CHAPTER 8

Techno-Economic Aspects of Production, Storage and Distribution of Ammonia

R.M. NAYAK-LUKE • C. FORBES • Z. CESARO • R. BAÑARES-ALCÁNTARA • K.H.R. ROUWENHORST

INTRODUCTION

This chapter mirrors the structure of the technical overview of production, storage and distribution in previous chapters. It aims to outline the key components to consider when performing a techno-economic analysis of green ammonia production, storage and/or distribution, present the existing cost estimates and explain the applicable methodologies.

TECHNO-ECONOMICS OF GREEN AMMONIA PRODUCTION

This section focuses on the electrolytic production of ammonia. The rationale for this is due to its higher technology readiness level (TRL) enabling large-scale production, and the significantly more accurate cost estimates available for this technology. Biomass-based production has not been focused on because it is likely more expensive [1], but the key components and methodology outlined in this section are highly transferable. Other nonconventional technologies of ammonia production, including electrochemical and photochemical synthesis, are not covered in this chapter due to their comparably low TRL level.

Key Components to Consider

Performing a robust and reliable techno-economic analysis of green ammonia production requires the definition of the problem and the decision on which assumptions have to be made. Comparison of previous investigations must be done with caution, particularly being aware of any discrepancies in the defined problem and assumptions when making direct comparisons of results. This subsection provides an overview of some of the key components to consider and how they impact the results of the techno-economic assessment of the production process design and its operation.

Use of ammonia

One of the most important considerations is the purpose of the ammonia production. In other words, is the ammonia product from the production plant being used as a commodity, for energy storage, as a fuel, or a combination of these? This can have an impact on the plant design, operation and cost of the production process. The definition of the product's use determines if there is a specified demand and, if so, its profile with respect to time. Ammonia's use for energy storage is the most impactful of these. In these scenarios, relatively inflexible demand profiles for ammonia-to-power may have to be accommodated. The other important aspect of considering the use of the ammonia product is the objective function that is being considered. At its simplest, this could be the levelized cost of ammonia (LCOA) or the levelized cost of energy (LCOE). However, if multiple revenue streams (i.e. uses) are considered, the net present value or internal rate of return may be more appropriate. The growing interest about ammonia's potential as an energy vector has led to a greater proportion of investigations considering more than one use.

Grid connection and VRE sources

The grid connection and the available variable renewable energy (VRE) sources are highly influential on the plant design, operation and cost of production. The reason for this is that grid connection, and/or

Techno-Economic Challenges of Green Ammonia as an Energy Vector. https://doi.org/10.1016/B978-0-12-820560-0.00008-4

the optimal selection of VRE sources, can mitigate the flexibility required in the plant operation due to the variability of renewable energy sources. This thereby reduces the oversizing of production components and storage as well as increases each components' load factor (i.e. requiring less capital and using it more effectively). With a grid connection, purchasing energy when required is commonly more economical than implementing other methods of plant flexibility.

The grid connection of the production process can be considered either grid dependent, semi-islanded or islanded (examples shown in Table 8.2). Each method of grid connection has its own considerations. Grid dependent systems are solely reliant on energy provided from the grid. The significant advantage of such a connection is the availability of dispatchable power to the production process (up to its rated power) which can significantly reduce the flexibility requirement of the production process. However, this does require consideration of any time-of-use restrictions as well as the dynamic pricing of electricity. Islanded systems have no grid connection and have to manage the variability of the VRE sources independently. In studies to date, this requirement for flexibility has been managed through VRE curtailment, storage of feedstock (buffering), and energy storage. Semi-islanded systems are dependent on VRE sources, but also have a grid connection. This connection is often power or energy limited. Analysis of these systems requires management of all the considerations previously described for grid dependent and islanded systems, in addition to the potential sale of VRE back to the grid. When applicable, the integration of a non-variable renewable energy source, such as hydroelectric, can be highly effective as a dispatchable energy source (similar to a grid connection) to manage flexibility requirements [2].

The mix of VRE sources considered is important in the case of semi-islanded or islanded systems. The magnitude of each VRE source is commonly characterized by their capacity factor or full load hour (FLH) equivalent. This, as shown by Ref. [3] when considering independent green hydrogen production, can have a significant impact on key cost components. Taking into account the power profiles, however, is also important [4]. The consideration of multiple VRE sources, even those with higher LCOE, can be highly beneficial due to anti-correlation in mitigating the production process flexibility requirement, thereby reducing the requirement to purchase energy from the grid (if available) or other costly methods of flexibility.

A final important consideration, particularly when designing grid-connected systems, is the sustainability of the production process. This is essential in the context of the environmental imperative for net-zero greenhouse gas emissions and the existing demand for ammonia and its predicted growth. Consider an extreme case for illustrative purposes: an ammonia production process operating on electrical power generated solely from either natural gas or coal-based sources is a less efficient, likely more expensive, and less sustainable method of production than direct production by conventional fossil-fuel-based methods (using steam methane reforming (SMR) or coal gasification). [5] is a practical example where in a semi-islanded electrolytic production process would emit 478 kg CO_2/t NH_3 compared with 2,322 kg CO_2/t NH_3 for conventional production.

Location

Beyond the limitations of the available power supply discussed previously (i.e. if the production is islanded or semi-islanded), the location of the production process has a significant impact on the design and the cost of production. The main reason for this is the variation of the VRE resources, capital and operating costs. Water availability has, justifiably because of the locations considered, been assumed as existing in studies to date. However, water availability should be considered in greater detail as other locations with favorable VRE resources are studied. The impact of the location (with comparable grid connection) in studies to date has been largely dependent on the VRE capacity factor [6], anti-correlation of the VRE profiles (when considering multiple VRE sources) [7], correlation with the optimal demand profile and the VRE cost (LCOE).

