

Review of ammonia production and utilization: Enabling clean energy transition and net-zero climate targets

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Review and evaluation of sustainable ammonia production, storage and utilization

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Abstract

In 2015, the Paris agreement was signed by 196 countries in attendance at COP21 that highlighted the need for rapid decarbonization and carbon dioxide removal (CDR) and sets ambitions to reach net zero emissions by mid-century. The production of ammonia can contribute to achieving net-zero emissions in several ways including energy storage, clean fuel, industrial applications and carbon capture and utilization (CCU) processes, if produced using renewable energy (RE) sources with very low greenhouse gas (GHG) emissions during production and utilization. This review study highlights the potential of green ammonia production pathways, utilization, ammonia storage and transport, ammonia infrastructure and economy, to serve various roles and provide potential benefits in decarbonizing industry and clean energy transitions to meet net-zero climate targets. Renewable ammonia cannot only help decarbonize existing ammonia markets by displacing fossil fuels, but can also help greening the industrial sector such as fertilizer and chemical industries and accelerate decarbonization in hard-to-abate industries, including retrofit of existing ammonia plants. Ammonia is also expected to be used in the stationary power sector as renewable fuel as the technology matures. It can also play an imperative role as a promising maritime fuel, owing to its zero-emission properties, high energy density and compliance with ever more stringent environmental regulations, transporting RE, in the shipping industry that is one of the largest GHG emitters. Moreover, as a hydrogen carrier, ammonia can deliver industrial feedstocks and enable lower-cost hydrogen imports as compared with renewable hydrogen. Encouraging green ammonia production technologies and near-zero-emission technology progress can guide desirable future pathways for the ammonia industry, including handling important safety considerations of production, storage and end-use.

Keywords: Renewable ammonia; Green ammonia production methods; Ammonia utilization, storage, transport, economy and infrastructure; Sustainable ammonia production; Challenges and opportunities; Net-zero climate targets

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63 **1. Introduction**

64 Ammonia (NH₃) plays a vital role in global agricultural systems owing to its fertilizer usage. It is
65 a prerequisite for all nitrogen mineral fertilizers and around 70% of globally produced ammonia is
66 utilized for fertilizers [1]; the remnant is employed in numerous industrial applications namely:
67 chemical, energy storage, cleaning, steel industry and synthetic fibers [2]. While ammonia's
68 potential as fuel shows promise in the clean energy transitions context. It remains emerging and
69 can contribute significantly to meeting the net-zero emissions targets set to be achieved by mid-
70 century [3]. At present, ammonia production relies heavily on fossil fuels. From the total energy
71 consumption, global ammonia production accounts for ~2% (8.6 EJ) and feedstock accounts for
72 ~40% of this energy including raw materials that supply hydrogen (H₂) to the ammonia production
73 and process energy. The ammonia production sector is emissions intensive owing to the fossil fuels
74 utilization and accounts for emitting ~450 Mt CO₂/year direct emissions [4]. Indirect emissions
75 account for ~170 Mt CO₂/year [4] attributable to two key sources: chemical reactions when urea-
76 based fertilizer is fed to the soil and electricity generation. This trend needs to shift towards green
77 ammonia production to decarbonize this sector to align with the clean energy transition.

78 Ammonia has the potential to be used as a green energy carrier (clean fuel) as it offers high energy
79 density compared with neat hydrogen's energy density. Furthermore, ammonia storage is less
80 energy intensive as compared with cryogenic conditions to store liquid hydrogen. Even though
81 ammonia is hazardous to handle, it is less flammable as compared with hydrogen and can also be
82 used as hydrogen carrier or hydrogen storage media [5]. Greener production routes will be
83 comparatively more expensive encompassing the air separation and hydrogen buffer storage cost
84 to meet intermittency challenges (wind/solar). Many under-development projects are still facing
85 challenges to deal with the intermittent nature of renewable energy (RE) sources and much is being
86 done to tackle this challenge using hydrogen buffer storage. An upsurge in ammonia demand is
87 expected to appear with the progressively numerous and prosperous global population that comes
88 in a period where governments have declared net-zero emissions strategies from energy systems
89 [4,6]. The prime focus and emphasis of this review study is to highlight the potential of green
90 ammonia production, utilization and storage methods, challenges and opportunities, ammonia
91 infrastructure and economy and enabling more sustainable ammonia production to help meet net-
92 zero climate targets.

93 The synthesized ammonia is termed “green” where the involved process does not undergo any
94 carbon emissions and is 100% renewable (excluding embodied systems emissions). The most
95 widely used green ammonia production involves the production of hydrogen through the water
96 splitting process and separating nitrogen from air, both processes carried out employing RE. The
97 renewable hydrogen and separated nitrogen are then inputted into the Haber-Bosch process for
98 ammonia production (reacting nitrogen and hydrogen at high pressure and temperature in the
99 presence of a catalyst). Natural gas reforming-based ammonia production plants are now
100 integrating carbon capture, utilization, and storage (CCUS) systems to remove the process
101 emissions emitted by the reforming process. The commercially existing ammonia production
102 process is not “green” as it encompasses the steam methane reforming (SMR) process for hydrogen
103 production followed by the Haber-Bosch process. Around 90% of the CO₂ emissions produced in
104 commercial ammonia production plants come from SMR process which is a highly energy-
105 intensive process and contributes about 1.8% of global CO₂ emissions [7].

106 ***Decarbonisation of ammonia production.*** In order to achieve net-zero by mid-century, it is critical
107 to reducing CO₂ emissions from the ammonia production process and the best pathway to reduce
108 these emissions is by employing low-carbon hydrogen production methods as SMR process for
109 hydrogen production emits the major chunk of these CO₂ emissions.

110 The almost certainly immediate option to produce carbon-free H₂ at scale is employing renewable
111 hydrogen using a water electrolysis process. SMR process and pyrolysis integrated with CCS
112 technology can produce blue hydrogen, however, RE energy based renewable hydrogen
113 production or direct RE based ammonia synthesis offer decarbonization options. Green ammonia
114 production can offer the following opportunities in the transition to net-zero CO₂ emissions:

115 ***Energy storage.*** Ammonia energy storage is a promising technology to store and transport RE
116 which is carried out by converting renewable electricity into chemical energy stored in ammonia.
117 To extract energy, ammonia can either be employed to fuel cells or in combustion engines to
118 generate electricity. High energy density, existing infrastructure, and easy transportation are the
119 advantages of ammonia energy storage. Ammonia can easily be stored as a liquid in large volumes
120 at different pressures ranging from 10-15 bar or cooled to -33°C which makes ammonia suitable
121 and potential chemical storage of the RE. For this purpose, the existing distribution network of

122 refrigerated tanks can be used for storage while road tankers, pipes and ships can be used for
123 transport.

124 **Zero-carbon fuel.** Ammonia (NH_3) is gaining attention as a potential zero-carbon fuel mainly
125 because it can be produced using a zero-carbon process and offers zero-carbon combustion.
126 Ammonia can be burnt/combusted in engines or utilized in fuel cells to generate electricity
127 producing nitrogen and hydrogen/water as by-products. The zero-carbon fuel does not only offer
128 applications in power generation and transportation sector, but also marine industry is probable to
129 adopt ammonia as maritime fuel in the near-term future.

130 **Hydrogen carrier.** Ammonia can also be used as hydrogen storage media to support hydrogen
131 applications (e.g. fuel cells) as bulk hydrogen storage is comparatively complex and expensive.
132 Hydrogen has low volumetric energy density in its gaseous state due to its low density. Even when
133 compressed (~ 700 bar), the compressed hydrogen offers energy density of 5.6 MJ/l and in its liquid
134 state ($\sim -253^\circ\text{C}$), the liquid hydrogen (LH_2) offers improved energy density of 8.5 MJ/l, however,
135 entails energy intensive and expensive cryogenic storage systems. In contrast, ammonia offers
136 volumetric energy density of 15.6 MJ/l at normal pressure and temperature, which is higher than
137 that of LH_2 . Furthermore, ammonia can be stored as a liquid at room temperature under moderate
138 pressure (~ 10 bar), which is far more practical than storing hydrogen at high pressure or extremely
139 low temperature.

140 Table 1 displays the ammonia properties in comparison with other competitive fuels including
141 hydrogen, methane, and methanol at the ambient conditions. Ammonia has the potential to be used
142 as a green hydrogen carrier offering high energy density (15.6 MJ/l) [8] and density (0.73 kg/m^3)
143 [9] that are higher than compressed hydrogen (5.6 MJ/kg) and liquefied hydrogen energy density
144 (8.5 MJ/kg) [10] and density (0.083 kg/m^3) [11]. The autoignition temperature of ammonia is also
145 higher (930K) [12] than hydrogen (773-850K) [13]. Furthermore, cryogenic conditions (-253°C)
146 [14] are required to store liquid hydrogen, however, less energy-intensive conditions (-33°C) [8]
147 are required for liquid ammonia storage.

148

149

150 **Table 1** Ammonia characteristics and properties compared with other competitive fuels (data
 151 from [9,12,15–20])

Properties	Methanol (CH ₃ OH)	Methane (CH ₄)	Hydrogen (H ₂)	Ammonia (NH ₃)
Density (kg/m ³)	786	0.66	0.08	0.73
Dynamic viscosity ×10 ⁻⁵ (P)	594	11.0	8.80	9.9
Energy density (MJ/l)	22	50-55.5	8.5 (LH ₂)	15.6
Lower heating value (MJ/kg)	19.92	50.05	120	18.80
Laminar burning velocity (m/s)	0.36	0.38	3.51	0.07
Minimum ignition energy (mJ)	0.140	0.280	0.011	8.000
Auto-ignition temperature (°C)	439	586	500-575	657
Octane number	119	120	>100	130
Adiabatic flame temperature (°C)	1637	1950	2210	1577
Heat capacity ratio	1.20	1.32	1.41	1.32
Gravimetric hydrogen density (wt%)	12.5	25.0	100.0	17.8

152

153 **2. Ammonia Production**

154 RE offers some important benefits in comparison to traditional energy fuels. It offers environmentally
 155 benign and clean energy solutions and is not dependent on any fossil fuel type. In order to draw a fair
 156 comparison, the emission factors from the plant operation are highlighted. Coal based power
 157 production has the emissions factor of 850-1050 kg of CO₂ eq per MWh followed by the natural gas
 158 based power generation that undergoes emissions factor of 450-550 kg of CO₂ eq per MWh. RE
 159 sources, in comparison, have very low emissions factor such as wind energy (3-15 kg of CO₂ eq per
 160 MWh), Solar PV (40-50 kg of CO₂ eq per MWh) and hydroelectric power (1-20 kg of CO₂ eq per
 161 MWh) considering the lifecycle of the RE technologies [21]. RE has a unique significance concerning
 162 energy security. Being a critical implementing means of societal sustainable development, RE sources
 163 will endure by offering cost-effective solutions. This emissions factors consequently reflect on the RE
 164 based and fossil based ammonia production as well.

165 Fig. 1 displays the different electricity pathways for ammonia production and different colors used
 166 refer to the different inputs of energy and technologies for ammonia production including green
 167 ammonia (RE), pink ammonia (nuclear), black ammonia (coal) and grey ammonia (natural gas).

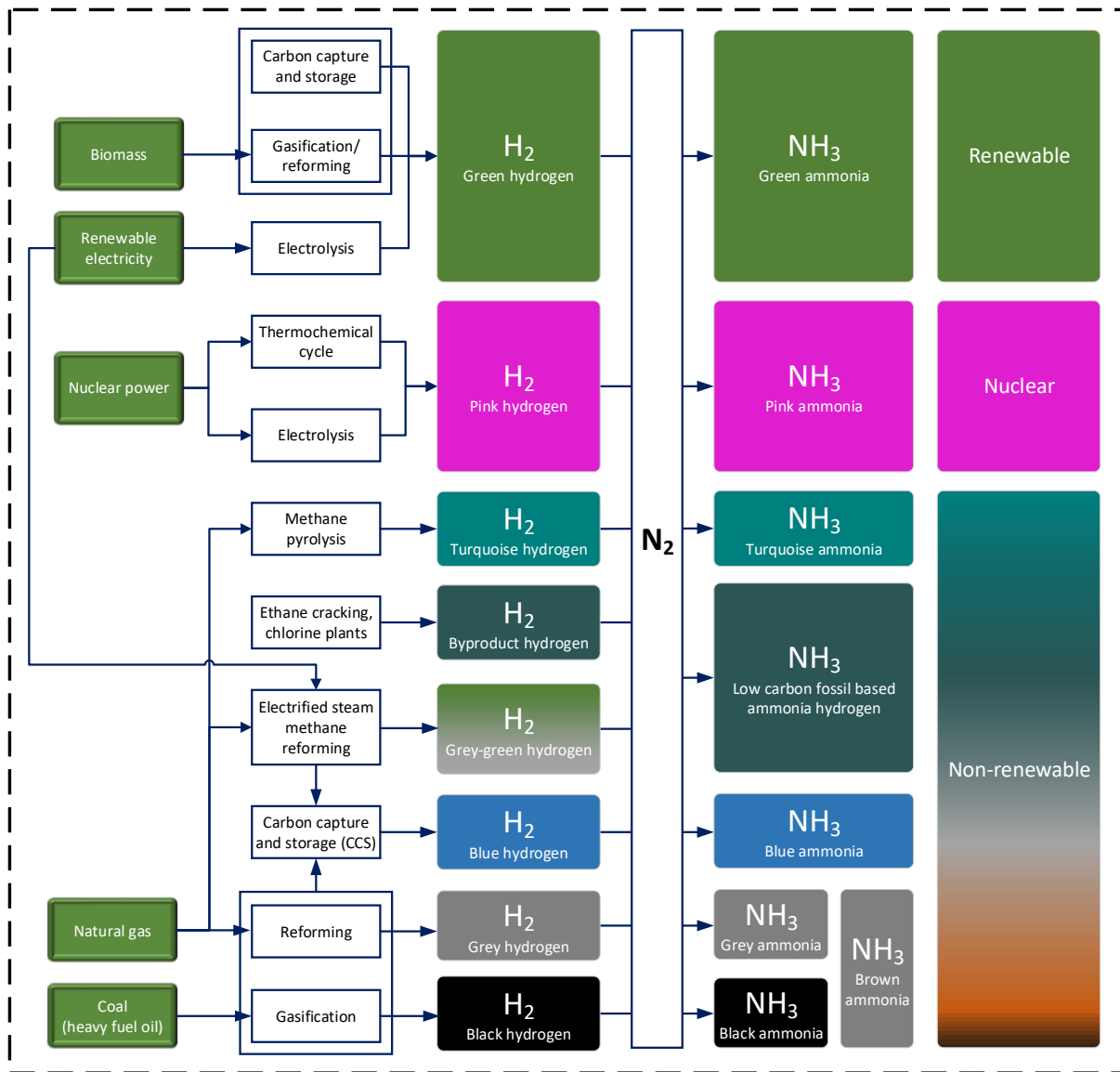


Fig. 1 Ammonia production pathways from different feedstocks (modified from [22])

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170 For the specific process employment, ammonia can be divided into further color-coding such as
 171 methane pyrolysis-based ammonia is termed as turquoise ammonia, renewable electricity driven
 172 electrified steam methane reforming based ammonia is known as grey-green ammonia and if electrified
 173 steam methane reforming, natural gas reforming or coal gasification processes are coupled with carbon
 174 capture and storage (CCS), the pathway will be termed as blue ammonia. Some argue that colors are
 175 not useful descriptors and that carbon intensity of the final product (H_2 or NH_3) is a better comparison
 176 metric, however colors are useful at least for describing the pathways, but that final intensity of the
 177 produced fuel based on full life cycle accounting (LCA) across the system is ultimately the best
 178 comparison metric.

