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

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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.

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ABSTRACT

This paper contributes to understanding the transformation of global energy trade to green energy carriers, focusing on green ammonia as the foreseeable first green hydrogen carrier. We provide a comprehensive overview of today's ammonia trade and assess scaling options for the trade of green ammonia. To that aim, we develop an optimization model for the integrated assessment of the green ammonia value chain that covers all steps from green ammonia production in an exporting country, up to delivery to a harbor in an importing country. The model endogenously chooses among different technology options and determines cost minimal operation. In a case study, we apply the model to the large-scale import of ammonia from Australia to Germany in a scenario for 2030. The results show that green ammonia can reach cost parity with gray ammonia even for moderate gas prices (but not necessarily with blue ammonia) if CO_2 prices are high enough. We also provide a sensitivity analysis with respect to the interest rate and other key technical and economic parameters and show that cracking ammonia to provide pure hydrogen comes at a 45 % cost markup per MWh at the destination.

1. Introduction

To mitigate climate change effectively and timely, rapid decarbonization of the global economies is required. The transformation is already well advanced in the electricity sector of various industrialized countries, where competitive renewable energy technologies increasingly replace coal- and gas-fired power plants. Climate-neutral electricity will now be used directly or indirectly – via hydrogen and its derivatives – to decarbonize all remaining sectors of the economy [46]. In this context, the production and transport of hydrogen and energy carriers is getting increasing attention, as they have the potential to replace fossil coal, oil, and gas as a global energy commodity. Global hydrogen trade allows import-dependent countries with limited and mediocre potential for renewable energies, to replace fossil fuel imports by imports of sustainable hydrogen based energy carriers. In turn, export opportunities are opening up for many countries that have high potential for renewable energy [31,32].

Various options are being discussed for the overseas transport of hydrogen, among them the transport of cryogenic hydrogen, liquid organic hydrogen carriers (LOHCs) or energy carriers like ammonia or methanol [44,52,31,51,53]. In the short term, the transport of ammonia is particularly attractive, since ammonia and its derivates are already traded worldwide and therefore existing infrastructure can be used [60]. Furthermore, all links in the process chain of large-scale renewable ammonia production are already established and have a very high technology readiness level [56]. Ammonia today is mainly used for the

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production of fertilizers but also for other industrial applications like explosives and textiles [3]. It is currently produced from fossil energy sources, either upstream near gas or coal extraction sites or downstream from imported fossil energy sources [59]. Global annual ammonia production of about 180 Mt in 2019 emitted about 0.45 Gt carbon dioxide (CO_2).[1] Existing production capacity, if plants are run until the end of their lifetime (20–50 years), would result in locked-in CO_2 emissions of 4.4 to 15.5 Gt CO_2. Projections for net zero emission scenarios in 2050 [34] see a 25 % increase of global ammonia demand for existing users and additional energy demand for maritime fuel and power generation in the range of twice the global ammonia demand of today.

Ammonia production with green hydrogen (electrolysis with renewable energy sources), and with blue hydrogen (fossil fuels with carbon capture technologies) during a transition period, could allow for significant emissions reductions in a timely manner by satisfying projected increases in global demand and by replacing existing ammonia production [21,52,34]. While there are still plans for the expansion of fossil ammonia production in some regions, with related greenhouse gas emissions, projects of several megatons in annual capacity will use low-carbon technologies until 2030 and mark the first step towards the defossilization or decarbonisation of ammonia production [34,35,58]. High fossil fuel prices resulting from Russia's war of aggression on Ukraine could accelerate this transition from fossil to green ammonia.

During the transition to carbon neutrality, ammonia production is likely to shift, at least in part, to regions with the most favorable conditions for renewable electricity generation, which would lead to a redirection and possibly an increase in global ammonia trade [27]. This development will also affect the production and trade of important ammonia derivates, such as urea and ammonium nitrate [34]. The transition will therefore likely require investment in new vessels for ammonia transport, new infrastructure at ports for loading, unloading, and storage, as well as downstream integration into consumption centers [38,18]. Incentivizing these investments requires an appropriate regulatory framework that, among others, internalizes external costs of fossil fuels, reduces climate-damaging subsidies, and allows for the certification of CO_2-reduced derivatives.

This paper contributes to understanding the challenges and opportunities that arise from the transformation of global energy trade to green energy carriers. We focus on green ammonia production and long-distance transportation, which is likely to be of high relevance for early global green energy trade. We first describe the current global ammonia trade and outline which parts of the value chains could continue to be used in the context of the transition to green ammonia. We then develop a comprehensive techno-economic model for green ammonia value chains, which can be applied for a wide range of technologies and production processes that could become relevant for global ammonia trade. Based on input cost assumptions, the model provides assessments of the future levelized cost of green ammonia – i.e., as feedstock for industry or for direct energy usage – and the levelized cost after an optional conversion back to hydrogen. In particular, the model endogenously derives optimal investment levels and operation for different technologies of renewable energy supply, hydrogen and nitrogen production, ammonia synthesis, storage, transport, and (optional) reconversion of ammonia back to hydrogen. This holistic view along the entire value chain in one model enables us to analyze explicitly the interdependencies between energy supply, the various production steps for ammonia, and transportation to the demand centers. Decisions on the selection of different technologies for power generation, hydrogen production, heat integration, storage units, etc., and their optimal operation are endogenous in our model.

We apply our model to a case study exploring trade of green ammonia from Australia to Germany and analyze the results with respect to various parameter uncertainties. The case study for Australia is particularly well suited because, first, the continent will export increasing amounts of green energy due to its immense renewable energy potential and, second, its long distance from Germany allows us to assess the importance of transportation costs relative to the production costs of green ammonia. The results with different parameter sensitivities for 2030 indicate that green ammonia is on the way to become competitive to gray ammonia production well before the end of this decade. In addition to decreasing cost for green ammonia, this development could accelerate by the fact that the price for ammonia production from fossil fuels is likely to increase due to higher costs for carbon emissions and uncertainty on fuel fossil prices. Thus, green ammonia can contribute to timely decarbonization of the feedstock for several industry sectors and become a green energy carrier for direct energy applications or reconversion into hydrogen. Depending on the assumption for economic and technical parameters, the technologies used and their operational management of an ammonia process chain differs significantly. Transportation costs account for only a small portion of the levelized cost of imported ammonia. However, ammonia loses some of its cost advantage when it has to be converted back to hydrogen for specific applications. The energetic usage of ammonia will therefore likely depend on technological advances in its direct utilization as maritime fuel and in power and heat generation plants.

Recent literature provides a wide range of cost analyses for green and blue ammonia. Often simplified models are used, which can provide a good approximation but do not allow endogenous decisions about optimal technology choices. Possible synergies between different technologies are often not modeled and the dynamic operational management inherent for volatile renewable production is not accurately represented. Several among the existing studies focus only on the production of green ammonia, but not on its storage, transport or usage [45,21,15]. Other studies go beyond this and look at the storage and transport of ammonia. For example, Hank et al. [31] estimates the cost of production and long-distance transport of green ammonia from Morocco to Germany in 2030. Similarly, Ishimoto et al. [38] conduct a case study to determine the levelized cost of supplying hydrogen to the European market based on the production of blue and green ammonia in Norway and subsequently ammonia transport and decomposition to hydrogen. In contrast, Salmon and Bañares-Alcántara [52], Li et al. [39], Ikäheimo et al. [36], Del Pozo and Cloete [22], Fasihi et al. [27], Nayak-Luke and Bañares-Alcántara [43] present dynamic models of green ammonia production by fluctuating renewables. Salmon and Bañares-Alcántara [52] show economies of scale for green ammonia production and focus on land availability for large-scale ammonia production. Li et al. [39] compare different supply modes for energy from wind plants, for ammonia production plants in China including onsite production, supply via trucks transporting gaseous hydrogen, and energy transport via transmission lines. Ikäheimo et al. [36] also model the application of ammonia and compare costs for ammonia-based district heating in different northern European countries. Del Pozo and Cloete [22] focus on the production costs of various processes for the production of blue ammonia and set these in relation to the production of green ammonia. Fasihi et al. [27] and Nayak-Luke and Bañares-Alcántara [43] examine a large number of possible production sites for green ammonia, with Fasihi et al. [27] also providing an overview of the transport costs of the derivative.

In the above-mentioned publications, the authors make various ex-ante decisions about technology choices and apply cost-optimized models with linear constraints to the configuration of green ammonia supply chain components [27,43,52]. The optimization model in this paper relates to these studies and extends the literature with endogenous decisions on investment and operation for different technologies along the entire value chain of green ammonia. This includes seawater desalination, renewable energy supply, electrolysis, ammonia synthesis, large-scale long-distance transport of green ammonia, and its possible application as hydrogen carrier by including later reconversion.

[1] Global production figures vary by source. 173 Mt [58] and 182 Mt [35]: no public data per country).