Few investigations have directly considered the impact of location within a single study ([4,8−11]). However, these have noticed the notable impact that it can have (e.g. Table 8.1). Whilst the range of locations considered across different studies (Table 8.2) do show a range of plant designs, scheduling and costs, their results should be compared with caution because of their differing objective function and assumptions.

Predictability

The uncertainty of VRE sources, cost of grid energy and demand is likely to have an impact on the process design as well as the cost of production. Whilst there has been considerable work both academically and commercially on the prediction of these variables, there has been little to no research into their impact on the production of green ammonia. Even those investigations that have incorporated uncertainty, such as [6] with a receding 48-hour horizon, have not conducted a sensitivity analysis with respect to uncertainty.

TABLE 8.1
Impact of Location on the LCOA. List of Potential Green Ammonia Production Facilities With a Predicted Low Production Cost [7].

Country	Location	LCOA [USD/T]	Latitude	Longitude
Australia	Cape Grim	473	−40.782375	144.881971
Austria	Sonnblick	518	47.032049	12.858682
Denmark	List	528	55.88361	8.56014
Ireland	Malin Head	554	55.364858	−7.337961
South Africa	Upington	552	−28.439061	21.276476
Russia	Dickson island	565	73.50611	80.51895
UK	Lerwick	584	60.138772	−1.19099
India	Jodhpur	636	26.303394	73.020097
Senegal	Dakar	661	14.732273	−17.471286

Plant sizing

The size of the ammonia production process, usually either defined (by rated power or production rate) or determined by the available energy, is an important consideration due to economies of scale. Accepting that the studies considered have different objectives and assumptions (as outlined in Table 8.2), Fig. 8.1 shows that there is a strong relationship between the capacity of the plant (t/day) and its installed capital cost. The impact on the operational cost of production has been less focused on, but was directly considered by Ref. [6] for 10 locations in the United States (Minnesota, Iowa and South Dakota).

Technical and Economic Assumptions

The nonlinearity of this problem means that not only do the technical and economic assumptions impact the optimal plant design, operation and cost, but also the sensitivity of the optimal solution to these same inputs. For all types of grid connection, the production of hydrogen feedstock is a dominant cost. Therefore, the specific energy consumption of the electrolyzer (Table 8.2) and its installed capital cost are highly influential variables.

Capital Costs

The installed investment cost of an electrolysis-based Haber-Bosch plant consists of equipment for hydrogen production, nitrogen production, ammonia synthesis (including compression and separation), and ammonia storage. Additional equipment such as hydrogen storage and batteries may also be included depending on the grid connection of the scenario considered. Currently, the capital and operational costs attributable to the production of hydrogen feedstock are dominant [4,8,12,14]. However, the magnitude in previous investigations varies depending on the objective function and assumptions used (outlined in Section 8.1.1). Islanded systems, for example, may have a greater dependence on a hydrogen buffer to meet feedstock and power requirements in periods of low VRE supply [21,23].

Total estimate

Various cost-scaling relations were proposed for alkaline electrolysis-based and proton-exchange membrane (PEM) electrolysis-based Haber−Bosch processes with PSA for nitrogen purification [12,15,26]. The best initial estimate of the cost-scaling relation (shown in Fig. 8.1) including hydrogen production, nitrogen production, ammonia synthesis, and storage was proposed by Morgan et al. [5]. The cost-scaling relation is given by Eq. (8.1), where C_{Total} is the installed cost in USD and X the ammonia capacity in t_{NH3}/day. The cost-scaling relation is valid in the range of 0.1−50 MW. For comparison, a biogas-based plant with a capacity of 22.5 t_{NH3}/day has an investment cost of about 16.3 MUSD [27]. An SMR-based plant with a capacity of 1800 t_{NH3}/day has an investment cost of about 225 MUSD [13].

$$C_{Total} = 3.73 \times 10^6 \times X^{0.6} \tag{8.1}$$

TABLE 8.2
Comparison of Previous Investigations Into Electrolytic Green Ammonia Production Arranged by Their Date of Publication.

	PROBLEM DEFINITION AND ASSUMPTIONS							RESULT
Author and Reference	**Ammonia Use**	**Grid Connection**	**VRE Sources**	**Location**	**Plant Size [T NH_3/day]**	**Electrolyzer-Specific Energy Consumption**	**Discount Rate**	**LCOA[a] [USD/t]**
Tunå et al. [19]	Commodity	Grid dependent	General (specifies cost)	Not specified	18.5 5.6	Constant (4.25 kWh/Nm^3)	5% −12%[b]	1015−2328 1078−2392
Beerbühl et al. [23]	Commodity	Grid dependent	N.A.	Germany	Not specified	Nonlinear (3.54 −4.40 kWh/Nm^3)	Not specified	588
Bañares-Alcántara et al. [14]	Commodity or energy storage	Islanded	Wind	Victoria, Australia	48	Constant (47 −64.5 kWh/kg)	8%	655
ISPT (Goeree-Overflakkee: Case 2) [20]	Commodity	Semi-islanded	Wind	Middelharnis, Netherlands	109.6 (40MW_e)	Constant (PEM = 53 kWh/kg)	7%	524−857 (2023)[c] 429−926 (2030)[c]
Wang et al. [24]	Energy storage	Grid dependent	N.A.	Germany	100MW_e	RSOFC: Not specified	7.49%	709−1450[d]
Morgan et al. [5]	Commodity	Semi-islanded	Wind (370MW_e)	Gulf of Maine, USA	300	Constant (4.8 kWh/Nm^3)	7%	1224 (580 minimum)
Sánchez et al. [25]	Commodity	Islanded	Wind and solar PV	South of Europe	300	Constant (53.15 kWh/kg)	Not specified	1528−1562
Ikäheimo et al. [2]	Commodity	Semi-islanded	Wind, solar PV and hydroelectric	Northern Europe	Not specified	Piecewise (41 −47 kWh/kg)	7%	488−597