179 Ammonia is not only considered a feedstock for the fertilizer sector but is also well known as an
 180 energy carrier and clean fuel. At present, over 90% of the global ammonia synthesis is carried out
 181 using the Haber-Bosch ammonia synthesis process named after scientists Fritz Haber and Carl
 182 Bosch who established the ammonia synthesis method back in 1913 [23]. Ammonia is known as
 183 the backbone of the fertilizer sector. The natural gas feedstock is the main source utilized for
 184 synthesizing ammonia globally. The Haber-Bosch process principally combines nitrogen and
 185 hydrogen at high-pressure and temperature using an iron-oxide catalyst. Alternatively, novel solid-
 186 state and electrochemical ammonia synthesis techniques are in R&D phase. Table 2 displays the
 187 recent literature on ammonia production techniques and methods, technoeconomics, life cycle
 188 assessments and ammonia technology roadmaps and Table 3 tabulates the ammonia utilization and
 189 end-use.

190 **Table 2** Recently published literature on ammonia production techniques and methods

Authors	Focus of study	Approach	Description
Chang et al. [24]	Renewable ammonia synthesis	Recent advances in ammonia synthesis, storage, and conversion	Investigated emerging methods and materials for renewable ammonia synthesis, separation, and utilization
Ganzer and Dowell [25]	Sustainable fuels production	Comparative assessment	A framework for sustainable fuel production accounting for intermittency
Wang et al. [26]	Sustainable ammonia synthesis	Comparative assessment	Comparative assessment of sustainable ammonia synthesis and fossil-based Haber-Bosch processes
Salmon and Bañares-Alcántara [27]	Green ammonia offshore	Techno-economic analysis	Techno-economic assessment of offshore green ammonia production
Parmar et al. [28]	Floating offshore wind driven ammonia	Technical and economic feasibility	Production of ammonia from floating offshore wind farm
MacFarlane et al. [29]	Ammonia Economy	Potential, challenges and applications	Ammonia economy roadmap
Fernandez et al. [30]	Intermediate temperature renewable ammonia	Electrosynthesis	Explored opportunities for renewable ammonia electrosynthesis at intermediate temperature
Sanchez and Martín [31]	Renewable ammonia	Optimization	Optimal production of renewable ammonia from air and water
Osman et al. [32]	Scaling of renewable ammonia	Techno-economic optimization	A techno-economic optimization on scaling renewable ammonia production
Morgan et al. [33]	Sustainable ammonia production	Techno-economic review	Sustainable production of ammonia from U.S. offshore wind farms
Hollevoet et al. [34]	Ammonia synthesis	Plasma-based	Plasma-driven green ammonia synthesis
Zhao et al. [35]	Green ammonia production	Potential opportunities	Green ammonia production potential in reducing renewable power curtailment

Lee et al. [36]	Ammonia production methods	Techno-economic and life cycle assessment	Techno-economic analyses and life cycle assessment of ammonia production pathways
International Energy Agency (IEA) [4]	Towards sustainable ammonia production	Report	Ammonia Technology Roadmap

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Table 3 Recently published literature on ammonia utilization and end-use

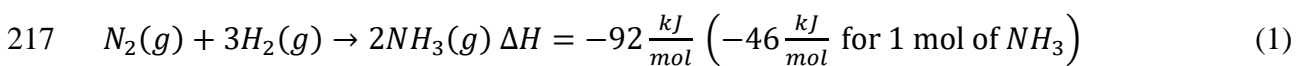
Authors	Focus of study	Approach	Description
Smith et al. [37]	Haber-Bosch ammonia role	Energy landscape	Prevailing and prospective role of Haber-Bosch process-based ammonia in carbon-free energy landscape
Nayak-Luke et al. [38]	RE intermittency impacts	Comparative assessment	Renewable energy intermittency impacts of green ammonia plant sizing and levelized cost
Chai et al. [39]	Ammonia and derived fuels	Review	A review study on ammonia, ammonia-methane and ammonia-hydrogen fuels
Yapicioglu and Dincer [40]	Ammonia as fuel	Review	A review study on employing ammonia as fuel for power generators
Al-Hamed and Dincer [41]	Ammonia-based carbon capture	Comparative review	A review study on ammonia-based carbon capture technologies
Machaj et al. [42]	Ammonia as marine fuel	Review	A review study on ammonia as a potential fuel for marine industry
Lamb et al. [43]	Ammonia for hydrogen storage	Review	A review study on catalytic ammonia decomposition for hydrogen storage
Sánchez et al. [44]	Ammonia as fuel	Thermo-chemical standpoint	A thermo-chemical standpoint on evaluating green ammonia as fuel for power generation
Juangsa et al. [45]	Ammonia as hydrogen carrier	Review	A review study on electrochemical and thermochemical processes for ammonia production as potential hydrogen carrier
Palys et al. [46]	Renewable ammonia	Systems engineering	Explored systems engineering opportunities of employing renewable ammonia for sustainable energy solutions and agriculture
Kurien and Mittal [9]	Green ammonia production and utilization	Review	A review study on green ammonia production and utilization as dual-fuel compression ignition engine fuel
Elbaz et al. [47]	Recent advances in ammonia combustion	Review	A review study on recent developments in ammonia combustion
Sánchez and Martín [48]	Renewable ammonia plant scaling	Scale-up and down	Explored modular design to address scale-up and -down issues in renewable ammonia plants
International Renewable Energy Agency (IRENA) [22]	Renewable ammonia and potential barriers	Report	Innovation Outlook: Renewable Ammonia

193

194 Ammonia is among the largest industrial chemicals produced globally. Ammonia production
 195 consumes approximately 1.2% of overall primary energy and results in approximately 1% of total
 196 GHG emissions. Around 1.5-2.5 tonnes of CO₂ is released to the environment during 1-tonne
 197 ammonia production depending on the feedstock usage [7,49].

198 Even though there are numerous ammonia synthesis methods, two different commonly available
199 routes of ammonia synthesis globally are Haber-Bosch and solid-state synthesis process. An air
200 separation unit is employed to deliver nitrogen in both processes. High purity of nitrogen is
201 required for almost all the ammonia production processes and three key methodologies that are
202 used for nitrogen separation from the air are pressure swing adsorption (PSA) [50,51], membrane
203 separation [52,53] and cryogenic air separation [54,55] that is employed depending on the
204 applications and resource availability. Generically, the membrane technology separation is
205 recommended for low production while PSA is the option for medium capacities and cryogenic
206 air separation for large capacities. Nitrogen is required to be produced in a high-effective manner
207 and low cost since ammonia is synthesized in high quantities and required electrical power for
208 nitrogen separation can be either supplied using conventional or alternate energy resources.

209 The Haber-Bosch is an exothermic process that combines nitrogen and hydrogen in 1:3 ratio to
210 synthesize ammonia [56]. Fig. 2 displays the commonly employed Haber-Bosch conversion loop.
211 This reaction is exothermic with a standard enthalpy change (ΔH) of about -92.22 kJ/mol. The
212 NH_3 synthesis reaction is supported by a catalyst and is desired to occur at an optimum temperature
213 range. The catalysts used in the process are sensitive to impurities, requiring additional energy for
214 purification of the feedstock gases. The Haber-Bosch process was established in the early
215 twentieth century to react nitrogen with hydrogen thermocatalytically rendering the following
216 reaction [57]:



218 The method characteristics are based on the reactant's temperature rise since the nitrogen molecule
219 requires adequate energy for cracking. A high temperature is required by the reaction to support
220 the catalyst in breaking nitrogen bonds as nitrogen atoms are toughly bound and constrain the
221 catalyst from executing a new catalytic cycle. However, since 1 mol of product is produced in the
222 reaction using 2 moles of reactants, the forward reaction is accelerated by high pressure and low
223 temperature. Since the temperature of the reaction is not anticipated to be conventionally low
224 owing to catalyst poisoning, the pressure of the reaction is quite high. Characteristically, the
225 operational temperature is ranged from 400-500 °C, the pressure is 150-250 bar and the energy
226 efficiency of 15-30% [58].

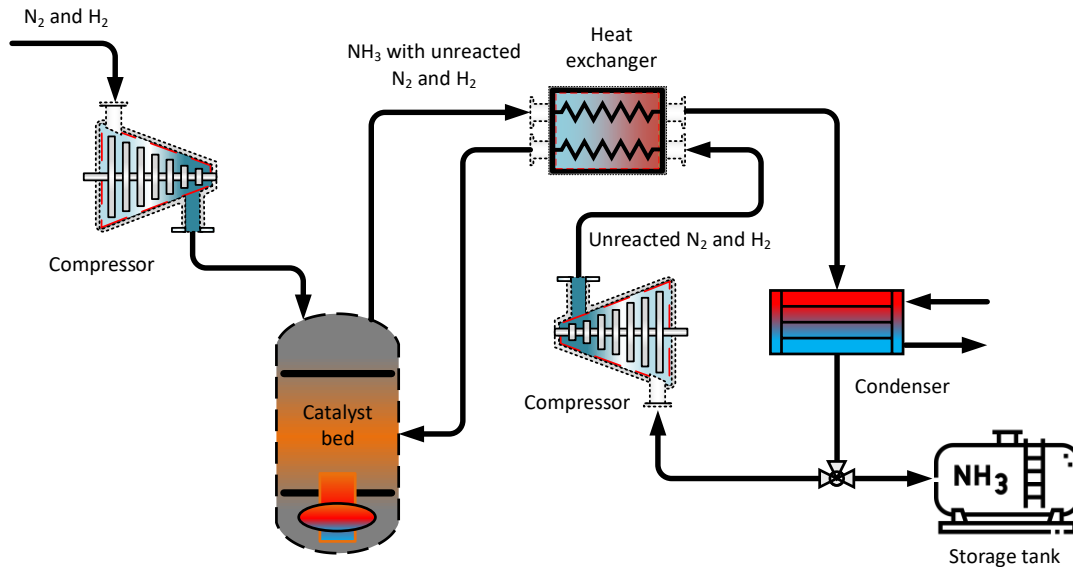
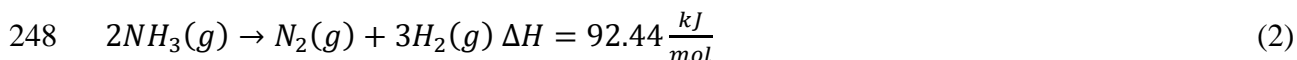


Fig. 2 Simple layout of Haber-Bosch ammonia synthesis process

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229 Make-up gas involving a mixture of nitrogen and hydrogen is compressed and delivered at an
 230 intermediate pressure. This input gas is combined with unreacted nitrogen and hydrogen gases
 231 returning from the reactor and compressed through another compressor to achieve conversion
 232 pressure. The input gas is fed to the catalytic reactor that contains an iron-based catalyst. The
 233 resultant gases including ammonia and unreacted nitrogen and hydrogen gases reach the ammonia
 234 separation unit operational at intermediate pressure where unreacted gases are separated by
 235 condensing ammonia as a liquid. A refrigeration system is employed to cool, condense and
 236 separate liquified ammonia and residual gases are recycled by recompression through another
 237 compressor and combined with make-up gas and partially employed in the combustor to generate
 238 process heat.

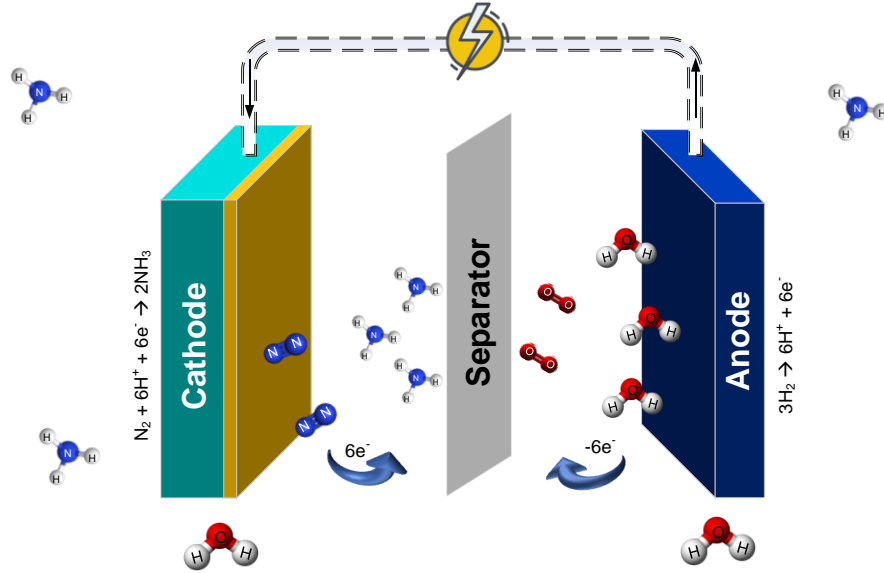
239 The challenges of storing and transporting H_2 can be mitigated using green ammonia as hydrogen
 240 storage medium/hydrogen carrier to ease the storage and transportation. Even though ammonia
 241 offers distinctive benefits including high hydrogen density, easy storage and transportation and
 242 well-established infrastructure, it also poses some challenges to employ NH_3 as H_2 storage
 243 medium, such as catalyst and heat requirements for cracking process and ammonia toxicity. While
 244 storing hydrogen in the form of ammonia, cracking process is employed to recover hydrogen. This
 245 cracking process decomposes ammonia into its component elements at high temperature (750-
 246 850°C) in the presence of a suitable catalyst, where ammonia (NH_3) is decomposed into its
 247 component elements, hydrogen and nitrogen. The reaction is as follows:



249 The ammonia cracking process starts from preheating ammonia and feeding it to the reactor that
250 decomposes it using nickel/iron catalyst at high temperature. The hot gases leaving the reactor are
251 then cooled and hydrogen is purified using different techniques such as water scrubbing,
252 membrane separation or PSA. The produced hydrogen is often used in applications where high-
253 purity hydrogen is required, such as in fuel cells, hydrogenation reactions in chemical industry,
254 and for reduction in metallurgical processes.