Table 1
Main ammonia producers in 2019 (anhydrous or aqueous solution).[5]

[in Mt product/year]	Production	Export	Import	Consumption*
China	46.3	–	1.1	47.3
Russia	18.3	5.2	0.1	13.1
U.S.	16.4	0.5	2.5	18.5
European Union	16.0	1.7	5.7	20.1
India	14.9	–	2.9	17.8
Indonesia	6.1	1.8	–	4.3
Trinidad and Tobago	5.5	3.7	–	1.8
Egypt	5.1	0.7	–	4.4
Saudi Arabia	4.9	1.5	–	3.4
Canada	4.8	1.0	–	3.8
Iran	4.3	0.2	–	4.0
Qatar	3.8	0.6	–	3.3
Pakistan	3.8	–	–	3.8
Algeria	2.7	1.2	–	1.5
Oman	2.1	0.2	–	1.9
Ukraine	1.8	0.5	0.9	2.2
Australia	1.6	0.3	–	1.3
Sum	158.4	19.1	12.3	152.5
(Global share)	(92 %)	(93 %)	(64 %)	(88 %)

[5] Production: [60], Trade: [14],*calculated from other values.

Table 2
Trade of mixtures of urea and ammonium nitrate in aqueous or ammonia solution in 2019.

[in Mt product/year]	Export	Import
Countries in European Union	2.99	3.83
Russian Federation	2.87	–
Trinidad and Tobago	1.44	–
USA	1.02	3.34
Belarus	0.52	–
Canada	0.42	0.35
Australia	–	0.31
United Kingdom	–	0.48
Argentina	–	0.57
Sum	9.26	8.88
(Share global)	(99 %)	(95 %)

[6] [14].

The remainder of the paper is organized as follows. Chapter 2 provides an overview of today's ammonia market and discusses the transition to green ammonia production with additional applications for ammonia in the future. Chapter 3 outlines the green ammonia value chain and the mathematical model framework. The optimization model is applied to a case study with green ammonia production in Australia and export to the European market in chapter 4, before chapter 5 concludes.

2. Ammonia today

2.1. Global ammonia production, consumption, and trade flows

Global ammonia production in 2019 had been in the range of 180 Mt (product weight) and was produced mainly from fossil gas worldwide (72 %) and from coal in China (26 %).[2] More than two thirds of the ammonia production is used for mineral nitrogen fertilizers, the largest share in the form of urea, followed by other fertilizers whose production is via nitric acid and ammonium nitrate [34,1]. The remaining part is used in industrial applications, such as the production of textiles and explosives, as an intermediate for pharmaceuticals, in the production of synthetic polymers, and in commercial refrigeration and air conditioning units [3].

The overview on major ammonia producers in Table 1 shows that global production is concentrated in certain countries and only 20.6 Mt (12 %) of global production is traded between countries. This is also evident from the fact that the largest consumers, China, the European Union, the U.S., and India, produce most of their ammonia demand locally using domestic or imported fossil fuels. Although they only rely on ammonia imports to a small extent, their combined share of global imports is nevertheless almost 60 %. Main other importers of ammonia with limited own production capacity are Morocco (1.4 Mt), South Korea (1.4 Mt), Turkey (1.0 Mt), and Norway (0.5 Mt). Large exporters of more than 1.0 Mt are mostly gas producing countries, i.e., Russia (5.2 Mt), Trinidad and Tobago (3.7 Mt), Indonesia (1.8 Mt), Saudi Arabia (1.5 Mt), Algeria (1.2 Mt), and Canada (1.0 Mt). A large share of ammonia is processed into urea and ammonium nitrate, yet only nine countries worldwide are involved in significant trade with urea and ammonium nitrate (Table 2). The main exporters of ammonia derivates are Trinidad and Tobago as well as Russia, and the largest net importer is the U.S. followed by the European Union. Future projections [34] predict an increase in ammonia demand from current applications and a very high demand for energetic usage e.g., in maritime transport and power generation, either directly or after conversion back to hydrogen.

Fig. 1 provides a more detailed picture of global ammonia trade flows between countries. The highlighted countries stand for 96 % of exports and 95 % of imports in international trade and the lines for trade larger than 0.1 Mt per year illustrate about 80 % of the 20.6 Mt in global ammonia trade in 2019. The trade routes indicate the importance of maritime ammonia trade. In fact, ammonia terminals already exist in 200 harbors worldwide [34]. Although a remarkable share of global ammonia demand is served by countries with the highest shares in worldwide production, the spread of consumers and producers around the world has contributed to the creation of a decentralized market.

Ammonia at medium to large scale is usually shipped in liquefied petroleum gas (LPG) carriers [27]. Today, 170 ships with the capability of carrying ammonia are available. Many of them transport also LPG and other similar products, whereas 40 ships are in operation to carry ammonia permanently [11]. In addition to maritime shipment, pipelines can serve the down-stream integration from import terminals to demand centers and vice versa connect production to export terminals. The main example for import integration is the U.S. where an ammonia pipeline system transports about 1.5 Mt per year from the Gulf of Mexico to agricultural and industrial customers in the Midwest [1]. For export integration, the Tolyatti-Odessa pipeline system transports more than 2.0 Mt per year connecting the world's largest ammonia producer in Russia to the Black Sea. The initial endpoint in Odessa (Ukraine) has been rerouted to the Russian Black Sea port Taman in the last years. Except for the U.S. and Russia, only shorter routes exist for liquid ammonia pipelines across Europe where railway transport plays a more significant role. In Germany, for example, ammonia pipelines have a length of only 38.8 km and are used as distribution route to industrial consumers, while trucks are the most common means of short-distance transport to the end users [24].

2.2. Conventional and green ammonia production

Ammonia production consists of the two steps as shown in Fig. 2, i.e., production of feedstock and ammonia synthesis. Decarbonization of ammonia production requires a transition from conventional (gray) towards green technologies. In particular, this requires sustainable processes for feedstock production, i.e., electrolyzers for hydrogen (H_2) to replace coal gasification and steam methane reforming (SMR), while air separation unit for nitrogen (N_2) and ammonia synthesis, depending on their locations, could take place in existing plants. A transitionary step for existing fossil plants with specific emission of about 3.0 t_{CO2}/t_{NH3} for coal and 1.6 t_{CO2}/t_{NH3} for fossil gas could also be an extension with carbon capture and storage (CCS) to reduce emissions to about 0.2 t_{CO2}/t_{NH3} [49], so-called blue ammonia. Since there are no chemical differences between green and gray ammonia molecules, direct integration in

[2] 172 Mt [58] and 182 Mt ([35]: no public data per country).

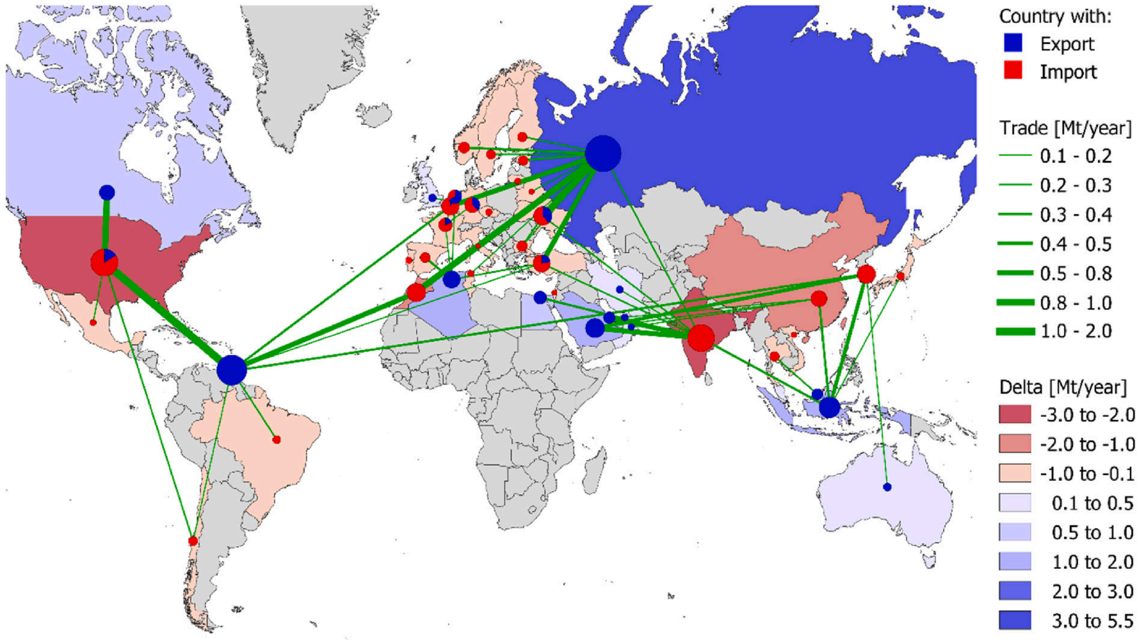
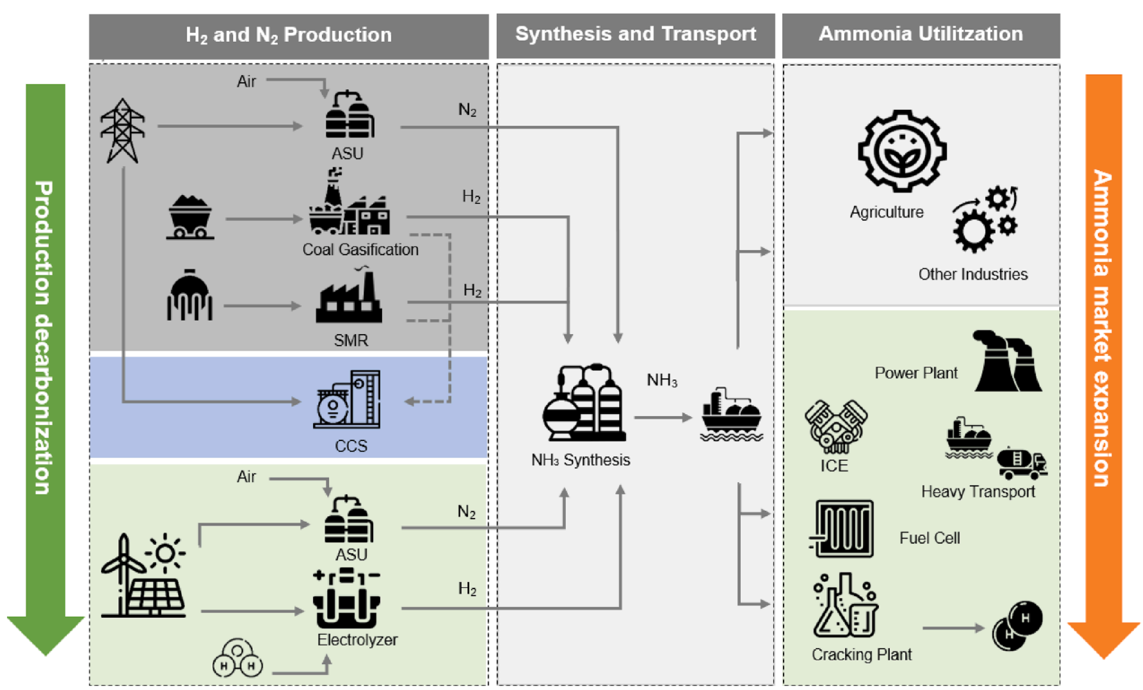


