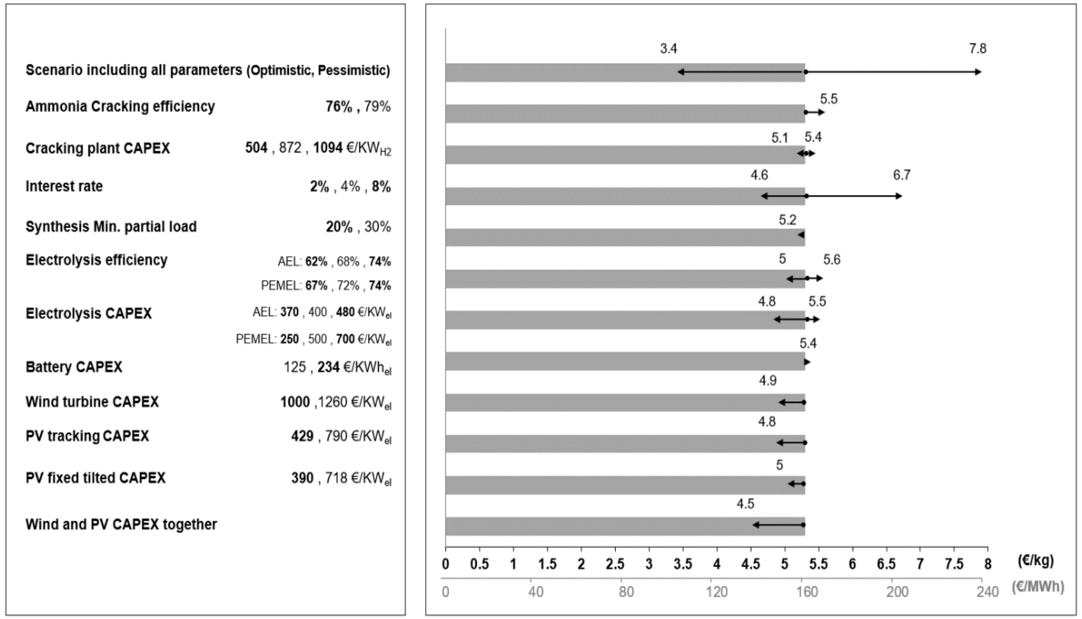
- **Levelized cost for green ammonia at the German harbor: 109.39 €/MWh (566.64 €/t)**
  - ➢ Green hydrogen is produced at 59.4 €/MWh (1.98 €/kg) in Australia.
  - ➢ Electricity supply is the biggest fraction of total levelized costs (about 81 %).
  - ➢ 9 % of total costs is due to green ammonia synthesis (9.86 €/MWh).
  - ➢ Transport and storage costs: 10 % of total cost (11.14 €/MWh).
- **Levelized cost of green hydrogen obtained by cracking imported green ammonia : 159.18 €/MWh (5.3 €/kg) hydrogen**

Sensitivity analysis for technical and economic parameters

Levelized costs of green ammonia



Levelized costs of green hydrogen after cracking ammonia



- The sensitivities for the lower and upper bounds of key parameters
- Combining all positive and all negative parameter variations in two extreme scenarios
- Levelized costs of green ammonia vary from **355 to 822€/t** and for green hydrogen could be offered in a range from **3.4 to 7.8 €/kg.**

Optimal installed capacities and investment costs

Production, installed capacities and utilization rate (UR) of technologies

	Technology	Unit	Value	UR
Electricity Supply	Wind	GW_{el}	3.60	47 %
	PV (tilted)	GW_{el}	–	
	PV (tracked)	GW_{el}	2.90	26 %
	Battery	GWh_{el}	0.62	
	Transmission line	GW_{el}	3.36	74 %
Electricity produced		TWh_{el}	21.56	
Curtailment		TWh_{el}	2.72	
Electrolysis	RO Desalination Plant	m^3/h_{Water}	0.16	49 %
	MED Desalination Plant	m^3/h_{Water}	0.38	87 %
	Electrolyzer (AEL)	GW_{el}	1.08	54 %
	Electrolyzer (PEMEL)	GW_{el}	1.80	88 %
	H_2 Storage tank	GWh_{H2}	8.99	
	H_2 compressor	GW_{el}	0.07	81 %
H_2O produced		Mm^3	3.63	
H_2 produced		TWh_{H2}	13.56	
NH_3 Synthesis	Synthesis	GW_{H2}	1.89	81 %
NH_3 produced		TWh_{NH3}	10.56	
Transport	Tanker volume	m^3 $_{NH3}$	160,000	
	Tanker capacity	t $_{NH3}$	109,248	
	No. of tours per ship / year		8	
	NH_3 storage tank	GWh_{NH3}	67.5	
NH_3 consumed as tanker fuel		TWh_{NH3}	0.32	
Final NH3 at destination		TWh_{NH3}	10.00	
NH_3 Decomposition	NH_3 decomposed	TWh_{NH3}	10.00	
	Cracking plant	GW_{H2}	0.90	100 %
	H_2 compressor	GW_{H2}	0.90	100 %
Final H2 at destination		TWh_{H2}	7.86	