255 Further existing and emerging green ammonia production techniques other than renewable energy-
256 power Haber Bosch process are as follows.

257 ***Electrochemical Synthesis:*** Also known as electrochemical reduction, encompasses renewable
258 electricity to power the reduction of H₂O and N₂ to produce NH₃. This technique employs
259 renewable energy sources, such as solar, wind or hydropower, to drive the electrochemical process,
260 resulting in a minimal carbon footprint in green ammonia production. Fig. 3 illustrates the basic
261 conceptual illustration of the electrochemical ammonia synthesis process. Electrochemical process
262 uses electricity to drive the ammonia synthesis reaction combining N₂ and H₂ [59]. This method,
263 if scaled-up, offers the potential of producing cleaner and more sustainable as compared with
264 traditional Haber-Bosch process. Also, electrochemical ammonia synthesis can potentially be
265 performed and carried out at lower pressures and temperatures and reducing energy consumption
266 that can potentially allow the RE utilization. The key challenge in electrochemical ammonia
267 synthesis is finding the suitable catalyst that can enable the reaction at lower pressures and
268 temperatures [60,61]. The N₂ requires heaps of energy to react and suitable catalysts can help lower
269 this reaction energy barrier to making electrochemical ammonia synthesis feasible.



270

271 **Fig. 3** Basic illustration of electrochemical ammonia synthesis process (modified from [59])

272 **Biomass Gasification:** Biomass gasification involves converting biomass, such as crop residues
 273 or agricultural waste, into syngas through thermochemical process. Biomass gasification is a
 274 developed technology that undergoes a precise process involving controlled amount of steam
 275 oxygen and heat to produce syngas without undergoing combustion. The overall carbon emission
 276 of the processes undergoing biomass gasification can be comparatively low as growing biomass
 277 sucks CO_2 from the atmosphere, particularly when coupled with CCUS systems. Biomass
 278 gasification can be classified contingent to the gasifying agent such as steam, air, steam-oxygen,
 279 O_2 -enriched air, air-steam, etc. The gasification product is a blend of gases also known as syngas,
 280 with key components H_2 , CO_2 , H_2O , CH_4 , CO , N_2 and air [62]. The syngas can formerly be
 281 employed as a feedstock for ammonia production, reducing the dependence on fossil fuels and
 282 resulting in green ammonia production.

283 **Carbon Capture and Utilization (CCU):** Carbon capture and utilization (CCU) technologies can
 284 be integrated with the traditionally used ammonia production methods, such as Haber-Bosch
 285 process, to reduce GHG emissions [63]. Also, ammonia itself can be used as a sorbent for point-
 286 source CO_2 capture. The in-process carbon dioxide (CO_2) emissions can be captured, stored and/or
 287 utilized, resulting in a further environment-friendly ammonia production process.

288 Green ammonia production is an active R&D area and quite a few novel methods are being
 289 explored to produce sustainable and green ammonia [64,65]. Even though these novel green

290 ammonia production techniques are still in the R&D stage and their scalability and commercial
291 viability are being explored. Additional research studies, testing, pre-commercial deployment and
292 optimization are obligatory to implement such technologies at a large scale for commercial
293 ammonia production. A few of these novel green ammonia production methods include:

294 ***Renewable Energy-Powered Haber-Bosch Process:*** Haber-Bosch process that uses high-
295 temperature and high-pressure conditions for ammonia production, can also be driven using
296 renewable energy sources such as solar, wind, hydropower or geothermal. This technique helps
297 replace the fossil fuels utilization to provide process energy and offers the production of ammonia
298 more sustainably. Even though the ammonia synthesis process is exothermic and releases energy,
299 the activation energy requirements and equilibrium considerations make it energy intensive
300 process overall. As the Haber-Bosch process efficiency is typically around 60-70% and assuming
301 80% electrolysis efficiency, the overall system efficiency will be highly dependent on the RE
302 source efficiency.

303 ***Photoelectrochemical Synthesis:*** This technique involves employing specialized
304 photoelectrochemical cells that use sunlight to directly split water into its constituents and
305 hydrogen is further employed in the ammonia synthesis [66,67]. This approach exterminates the
306 external electricity need which makes it a renewable and sustainable ammonia production method
307 and can potentially bypass the high pressures and temperatures requirements in ammonia synthesis
308 methods. In a distinctive system, light-absorbing semiconductor materials known as
309 photoelectrodes capture light energy and generate electron-hole pairs that drive the nitrogen
310 reduction to ammonia and also drive photoelectrochemical water splitting of process to provide
311 hydrogen. However, a few challenges associated with this process are finding suitable catalysts,
312 efficient light absorption and charge separation, stability and scalability.

313 ***Electrobiological/Bioelectrochemical Synthesis:*** Bioelectrochemical synthesis involves
314 employing microorganisms/enzymes to facilitate the N_2 gas reduction to NH_3 in an
315 electrochemical setup. Integrating biological and electrochemical processes in a single process
316 (bioelectrochemical synthesis) offers the potential for sustainable and green ammonia production
317 [68,69]. The efficiency of this method can depend on several factors including type of
318 microorganisms used, operational conditions, specific electrochemical cell design and electron
319 transfer efficiency from electrode to microorganisms. Some primary challenges include

320 comparatively low efficiency, slow reaction rates, suitable supply of electrons to the microbes and
321 reaction selectivity.

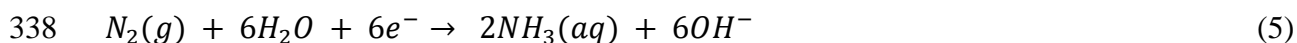
322 ***Plasma-Assisted Ammonia Synthesis:*** This technique involves using plasma (a highly energized
323 state of matter) to facilitate the reaction between hydrogen and nitrogen gases to produce ammonia
324 [70,71]. The high energy associated with plasma helps augment the reaction kinetics, possibly
325 leading to the production of ammonia in a more sustainable and efficient manner. In this process,
326 N₂ and H₂ are exposed to plasma, a state of matter comprising of charged particles that help break
327 the strong nitrogen triple bonds, which is a critical step in ammonia production. The plasma-
328 assisted ammonia synthesis process efficiency depends on several factors such as type of plasma
329 used, plasma reactor design, operational conditions and presence of catalysts. A main challenge
330 associated with this technique is that reaction generates lots of heat and high temperature can cause
331 ammonia to decompose back into its constituents, thereby reducing process yield.

332 ***Alkaline Membrane Electrochemical Ammonia Synthesis:*** In an alkaline membrane cell, the
333 reactions for the ammonia synthesis occur as follows:

334 Reactions in acidic electrolytes:



337 Reactions in basic electrolytes:



340 This process is performed in an electrochemical cell where alkaline exchange membrane separates
341 two electrodes and allows certain ions (OH⁻ in this case) to pass while blocking others, that helps
342 maintaining the ions balance and prevent the products mixing from different electrode reactions.
343 The major advantages of this technique include process operation under milder conditions and
344 relatively easy nitrogen reduction in alkaline environment that improves the process efficiency
345 [72,73]. Moreover, finding suitable catalyst materials owing to the activity and stability in alkaline
346 environment and stability and good ionic conductivity of the alkaline membrane are the challenges
347 that need to be addressed to ensure efficient cell operation.

348 ***Solar Thermal Ammonia Synthesis:*** This methods produces ammonia using the heat from
349 concentrated sunlight that drives the reaction and offers the potential for a more sustainable and
350 lower-carbon process for ammonia synthesis. The process starts with solar concentration where
351 sunlight is collected and concentrated and transferred to the heat transfer medium that provides the
352 high temperature for ammonia synthesis process in the presence of catalysts [74,75]. Theoretically,
353 the solar thermal ammonia synthesis efficiency could potentially be higher than traditional
354 ammonia synthesis methods as the solar thermal process directly employs heat to drive the
355 reaction, instead of converting heat into other forms of energy that helps eliminating some energy
356 losses. To achieve the high required reaction temperatures (400-500°C) consistently and
357 controlling the process are the key challenges owing to the intermittent nature of solar energy along
358 with the costing and scalability.

359 **3. Renewable Ammonia Production Methods**

360 Currently, natural gas reforming process is employed commercially to produce hydrogen for ammonia
361 synthesis which accompanies several drawbacks of high cost and environmental impact. One of the
362 key motivations is to eliminate fossil fuel usage and replace it with RE-based hydrogen production to
363 produce clean ammonia. Fig. 4 displays the green ammonia production routes based on RE sources
364 that are described in detail in this section along with ongoing and under-deployment green ammonia
365 projects.

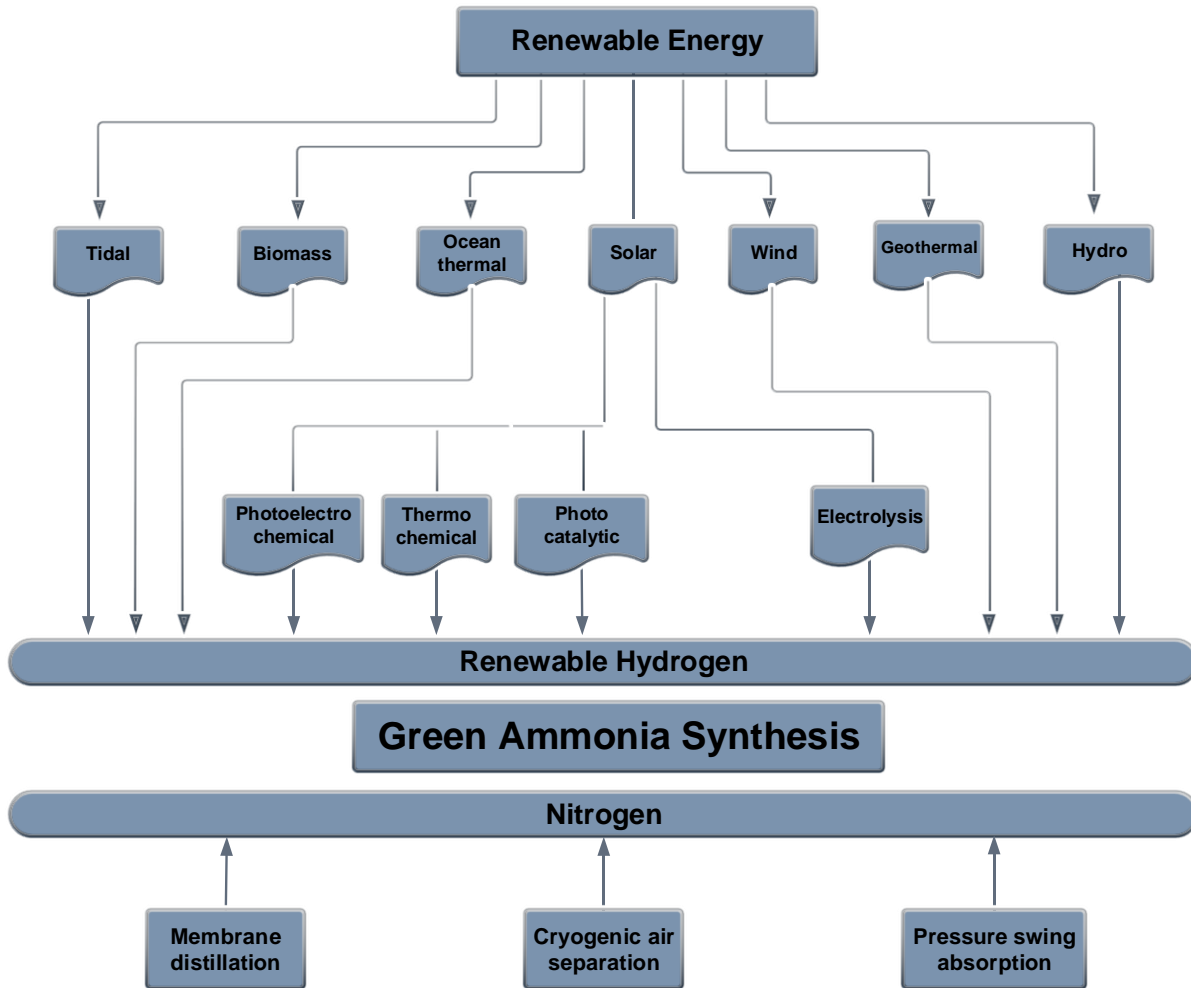


Fig. 4 Green ammonia production methods

366
367

368 3.1. Solar energy

369 Solar energy possesses great potential for renewable hydrogen production and thus, green
 370 ammonia. However, it faces some challenges owing to the intermittent nature of the energy source.
 371 Recent advances are carrying out research studies and developing technologies to overcome this
 372 challenge either by integrated battery storage or hydrogen buffer storage to meet the continuous
 373 demand. Renewable hydrogen can be produced using solar energy using different routes [76]
 374 namely; thermal, photovoltaic and photoelectrochemical and produced renewable hydrogen can
 375 thus be employed to produce green ammonia as shown in Fig. 5.