Fig. 1. Global ammonia trade flows and balances larger 0.1 Mt per year in 2019 [14].



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*

Fig. 2. Evolution of green ammonia versus conventional/gray ammonia.

existing transport infrastructure is possible. Nevertheless, the production of ammonia from fossil fuels results in very small but specific impurities, which potentially allows specifying the production source at a later stage. Production will likely shift to some extend to regions with favorable renewable potentials and can result in a growing global ammonia markets, which requires additional transportation assets. This development could allow ammonia to gain a foothold in several new sectors, e.g., the energy sector, internal combustion for ships and heavy transport, fuel cells, and as hydrogen carrier with later cracking.

The production process for hydrogen is key to the transition towards green ammonia. Hydrogen is currently produced mainly from hydrocarbons by partial oxidation of hard coal ($C_{24}H_{12}$) in Eq. (1) or from natural gas (CH_4) by SMR in Eq. (2) [8]. To further increase the hydrogen fraction in the synthesis gas, the carbon monoxide (CO) is oxidized in the water gas shift reaction, as shown in Eq. (3) [28].

$$C_{24}H_{12} + 12\ O_2 \leftrightarrow 24\ CO + 6\ H_2 \tag{1}$$

$$CH_4 + H_2O \leftrightarrow CO + 3\ H_2 \tag{2}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{3}$$

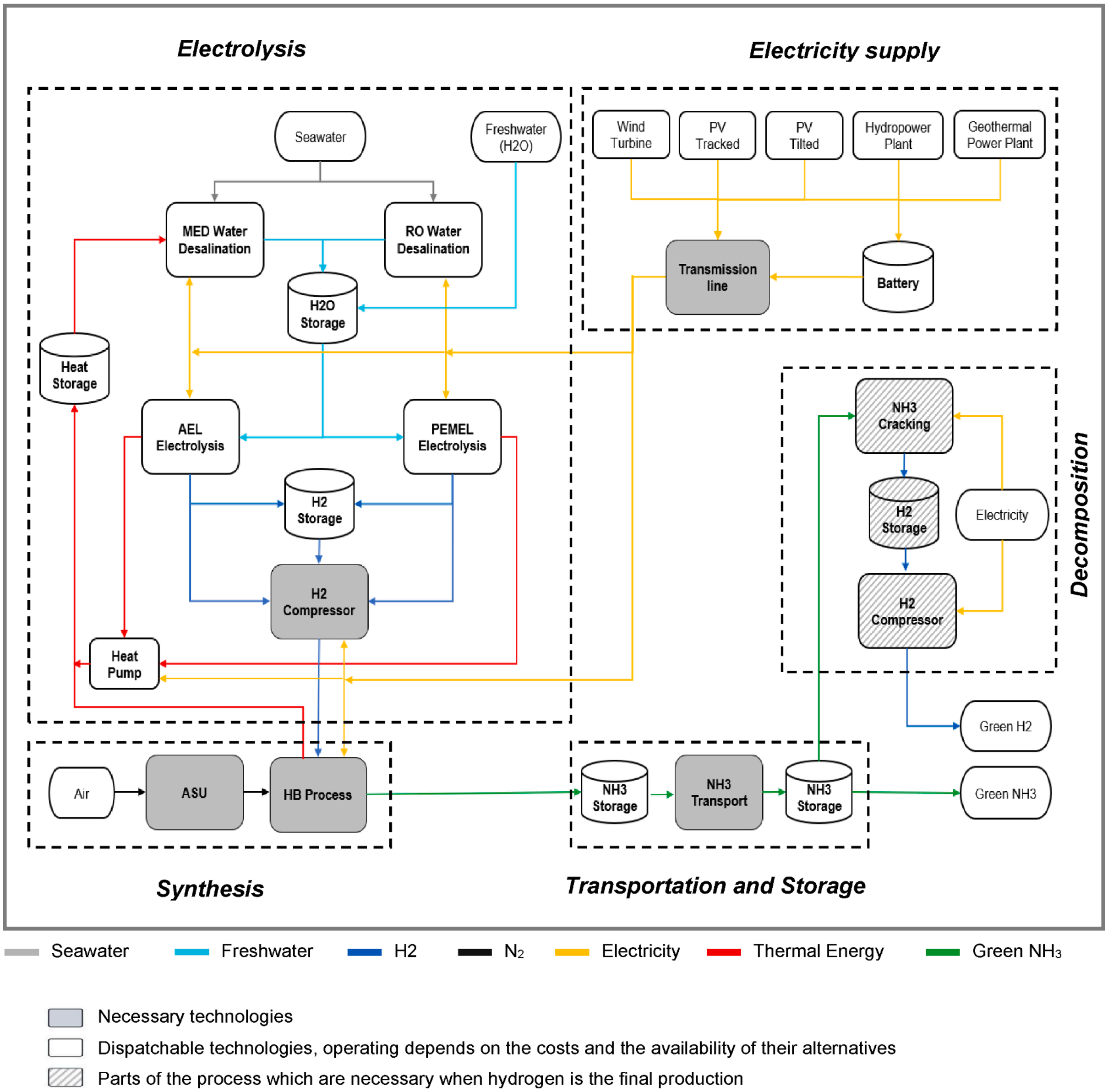


Fig. 3. Value chain of green ammonia and green hydrogen.

Production of hydrogen for green ammonia uses renewable electricity for the electrolysis of pure water into hydrogen (H_2) and oxygen (O_2).

$$H_2O \leftrightarrow 2\,H_2 + O_2 \tag{4}$$

Various technologies can recover purified nitrogen from the atmosphere for Haber-Bosch synthesis: air separation unit (ASU), pressure swing absorption (PSA), and membrane separation. Unlike other available technologies, ASU has the disadvantage of complexity with different fluid flows. However, it delivers a high product output with high purity while requiring low energy input and is very suitable for large-scale ammonia production plants [45].

In the second step, nitrogen (N_2) is hydrogenated to ammonia (NH_3) in the exothermic Haber-Bosch (HB) process, as shown in Eq. (5) [23].

$$H_2 + N_2 \leftrightarrow 2\,NH_3 \tag{5}$$

As illustrated in Fig. 2, the Haber-Bosch process will remain unchanged for gray, blue, and green ammonia. In case of hydrogen demand, cracking of ammonia into its constituents can provide local supply of hydrogen and nitrogen. This process is the reverse reaction of the ammonia synthesis, requires heat at a temperature level of about 500 °C, and is followed by hydrogen separation and purification through a metal membrane reactor. Although, small scale ammonia crackers are already available in some industries, large scale ammonia decomposition plants are not in common use but the technological readiness level is improving with the experience of demonstration plants [56].

3. Green ammonia

3.1. The green ammonia value chain

The uneven distribution of the world's renewable energy potential and the distance between locations with favorable conditions for renewable energy and consumption in population and industry centers will lead to increasing global trade of sustainable energy carriers. Various hydrogen-based carrier systems are being considered due to their high energy density and comparatively low transportation costs. In the medium term, these fuels have the potential to replace trade in fossil resources such as coal, oil, and gas. The existing trade and widespread use of ammonia qualify ammonia as one of the first carrier systems for renewable energy in the near future. Countries with excellent conditions for renewable energy sources such as PV, wind, hydropower or geothermal energy are ideal production locations. In addition to electrical energy, the process chain also requires nitrogen and fresh water. With about 1.5 tons of water per ton of ammonia, the water demand is relatively low [41], but may further exacerbate potential water shortages in arid areas for large-scale production. Therefore, it may be necessary to desalinate seawater in these areas. Together with the necessary access to port infrastructures, this makes ammonia production near the coast a viable option and allows the exploitation of synergies between exothermic ammonia production and endothermic seawater desalination. Ammonia, after being cooled to a temperature of about –33 °C, can be transported by vessels similar to today's LPG tankers. Such vessels are equipped with pumps and cooling systems [7,16]. In the country of destination, either ammonia can be used directly for applications, as described in section 2, or it can be converted back to hydrogen. The decomposition of ammonia into hydrogen and nitrogen is a reverse reaction of ammonia synthesis, which is an endothermic reaction and requires high temperatures (>500 °C) [7]. In the following subsection, we present a detailed mathematical model to analyze the optimal setup of a green ammonia process chain.