Nayak-Luke et al. [21]	Commodity	Islanded	Wind and solar PV	Lerwick, Scotland	228 (202MW$_e$)	Constant (53.4 kWh/kg)	0%	736 (2025/ 2030)
Eichhammer et al. [22]	Commodity	Islanded	Wind and solar PV (specifies FLH)	Morocco	77.55 (802 −1426 724−1287 MW$_e$)	Constant (45.4, 42.0 and 41.0 kWh/kg)	2%−6%[b]	765−1237 (2017) 471−758 (2030) 324−558 (2050)
Armijo et al. [8]	Commodity	Semi-islanded	Wind and solar PV	Chile and Argentina	95.9 (87.8 MW$_e$)	Constant (48.0 kWh/kg)	7% 10%	462−571
Palys et al. [9]	Energy storage	Islanded	Wind and solar PV	America (15 locations)	0.30 −2.33[e]	Constant (45 and 50 kWh/kg PEM and alkaline)	10%	391−644[f]
Allman et al. [10]	Commodity and energy storage	Semi-islanded	Wind	America (10 locations)	0.1812	Constant (60.0 kWh/kg)	8.3%	Not specified
Nayak-Luke et al. [4]	Commodity	Islanded	Wind and solar PV	534 locations in 70 countries	329−623 (2020) 141−600 (2030)	Constant (53.4 kWh/kg)	7.14%	473−2464 (2020) 310−1687 (2030)

[a] LCOA has been converted from other currencies (when appropriate) and rounded to the nearest United States Dollar using the following exchange rates: 100,000 USD = 0.883,702 EUR = 0.799,082 GBP (XE.com, 2020).
[b] Stated as the ‘interest rate’.
[c] Range due to low/high fuel costs, standard/high VRE costs and use different hydrogen production processes (PEM, battolyser and SOFC).
[d] Back calculated from the 0.23−0.47 USD/kWh estimates and η_LHV = 60%. Unlike all other studies, these LCOA estimates include the cost of ammonia to power.
[e] Results for the hybrid hydrogen and ammonia energy storage systems. The ammonia-only energy storage system design was not specified.
[f] Back calculated from the 0.17−0.28 USD/kWh estimates and ICE genset energy production of 2.3 kWh/kgNH_3 (despite SOFCs with 3.1 kWh/khNH_3 also being considered the plant design for ammonia only systems was not specified).
Adapted from Nayak-Luke R, Bañares-Alcántara R. Techno-economic Viability of the islanded-production of ammonia from renewable power. 2020.

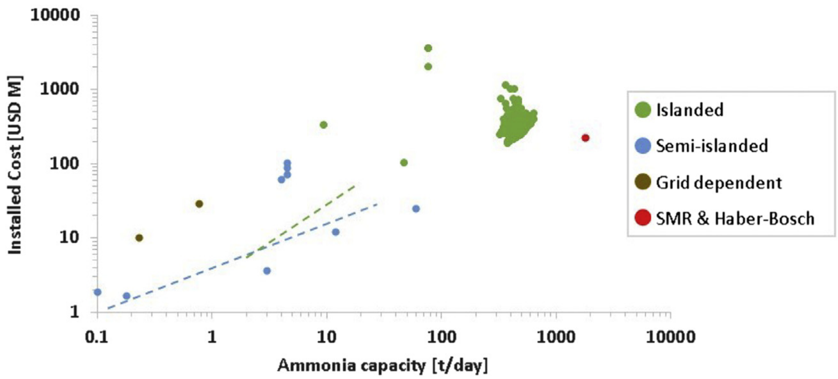

FIG. 8.1 Installed cost of electrolysis-based Haber—Bosch processes. The installed cost of Morgan et al. Sanchez et al., and Morris plant include equipment for H_2 production, N_2 production, NH_3 synthesis and storage. The quote from Proton Ventures only includes the NH_3 synthesis loop. As a point of reference, a 1800 t_{NH3}/d SMR-based ammonia plant is included as well (lump turnkey cost of plant). (Based on Refs [12-22,4,8,10].)

TABLE 8.3
Comparison of the Current and Predicted Future Installed Capital Cost of Electrolysis Methods [USD/kW] [1].

Year	Alkaline	PEM	Solid Oxide
2019	500—1000	1100—1800	2800—5600
2030	400—850	650—1150	800—2800
2050	200—700	200—900	500—1000

TABLE 8.4
Comparison of the Current and Predicted Future Cost of Alkaline Electrolysis Within and Outside China [USD/kW] [30].

Year	Outside China	China
2019	1200	200
2022	600	150
2025	400	128
2030	115	115
2050	80	80

Electrolyzer

About half to two-thirds of the capital investment is required for the electrolyzer [12,14]. The expected decrease in the capital cost of electrolysers in the next decade and beyond (Tables 8.3 and 8.4) is one of the main reasons that green ammonia is becoming more commercially competitive.

The rate of this reduction by technology however is highly contested. Some academic studies show similar reductions but at a slower rate [28,29], whereas Bloomberg New Energy Finance predicts an even greater and more rapid decrease Table 8.4. If these predictions are to be believed, this cost reduction in combination with other falling costs (such as LCOE of VRE sources) is likely to make green production highly competitive with conventional methods in the future.