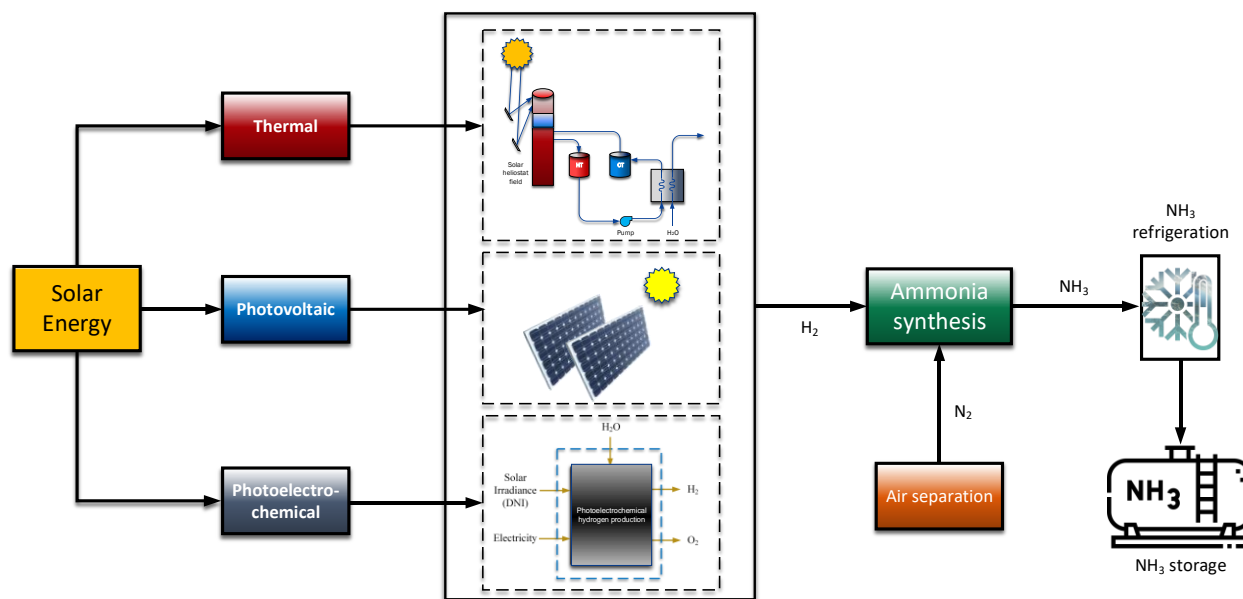


Fig. 5 Solar energy-powered green ammonia production

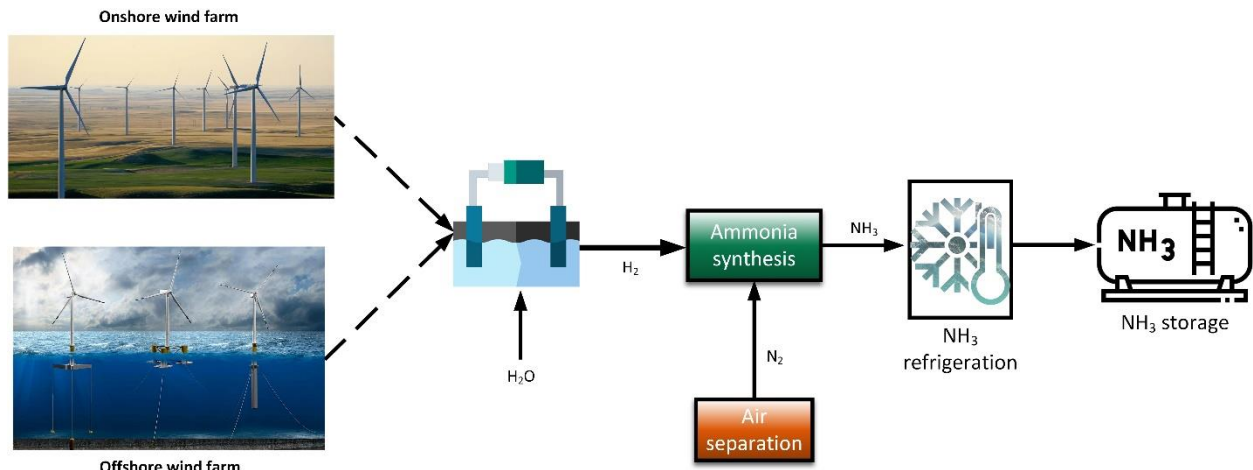
376
377

378 A plethora of recent studies highlighted the advancements in heliostat technology and their
 379 possible integration with energy systems [77,78]. Similarly, many research studies investigated
 380 and explore using solar thermal energy to produce clean hydrogen directly from thermal energy
 381 using thermochemical cycles [79,80]. Using solar photovoltaics (PV) is among the mature
 382 technologies that is currently being used and operational in many commercial plants as well. Many
 383 research studies are conducted on solar PV-based clean hydrogen production and many renewable
 384 hydrogen facilities are operational as well as being converted to green ammonia facilities [81,82].
 385 Photoelectrochemical is comparatively an emerging technology for clean hydrogen production,
 386 however, investigated in numerous research studies proposing renewable hydrogen for green
 387 ammonia production as well [83,84].

388 3.2. Wind energy

389 Ammonia emerges among the most suitable contenders for future fuel as it is a zero-carbon fuel
 390 that offers a net-zero solution when produced via renewable hydrogen [85]. To deal with the
 391 intermittency of wind energy sources, a battery/hydrogen storage media is required to be integrated
 392 with the energy system to provide a steady demand for electricity/hydrogen and renewable
 393 hydrogen can further be converted to green ammonia. Onshore/offshore wind energy can directly
 394 be coupled with water electrolysis system to produce renewable hydrogen along with a storage

395 unit to deal with the intermittency and hydrogen can further be converted to green ammonia as
396 demonstrated in Fig. 6.



397
398 **Fig. 6** Wind energy-powered green ammonia production

399 Numerous research studies and commercial plants are exploring and installing onshore wind farms
400 [20,86,87] for clean hydrogen production, many ongoing projects are proposing to employ
401 offshore wind farms [33,86,88,89] for renewable hydrogen and green ammonia production and
402 further research is exploring the floating offshore wind farm [90,91] for renewable hydrogen and
403 green ammonia production.

404 3.3. Geothermal energy

405 Geothermal energy is heat produced and extracted from the Earth's subsurface and it is a clean and
406 renewable source that is either used directly for heating/cooling or used to generate electricity [92].
407 However, in order to be converted into electricity, medium to high resources of temperature are
408 desirable. Fig. 7 exhibits the geothermal energy-powered green ammonia production system.
409 Existing types of geothermal technologies are as follows:

- 410 • Dry steam plants: Employ hydrothermal fluids that are mainly steam which drives the
411 turbine and thus generator.
- 412 • Flash steam plants: Hydrothermal fluid at a temperature $>182^{\circ}\text{C}$ is employed in flash steam
413 plants. The tank is kept at a pressure lower than fluid which is sprayed inside the tank and
414 causes fluid to rapidly vaporize/flash and these vapors then drive the turbine.

- Binary plants: Hot geothermal and a secondary (comparatively low boiling point) fluid are passed through the heat exchanger. Geothermal fluid's heat causes the secondary fluid to flash to rapidly vaporize/flash which drives the turbine.

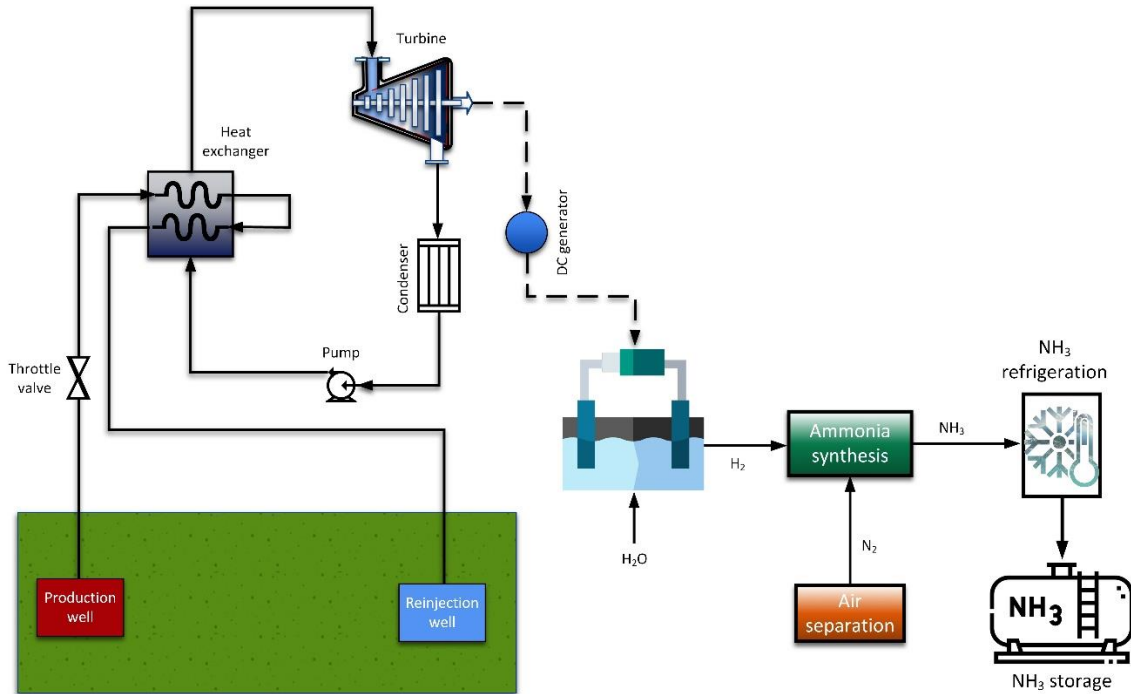


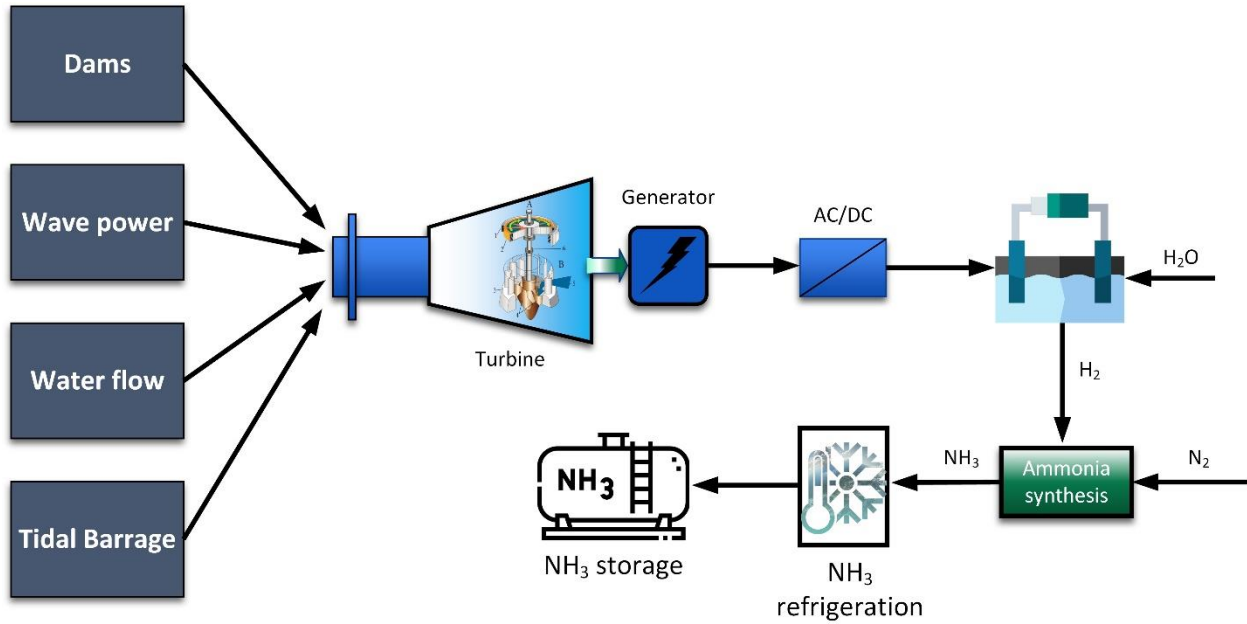
Fig. 7 Geothermal energy-powered green ammonia production

The geothermal power projects offer the levelized cost of electricity (LCOE) between \$0.049-0.085/kWh between 2010 and 2020 [93]. As a renewable resource, Geothermal resource covers a substantial share of electricity and heating demand in many countries. The key geothermal energy resource benefits are the low cost and continuous operation at a high capacity factor that allows this source to deliver stable, dispatchable electricity that can be used directly to produce renewable hydrogen and thus green ammonia [94,95].

3.4. Hydro power

Hydropower is among the largest RE sources that generate electricity by utilizing the natural flow of moving water. Hydropower technology generates power employing elevation difference of flowing water from a dam, water flow, diversion structure or tidal barrage. Hydropower-based ammonia production employs electricity generated by hydroelectric powerplant and produces ammonia from hydrogen and nitrogen as shown in Fig. 8. This includes two core steps of producing hydrogen through the water electrolysis method using hydropower and producing ammonia from

433 renewable hydrogen [96]. One of the key advantages of producing renewable fuel (ammonia) using
 434 hydropower is that it is a renewable and carbon-free process and does not produce greenhouse gas
 435 (GHG) emissions. Furthermore, it can be an efficient route for energy storage and produced
 436 ammonia can be stored, transported and utilized for numerous applications.

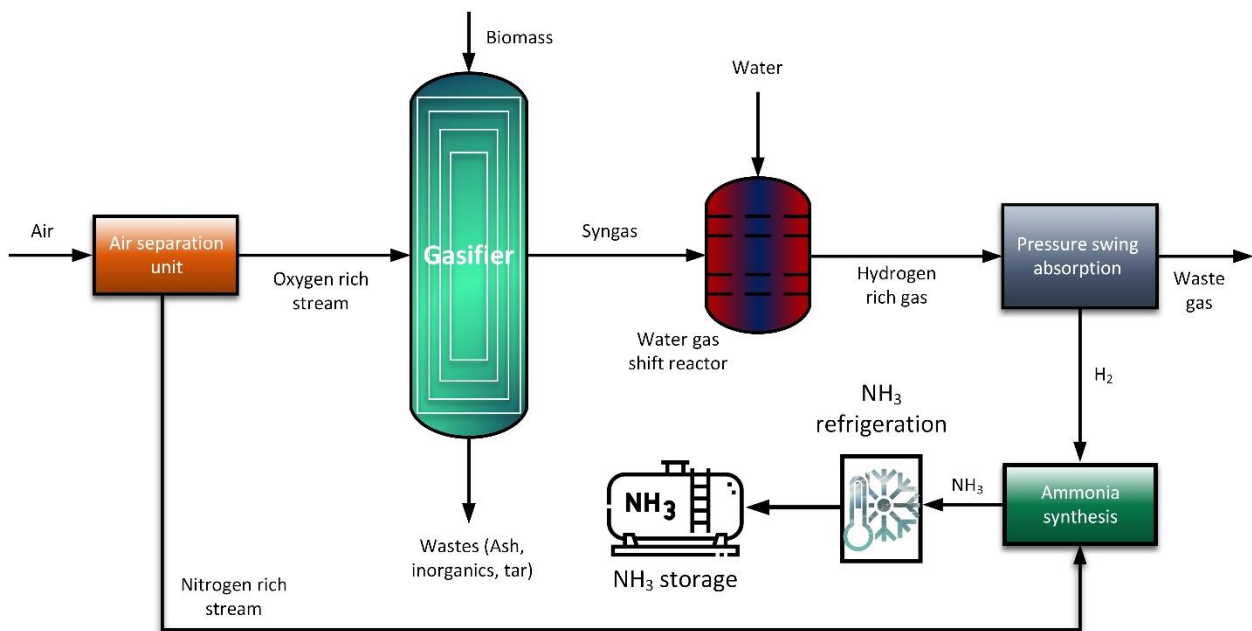


437
 438 **Fig. 8** Hydro energy-powered green ammonia production

439 Many research studies are conducted to explore and investigate renewable hydrogen and ammonia
 440 production using hydropower [97,98]. Some of the challenges associated with this green ammonia
 441 production route are high electrolysis equipment cost, large electricity requirements and variability
 442 of hydropower. Nevertheless, the advantages associated with this carbon-free route can contribute
 443 towards sustainable energy development. Ocean thermal energy conversion (OTEC) can also be
 444 accounted as a hydropower branch that is driven by the temperature difference between deep cold
 445 and warm surface water. This process utilizes the warm surface water heat and vaporizes the
 446 system's working fluid that drives the turbine. Several research studies are investigating renewable
 447 hydrogen production using hydropower [99,100]. The produced electricity is then employed to
 448 produce renewable hydrogen and thus green ammonia that can reduce ammonia production
 449 dependency on fossil fuels.