3.2. The model

This section gives a brief overview of our techno-economic optimization model. Fig. 3 shows the modeled processes together with the mass and energy flows. The Appendix provides additional information, including a description of all variables and parameters. With the objective of cost minimization, we seek to determine the levelized costs of green ammonia and green hydrogen to meet (exogenous) demand at the import location. Investment decisions in different technologies as well as their hourly operations are endogenously taken as to minimize levelized cost of the entire process chain and depend on exogenous parameters fed into the model, such as power generation vectors (wind profile, solar profile, etc.), demand profiles for ammonia or hydrogen, as well as economic and technical parameters on costs and efficiencies.

The modelled value chain includes certain necessary process steps, which cannot be substituted, but where the capacity and hourly operation can nevertheless be optimized. Those technologies are highlighted in gray in Fig. 3. For other technologies – depicted in white in Fig. 3 – the model can provide several options, e.g., different renewable power generation technologies, electrolysis technologies or desalination plants. Optimization can lead to the selection of a single technology or a mix of technologies.

The model allows investment in five technologies for electricity generation from renewable energy sources, i.e., hydropower, geothermal, wind power, and PV with either fixed solar panel mounting or with solar trackers. In addition, an endogenous decision is made between the two electrolysis technologies, alkaline electrolysis (AEL) and proton exchange electrolysis (PEMEL), that differ in terms of installation costs and efficiency. The fresh water demand of the electrolysis plants can, depending on the location, either be purchased or produced by seawater desalination. We allow for two different technologies for seawater desalination: reverse osmosis (RO) and multi-effect desalination (MED) plants. The reverse osmosis technology only uses electrical energy for desalination. In contrast, multi-effect desalination plants also use thermal energy, which in our model is either provided by waste heat from the Haber-Bosch (HB) process or produced by heat pumps. Once produced, ammonia is liquefied, pumped onto a ship, and transported to the destination country. We calculate the transport costs, which depend on the transport distance and the technical and economic assumptions of the vessel, and take into account any boil-off losses that occur. At its destination, the ammonia is either sold directly or decomposed into its components hydrogen and nitrogen in a cracking plant. In order to flatten mass and energy flows, the model allows investment in storage technologies between different process steps.

The objective in Eq. (6) is to minimize the sum of annual total cost of the whole supply chain as illustrated in Fig. 3. According to Salmon and Bañares-Alcántara [52] and Zauner et al. [62], technologies like renewable energy plants or electrolyzers are mainly modular and therefore scale approximately linearly. It is therefore adequate in the context of our mathematical model to adopt a linear cost-minimization approach.

$$\text{Objective function}: \ \min c^{T} = c^{ES} + c^{E} + c^{S} + c^{Tr} + c^{De} \tag{6}$$

Total cost (c^{T})is the sum of cost modules including electricity supply (c^{ES}), electrolysis (c^{E})and synthesis (c^{S}), transport and storage (c^{Tr}), and decomposition (c^{De}).However, not individual costs of the modules are minimized and summed up, but the model optimizes across the entire process chain. As illustrated in Fig. 3, the boundaries between the modules are not clearly defined, due to the synergies and interdependencies. However, the modules are useful to facilitate a later evaluation of the results.

The constraints come either in the form of power production and consumption balances or inter-temporal generation capacity and storage upper limits. As an example, the power balance in Eq. (7) includes all electricity suppliers and consumers in the upstream part.

$$\left(y_t^{Wi} + y_t^{PV,f} + y_t^{PV,t} + y_t^{G} + y_t^{Hy} + \Delta v_t^{Ba,-} * \eta^{Ba} - \Delta v_t^{Ba,+}\right) * \eta^{TL}$$

$$=$$

$$d_t^{RO,El} + d_t^{MED,el} + \sum_{e \in E} d_{t,e}^{El} + d_t^{Co,S,H} + d_t^{S,el} + d_t^{HP,el} \ for\ all\ t \in T \tag{7}$$

In the power balance, $y_t^{Wi}, y_t^{PV,f}, y_t^{PV,t}, y_t^{G}, y_t^{Hy}$refer to the power produced by wind, fixed and tilted PV, geothermal, and hydropower plants respectively. $\Delta v_t^{Ba,-}$ and$\Delta v_t^{Ba,+}$present battery power input and output. The generated power is factored by the efficiency of the battery and the transmission line, shown by $\eta^{Ba}$and η^{TL}. As illustrated in Fig. 3, the produced power is fed into power consumers, i.e., water desalination RO ($d_t^{RO,El}$), water desalination MED ($d_t^{MED,el}$), each electrolysis plant ($d_{t,e}^{El}$), H_2 compressor ($d_t^{Co,S,H}$), synthesis plant ($d_t^{S,el}$), and heat pump ($d_t^{HP,el}$), if it is required.

Apart from techno-economic assumptions on various components of the green ammonia supply chain, the model also relies on the other case-specific input data such as wind and solar potentials at the production sites, prices of electricity at the destination, and financing conditions, such as interest rates. In addition to total levelized costs and details on various cost components, the model yields insights on other process design aspects, such as maximum capacity and utilization rates of each individual technology. The linear optimization problem has been set up to allow for an hourly resolution (which could be adapted if desirable) and has been solved for a representative year with the solver Gurobi (version 9.1) in the General Algebraic Modeling System (GAMS) environment.

4. Case study: ammonia imports from Australia to Germany

4.1. General setting

The following case study applies the techno-economic optimization model to a bilateral project for ammonia trade between Australia and Germany. In the case study, Germany represents an industrialized economy with significant industrial energy demand and mediocre conditions as well as limited potential for renewable electricity generation. Germany – as well as other industrialized economies worldwide such as other EU member states or Japan – will have to become an importer of sustainable synthetic energy carriers, in particular to achieve the defossilization of certain industry sectors and processes. The transformation pathway of the IEA [34] towards net zero emissions by 2050

Table 3
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	

requires overall net-zero emissions in electricity generation for advanced economies in 2035 and 850 GW of global electrolysis capacity in 2030. These figures highlight the need for advanced economies to increase their investment in renewable capacity but also the future reliance on sustainable energy carriers. The location of electrolysis capacity for the production of sustainable fuels and feedstock could be either in regions with favorable conditions for renewable energy sources or closer to demand centers at the cost of less favorable renewable conditions. Investment in a limited capacity for electrolysis will likely take place in demand centers utilizing surpluses of volatile renewable electricity generation. However, most investment in electrolysis capacity will go to locations with more favorable conditions for renewable electricity generation at a global level due to lower average electricity costs. Australia is such a country and is analyzed in our case study.

Australia is the sixth-largest country in the world with a low population density, abundant renewable potential and a long coast line with available large-scale shipping infrastructure and the potential for desalination plants [18]; COAG [17]. According to previous studies, lowest cost for power supply, e.g., in Western Australia, would be achieved through a combination of wind and solar power [52,51]. The export of green ammonia and other sustainable energy carriers provides Australia with an opportunity to overcome its economic dependency on the export of fossil fuels. When it comes to ammonia, annual fossil-based production of 1.6 Mt per year, which is mostly used domestically, could be replaced by green ammonia. With investments in its vast renewable potential and in additional production capacity for green ammonia and other sustainable energy carriers, Australia could become one of the leading exporters of green energy in the next decades.

On the contrary, Germany has one of the most ambitious renewable targets for 2030 among the industrialized economies and plans to rely on renewable electricity production in Germany and other green energy carriers, like hydrogen, in the context of the German energy transition [9]. Although the government plans include significant domestic production capacities for green hydrogen, covering feedstock and energy demand with sustainable fuels requires the import of additional sustainable energy carriers, such as ammonia. Already today, Germany participates in international ammonia trade with 0.3 Mt in imports and 0.6 Mt in exports, in addition to its domestic production of about 2.5 Mt per year [35], which is produced from imported fossil gas. Approximately 80 % of total demand is used as the feedstock for the production of fertilizers and the rest goes into the organic chemical industry, such as for the production of plastics and synthetic fibers [40]. Since 2000, the annual consumption of nitrogen fertilizers has decreased from 2.0 Mt to 1.3 Mt nitrogen in Germany [25]. This trend will likely continue due to EU regulations on nitrate emission and an increasing share of organic farming while new ammonia demand could develop for back-up capacity in electricity generation.

In their joint interest to develop a global market for sustainable energy carriers. Germany and Australia recently signed a joint declaration of intent in 2021 to establish a German-Australian hydrogen alliance and since then strive to establish trade of renewable energy carriers [10] This could result in the development of green ammonia production in Australia and export to Germany, which could take place in multiple expansion steps. Our case study assumes an implementation at industrial scale for 2030 with an annual production of 10 TWh (1.93 Mt) of ammonia, which is in range of the annual ammonia demand in Germany for 2019. For the case study, we assume sensitivities for technical parameters and cost projections for the year 2030 (see the Appendix A for an overview of all parameters). The cost parameters include investment cost (capex) and operating costs (opex) and an interest rate of 4 % to calculate average cost of supply. Renewable power generation technologies are fixed-tilt photovoltaic (PV), single-axis tracking PV, and onshore wind turbines. Ammonia production plants are located in coastal regions and use seawater desalination. Transportation cost from Australia to Europe, including the empty return trip, depend on the parameters of transport distance (17,600 km through the Suez Canal), canal fees, fuel consumption, and speed of the vessel. In case of conversion back into hydrogen, costs for electricity consumption consider an hourly price vector for the German spot market with an average price of about 60 EUR/MWh. The model is agnostic of any taxes or levies in either Australia or Germany.