The capital cost of electrolysers scale with a factor of 0.6 by capacity in the range of 0.1—50 MW [12] or, as shown in Fig. 8.2, depending on technology [1]. At larger scales (50—1000 MW), the cost-scaling increases from 0.6 to 0.85 for PEM electrolysis-based Haber—Bosch plants [31].

Ammonia synthesis

A cost-scaling relation based on installed costs of ammonia synthesis loops is given by Eq. (8.2), where C_{HB} is the installed cost in USD and X the ammonia capacity in t_{NH3}/day. The cost-scaling relation is valid in the range of 1—20 MW [12]. Other studies have simply estimated the cost linearly as a function of the rated production, such as 3395 USD/kg_{NH3} [2,20]. Consideration does need to be taken about the output pressure from the electrolyzer and the air separation unit so that the precompression of the feed stream is not duplicated.

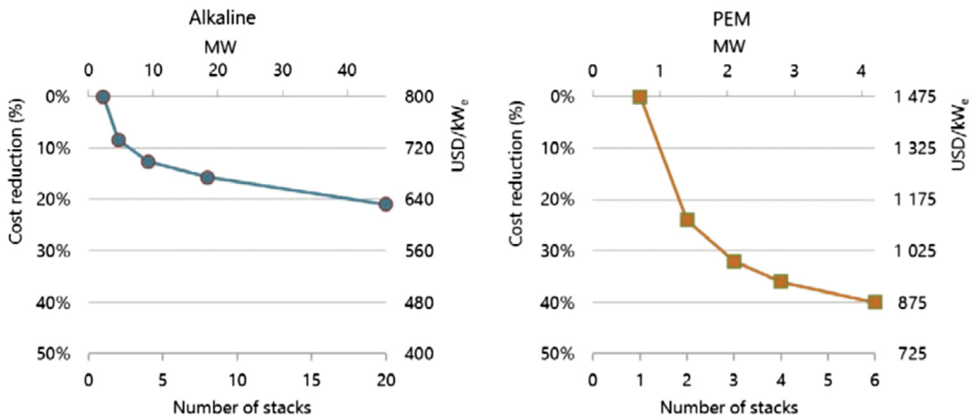

FIG. 8.2 Expected reduction in electrolyzer CAPEX from the use of multi-stack systems [1]. Based on a single stack of 2 MW for alkaline electrolysis and 0.7 MW for PEM electrolysis.

$$C_{HB} = 2.26 \times 10^6 \times X^{0.6} \tag{8.2}$$

Air separation unit

The method of air separation that should be costed is dependent on the magnitude and purity of the nitrogen required. With cryogenic production, the oxygen side product from both this process and electrolysis can also be sold without the requirement for additional capital [24] (Table 8.5).

Hydrogen storage

The storage of hydrogen is currently a topic of significant interest. Commercially, at the scale required for green ammonia production, there are two main pressurized methods: above ground tanks and subsurface. The first of these is significantly more expensive due to the materials required to avoid corrosion at the temperature and pressure of operation. The cost for these vessels varies from 460 USD/kg$_{H2}$ (700 bar) [34], 470 USD/kg$_{H2}$ (172 bar) [35] and 500 USD/kg$_{H2}$ [36] to 670 USD/kg$_{H2}$ [37], 1070 USD/kg$_{H2}$ [38] and 1400 USD/kg$_{H2}$ (875 bar) [35]. Whereas, subsurface storage in salt caverns, depleted oil/gas reservoirs and aquifers has been estimated as low as 0.6 USD/kWh [36].

TABLE 8.5
Comparison or the Current Cost of Air Separation Methods [EUR/tpd NH_3] [14,15,25,32,33].

Cryogenic	Pressure Swing Adsorption	Membrane
<8	4–25	25–45

Operational Costs

The operating costs of an electrolysis-based Haber–Bosch process can be divided into the electricity costs and the owner's costs. About 75%–95% of the electricity is required for the electrolyzer in a large-scale electrolysis-based Haber–Bosch process [4,5,39–41]. This leads to the efficiency of the electrolyzer and the LCOE to be highly significant in the final LCOA. The electricity consumption and cost depends on the scale and location of the plant, as shown in Fig. 8.1. However, the LCOE of VRE sources has notably decreased in recent years and is predicted to continue [42]. Most studies to date have assumed the operation and maintenance of each process (e.g. electrolyzer) as a fixed fraction between 2% and 5% of capital expenditure per year, for example 1.5% of CAPEX in Ref. [1].

Hydrogen production is the main cost contributor for ammonia synthesis. Depending on the location, various alternatives can be considered. Brown hydrogen produced from SMR costs 956–1794 USD/t (excluding carbon capture and storage (CCS), costs increase to 1477–2427 USD/t with CCS) [1]. On the other hand, the cost of electrolysis-based, renewable hydrogen ranges from below 1630 USD/t to above 4079 USD/t, depending on the cumulative solar and wind load hours at a given location [1]. Electrified SMR may be of interest when the electricity cost is below 17–28 USD/MWh, depending on the cost of natural gas at a given location. As compared to electrolysis, a benefit of electrified SMR reforming is the compatibility with existing steam methane reforming plants for hydrogen production and the lower capital investment.

Biomass-based ammonia with thermochemical processing costs 430−2122 USD/t, depending on the scale of application, the source of the biomass and the location [11,43−45]. The cost of ammonia produced from municipal waste is as high as 2416 USD/t [46].