450 **3.5. Biomass**

451 Biomass is known as a renewable organic resource that takes in agriculture crop residues forest
452 residues, organic municipal waste, crops grown explicitly for energy use and animal wastes.
453 Biomass is considered to be one of the most promising hydrogen production routes [101,102].
454 Thermochemical processes are the major pathways used for biomass-based hydrogen and
455 ammonia production including steam gasification, supercritical water gasification, reforming, and
456 fast pyrolysis [103]. In comparison with pyrolysis, gasification is globally recognized as a
457 promising technique for large-scale deployment and offers improved hydrogen yield and higher
458 efficiency [104].



459
460

Fig. 9 Biomass gasification based green ammonia production

461 Biomass gasification is considered a matured technology that undergoes a controlled process of
462 converting biomass into hydrogen and other products involving heat, oxygen and steam. As
463 growing biomass residues remove carbon dioxide from the atmosphere, net carbon emissions are
464 very low particularly if integrated with CCUS in long term. The gasification process converts
465 organic carbonaceous materials into carbon dioxide (CO₂), hydrogen and carbon monoxide (CO)
466 at high temperatures (>700°C), with a controlled oxygen and/or steam amount. The CO is then
467 converted to CO₂ and hydrogen by reacting it with steam through a water-gas shift reaction. The
468 produced renewable hydrogen then reacts with nitrogen and produces green ammonia as displayed
469 in Fig. 9.

470 **4. Green Ammonia Advancements and Projects**

471 The electrolytic ammonia production route is somewhat expensive owing to the costs of air
 472 separation and hydrogen buffer storage while integrating with intermittent solar/wind sources to
 473 limit hydrogen input variation. Today, the cost of electrolytic ammonia production ranges from
 474 \$680-900/tNH₃ which is anticipated to reach \$400/tNH₃ by 2030 [105]. Many novel and promising
 475 ammonia production techniques are still in the research, development and demonstration (RD&D)
 476 phase such as alkaline membrane electrochemical ammonia synthesis, photoelectrochemical
 477 synthesis, electrobiological synthesis, plasma-assisted ammonia synthesis and solar thermal
 478 ammonia synthesis. Green ammonia production is said to be in its primitive commercial
 479 deployment stages. However, many projects and initiatives are underway around the globe
 480 predicting ammonia as a potential renewable fuel. Table 4 lists the ongoing/under-deployment
 481 projects all around the world and summarizes the companies and government agencies handling
 482 the projects, geographical location, project capacities and electricity resources for the projects.

483 **Table 4** List of green ammonia production facilities

Project	Companies	Capacity	Electricity resource	Location	Status	Source
REFUEL	Nutrien and other 14 organizations collaboration with US Department of Energy (DOE) funded RE to Fuels	1 metric tonne of ammonia per day	RE	United States	Expected start 2024	[106]
REDDAP	Topsoe, Vestas and Skovgaard	5,000 tonnes of green ammonia per year	Wind and solar energy	Western Jutland	Operational by 2023	[107]
HOST	Hafnia and Clean Hydrogen Works (CHW)	600,000 tonnes of green ammonia production per year	RE	Louisiana	Construction start 2028/29	[108]
Green Ammonia Project	Ørsted and Yara	75,000 tonnes of green ammonia per year	Wind power	Netherlands	Operational by 2024/25	[109]
Future green bunker fuel hub	Ørsted, Haldor Topsoe, Molslinjen, Bunker Holding Group, Bureau Veritas, Wärtsilä, Port of Roenne and Rambøll	Maritime fuel for 60,000 ships	Wind and solar energy	Bornholm	Construction start 2028/29	[110]
Green ammonia production facility	Hy2gen, Trafigura and Copenhagen Infrastructure Partners (CIP)	600 metric tonnes of green ammonia per day	RE	Norway	Construction start 2023	[111]
K-Green ammonia-powered offshore drilling	KBR, Odfjell, Equinor and Wärtsilä	-	RE	Norway	Under planning	[112]

Green ammonia marine fuel	IRVING, Texas – ExxonMobil, Grieg Edge, North Ammonia, and GreenH	100,000 metric tonnes of green ammonia per year	RE	Norway	Memorandum of understanding (MOU) stage	[113]
Green ammonia production	Yara and Linde Engineering	20,500 tonnes of green ammonia per year	RE	Norway	Product supply by 2023	[114]
Green ammonia supply and offtake agreement	Trammo and Canada-based Teal Corporation	800,000 tonnes of green ammonia	Hydro power	Canada	Strategic Plan 2022-2026	[115]
Courant	Hy2Gen and Trafigura	500 tonnes of green ammonia per day	Hydro power	Canada	Completion by 2028	[116]
Containerized green ammonia production system	FuelPositive	300 kg per day of green anhydrous ammonia	RE	Canada	Under construction	[117]
Independent ammonia making machine	AmmPower Corp.	4 metric tonnes of green ammonia per day	RE	Brazil	Under construction	[118]
HyEx	Engie and Enaex	700,000 tonnes of green ammonia per year	RE	Chile	Construction start by 2024	[119]
HNH	Copenhagen Infrastructure Partners (CIP), AustriaEnergy and Ökowind	1 million tonne of green ammonia per year	Onshore wind power	Chile	Under planning	[120]
H ₂ Magallanes	Wood. Total Eren and UMAG	10 GW of onshore wind power capacity	Onshore wind power	Chile	Completion by 2030	[121]
FFI	Fortescue Future Industries (FFI)	700,000 to 900,000 tonnes of green ammonia per year	Wind power	Canada	Under planning	[122]
Yara HEGRA	Aker, Yara and Statkraft	-	RE	Norway	Completion by 2026-28	[123]
CIP	Arla, Danish Crown, DLG, A. P. Moller – Maersk and DFDS	1.5 million tonnes of CO ₂ emissions reduction per year	Offshore wind energy	Denmark	Completion by 2026	[124]
HT/Aquamarine	Haldor Topsoe and AQM Capital LLC (Aquamarine)	300 tonnes of green ammonia per day	RE	Germany	Facility commissioning by 2024	[125]
MadoquaPower2X	Madoqua Renewables, Power2X and Copenhagen Infrastructure Partners (CIP)	500,000 tonnes of green ammonia per year	RE	Portugal	Full commissioning before 2030	[126]
HEVO	Fusion Fuel Green PLC and CCC	183,000 tonnes of green ammonia per year	Solar and fusion fuel	Morocco	Completion by 2026	[127]
Scatec	Scatec, Suez Canal Economic Zone (SCZONE), Egyptian Electricity Transmission Company (EETC), The Sovereign Fund of Egypt (TSFE) and New and RE Authority (NREA)	1 million tonne of green ammonia per year	RE	Egypt	Agreement signed	[128]

Acme	Scatec and ACME	1 million tonne of green ammonia per year	RE	Oman	Operational by 2022	[129]
Gente Grande Project	Petrofac, and Transitional Energy Group (TEG)	1.3 million tonnes of green ammonia per year	Wind Energy	Chile	Environmental authorizations by 2024	[130]
NEOM	Acwa Power and Air Products	1.2 million tonnes of green ammonia per year	RE	Saudi Arabia	Completion by 2023	[131]
Ammonia production plant	OQ, the global integrated energy group	1,000 metric tonnes of green ammonia per day	Wind and solar energy	Oman	Operational	[132]
World-scale green hydrogen-based ammonia production facility	ACWA Power, OQ, and Air Products	1,200,000 tonnes of green ammonia per year	RE	Oman	Joint development agreement (JDA) signed	[133]
TAQA	Abu Dhabi National Energy Company PJSC (TAQA) and Abu Dhabi Ports	2 GW solar photovoltaic (PV) power plant	Solar Energy	Abu Dhabi	Techno-feasibility stage	[134]
GEO	OQ, InterContinental Energy and EnerTech,	9,900,000 tonnes of green ammonia per year	Wind and solar energy	Oman	Feasibility stage	[135]
World's largest renewables and green hydrogen energy hubs	bp and AREH	9 million tonnes of green ammonia	RE	Australia	Under planning	[136]
H ₂ Perth	Woodside Energy Ltd and several Japanese companies	600,000 tonnes of ammonia per year	RE	Australia	Under development	[137]
H ₂ -Hub™	Orica and H ₂ U Group	5,000 tonnes of green ammonia per day	RE	Australia	Operational by 2025	[138]
H ₂ TAS	Woodside Energy Ltd (Operator), Marubeni Corporation, IHI Corporation	800,000 tonnes of green ammonia per year	RE	Australia	Under development	[139]
Export scale green hydrogen and ammonia plant	Origin, integrated energy company	420,000 tonnes of ammonia per year	RE	Australia	Under development	[140]
FFI Brisbane	Fortescue Future Industries (FFI) and Incitec Pivot Limited (IPL)	350,000 tonnes per year green ammonia	RE	Australia	Front End Engineering Design (FEED) stage	[141]

484

485 Key focus area categories (competitiveness, market feasibility and economic feasibility and risk
486 analysis) used to assess the commercial feasibility of green ammonia projects are as follows:

487 **Competitiveness**

- 488 • Competitor analysis → Project pipeline evaluation, Company profiles, Market balances →
489 How well positioned is the project relative to existing and future producers? → Plethora of
490 green ammonium projects - what makes the project different and less risky?
491 • Cost analysis → Delivered costs of markets, Cost curve and emissions analysis, Feedstock
492 price forecasts/carbon pricing, Freight/logistical analysis → Will this project be cost-
493 competitive enough to place its product? → RE vs. fossil fuel pricing importance, including
494 carbon pricing

495 ***Market feasibility***

- 496 • Product and geographical markets → Demand, supply and trade analysis, Analysis of
497 alternative scenarios for "new" markets → Will the project be able to place its planned
498 sales volumes in target markets? → Nascent green ammonia market poses an increased risk
499 to investors
500 • Sales and marketing strategy → Identification of target markets and forecast sales volumes
501 and prices, Obstacles and success factors → Will the project be able to place its planned
502 sales volumes in target markets? → Barriers to market entry could be higher for new
503 markets e.g. infrastructure and logistics
504 • Off-takers → Review of off-takers capabilities/risks, Review of off-take contracts → How
505 certain is it that off-takers will take sales volumes long-term? → Firm commitments from
506 reputable off-takers - ideally take or pay-provide comfort to investors, especially for new
507 markets

508 ***Economic feasibility and risk analysis***

- 509 • Price forecasts → Benchmark and netback price forecast, Green premium analysis, Floor
510 price analysis → What returns will be made investing in the project? Can it withstand
511 cyclical lows? → Potential for green premium could bridge gap versus brown ammonia
512 • Sensitivity analysis → Financial modeling, Alternative scenarios for key assumptions →
513 What market developments could make or break this project? → Increased risk of green
514 versus brown ammonia projects. Expect investors to place more emphasis on
515 understanding the magnitude and likelihood of risks

- Risk analysis → SWOT analysis of project mitigation strategies → What Market developments could make or break this project? → Key focus area for assessing the commercial feasibility of green ammonia projects

5. Ammonia Utilization

Green ammonia has diverse usages and can be utilized in numerous applications. Ammonia offers the potential to be the future clean fuel as it offers carbon-free applications when utilizes and can also be used as an energy carrier and energy storage media. Currently, ammonia is mostly utilized in the fertilizer industry and refrigeration. The current market is also working on manufacturing prototypes of ammonia-fueled vehicles employing fuel cell or engine [142,143]. Ammonia, along with its applications in the fertilizer industry, can also be utilized as a renewable fuel in the maritime industry, ICEs, fuel cells, and gas turbines undergoing zero carbon footprint if produced consuming RE sources. Fig. 10 displays the breakdown of ammonia production and utilization by energy source and sector respectively. Currently, natural gas is being used significantly (76%) for ammonia production followed by coal (4%) as shown in Fig. 10(a). However, this trend is now switching towards producing more sustainable ammonia and utilizing RE for green ammonia synthesis. Fig. 10(b) exhibits the ammonia utilization by sector and it is obvious that a major portion of ammonia utilization is dominated by the fertilizer industry as ammonia is the most commonly used nitrogen fertilizer, followed by the industrial chemical (10%) and refrigeration sector (5%).

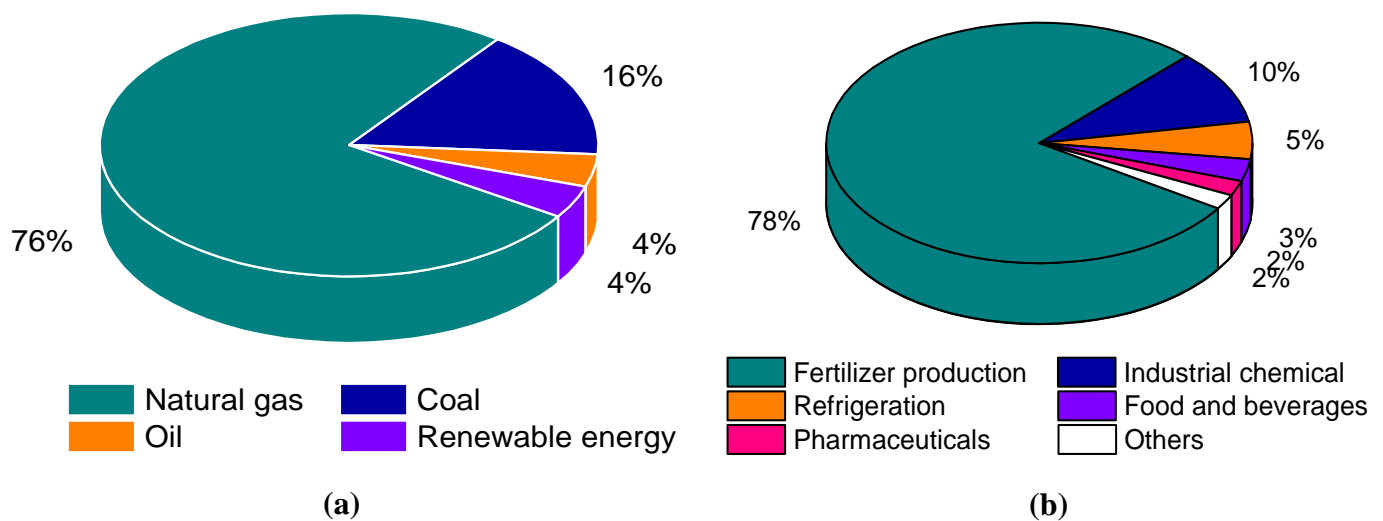


Fig. 10 Breakdown of ammonia production and consumption (a) ammonia production by energy source 2020 (b) ammonia utilization by sector 2020 (data from [144])

537 Being a versatile chemical, ammonia can be utilized in various applications using a variety of ways
538 and some of the paramount ammonia utilization techniques are as follows:

- 539 • **Agriculture** Ammonia is extensively and globally utilized in agriculture which makes it a
540 backbone of nitrogen-based fertilizer.
- 541 • **Direct use** Ammonia can directly be used in irrefutable applications namely; refrigeration,
542 fuel sector and as cleaning agent.
- 543 • **Fuel cells** One of many techniques where ammonia can be employed as fuel is fuel cells
544 and produces electricity. It can also be an option to store ammonia and utilize it to meet
545 peak demands, however, ammonia fuel cells are at their early stage and further research is
546 required to meet the ammonia fuel cell efficiencies.
- 547 • **Hydrogen production** Ammonia can be utilized as hydrogen storage media and can be
548 catalytically cracked on-site into its constituents (hydrogen and nitrogen).
- 549 • **Combustion** In the combustion technique, ammonia cannot only be combusted in internal
550 combustion engines (ICEs) for power generation but can also be utilized to drive gas
551 turbines by burning.
- 552 • **Chemical synthesis:** Ammonia can also be utilized as raw material to produce numerous
553 chemicals namely; urea, ammonium carbamate, nitric acid and ammonium nitrate.
- 554 • **Gasification** Syngas can be produced from ammonia gasification that can further be used
555 for the production of chemical and electricity generation.