4.2. Investment and cost results

In our results, a bilateral project between Australia and Germany for green ammonia supply of 10 TWh (1.93 Mt) per year, which is produced in Western Australia and supplied to a harbor in Northern Germany, requires an initial investment of 10.69 bn € and has annual operation costs of 0.33 bn €, see Appendix A and Table 3. The largest single investment position is for the construction of 3.6 GW in wind capacity and 2.9 GW in tracked PV capacity. Including the costs for battery storage and transmission lines, initial investment for the renewable electricity supply is 6.93 bn €. This system provides an annual electricity production of almost 21.5 TWh for the electrolysis, desalination of see water, the ASU, and the synthesis plant.

The optimal installed input capacity of the electrolysis is 1.08 GW for AEL and 1.80 GW for PEMEL. The mix of PEMEL and AEL results from the different economic and technical assumptions for the two technologies. The more expensive but more efficient PEMEL has a utilization rate of 88 %, which is significantly higher than the less expensive but more inefficient AEL. With the assumed generation profile for renewable electricity, 0.62 GWh of battery storage is sufficient to allow for a high utilization rate of electrolyzers and other downstream consumers. An additional 8.99 GWh of hydrogen storage for temporary surplus production is optimal to meet the demand of the synthesis plant during periods with insufficient hydrogen supply from electrolyzers. Investment cost of 1.52 bn € have to be projected for the electrolysis plant including water desalination, electrolysis capacity, and hydrogen

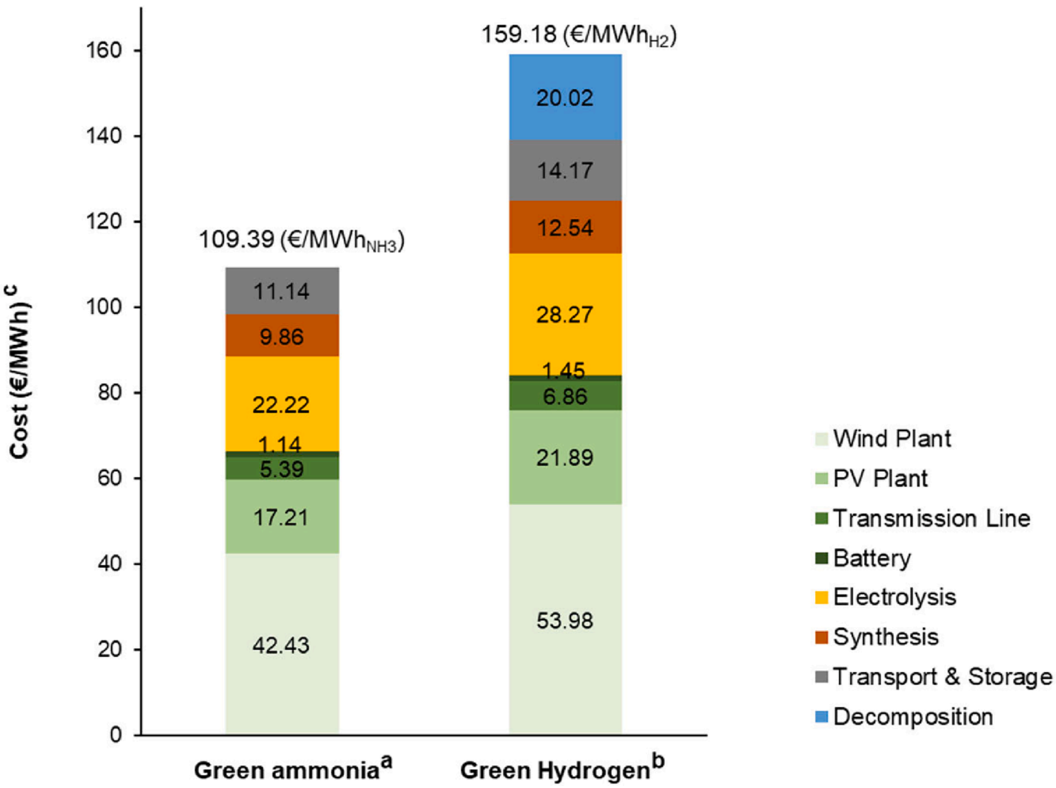


Fig. 4. Total levelized costs and cost components (€/MWh) of green ammonia and green hydrogen, based on cost-optimised hybrid RE power plants in Australia and transport to Germany for the year 2030.

storage. The plant has an annual water consumption of 3.63 Mm^3 and produces over 13.5 TWh in hydrogen. This is enough to synthesize 10.56 TWh of green ammonia in the synthesis plant, which has investment costs of 1.35 bn €. Besides that, the synthesis plant produces over 1.46 TWh of thermal energy, which is sufficient to meet the heat demand of the total MED desalination plant (0.09 TWh) at no additional cost.

Three large ships – exact number is 2.26 – are needed to deliver 10 TWh (1.93 Mt) of green ammonia with a volume of 160,000 m^3 from Australia to Germany and consume 0.32 TWh ammonia as fuel. According to the shipping distance (17,600 km) and considering the travel time in both directions as well as the working availability of the vessel per year (95 %), eight tours per vessel are possible each year. Since the ammonia synthesis plant runs at 81 % capacity utilization, i.e., it is not in continuous operation, an ammonia storage facility with a capacity of 67.5 GWh (13,000 t) should be installed in the Australian port. The size of the ammonia storage at the German harbor depends on considerations for security of supply and the temporal profile of ammonia demand, which is not part of this analysis. In case of reconversion of all ammonia into hydrogen, an additional cracking plant at the German harbor is required, which has an optimal output capacity of 0.9 GW and an annual hydrogen production of 7.9 TWh (0.23 Mt).

We calculate levelized cost for green ammonia at the German harbor of 109.39 €/MWh (566.64 €/t), which includes the cost components in Fig. 4. With the production costs of 30.43 € per MWh electricity supply, green hydrogen is produced at 59.4 €/MWh (1.98 €/kg) in Australia. As Fig. 4 shows, 88.39 €/MWh (457.8 €/t) of the total levelized costs of delivered green ammonia (109.39 €/MWh) results from the total electricity supply for the entire upstream part of the supply chain, in addition to hydrogen production and storage. With about 81 %, this is by far the biggest fraction of total levelized costs of green ammonia. Less than 10 % of total costs is due to green ammonia synthesis (9.86 €/MWh). Transport and storage costs for ammonia, which refer to the oversea transportation and the storage at the Australian and the German harbor, account for almost 10 % of total ammonia cost (11.14 €/MWh) including the boil-off of ammonia and the additional consumption of ammonia as tanker fuel. Green ammonia can be decomposed to green hydrogen in Germany and requires up to 1.27 MWh of green ammonia per MWh of dispensed hydrogen. This efficiency of 79 % and further compressor losses result in higher levelized cost of hydrogen for all cost components compared to ammonia. In addition, the decomposition process costs 20.02 €/MWh$_{H2}$, which includes investment and electricity demand for operation in Germany (0.14 MWh$_{el}$/MWh$_{H2}$). Overall, levelized cost of green hydrogen obtained by cracking imported green ammonia from Australia is estimated to be 159.18 €/MWh (5.3 €/kg) hydrogen at the German harbor, before injecting it into the pipeline system.

4.3. Sensitivity analysis for technical and economic parameters

For the scale of green ammonia production considered in this case study, there is no utility scale value chain today. To account for the uncertainty in the assumptions, we evaluate the sensitivities for the lower and upper bounds of key parameters among a variety of values considered in previous studies of similar timeline, scope and magnitude. In addition, we combine all positive and all negative parameter variations in two extreme scenarios: one with a pessimistic parameter set and one with an optimistic one. The sensitivity analysis performed aims to identify the widest possible range of levelized costs of green ammonia and hydrogen, rather than to show the relative impact of parameter variability on final costs.