TECHNO-ECONOMICS OF AMMONIA STORAGE

One of the reasons that ammonia is gaining significant traction as a green fuel is that its boiling point is much closer to standard conditions than that of hydrogen. Furthermore, it is much more advantageous to store and transport ammonia in its liquid phase because of its higher energy density compared to its gaseous phase [47].

As outlined in Chapter 5, liquid ammonia storage is mature across the world using mild pressure, refrigeration, or a combination of both.

Small Scale Storage

The preferred method to store ammonia at a small scale is using pressurized storage cylinders (bullets) at 10 bar and standard temperature 20°C. The pressure cylinders have a maximum capacity of 270 tonnes [48], are normally made of carbon steel, and require one tonne of steel per 2.8 tonnes of stored ammonia [49]. This is a very large amount of steel when compared to refrigerated tanks, however, the advantage is that once ammonia has been pressurized no additional energy is required to keep it in a liquid phase, so operating costs are minimal. In the following sections of this chapter, it is assumed that pressure cylinders are used on heavy goods vehicles and railway carriages during transportation, and for warm input to a refrigerated storage tank, allowing for greater filling rates.

Small pressurized tanks used in agricultural settings, that is nurse tanks, have an installed CAPEX of around 3 USD/kg NH3 [50].

Large-Scale Storage

Large-scale liquid ammonia storage is achieved using refrigerated tanks. In this method, ammonia is cooled to −33°C at standard atmospheric pressure, and storage tanks have a wide capacity range from 4550 to 50,000 tonnes [48]. A typical tank is made of carbon steel and requires 1 tonne of steel per 45 tonnes of stored ammonia − a large decrease in the materials of construction compared to pressure vessels. The lower capital expenditure of refrigerated tanks, when compared to pressured cylinders, is why they are preferred for large-scale storage.

There are two types of tank construction: single and double walled. Single-walled tanks are built with insulation on their exterior; double-walled tanks have insulation filling the gap between the two walls. The capital expenditure for double-walled tanks is greater than for single-walled tanks, but maintenance and operating costs are lower. Double-walled tanks also have the added safety benefit of two containment layers in case a crack develops.

Various estimates for the CAPEX of installed refrigerated storage have been reported in the literature ranging from 0.56[1] to 1.06[2] USD/kg NH_3 (all USD values updated to 2019). A value of 0.81 USD/kg NH_3 is used in the rest of the chapter based on a 25,000-tonne tank with an updated cost of 26.1 MM USD,[3] and assuming a 25-year fixed annual repayment loan with an interest rate of 5% as suggested by Ref. [51]. Capital costs would also include the construction of the tank and safety bunks surrounding the tank in the case of a leakage, with the majority of the cost from the tank walls and smaller costs from the refrigeration loop consisting of a compressor, flash tank and condenser [12]. Note that capital costs for large-scale refrigerated storage outside of production and manufacturing facilities, for instance at a maritime terminal, are likely to be 50% more than at a plant [49].

As an example, the capital costs for a 25,000-tonne refrigerated storage plant were approximately 26.1 MM USD (updated to 2019 value) [47] and the annual operating costs of a large-scale ammonia storage system can be roughly estimated by Ref. [49]:

Loan interest and capital repayments	8.5% of CAPEX	2,218,500 USD
Maintenance	3.0% of CAPEX	783,000 USD
Tax and insurance	2.0% of CAPEX	522,000 USD
Utility		100,000 USD
Labor and overheads		100,000 USD
Total annual cost		3,723,500 USD

[1]Based on a cost of 15 MM USD for a 30,000-tonne tank in 2012 [64].

[2]Based on a cost of 6.47 MM USD for a 9000-tonne tank in 2010 after breaking down the system into major components and using chemical engineering plant design and costing methods from the bottom up [12].

[3]Original cost reported is 20.2 MM USD for a 25,000-tonne tank, cooling systems and construction in 2006 [47].

A net present cost per tonne of NH_3 per day can be calculated by estimating the discounted annual throughput of ammonia and annual cash flow over the lifetime of a storage tank. For the 25,000-tonne storage facility, the 25-year levelized cost of storing ammonia is 0.549 USD/t/day. This assumes an average ammonia level of 80% of its capacity, that it is operational for 340 days per year, and that the project has a discount factor of 5%.

Large-scale storage annual OPEX can also be estimated at 3% of CAPEX and an electricity consumption for refrigeration of 0.0378 kWh/kg NH_3 [52]. Boil-off is small and caused by heat transfer through the tank walls, at 0.03% [12] to 0.10% per day [52]. Ammonia is not lost in the boil-off due to the closed refrigeration loop, but rather it is used in the refrigeration cycle and added back to the tank as a cool liquid.

TECHNO-ECONOMICS OF AMMONIA DISTRIBUTION

Distribution of ammonia can encompass various transport modes: inland (including pipelines, heavy goods vehicles (HGVs), and train), and offshore (using gas carriers of different sizes). In most cases, green ammonia will need to be distributed using several modes of transport from production facility to consumption site, for example pipeline to a port, ship to another port and train to final destination.

Pipeline

Pipeline transport of liquid ammonia is a safe, low risk and, once installed, cost effective mode of transporting ammonia between locations. A major drawback is the lack of flexibility when compared to other transportation modes. Pipelines are extensively used worldwide, for example the NuStar pipeline in the United States is over 3000 km long and transports up to 2.9 million tonnes of ammonia per year, and the ammonia pipeline connecting Russia to the Black Sea is 2400 km long with a capacity of three million tonnes of ammonia per year [53].