556 Ammonia as potential renewable fuel has also widespread applications in transportation, aviation
557 and marine industry and appeared as a potential maritime fuel. Ammonia is used in different
558 sectors in many ways as shown in Fig. 11 and some of the streamlined usages of ammonia are; as
559 nitrogen fertilizer, as feedstock for the chemical industry, in refrigeration applications, as an
560 energy source, as carbon-free fuel, as hydrogen storage media and as sorbent for point-source CO₂
561 capture.

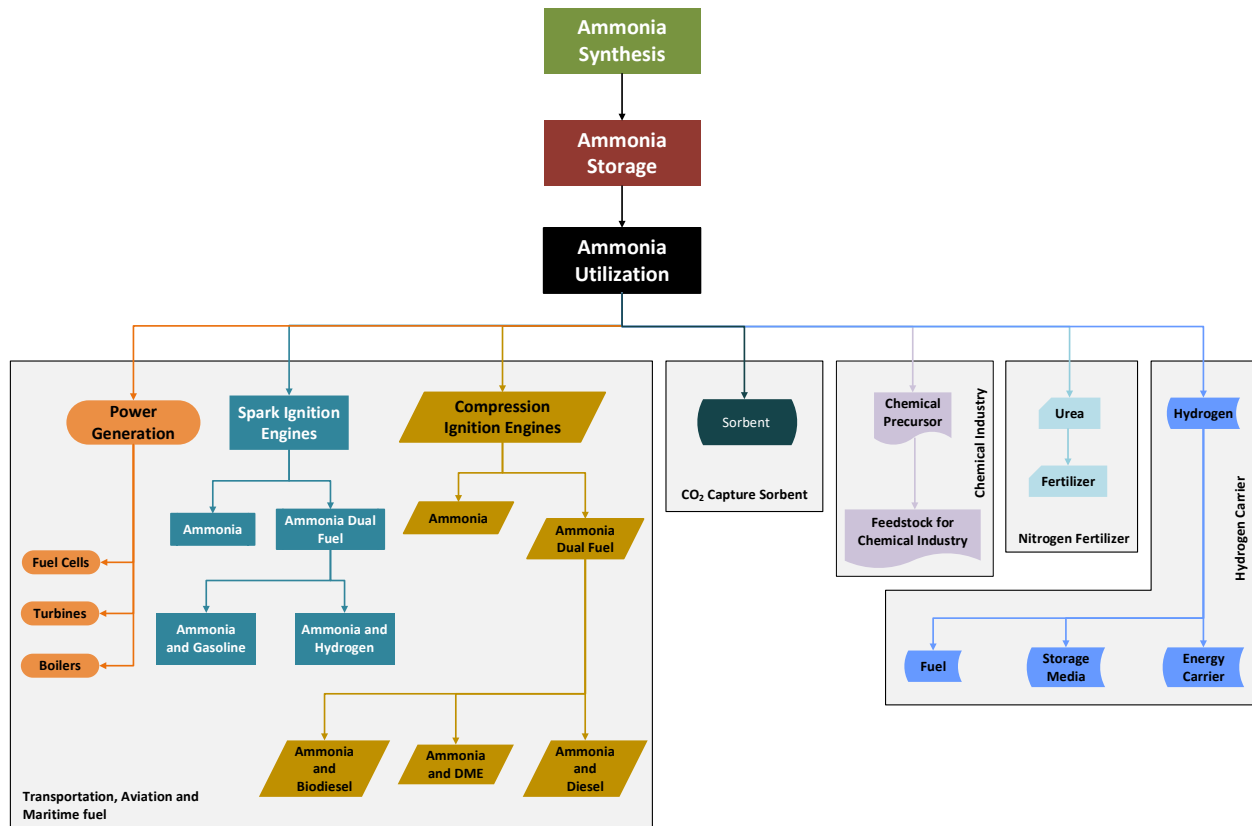


Fig. 11 Ammonia utilization in different applications

562
563

564 Moreover, in the transportation, aviation and maritime industry, ammonia can be utilized in
 565 compression ignition engines designed for ammonia or ammonia dual-fuel engines, spark ignition
 566 engines designed for ammonia or ammonia dual-fuel engines and ammonia mixed with different
 567 fuels can also be utilized, and for power generation through different pathways such as fuel cells,
 568 gasification, engines/generation and turbines. Ammonia can also be used for water purification, as
 569 refrigerant gas, for manufacturing textiles, explosives and many other chemicals. Numerous
 570 ammonia production methodologies are under research for a more efficient and cost-effective
 571 process.

572 **5.1 Ammonia Fuel Cell**

573 The working principle of a fuel cell is the reverse process of an electrolyser. Ammonia (NH₃), as
 574 fuel source, can be used fuel cells that convert fuel's chemical energy into electricity. In particular,
 575 Alkaline fuel cells and solid oxide fuel cells have shown promising potential to use ammonia as a
 576 fuel and process steps of ammonia fuel cell are as follows:

- 577 • Ammonia is fed into the anode side of the fuel cell.

- 578 • A catalyst at the anode helps splitting ammonia into hydrogen and nitrogen and specific
579 reaction and operating conditions depend on the fuel cell type.
- 580 • The hydrogen produced at the anode is then oxidized to produce protons (H⁺) and electrons.
581 The electrons then travel through an external circuit that creates the electrical power.
- 582 • At the cathode, oxygen from the air combines with the protons and electrons to produce
583 water, which is typically the only byproduct of a hydrogen fuel cell.

584 **5.2 Ammonia Combustion Engine**

585 Ammonia can be used as fuel in ICEs, similar to the other fuels such as gasoline, diesel or natural
586 gas [145,146]. Ammonia undergoes zero carbon emissions when burnt, which makes it an
587 attractive option for a carbon-free fuel.



589 The utilization of ammonia in combustion engine faces following challenges:

- 590 • Ammonia has a lower energy content in comparison with other traditional fuels (e.g.
591 gasoline, diesel).
- 592 • Ammonia has relatively high ignition temperature that makes it difficult to ignite and
593 characteristically requires a spark plug to initiate combustion process.
- 594 • Even though burning ammonia doesn't produce CO₂ emissions, it produces nitrogen oxides
595 (NO_x) that are harmful pollutants.
- 596 • Ammonia requires careful handling and storage process owing to the toxic nature of
597 ammonia.
- 598 • Infrastructural changes need to be modified to work with ammonia.

599 The experimental combustion engine has been developed to run as ammonia, often in a dual-fuel
600 configuration with a traditional fuel like gasoline/diesel that helps initiate combustion [147].
601 Further research is being directed to mitigate the NO_x emissions from ammonia combustion and
602 other processes including catalytic converters and exhaust gas recirculation techniques.

603 **6. Ammonia Storage, Transport and Infrastructure**

604 This section contains the storage and transport of ammonia including the ammonia economy and
605 requirements of new infrastructure.

606 **6.1. Ammonia Storage**

607 Depending on the projected application and usage, numerous forms can be used to store ammonia.
608 Ammonia can be stored in liquid form at high pressure and low temperature for applications in
609 refrigeration and chemical feedstock. Ammonia can be adsorbed in solid materials namely; zeolites
610 and activated carbon and can be stored and transported for small-scale applications. Ammonia can
611 be stored in underground caverns for large-scale storage such as excess RE seasonal storage in the
612 form of ammonia. Ammonia can be stored in the form of ammonium hydrate, which offers lower
613 vapor pressure as compared with pure ammonia, by reacting it with water and used for long-term
614 ammonia storage and transport. Ammonia can be stored in the form of chemical compounds
615 namely; urea, ammonium carbamate and ammonium nitrate that can be safely transported over
616 long distances.

617 Ammonia, synthetic natural gas, hydrogen and methanol are the main chemical storage routes for
618 energy storage technologies and the advantages and disadvantages of these chemical storage
619 technologies are displayed in Fig. 12. Ammonia and hydrogen are emerging as clean future
620 fuels/energy carriers and offer the potential of playing a significant role in global decarbonization
621 and to help meet net-zero emission targets. However, regardless of the great potential offered by
622 hydrogen, some issues are linked to the storage and distribution of hydrogen which is making the
623 implementation challenging. In contrast, as ammonia is already being used as a nitrogen fertilizer
624 for decades, the existing infrastructure and distribution system is compatible with ammonia.
625 Moreover, ammonia can be liquefied and stored easily at low temperatures and high pressure
626 which makes storage and transportation easy in the liquid phase.

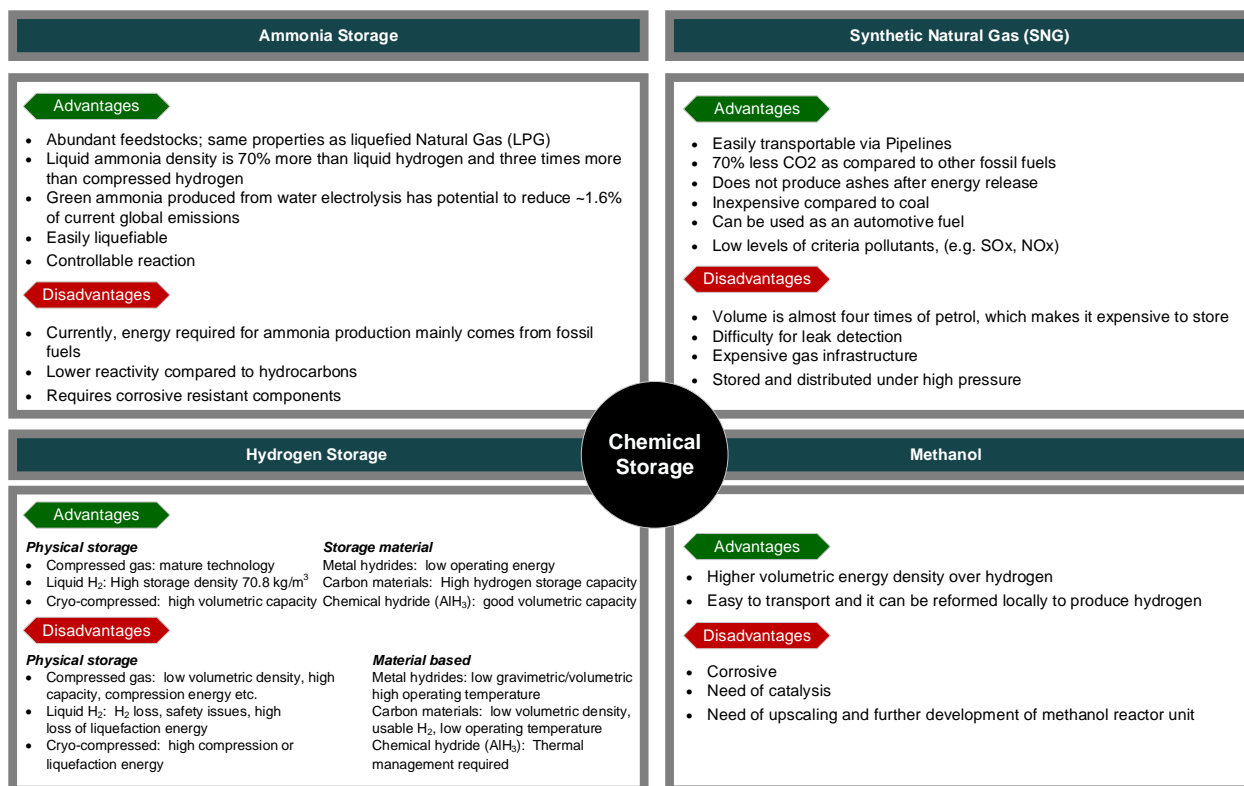


Fig. 12 Pros and cons of different chemical storage technologies (Modified from [148])

Ammonia offers significant potential to the marine industry and is being proposed to be adopted as maritime fuel in many ongoing/under-deployment projects. The criterion used to identify the closest ideal liquid alternative transportation fuel is described as follows:

- Production flexibility:** Should be easily integrated with all prime energy sources such as wind, solar, biomass, nuclear, OTEC, coal with CCS, natural gas with CCS, etc). The fuel production process should rather be simple with possible scalability.
- Distribution infrastructure:** Should be supported by an extensive existing storage and delivery infrastructure
- Affordability:** Affordability involves production CAPEX and OPEX costs, infrastructure costs and other considerations.
- Economic development:** The aptitude for nationwide fuel production to become fuel and power independent.
- High efficiency potential:** Octane rating is critical for highly efficient SI engines that permit high engine compression ratios followed by high efficiency. The high-efficiency potential of fuel cells is also imperative.

- 644 • **End use flexibility:** Should be appropriate for use in SI engines, CI engines, fuel-cell,
645 combustion turbines, etc.
- 646 • **Environment and health:** Should have excellent environmental and health performance.
- 647 • **Safety:** Should have acceptable safety characteristics.
- 648 • **Sustainability:** Should be based on renewable sources and widely available, low-cost raw
649 materials.
- 650 • **Additional benefits:** Having supplementary non-fuel usages add significant utilization
651 potential to society e.g., fertilizer, chemical precursor, RE storage, refrigerant, energy
652 carrier, hydrogen source, cleaner, etc.