The literature states a wide range of investment costs for green hydrogen production technologies in expectation of continuous but uncertain levels for further cost reductions. Those variations are mainly driven by learning rates resulting from technological progress and more efficient production processes. While significant potential for further cost reduction for renewables is projected by researchers, cost degression for wind turbines appears to be much more challenging than for

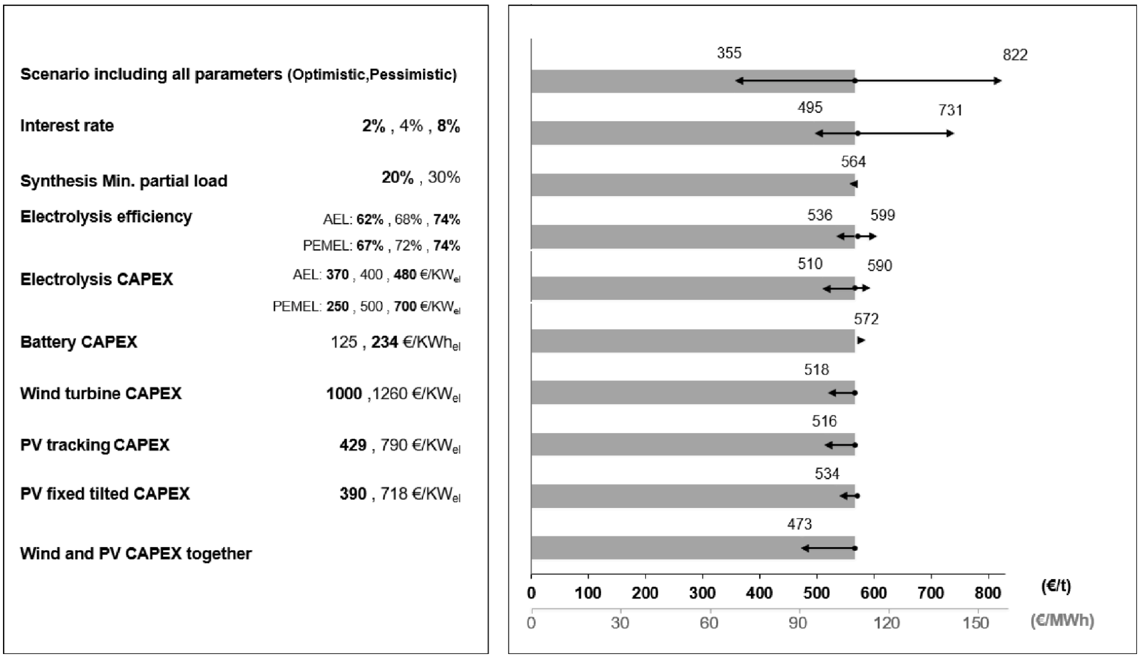


Fig. 5. Levelized costs of green ammonia, sensitivity analysis.

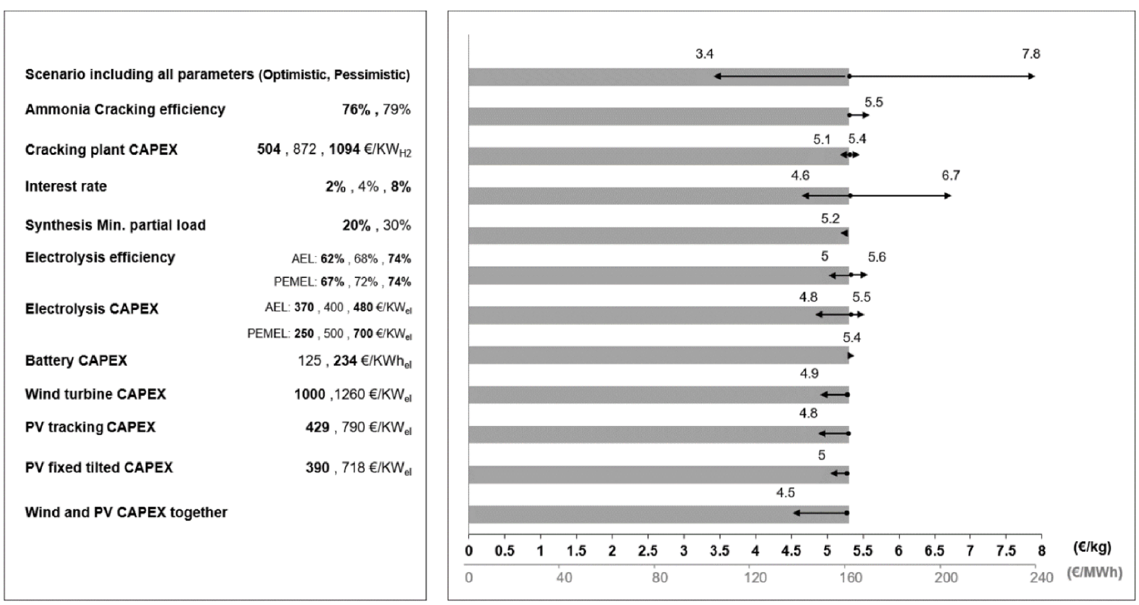


Fig. 6. Levelized costs of green hydrogen after cracking ammonia, sensitivity analysis.

solar panels [27,52]. Similarly, cost degressions are possible in the capital costs of electrolysis over the next few years, with higher potential for PEMEL than for AEL. The same uncertainty exists for electric batteries, using the same principle and component types as for electrolyzers [37]. In the meantime, electrolyzer systems can achieve further efficiency improvements due to technological advances [19].

In our analysis, we assume that there is no sensitivity for the investment costs of synthesis plants due to the maturity of the process. However, we evaluate a sensitivity for a possible reduction of the minimum partial load [38]. When it comes to the reconversion of green ammonia to green hydrogen, the assumptions for the ammonia cracking plant in this analysis are subject to uncertainty because there are no large-scale plants in use today. Moreover, the electricity consumption for cracking plant assumed in the base-case scenario (400 kWh/t-NH3) might not be realized in future [30]. Finally, the interest rate as a region-specific parameter has a significant impact on the annualized capital costs for all technologies in a green ammonia plant. The range of the interest rate which is set at 4% in our base scenario [18], has a sensitivity range from 2% to 8% for 2030, consistent with the latest renewable energy projects in Australia [52,2]. For a more detailed overview on all assumptions for the sensitivity analysis and the corresponding literature, see Table A.3 in the Appendix A.

The results of the sensitivity analysis based on the levelized cost of green ammonia, are compared to the base-case, as illustrated in Fig. 5. The same analysis has been performed for the levelized costs of green hydrogen after cracking green ammonia, as shown in Fig. 6. The overall results show that levelized cost are more sensitive to the variation of the interest rate as well as investment costs for renewable generators and

Table 4
Installed capacities, utilization rates, and costs for different sensitivities compared to the base-case scenario.[a]

	Technology	Unit	Base-case	Lower Capex PV Tracked	Lower Capex Wind	Lower Capex Electrolyzers	Higher Capex Electrolyzers	Lower Interest rate (2 %)	Higher Interest rate (8 %)	Optimistic	Pessimistic
Electricity Supply	Wind	GW_{el}	3.60 (47 %)	3.20(42 %)	3.90(48 %)	3.50(48 %)	3.70(47 %)	3.50(48 %)	3.60(48 %)	3.16(43 %)	4.15(48 %)
	PV (tilted)	GW_{el}	–	–	–	–	–	–	–	–	–
	PV (tracked)	GW_{el}	2.90 (26 %)	4.09(27 %)	2.30(25 %)	2.60(26 %)	3.00(26 %)	3.00(26 %)	2.70(26 %)	3.70(27 %)	3.06(25 %)
	Battery	GWh_{el}	0.62	0.62	0.62	0.65	0.62	0.62	0.63	0.35	0.58
	Transmission line	GW_{el}	3.36(74 %)	3.32(75 %)	3.43(73 %)	3.42(71 %)	3.47(74 %)	3.37(74 %)	3.36(74 %)	3.18(75 %)	3.75(74 %)
Electricity produced		TWh_{el}	21.55	21.67	21.74	21.25	22.42	21.61	21.51	20.73	24.21
Curtailment		TWh_{el}	2.72	3.83	2.56	2.28	3.02	2.79	2.60	3.47	3.02
Electrolysis	RO Desalination	m^3/h_{Water}	0.16(49 %)	0.17(53 %)	0.24(54 %)	0.19(46 %)	0.15(50 %)	0.14(49 %)	0.17(49 %)	0.22(56 %)	0.17(51 %)
	MED Desalination	m^3/h_{Water}	0.38(87 %)	0.36(88 %)	0.31(89 %)	0.38(86 %)	0.39(86 %)	0.39(88 %)	0.37(88 %)	0.32(89 %)	0.37(86 %)
	Electrolyzer (AEL)	GW_{el}	1.08(54 %)	1.35(61 %)	1.60(59 %)	–	2.99(76 %)	1.21(51 %)	0.98(51 %)	–	3.09(73 %)
	Electrolyzer (PEMEL)	GW_{el}	1.80(88 %)	1.53(90 %)	1.38(91 %)	2.97(72 %)	–	1.67(87 %)	1.93(87 %)	2.78(75 %)	0.21(98 %)
	H_2 Storage tank	GWh_{H2}	8.99	8.35	9.63	9.40	8.90	8.87	9.19	5.34	9.15
	H_2 compressor	GW_{el}	0.07(81 %)	0.06(85 %)	0.07(81 %)	0.07(80 %)	0.07(82 %)	0.07(81 %)	0.07(81 %)	0.07(83 %)	0.07(81 %)
H_2O produced		Mm^3	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
H_2 produced		TWh_{H2}	13.56	13.56	13.56	13.56	13.56	13.56	13.56	13.56	13.56
NH_3 Synthesis	Synthesis	GW_{H2}	1.89(81 %)	1.81(85 %)	1.90(81 %)	1.92(80 %)	1.88(82 %)	1.88(81 %)	1.90(81 %)	1.85(83 %)	1.90(81 %)
	NH_3 storage tank	GWh_{NH3}	67.50	58.40	71.30	75.40	66.80	66.60	69.40	62.48	69.90
NH_3 produced		TWh_{NH3}	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
NH_3 Decomposition	Cracking plant	GW_{H2}	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.86(100 %)
	H_2 compressor	GW_{H2}	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.90(100 %)	0.86(100 %)
Final H2 at destination		TWh_{NH3}	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.56
Investment cost	Total cost	bn €	10.69	9.58	9.62	9.90	11.11	10.71	10.65	7.68	11.94
	Annuity	bn €	0.86	0.78	0.79	0.77	0.89	0.71	1.19	0.50	1.35
Operation cost	Annual variable cost	bn €	0.33	0.31	0.31	0.30	0.34	0.33	0.33	0.25	0.37

a- The numbers in parentheses refer to the utilization rate of the technologies.

electrolyzers. Assuming an interest rate of 8 % instead of 4 % increased the estimated cost of hydrogen at the German harbor by 30%. In contrast, the battery cost and the minimum partial load of the synthesis plant have a very small impact. The same applies to the cost of ammonia decomposition, even though there is great uncertainty in terms of technical and economic parameters due to the low level of technological readiness. In the following, we analyze investment levels and costs for the parameter variations that have a particularly large impact on the levelized cost of hydrogen. Table 4 shows the results for different values for the interest rate and capex for PV (tracked), wind turbines, and the electrolyzers. In addition, the table contains data for the two scenarios *optimistic* and *pessimistic*, in which all parameter changes are combined as shown in Figs. 5 and 6.