Pipelines can transport 'warm' or 'cold' liquid ammonia: warm ammonia is transported at higher pressures, and cold at lower pressures. This is normally decided in terms of the source and end ammonia storage terminals connected by the pipeline. Ammonia pipelines have a range of maximum flow rates that are defined primarily by their internal diameter and maximum velocities of 40% the erosional velocity [47].

Capital costs for pipelines vary depending on the required flowrate, distance, temperature and elevation changes of the pipeline, and they include the cost of the pipe, booster stations and construction. Pipelines transporting ammonia are normally made from carbon steel. Costs should also factor for rural and urban sections of pipeline with a typical km of urban pipeline costing significantly more to install than in rural areas. Rural capital expenditure for a 10″ diameter ammonia pipeline using X42 steel, adjusted to 2019, is around 857,000 USD/km and urban capital expenditure is significantly more at 1,469,000 USD/km. The capital costs are assumed to be funded using a 25-year fixed annual repayment loan as in the case of storage CAPEX.

In addition, long-distance pipelines require pumping booster stations to maintain required flowrates and temperatures. The spacing of booster stations depends on the power of the pumps, flowrate of ammonia, roughness and diameter of the pipe, temperature, and changes in elevation. Bartels showed that ammonia can be piped long distances using a repeat pumping booster system with pumping stations at regular intervals of 128 km for a large pipe diameter and flowrate [47]. The CAPEX of a booster station depends on the power rating of the pump(s) used and the cost of construction. Capital expenditure for a 600 kW boosting station consisting of two pumps is approximately 1.22 MM USD adjusted to 2019, and 1 MM USD for construction of each booster station [54].

The general O&M costs of the pipeline are assumed to be 500 USD/km/year [54], and the operating cost of each booster station would be 408,000 USD/year assuming each station is operational for 8500 hours per year and an electricity cost of 0.08 USD/kWh [47].

A predicted net present lifetime cost per tonne of ammonia through a pipeline can be calculated using a similar model to storage. This is done by calculating discounted annual throughputs of ammonia and discounted yearly cashflows for the pipeline throughout its service life. This can be used to find the levelized cost of pipeline transportation for a tonne of ammonia. Tariff charges are very dependent on location, an indicative tariff in the USA is 0.05 USD/t/km reported by Ref. [55] [4] and 0.04 USD/t/km according to the Assumptions Annex of [1].[5]

Rail and Truck

Rail and truck both offer established ways to transport ammonia. Freight trains transport pressurized liquid ammonia in chemical rail tanks with capacities of up to 110 tonnes per tank; a freight train normally carries

[4] 0.08 USD/t/mile.

[5] Based on a CAPEX of 690,000 USD/GW/km, 75% utilization, 7% WACC, and a 40-year lifetime.

TABLE 8.6
Parameters Used in the Inland Transportation Calculations.

Parameter	HGV	Rail
Capacity [t trip]	36[a]	11,000[b]
Fuel Economy [t km/L]	110.9[c]	193.2[c]
Speed [km/h]	–	45
Availability [h/day]	18	12
Load Rate [t/h]	302[d]	600[d]
Staff Wage [USD/h]	23	23
Fuel Price [USD/L]	1.16	0.28
Maintenance [USD/km]	0.0976	0.0621
General [USD/day]	8.22	6.85

(a) [57]; (b) [56]; (c) [59]; (d) [49]; the rest are from [60].

between 50 and 150 tanks per journey [56]. Transporting ammonia via railway limits flexibility because it can only be used where a railway line already exists, however most medium to large seaports have well-connected rail links and pre-existing infrastructure that can be used to transport ammonia for import and export. As seen in Table 8.6, transporting ammonia by rail offers an efficient and cost-effective way of distributing large volumes of ammonia inland, offering both large capacities per journey and high fuel efficiencies per tonne-km.

Roads are a common transportation mode for liquid ammonia on land using HGVs. Compared with rail, HGVs are more expensive and polluting, but offer the most flexible method of ammonia transportation over short distances. HGVs use an ISO T50 storage pressurized cylinder with capacities limited to around 36 tonnes of ammonia per journey [57]. Therefore, they are not an efficient way to transport large volumes of ammonia for long distances, for example Ref. [58] suggests an upper bound distance of 770 km.

Typical truck and rail transport parameters can be found in Table 8.6. It should be noted that often a roundtrip cost calculation is required assuming a full tank on the first leg and empty on return, and the fuel economy in Table 8.6 takes this into account [59].

For an approximate calculation, the costs reported in Ref. [37] for rail are 0.03 and for HGV 0.21 USD/t/km.

Shipping

The locations of future green ammonia production facilities will likely be in remote locations and/or far from the end point of consumption, so there will be a requirement to transport ammonia offshore. Gas Carriers (GCs) provide a low-cost and effective method of offshore transport of ammonia. Liquefied ammonia-carrying vessels fall into three categories: (1) fully pressurized, with independent Type 'C' tanks; (2) semi-refrigerated, with independent Type 'B' tanks; and (3) fully refrigerated, with independent Type 'A' tanks [61].

Fully pressurized vessels are used to transport ammonia short distances at pressures of up to 20 bar; due to the large pressures their tanks are very heavy, and hence they have small capacities of up to 4000 m^3. Semi-refrigerated vessels are small-sized gas carriers used in the chemical industry to transport chemicals such as butadiene, vinyl chloride monomer (VCM) and LPG; their capacity is from 1500 up to 30,000 m^3. Fully refrigerated vessels have 15,000 to 85,000 m^3 capacity and are used to transport ammonia over long distances by sea. These GCs transport ammonia at −33°C with an onboard refrigeration system, working in the same way as a land-based refrigeration storage tank [61].