653 **6.2. Ammonia Transport**

654 Ships and pipelines have been carrying liquid ammonia for several decades for the fertilizer
655 industry. Ammonia is quite established in terms of worldwide transmission that currently relies
656 heavily on liquefied petroleum gas (LPG) tankers. This trend is now shifting towards using
657 ammonia tankers for shipping by directing efforts toward an ammonia technology roadmap [4].
658 Ammonia liquefies at a temperature of -33°C or at a pressure of 8.6 bar. The existing largest
659 refrigerated NH_3 tanks are sited in Qatar with a capacity of 50 kt. Saudi Arabia has the existing
660 largest ammonia plant (SAFCO IV) that offers 1.3 Mt/year ammonia capacity. The United States
661 has more than 10,000 ammonia storage sites and various of them are connected to the pipeline
662 network stretching over 3,000 km. Even though ammonia can be used as a hydrogen carrier, before
663 the end-use, ammonia transport and storage advantages need to be evaluated against the energy
664 losses that occur while cracking ammonia into its constituents ($\sim 25\text{-}30\%$) and required equipment
665 for producing ammonia and reversion into hydrogen. Ammonia for shipping decarbonization
666 and maritime fuel carries huge potential [149]; the International Maritime Organization (IMO)
667 [150,151] has aggressive targets with projections indicating ammonia will be the dominant zero-
668 emission fuel by 2050 [152]. Table 5 shows the properties of different fuels in comparison with
669 ammonia for international shipping in terms of energy densities, energy supply, relative tank
670 volume, injection pressure, supply pressure and SO_x and NO_x emissions from complete
671 combustion and ammonia offers promising properties to be employed as a shipping fuel.

672 **Table 5** Comparison of properties of different fuels for international shipping

Fuel	Energy density (MJ/L, LHV)	Supply energy (MJ/kg, LHV)	Relative tank volume	Injection pressure (bar)	Supply pressure (bar)	SO _x emissions from complete combustion (g SO _x /km)	CO ₂ emissions from complete combustion (g CO ₂ /km)
Ammonia (-33°C)	12.7	18.6	2.76	600-700	83	0	0
Hydrogen (-253°C)	8.5	120	4.12	-	-	0	0
Ethanol	21	26	1.75	500	10	-	-
Methanol	15	19.9	2.33	500	13	0.02	43
LNG (-162°C)	22	50	1.59	300-380	300-380	0.02	37
LPG	26	46	1.35	600-700	50	-	-
Heavy fuel oil	35	40.5	1.00	950	7-8	0.36	49

673

674 The selection of the ammonia transportation method is contingent on several factors such as the
675 ammonia quantity to be transported, the geography of the destination and the transportation
676 distance. Ammonia transportation can be carried out using the following techniques:

- 677 • Pipelines are known to be the most cost-effective and efficient way to transport large
678 ammonia quantities over extended distances.
- 679 • Road tankers are also used for ammonia transportation over short/medium distances and
680 are designed for safe handling. Safety, environmental risks, spill and leaks are avoided
681 while designing the specialized ammonia tankers.
- 682 • Rail transport is also among the common ammonia transportation techniques that are
683 employed for ammonia transportation over short/medium distances.
- 684 • Ammonia vessels are also being used for transporting large ammonia quantities
685 internationally and stored in refrigerated tankers that help maintain the low temperature to
686 avoid evaporation.

687 The cost estimations reveal that shipping costs of ammonia are much lower (\$40-60/tNH₃) for a
688 10,000 km distance as compared with LH₂ (\$1700-2300/tLH₂). In the longer run, process
689 optimization and efficiency improvements possibly will reduce transportation costs. The shipping
690 cost increases slightly with transportation distance. The cost estimation for shipping ammonia for
691 a 20,000 km distance is (\$60-80/tNH₃) compared to (\$2000-2700/tLH₂) for liquid hydrogen [105].
692 Table 6 tabulates and compares the efficiencies of employing low-carbon ammonia and hydrogen
693 as fuel in the marine transport of 10,000 km distance considering natural gas with CCUS and

694 electrolytic processes including ammonia production, hydrogen production, liquefaction, marine
 695 transport and overall efficiencies.

696 The required resource amount to supply fuel demand is directly linked with the fuel supply chain
 697 and it's overall energy efficiency as summarised in Table 6. An ample portion of energy is lost
 698 during the hydrogen production. Low-temperature water electrolysis currently offers around 64%
 699 efficiency while natural gas offers 74% hydrogen conversion efficiency. Converting hydrogen into
 700 ammonia causes another 15% loss of chemical energy as heat. Even though hydrogen route can
 701 avoid this conversion loss, however, hydrogen liquefaction for marine transport is very energy-
 702 intensive process. At present, 1 kg hydrogen liquefaction consumes around 10 kWh of electricity
 703 which is probable to be dropped down to 6 kWh/kgH₂ for largescale liquefaction plants. The
 704 marine transport of hydrogen, through liquefaction or by conversion to ammonia, requires a
 705 commensurable amount of energy

706 **Table 6** Efficiencies of employing low-carbon ammonia and hydrogen as fuel in the marine
 707 transport of 10,000 km (data from [105])

Technology	Ammonia value chain		Hydrogen value chain	
	Electrolytic	Natural gas with CCUS	Electrolytic	Natural gas with CCUS
Ammonia production	85%	85%	-	-
Hydrogen production	64% (69%)	74%	64% (69%)	74%
Liquefaction	-	-	70% (82%)	70% (82%)
Power plant	44%	44%	51%	51%
Marine transport	94%	94%	94%	94%
Overall efficiency	22% (24%)	26%	21% (27%)	25% (29%)

708

709 **6.3 Ammonia Infrastructure**

710 Ammonia infrastructure refers to the several systems and components required for the production,
 711 storage, transportation, and utilization of ammonia as an energy carrier. Ammonia infrastructure
 712 is critical to comprehending the ammonia potential as a sustainable energy carrier, predominantly
 713 for a transition to a low-carbon economy. New infrastructure requirements, investment and
 714 innovation are obligatory to achieve near-zero-emission ammonia production. This includes near-
 715 zero-emission technologies deployment, commercial-scale deployment, rapid deployment of new
 716 infrastructure and investment requirements for a sustainable pathway that are described below.

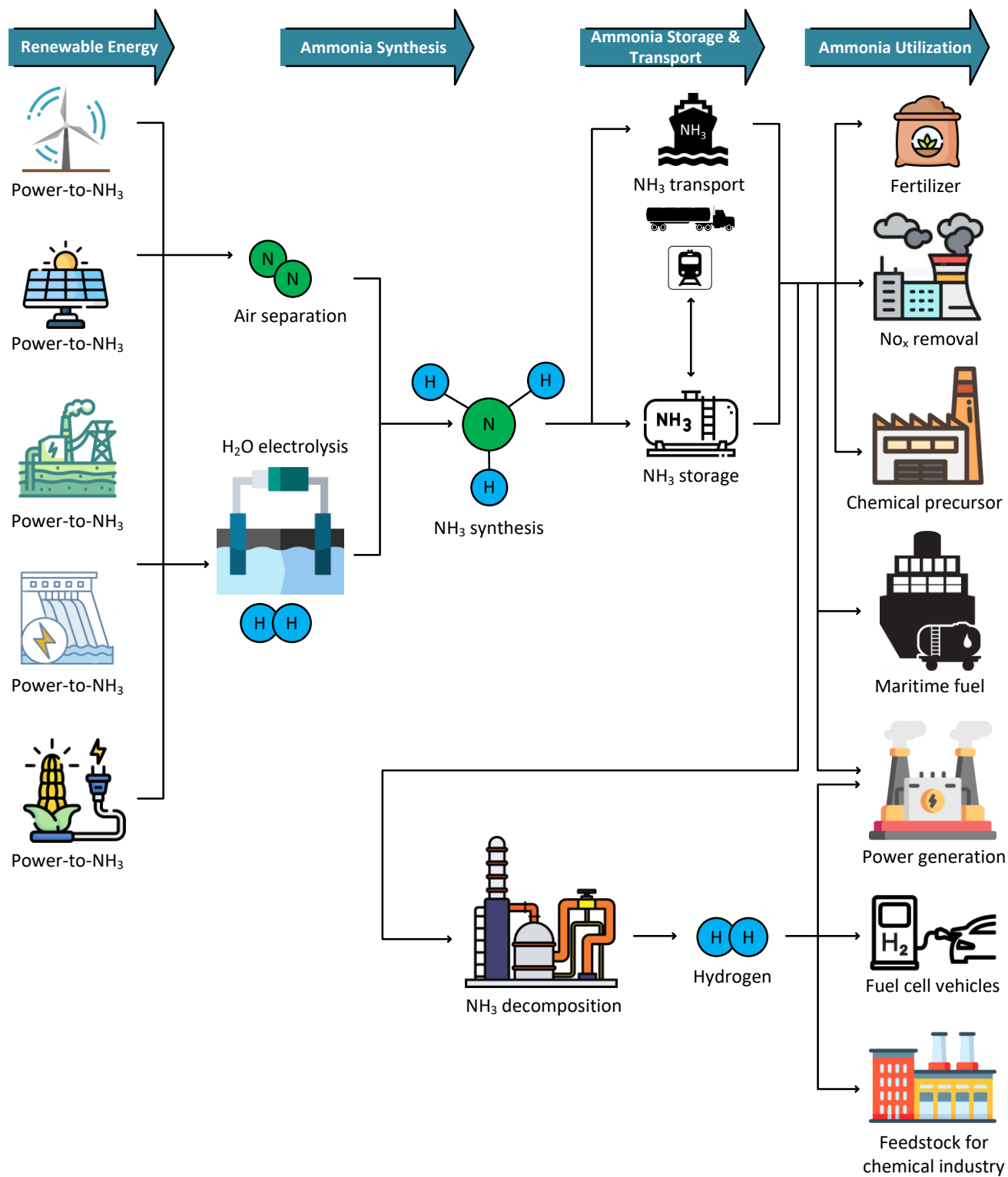
717 ***Deployment of near-zero-emission technologies.*** In sustainable development scenario (SDS)
718 presented in Ammonia Technology Roadmap [4], the near-zero-emission technologies share
719 strikes approximately 70% of the entire production by 2050 and electrolysis share in total
720 production contributes over 25%. While in NZES, near-zero-emission technologies realize almost
721 95% of the entire production by 2050 and electrolysis will contribute over 40%.

722 ***Commercial scale deployment.*** Near-zero-emission technologies need to be deployed at scale.
723 Electrolysis-based production of ammonia is now being conducted at scale in many projects
724 employing high-load-factor electricity, nevertheless, still facing challenges to deal with the
725 intermittent nature of RE sources (such as wind and solar) and much is being done to tackle this
726 challenge using hydrogen buffer storage.

727 ***Rapid deployment of new infrastructure.*** The SDS entails an electrolyzer capacity of over 110
728 GW and infrastructure to transport and store 90 Mt of CO₂ by 2050 which can be achieved by
729 installing ten 30 MW electrolyzers per month and a CO₂ capture, transport and storage facility
730 with 1 Mt CO₂ capacity every four months from today till 2050. In NZES, further emission
731 reductions entail an even quick technological deployment.

732 ***Investment requirements for sustainable pathway.*** The SDS requires \$14 billion capital
733 investment annually for the production of ammonia till 2050, 80% of which belongs to near-zero-
734 emission technology routes while NZES requires around \$15 billion capital investment annually.
735 In SDS, the investment per tonne of produced ammonia upsurges that of SPS only after 2040.

736 At present, ammonia is employed in numerous applications as described earlier in this section.
737 New ammonia decarbonization markets are proposing ammonia to be used in the marine industry
738 as maritime fuel for power generation [4,42,153,154] and also as a hydrogen carrier [155]. Fig. 13
739 displays a layout of the potential roles of green ammonia in the hydrogen economy including
740 energy input sources, ammonia synthesis, ammonia storage and transport and ammonia utilization.
741 Such an ammonia economy has the potential for four energy-related markets including (i)
742 ammonia as transportation fuel, (ii) ammonia for heating applications, (iii) ammonia for electricity
743 generation and (iv) ammonia as hydrogen feedstock.



744
745

Fig. 13 Layout of ammonia economy (modified from [22])

746 **7. Comparative assessment**

747 The choice of fuel depends on the explicit application and requirements. Ammonia offers several
748 advantages over other fuels, mainly in terms of storage and transport, nonetheless, each fuel offers
749 different advantages and disadvantages. Some of the key benefits and opportunities associated
750 with ammonia production (possible integration and production using RE, carbon capture and
751 utilization, circular economy, sustainable agriculture, energy carrier), ammonia storage
752 (alternative storage methods, technological advancements and ammonia for energy storage) and
753 ammonia utilization (decarbonization, RE integration, energy storage, innovation and sustainable
754 agriculture). Also, the challenges of ammonia production (high energy consumption, safety
755 concerns and cost), ammonia storage (toxicity and safety concerns, compatibility with materials
756 and energy requirements) and ammonia utilization (infrastructure, technological development,
757 safety concerns and public perception).

758 Even though hydrogen is often considered a promising energy carrier, ammonia offers numerous
759 advantages over hydrogen in certain applications as listed below.

760 **Safety:** Ammonia is less flammable as compared with hydrogen. Moreover, ammonia can be
761 stored and transported at lower pressures as compared with pressures required for hydrogen storage
762 which also condenses the associated safety risks.

763 **Toxicity:** Ammonia is a toxic and hazardous substance unlike hydrogen and entails vigilant
764 handling, storage, and transportation to avoid accidents and exposure to humans and the
765 environment.

766 **Infrastructure:** Ammonia has been used in fertilizer for decades and comes with existing storage
767 facilities and a supply chain with shows that ammonia production, storing, and distribution
768 infrastructure is developed as compared to hydrogen.

769 **Flexibility:** Ammonia offers flexible options as can be employed as an energy carrier, fuel and
770 hydrogen storage media that can be cracked catalytically into nitrogen and hydrogen.

771 **Storage:** High energy density of ammonia as compared with hydrogen makes liquid ammonia
772 storage much easy and efficient.

773 **Low-Emissions:** Ammonia offers the potential integration with RE sources to be produced in an
774 environmentally benign way resulting in fewer emissions as compared with fossil fuels-based
775 hydrogen production methods.

776

777 **Ammonia vs. Hydrogen:** Ammonia offers more than a few advantages over hydrogen as ammonia
778 is comparatively easier to store and transport as compared with hydrogen owing to the higher
779 energy density. Ammonia also has some more advantages over hydrogen such as safety (less
780 flammable and less volatile), flexibility and infrastructure.

781 **Ammonia vs. Natural Gas:** Ammonia offers higher energy density as compared with natural gas
782 and more energy per unit volume can be stored. Ammonia can also be transported easily as
783 compared with natural gas and emits no GHG emissions upon utilization. Nevertheless, natural
784 gas can be handled easily and is thus far extensively used as a fuel, particularly in hydrogen
785 production and power generation.

786 **Ammonia vs. Methanol:** Ammonia offers higher energy density as compared with methanol and
787 more energy per unit volume can be stored. Ammonia also has a higher boiling point as compared
788 with methanol which makes ammonia storage and transport easier and ammonia emits no GHG
789 emissions upon utilization. Nevertheless, methanol is thus far broadly used as fuel and is easier to
790 handle.