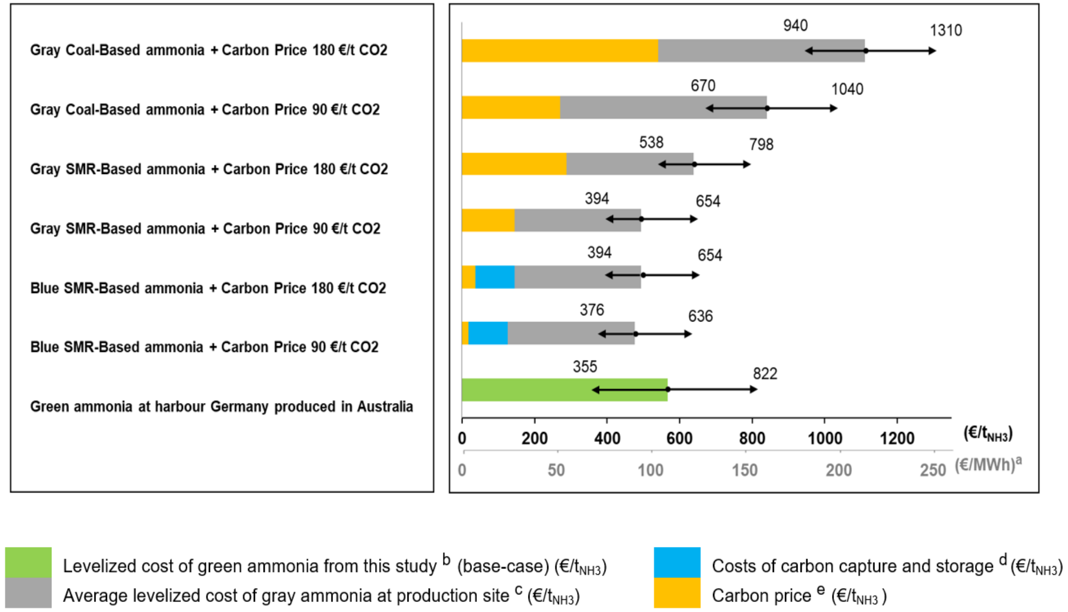
- Initial investment of 10.69 bn €.
- Annual operation costs of 0.33 bn €.
- 3 large ships (160,000 m^3) with 8 tours per vessel
- An annual electricity production of 21.5 TWh
- Annual water consumption of 3.63 Mm^3

Green ammonia supply of 10 TWh (1.93 Mt) per year

(Equivalent to 7.86 TWh green hydrogen)

Cost comparison for conventional and green ammonia

Levelized costs of green ammonia case study Australia-Germany (2030) versus levelized costs of conventional and blue ammonia in Europe



The average levelized cost of SMR-based and coal-based ammonia (without carbon taxes) were **350** and **570 €/t** respectively by the year 2020 (IEA 2021).

- Assuming gas price of **30 €/MWh** and hard coal price of **60 €/t** approximately.
- If CO_2 emissions cost **90 €/t**, there is no economic incentive to invest in gray ammonia production.
- Blue ammonia is more or less competitive to green ammonia production.
- All these comparisons look quite different for today's gas prices.
- Green ammonia will be faster economically favorable.

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HIGHLIGHTS

- Optimization model for the integrated assessment of the green ammonia value chain.
- Case study for ammonia trade between Australia and Germany in 2030.
- Sensitivity analysis on ammonia prices for technical and economic parameters.
- Cost comparison of conventional and green ammonia production.

Thank you for your listening!