Most ammonia is currently shipped long distances via two types of vessel: Medium Gas Carriers (MGCs), and Large Gas Carriers (LGCs) -both of which have independent Type 'A' tanks. MGCs are, in general, more economical (USD/tonne) over shorter distances and LGCs over longer distances. MGCs are by far the more popular vessel type currently used to transport ammonia, with more vessels in operation. Table 8.7 shows indicative parameters for MGC and LGC useful for offshore transport calculations. Table 8.7 is specific

TABLE 8.7
MGC and LGC Typical Parameters.

Gas Carrier	MGC	LGC
Capacity [t]	23,000	40,200
Hire [USD/day][a]	28,000	38,500
Fuel price [USD/t][b]	516	516
Load rate [t/hr]	1814	2730
Speed loaded [nm/hr]	15	16.14
Speed with Ballast [nm/hr]	15.5	16.14
LOA (length overall) [m]	174	200
Draft [m]	8.2	9.4
Suez Tonnage [t]	24,317	34,289

[a] Estimated values
[b] Depends on the bunker market.
Data From Poten and Partners, Personal Communication, March 13, 2020.

to two LPG tankers: Gas Ray and Denver, but they are taken as representative of MGCs and LGCs respectively.

Very Large Gas Carriers (VLGCs) are used to transport LPG and they could also transport ammonia [49], but they are not currently used for this purpose for two reasons: the lack of port infrastructure to accommodate the vessel at some ammonia trading ports, and because many current port storage tanks are not large enough to completely fill a VLGC thus creating tank ullage issues.

Transport costs for GCs depend on charter rates, distance traveled, fuel consumption, port charges, and tariffs. Charter rates and availability of GCs are linked to LPG market demand because ammonia can be transported in the same vessels as LPG. LPG markets tend to be seasonal, with high demand in winter (when it is used for heating) and lower demands in summer. Baltic gas indexes for transporting LPG can be used as an indicator for current market rates, and in turn these rates can be used as an indicator for current ammonia shipping rates. Shipping ammonia using GCs is conducted using a Time Charter Agreement between the shipowner and the charterer (the entity chartering the vessel). The hire rate per day of an average MGC was calculated to be 28,000 USD/day, and 38,500 USD/day for an LGC, which is in line with a VLGC hire rate of 48,100 USD/day [62].

Another cost factor to account for is time spent in ports at berth, which can cause port berthing costs to increase, as well as hire and fuel costs. Additionally, tariffs may apply to vessels crossing the Suez or Panama canals.

As an example, and because these data will be useful for the case study in the last section of this chapter, the total cost per tonne from Belfast Harbor to several other ports were calculated for two different quantities of ammonia to be transported and are compiled in Table 8.8. These costs include storage costs at export terminals, and a handling charge of 1.68 USD/t covering the loading/unloading of ammonia from a transport mode (apart from pipelines) [49]. Route distances between distribution and container ports were estimated using the SeaRoutes API[6] which uses historical shipping data to calculate the shortest route between two ports.

Table 8.8 shows that decreasing the flow rates results in transport costs per tonne to increase for both MGCs and LGCs. Whilst it increases slightly more for LGCs, it is never enough to make one mode more economical than the other. However, over shorter distances (from Belfast Harbor to Hamburg, Rotterdam, Antwerp or Le Havre) the MGC is more economical due to its lower hire rates and port fees, which are more significant for the LGC over these short ranges. LGCs have a lower cost per tonne over long distances as their larger hire and port costs are overcome by having a more economical fuel consumption per tonne of ammonia carried.

[6]https://developer.searoutes.com/api/v1 (last checked 12/05/2020).

TABLE 8.8
Calculated Offshore Transport Costs From Belfast Harbor, Ireland, to Other Ports [63].

USD $[T\ NH_3]^{-1}$	FLOW RATE			
From Belfast Harbor	1575 $[T\ NH_3/day]$		2100 $[T\ NH_3/day]$	
To Container Port	MGC	LGC	MGC	LGC
Shanghai	115.77	92.81	114.77	91.06
Yantian	108.89	87.55	107.89	85.80
Vung Tau	100.12	80.84	99.12	79.09
Singapore	93.74	75.96	92.74	74.21
Hamburg	12.43	13.75	11.43	12.00
Rotterdam	14.42	15.27	13.41	13.52
Antwerp	14.38	15.24	13.38	13.49
Le Havre	12.43	13.75	11.43	12.00
Malta	31.06	28.00	30.06	26.25
Jeddah	48.35	41.23	47.35	39.48
Nansha	109.27	87.84	108.27	86.09
Ningbo-Zhoushan	115.40	92.53	114.4	90.77

CASE STUDY – DISTRIBUTION REQUIREMENTS TO SUPPLY THE DEMANDS OF A FLEET OF THIRTY-SIX ULTRALARGE CONTAINER VESSELS

One predicted market for green ammonia is long-distance shipping, as green ammonia provides the most economical zero-carbon fuel alternative compared to traditional maritime carbon fuels. This case study, involving aspects of green ammonia production, storage and distribution, finds a distribution network from production sites to shipping container ports that minimizes the vessel operators' fuel costs [63].

The shipping cycle demand is for 36 Ultralarge Container Vessels (ULCV) operating along the Ocean Alliance FA3 service joining the ports of Shanghai and Rotterdam. This is representative of the total predicted number of ULCVs operating along this container service. Demands from this fleet of 36 ULCVs have been calculated using a bottom-up calculation applied to historical automatic identification system (AIS) data[7] of a journey of the 'CMA CGM Laperouse' ULCV completed as an example cycle for the fleet.