The reduction of the investment cost for PV leads to a shift in the ratio of installed renewable capacity in favor of PV capacity compared to wind power. Nevertheless, the model results show that a mix of different generation technologies is still preferable. The higher shares of PV and the associated lower electricity generation costs lead to a higher amount of curtailment, but also have a direct impact on downstream processes. The composition of electrolysis technologies shifts toward the cheaper but more inefficient AEL. Similar effects can be observed in the reduction of investment costs for wind energy. Significantly lower cost of electricity generation also favors reverse osmosis for seawater desalination, which has higher electricity consumption but lower investment costs than multi-effect desalination.

For the capex of electrolysis, we assume both lower and higher investment costs and a larger sensitivity for the more efficient PEMEL technology, which could become cheaper than AEL in case of a steep learning curve. Therefore, the model results use both technologies in the base-case but only PEMEL for the low cost and only AEL for the high cost sensitivity. At the same time, curtailment decreases with lower investment costs, which incentivize a larger electrolysis plant to utilize some of the previously curtailed electricity generation. With this more volatile utilization of the electrolysis, it is optimal to invest in a larger hydrogen tank and synthesis plant. The opposite effects can be observed for high capex levels of electrolysis plants.

The level of the interest rate has the largest impact on the levelized cost and leads to a significant change in the optimal process design, indicating a trade-off between up-front investment and operational costs. Higher interest rates incentivize a more efficient utilization (less curtailment) of electricity generation due to the increased financing cost for the investment in renewable capacity. The technology mix shifts towards wind power which allows a comparatively stable operation of electrolysis with PEMEL. Even though PEMEL is more expensive than AEL in this analysis, the reduction in electricity demand due to its higher efficiency outweighs its higher investment costs.

Total investment cost for a process design with an ammonia import of 10 TWh (1.93 Mt) per year to Germany range between 7.68 bn € in the optimistic and 11.94 bn € in the pessimistic scenarios. The sensitivity analysis for the case study shows that a mix of PV and wind power is reasonable in all cases. Depending on parameter variation and combination of generation technologies, battery storage, and electricity consumers, curtailment of renewable energies is between 10 % and 15 %. Waste heat from the exothermic Haber-Bosch process can be used for seawater desalination, although the low cost of electricity in Australia favors reverse osmosis for seawater desalination. In almost all scenarios, optimal investment levels combine electrolysis with AEL and PEMEL with higher utilization rates for the more expensive but more efficient PEMEL. Due to the different storage technologies, the synthesis plant operates in all scenarios relatively consistent with utilization rates between 80 % and 85 %.

4.4. *Cost comparison for fossil and green ammonia*

In the following, we compare the cost results for green ammonia from the case study for 2030 to the alternatives of gray and blue

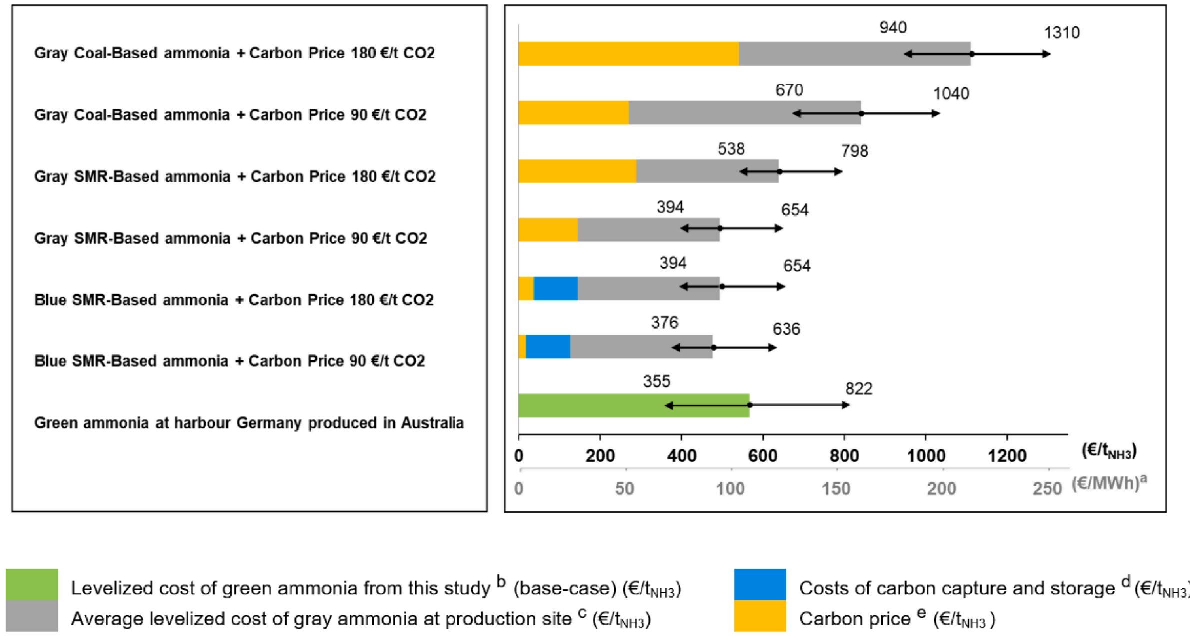


Fig. 7. Levelized costs of green ammonia case study Australia-Germany (2030) versus levelized costs of conventional ammonia in Europe with an average fossil gas price of 30 €/MWh and hard coal price of 61 €/t.

ammonia. Green ammonia produced in Australia and transported to Germany costs about 109.4 €/MWh (567 €/t) in our base-case with a price range from 68.5 €/MWh to 158.68 €/MWh (355 €/t to 822 €/t) depending on sensitivities for important parameters. Fig. 7 presents a comparison of green, gray, and blue ammonia assuming fossil gas prices of 30 €/MWh, hard coal prices of 61 €/t, and CO_2 emission cost of 90 €/t CO_2 or 180 €/t CO_2 in the year 2030. With these assumptions, green ammonia production becomes competitive and start to displace fossil-based ammonia production.

Calculated cost levels for green ammonia overlap with historic costs for gray ammonia. Between 2010 and 2020, production costs for SMR-based gray ammonia in Europe, excluding the cost for direct carbon emissions, have been on average 67.56 €/MWh (350 €/t) [27]. The range of 48.3 €/MWh to 98.5 €/MWh (250 to 510 €/t) for levelized cost of gray ammonia production during this period is illustrated in Fig. 7 [34]. The lower and upper bound for gray and blue ammonia cost relates to fossil gas prices, which varied between 15 €/MWh and 45 €/MWh [27]. According to IEA [34], the average levelized cost of coal-based ammonia until 2020 has been in the range of 400 €/t to 770 €/t (77.22 €/MWh to 148.64 €/MWh) at an approximate coal price from 38 €/t to 84 €/t, indicating that there is no economic incentive to invest in coal-based ammonia production.

Rising CO_2 prices could be an argument for carbon capture and storage (blue ammonia) which increases production costs, but hedges against increasing prices for CO_2 emission and, in part, allows utilizing already existing production facilities. This would allow to produce ammonia at similar price levels than today (500 €/t), which is more or less competitive to new green ammonia production. In addition, the speed of the transformation towards green ammonia will be determined by capacity limitations for investment in renewable electricity generation and electrolysis capacity. Blue ammonia production could therefore be an alternative to significantly reduce CO_2 emissions in the short term.

This comparison looks quite different for today's fossil gas prices. In Europe, total costs of feedstock and fuel demand historically account for approximately 85 % of total levelized costs of ammonia [42]. In late 2021, an upward trend in energy prices, because of global economic rebound after COVID-19 pandemic, caused a first surge in costs of ammonia production, which have been four to five times higher for European producers, in comparison to the previous decade. With Russia's invasion of Ukraine in early 2022, the skyrocketing gas price in Europe hit 219 €/MWh in March. Even though prices afterwards decreased to approximately 80 €/MWh to 100 €/MWh, mid-term future prices for fossil gas in the next years remain at about 60 €/MWh, which translates in costs for ammonia producers of about 580 €/t only for gas consumption[3]. Under these circumstances, our case study with green ammonia imported from Australia is competitive today and remains so, unless there will be a significant decrease in fossil gas prices to 36 €/MWh for 90 €/t CO_2 and 18 €/MWh for 180 €/t CO, respectively.