791 **Ammonia vs. Electricity:** Ammonia offers quite a few benefits over electricity. Ammonia can be
792 stored for extended periods of time and can be employed as fuel for diverse applications. Ammonia
793 can also be employed as a feedstock in the chemical industry. Nevertheless, electricity is more
794 efficient as compared with ammonia concerning energy conversion, and it is thus far widely used
795 in diverse applications. transportation and power generation.

796 **8. Challenges and opportunities**

797 This section sheds some light on the challenges and opportunities associated with ammonia
798 synthesis processes and techniques with the potential to produce green ammonia. Furthermore,
799 challenges and opportunities in the ammonia storage and ammonia utilization methods and
800 techniques are described herein.

801 **8.1. Challenges and opportunities in ammonia production**

- 802 • Electrolysis Haber-Bosch process
- 803 ○ *Challenges:* Lack of catalysts with satisfactory performance, low NH₃
- 804 concentration, NH₃ separation technologies, high energy cost, heat management
- 805 ○ *Opportunities:* Clean and decarbonized process, low operation temperature and
- 806 pressure, flexible scale
- 807 • Electro-catalytic process
- 808 ○ *Challenges:* Low activities and selectivities, reliable method for determination
- 809 and quantification of NH₃
- 810 ○ *Opportunities:* Clean and decarbonized process, mild operating conditions
- 811 • Chemical looping process
- 812 ○ *Challenges:* Lack of efficient N carriers, high operation temperature, high energy
- 813 cost, sluggish reaction kinetics
- 814 ○ *Opportunities:* Ambient pressure, circumvention of the competitive adsorption of
- 815 N₂ and H₂/H₂O, suitable for intermittent operation
- 816 • Photo-catalytic process
- 817 ○ *Challenges:* Low activities, fast electron and hole recombination, photocatalysis
- 818 by using visible lights
- 819 ○ *Opportunities:* Clean and decarbonized process, mild operating conditions
- 820 • Plasma-assisted process
- 821 ○ *Challenges:* Lack of high activity catalysts, high energy cost and low energy-
- 822 efficiency
- 823 ○ *Opportunities:* Milder operating conditions, suitable for intermittent operation and
- 824 facile switch-on/off.

825 **8.2. Challenges and opportunities in ammonia-based energy storage**

826 Challenges

- 827 • Low reactivity as compared with hydrocarbons
- 828 • High cost
- 829 • Comparatively expensive water electrolysis process
- 830 • Corrosive-resistant equipment's requirement

- 831 • Requires suitable handling (toxic)
- 832 • Trace amounts of ammonia in hydrogen after decomposition

833 Opportunities

- 834 • High volumetric energy density of ammonia as compared with hydrogen
- 835 • Energy density comparable to fossil fuels (22.5 MJ/kg)
- 836 • Controllable green ammonia production reactions
- 837 • Easily liquefiable
- 838 • Plentiful raw materials for ammonia production
- 839 • Existing expertise from the fertilizer industry in ammonia production

840 **8.3. Challenges and opportunities in ammonia utilization**

- 841 • Ammonia decomposition
 - 842 ○ Energy utilization form: Providing carbon-free hydrogen
 - 843 ○ Challenges: Insufficiently high hydrogen production rate, high operation
 - 844 temperature for full conversion of NH_3 ($T \geq 500^\circ\text{C}$), NH_3 ship
 - 845 ○ Opportunities: Carbon-free H_2 , available commercialized catalysts, compatible
 - 846 with hydrogen fuel cells
- 847 • Electro-oxidation or electrolysis of ammonia
 - 848 ○ Energy utilization form: Providing carbon-free hydrogen
 - 849 ○ Challenges: Low energy efficiency, large over-potentials on anode materials during
 - 850 electrolysis, production of NO_x , NH_3 ship, poisoning of electrode surfaces
 - 851 ○ Opportunities: Carbon-free H_2 , mild reaction conditions, suitable for small-scale
 - 852 applications
- 853 • Direct ammonia fuel cell
 - 854 ○ Energy utilization form: Providing electricity
 - 855 ○ Challenges: Large over-potentials on anode materials during electrolysis,
 - 856 production of NO_x , NH_3 ship, high operation temperature
 - 857 ○ Opportunities: Direct use of ammonia, reduction of the loss of energy efficiency by
 - 858 cracking ammonia
- 859 • Catalytic ammonia combustion

- 860 ○ Energy utilization form: Providing power (heat energy)
- 861 ○ Challenges: High-content NH_3 or pure ammonia combustion, insufficient
- 862 combustion efficiency at low temperatures, production of NO_x , NH_3 ship
- 863 ○ Opportunities: High octane number of NH_3 , direct use of ammonia, established
- 864 technology of combustion engines or turbines, suitable for hybrid fuel combustion
- 865 systems (NH_3 with another type of fuel such as diesel and H_2)

866 **8.4 Ammonia safety**

867 Ammonia is an important industrial chemical that can play a significant role in global energy
868 transition, however, misuse or accidental release can have serious negative impacts. Ammonia can
869 have toxic effects on plants, aquatic organisms, and wildlife, if released into the environment. High
870 ammonia concentrations in water bodies can cause eutrophication that depletes oxygen levels and
871 can cause harm to aquatic life. Despite the fact ammonia can be burned in internal combustion
872 engines (ICEs) and used in ammonia fuel cells, these technologies are not as efficient/well-
873 developed. Ammonia combustion also produces nitrogen oxides (NO_x), potent pollutants that
874 possess health effects, environmental effects, ozone formation and climate change and should be
875 captured or reused in ammonia synthesis to mitigate these challenges. Moreover, ammonia can
876 form fine particulate matter, when released into the air, which is harmful to air quality. Even
877 though NH_3 possesses potential to great many applications and can also be used as H_2 storage
878 medium to ease storage and transportation, some safety challenges need to be taken care of owing
879 to the hazardous nature of ammonia. Some of the major challenges associated with handling
880 ammonia include toxicity, corrosivity and flammability which are associated with NH_3 storage and
881 transportation. Also, ammonia can exert high pressure that can rupture/leak container if not
882 properly managed, when stored as liquid, if not properly managed.

883 In order to mitigate these safety challenges associated with handling ammonia, following measures
884 need to be taken:

- 885 ● Proper ventilation need to be ensured in the areas where ammonia is stored and handled to
- 886 prevent the accumulation of harmful ammonia concentrations.
- 887 ● Leak detection systems need to be utilized to detect leakages at very low concentrations to
- 888 help take proper safety measures.

- 889 • Pressure relief devices need to be equipped in storage and handling systems to help relieve
890 the high pressure in ammonia storage and transport container and prevent container rupture.
- 891 • Regular inspections and maintenance of all ammonia-related equipment need to be taken
892 to help detect potential issues such as signs of wear, damage, or corrosion.
- 893 • Ammonia scrubbing systems need to be equipped to neutralize the ammonia in the case of
894 leakage and to reduce the risk of exposure. Such systems use an acidic solution that reacts
895 with the NH₃ to produce a non-hazardous product.
- 896 • Proper design and installation need to be ensured that all systems involved in the ammonia
897 handling, storage and use are designed and installed to meet applicable safety standards
898 and regulations.

899 **9. Towards sustainable ammonia production**

900 Pathway towards more sustainable ammonia production can include encouraging green ammonia
901 production technologies, encouraging near-zero-emission technologies progress, desirable future
902 outline pathways for the ammonia industry, using ammonia efficiently and improving the
903 performance of existing equipments that are described herein.

904 *Encouraging green ammonia production technologies.* Emerging green ammonia production
905 methods are being explored and deployed to produce green ammonia using environmentally
906 benign routes and employing RE sources (wind, solar, geothermal, hydro, OTEC and biomass).
907 Greener routes will be comparatively expensive encompassing the air separation and hydrogen
908 buffer storage cost to meet the intermittency challenges (wind/solar). Many projects are under-
909 development and some are already functional and producing green ammonia and can help towards
910 achieving a net-zero future.

911 *Encouraging near-zero-emission technologies progress.* These near-zero-emission technologies
912 are emerging and do not only include electrolysis but also fossil-based routes and methane
913 pyrolysis with CCS. These pathways are characteristically 10-100% further expensive as
914 compared with conventional routes but in the long run, these cost numbers will drop down and
915 help significantly in sustainable development.

916 *Desirable future outline pathways for ammonia industry.* In Sustainable Development Scenario,
917 with the assumption of intensive policy efforts and expedited new energy technologies innovation

918 timelines, direct CO₂ emissions are expected to fall by more than 70% by 2050 relatively and 2050
919 Net-Zero Emissions Scenario [4] offers a trajectory to reduce emissions by 95% by mid-century
920 and the difference between scenarios is the difference in magnitude, not of direction.

921 *Using ammonia efficiently.* Utilizing ammonia proficiently can reduce the growth in demand
922 without negotiating the end-user services and it can also ease the technology deployment burden.
923 Slower production growth is the result of approaches such as improving nitrogen fertilizer and
924 ammonia production efficiency and augmented recycling and re-use of ammonia-derived goods.
925 By 2050, NZES and SDS scenarios show comparatively 10% lower ammonia production by 2050.

926 *Improving performance of existing equipments.* Technological enhancement in the existing
927 equipments is imperative, nonetheless alone is not enough to achieve the required emission
928 savings. The global average ammonia production energy intensity today is about 41 GJ/t and the
929 best available technology (BAT) adoption combined with a structural shift in ammonia production
930 and operational improvements can yield around a 25% reduction in average ammonia production
931 energy intensity by 2050.

932 **9.1. Enabling more sustainable ammonia production**

933 Enabling more sustainable ammonia production includes the industry being well-informed about
934 change, the central role of government, stakeholders' critical roleplay and vitally important time
935 and discussing how these can be enabled and play their role.

936 *Industry is well-informed for change.* Governments and other stakeholders already starting acting
937 to reduce ammonia industry emissions. Some governments are funding innovation by
938 implementing carbon pricing regimes, whereas, producers have defined and set targets for
939 emission reduction and are taking on RD&D projects.

940 *Central role of Government.* Governments should establish an ambitious emissions reduction
941 supportive policy environment by forming transition plans in cooperation with mobilizing
942 investment mechanisms. The targeted policy can also help address present emissions-intensive
943 assets, generate a near-zero-emission product market, fast-track RD&D and incentivize end-use
944 efficiency. Governments need to ensure the primed enabling conditions, including low-emission
945 product market, hydrogen and ammonia infrastructure and CCS.

946 ***Stakeholders' critical roleplay.*** It will be obligatory for ammonia producers to establish transition
947 strategies, fast-track RD&D and engage in infrastructure development supporting initiatives.
948 Farmers should prioritize superlative management practices for further effective fertilizer use.
949 Investors and financial institutions should implement sustainable investment structures to lead
950 finance in the direction of emissions reduction prospects. Researchers and organizations can
951 support developing schemes, continue early-stage technological research and galvanize key
952 technological support.

953 ***Vitally important time.*** The current decade is critical to enact long-term success in both 2050 SDS
954 and NZES. Vibrant near-term activities take in the launch and implementation of supportive and
955 robust policy mechanisms, act quickly on energy use and efficiency enhancement, originate
956 supporting infrastructure, and accelerate RD&D.

957 **10. Conclusions and future recommendations**

958 Ammonia is anticipated to become future zero-carbon fuel for transportation sector, marine
959 industry. aircrafts and other engines, energy storage and can replace oil/gas as fuel for industrial
960 boilers. This review provides an in-detail study on renewable ammonia including the methods of
961 green ammonia production, ammonia utilization, storage and transport along with challenges and
962 opportunities, new infrastructure requirements and actions that need to be taken toward more
963 sustainable ammonia production.

964 Renewable ammonia can help decarbonize the standing ammonia markets and displace fossil fuels
965 from new energy markets. It is also expected to play a substantial role in the energy sector, and the
966 production and utilization of electro-fuels can help stabilize the high-renewable grid. Greening the
967 industrial sector, particularly the fertilizer and chemical industries, ought to be the primary target
968 application, specifically for retrofits of standing ammonia plants. Ammonia also offers potential
969 to be used in the stationary power sector as renewable fuel with long-term purchase commitments
970 and will be adopted as technology gets mature and significant improvement and cost reduction is
971 still possible in electrochemical technologies.

972 The R&D should focus more on the advanced techniques for sustainable ammonia production
973 including electrochemical synthesis, renewable energy-powered Haber-Bosch process,
974 photoelectrochemical synthesis, bioelectrochemical synthesis and plasma-assisted ammonia
975 synthesis. Also, technological advancements and suitable measures are needed to address the

976 challenges associated with ammonia safety and toxicity to help ammonia storage and
977 transportation. In the long term, renewable ammonia is expected to turn out to be the key
978 commodity to transport RE among continents. Encouraging green ammonia production
979 technologies, encouraging near-zero-emission technologies progress, using ammonia efficiently,
980 and improving performance of existing equipments are the key factors that can help achieving
981 sustainable ammonia production. The ammonia market as fuel for stationary power and maritime
982 sector is expected to become bigger than the existing ammonia combined markets by 2050.

983 Sustainable, strong and stable policies will be essential to disseminating long-term and capital-
984 intensive renewable technologies. In an integrated ammonia-urea plant, therefore, fossil-based
985 ammonia cannot simply be substituted with renewable ammonia, because new sources of CO₂
986 would be required. A biomass-based green ammonia pathway will produce more than the required
987 CO₂, creating the opportunity to combine CCS with urea production. This will also open a carbon-
988 negative urea production pathway through a scalable route for bioenergy with carbon capture and
989 storage (BECCS). Further RD&D and cost reductions are deemed obligatory in the emerging
990 sustainable ammonia production techniques and to address ammonia safety/toxicity challenges.
991 Novel catalysts need to be explored to achieve ammonia synthesis at milder conditions. Some other
992 key takeaways and future recommendations are increasing CO₂ emission prices to help focus on
993 the deployment of renewable ammonia technologies, supporting the infrastructure and supply
994 chains development of entire, investments in electrolyzer manufacturing, retrofitting technology
995 in the direction of renewable ammonia production, re-assess the ammonia role in hydrogen
996 strategies and support demand-side fossil fuels phase-out.

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1000 **Nomenclature**

1001	BECCS	bioenergy with carbon capture and storage
1002	CAPEX	capital expenditure
1003	CCU	carbon capture and utilization
1004	CCUS	carbon capture, utilization, and storage
1005	CDR	carbon dioxide removal
1006	GHG	greenhouse gas

1007	ICEs	internal combustion engines
1008	IMO	International Maritime Organization
1009	LCOE	levelized cost of electricity
1010	LH ₂	liquid hydrogen (LH ₂)
1011	LPG	liquefied petroleum gas
1012	OPEX	operational expenditure
1013	OTEC	Ocean thermal energy conversion
1014	PSA	pressure swing adsorption
1015	PV	photovoltaics
1016	RD&D	development and demonstration
1017	RE	renewable energy
1018	SDS	sustainable development scenario
1019	SMR	steam methane reforming
1020		

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