5. Conclusion

Ammonia is one of the most widely produced chemical, which is traded on a large scale worldwide. Ammonia today is produced from fossil gas and coal, but green ammonia production – from green hydrogen – is also viable. While ammonia is classified as toxic and corrosive gas, long-standing expertise in conjunction with already existing regulations for its synthesis, transportation and use has increasingly led to the focus on ammonia as the first green hydrogen carrier. For ammonia, technologies for its storage and shipment are available worldwide, as well as the possibility to utilize the available large-scale infrastructure for LPG. In addition to current demand as feedstock in the production of fertilizer and for other industries, ammonia has the potential to be used directly as a fuel.

A precise prediction of the development of green ammonia demand, especially over its transition phase, is a challenge. To nevertheless address some important aspects, this study provides a techno-economic model of a green ammonia supply chain, based on a comprehensive optimization approach. As the optimal supply chain strongly depends on country-specific conditions like the availability of renewable energy sources, geographical and demographical features and more, we apply

[3] Total energy required for producing SMR-based ammonia in Germany, including feedstock and fuel demand, is 9.7 MWh/t [20].

Table A1
Green ammonia and green hydrogen supply chain components' techno-economic assumptions.

		Unit				Ref.
			Wind	**PV (tilted)**	**PV (tracked)**	
Renewable energies	Capex	€/kW$_{el}$	1,260	718	790	[4]
	Opex	%/a	2.50	1.50	1.50	[4]
	Lifetime	a	20	25	25	[4]
Transmission line	Capex	€/(MW$_{el}$*km)	612			[13,26]
	Opex	%/a	0.85			[13,26]
	Lifetime	a	50			[13,26]
	Efficiency	%/1000 km	98.4			[13,26]
Battery	Capex	€/kWh	125			[13,26]
	Opex	%/a	3.00			[13,26]
	Lifetime	a	20			[13,26]
	Efficiency	%	97			[13,26]
			RO	**MED**	**Water tank**	
Water desalination	Capex	€/(m^3/h)	15,120	18,888	65 €/m^3	[13]
	Opex	%/a	4	2.74	1.3	[13]
	Lifetime	a	30	25	30	[13]
	Electricity demand	kWh/m^3	3	1.5		[13]
	Heat demand	kWh/m^3	–	32		[13]
			AEL	**PEMEL**		
Electrolysis	Capex	€/kW$_{el}$	400	500		[12,54,51]
	Opex	%/a	4	4		[12,51]
	Lifetime	a	10	10		[47]
	Efficiency	%	68	72		[12,54,51]
	Pressure	bar	60	80		[12,54,51]
CGH2 storage	Capex	€/kg $_{H2}$	450			[12]
	Opex	%/a	1			[12]
	Lifetime	a	30			[47]
	Pressure	bar	25 – 60 or 80			[51]
Compressor	Capex	€/kW$_{el}$	730			[51]
	Opex	%/a	4			[47]
	Lifetime	a	15			[47]
	Electricity consumption	kW/kg $_{H2}$	Variable			[47]
Heat pump	Capex	€/kW$_{el}$	572			[51,13]
	Opex	%/a	3			[51,13]
	Lifetime	a	25			[51,13]
	Efficiency (COP)		4.5			[51,13]
Heat storage	Capex	€/kWh $_{th}$	20			[51,13]
	Opex	%/a	1.5			[51,13]
	Lifetime	a	30			[51,13]
	Efficiency	%	95			[51,13]
Ammonia Synthesis	Capex-HB	€/kW$_{H2}$	510			[6]
	Capex-ASU	€/kW$_{H2}$	197			[6]
	Opex-HB& ASU	%/a	2			[6]
	Lifetime	a	30			[6]
	Conversion Efficiency[a]	%	87			[57]
	Loss	%	10			[57]
	Electricity demand (HB &ASU)[b]	kWh/t$_{NH3}$	640			[6]
	Released heat	kWh/t$_{NH3}$	722			[36]
	Min. partial load	%	30			[36]
	Reactor pressure	bar	250			[6]
Storage Tank	Capex	€/t$_{NH3}$	900			[36]
	Opex	%/a	5			[27]
	Lifetime	a	30			[6]
Overseas transport	Capex	M €/pc.	142			[5]
	Opex	%/a	11			[5]
	Lifetime	a	15			[5]
	Net capacity	m^3	160,000			[5]
	Time at Port	h	48			[5]
	Speed	km/h	37.04			[5]
	Fuel consumption	t/day	37.6 HFO	(78.9 NH_3)		[5]
	Utilization	%	95			[5]
	Ammonia boil off	%/day	0.12			[5]
	Electricity demand for loading/unloading	kWh/t$_{NH3}$	80			[38]
	Suez Canal transit fees	€/ship passage	93,500			[55]
Cracking Plant	Capex	M €/t$_{NH3}$	3.58			[38]
	Opex	%/a	4			[33]
	Lifetime	a	30			[33]
	Efficiency	%	79			[38]
	Electricity demand	kWh/t$_{NH3}$	400			[38]
Compressor at Cracking Plant	Capex	€/MW$_{H2}$	144,000			[61]
	Opex	%/a	4			[48]
	Lifetime	a	20			[27]
	Loss	%	0.5			[48]

(*continued on next page*)

Table A1 (*continued*)

	Electricity demand	kWh/kWh_{H2}	0.04	[27]
	Pressure	bar	100	[61]

a- Conversion efficiency is defined as the ratio of the energy content of the produced ammonia to the energy content of the feed hydrogen. However, it is reduced due to the losses within the synthesis process. b- Similar as in [6], we modelled the ASU as an implicit part of the HB process.

Table A2
Western Australia versus northern Germany RE potential - Mean capacity factor.[a]

	Unit	Wind	Photovoltaic (tilted)	Photovoltaic (tracked)	Geothermal	Hydropower
Western Australia	%	54.3	21.5	28	0	0
Northern Germany	%	43.7	12.5	15.3	0	0
Germany	%	36.4	13.6	15	0	0

a-Mean capacity factor for a power plant is defined as the ratio of the number of hours that it can operate at full rated power to the total number of hours per year (8760), Data is obtained from open license online tool: https://www.renewables.ninja/ for the year 2019.

Table A3
Parameters for sensitivity analysis.

Parameter	Unit		Value		
			Optimistic	Base-case	Pessimistic
PV fixed tilted Capex	€/kW_{el}		**390** [27]	**718** (Agora [4]	–
PV tracking Capex	€/kW_{el}		**429** [27]	**790** (Agora [4]	–
Wind turbine Capex	€/kW_{el}		**1000** [27]	**1260** (Agora [4]	–
Battery Capex	€/kWh_{el}			**125** [13,26]	**234** [27]
Electrolysis Capex	€/kW_{el}	AEL	**370** [50]	**400** [12,54,51]	**480** [19]
	€/kW_{el}	PEMEL	**250** [50]	**500** [12,54,51]	**700** [19]
Electrolysis efficiency	%	AEL	**74** [37]	**68** [12,54,51]	**62** [23,29]
	%	PEMEL	**74** [37]	**72** [12,54,51]	**67** [23,29]
Synthesis Min. partial load	%		**20** [36]	**30** [6]	–
Interest rate	%		**2** [2]	**4** [18]	**8** [52]
Cracking plant Capex	€/kW_{H2}		**504** [33]	**872** [38]	**1094** [63]
NH_3 Cracking efficiency	%		–	**79** [38]	**76** [30]

our model to a region-based case study: the import of green Ammonia from Australia to Germany. However, it can readily be applied to ammonia supply and demand in other countries.

The Australian-German case study for the year 2030 yields average levelized cost of green ammonia of 109.39 €/MWh (566.64 €/t) at the harbor in Germany and 159.18 €/MWh (5.3 €/kg) for green hydrogen from cracked ammonia. Moreover, we show that costs of green ammonia will become competitive with current conventional ammonia, if CO_2 prices increase.

Projected costs might decrease substantially with technological progress; however, specific cost degression will depend on a variety of factors. In order to shed light on the range of possible developments we assess various sensitivities. In particular, we focus on interest rates, electrolysis efficiency, as well as capex of various relevant technologies. As it is well known from PV ramp-up, interest rates play a significant role for levelized overall cost. In this context, regulators have to be aware, that regulatory uncertainty has a substantial impact on interest rates through risk premia. Investment cost could thus be reduced through more reliable (and favorable) regulatory framework conditions, as well as commitment by the regulator.

Comparison of ammonia import to the import of hydrogen (by cracking ammonia) reveals a high cost difference of 49.79 €/MWh (45 %). This strongly suggests not to convert imported ammonia but to satisfy ammonia demand for feedstock or direct energy applications in the country of destination by ammonia imports and hydrogen demand by regional production or pipeline imports (which allows transporting compressed hydrogen). Over time, it is likely that various transport vectors will coexist, or options that are more attractive become viable and partly substitute ammonia imports. Those alternative energy vectors, like LOHC or cryogenic hydrogen are not yet ready for large-scale application today but will foreseeably play a bigger role in the future. Gaseous hydrogen imported by pipeline will likely be the cheapest option but ramp up and also long-term available quantities are likely not sufficient to cover European needs alone. Thus, overseas imports – that will be initiated by green ammonia imports – will play an important role on the way to a hydrogen economy.

CRediT authorship contribution statement

Jonas Egerer: Conceptualization, Methodology, Writing – original draft, Visualization. **Veronika Grimm:** Conceptualization, Writing – original draft, Supervision. **Kiana Niazmand:** Methodology, Software, Validation, Writing – original draft, Visualization. **Philipp Runge:** Conceptualization, Methodology, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. .

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