Nine potential green ammonia production facilities were considered in the network and were selected because of their predicted low cost of production [7]. These are listed in Table 8.1 and shown in Fig. 8.3. It was assumed that ammonia could be purchased ammonia from the facilities at the stated LCOA. Each facility is assumed to be capable of producing 2100 tonnes of green ammonia per day, which corresponds to a typical medium to large size Haber-Bosch ammonia plant. Ammonia can be transported in the network using five methods: inland by pipeline, rail, and/or HGVs; and offshore by MGCs and LGCs. Routes taken by the transport modes inland and offshore can also be seen in Fig. 8.3.

Each production site has been paired with a distribution port, selected following the criteria of distance to the production facility, maximum berthing LOA (vessel overall length) and draft, and the existence of pre-existing chemical liquid bulk storage. Port fees were split into fixed (pilotage, berthing and waste disposal) and variable (days berthed and security), and were retrieved from the corresponding port authorities websites. Port fees details could not be found for Dakar and Dikson ports, so the average of other port fees was used instead. Storage facilities are required at export terminals, these should be at least 25%–50% larger than the capacity of the GCs to cope with early and late arrivals. Import terminal storage was assumed to have a buffer storage of 7–20 days. A key assumption is that a container vessel stops at ports along its journey for trade reasons, but that it will only refuel in a subset of those ports. LGCs have been assumed to take the same routes as MGCs. The main difference in the model

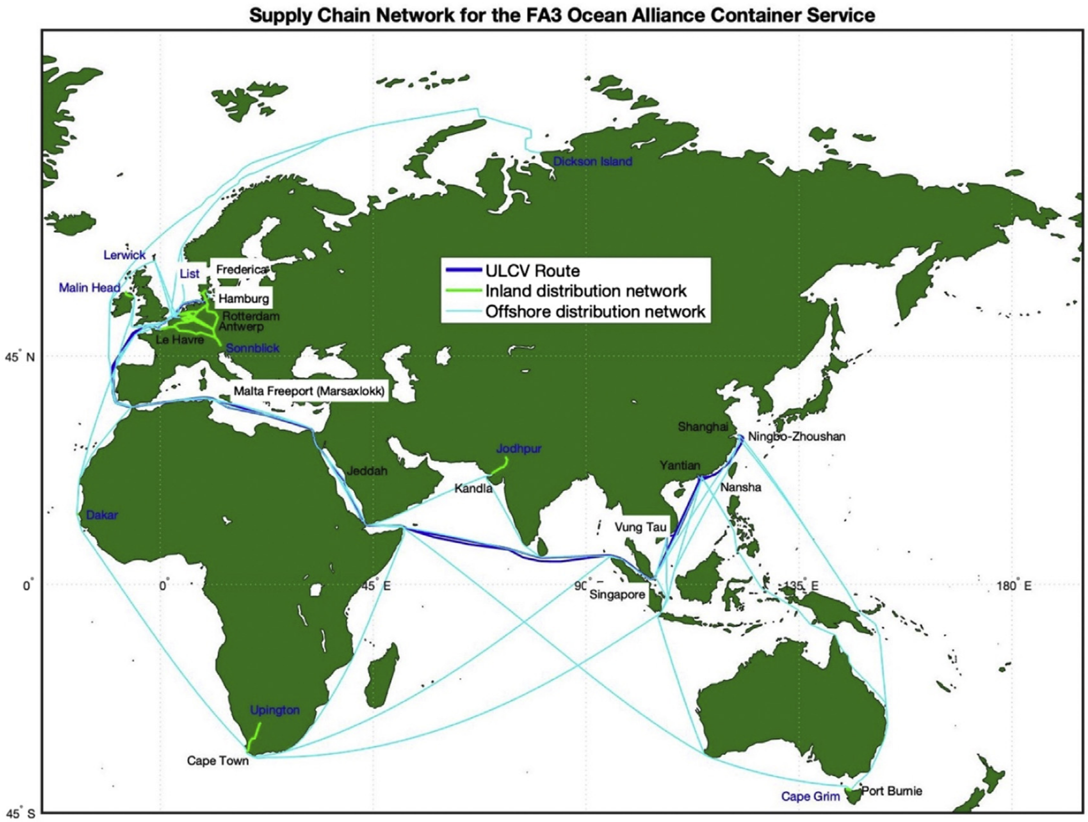

FIG. 8.3 Map of the global supply chain network for green ammonia supplying the FA3 container service.

[7] https://www.fleetmon.com (last checked 12/05/2020).

TABLE 8.9
Calculated Inland Transport Costs From Production Facility to Distribution Port [63].

USD/t		FLOW RATE [t/day]					
		1575			2100		
From	To	Pipeline	HGV	Rail	Pipeline	HGV	Rail
Cape Grim	Port Burnie	11.96	14.33	11.40	9.93	14.33	10.53
Sonnblick	Rotterdam port	83.83	–	13.24	63.83	–	12.37
List	Fredericia port	12.30	14.63	11.22	10.19	14.63	10.34
Malin Head	Belfast harbor	15.49	17.15	–	12.58	17.15	–
Upington	Port of Cape Town	60.87	–	–	46.61	–	–
Dikson	Dikson port	4.31	8.70	–	4.19	8.69	–
Lerwick	Lerwick port	4.95	8.94	–	4.67	8.94	–
Jodhpur	Kandla port	58.04	54.58	12.60	44.49	54.58	11.73
Dakar	Port of Dakar	6.66	9.55	–	5.95	9.55	–

is that, due to their larger size, LGCs cannot berth at all the distribution ports.

Pipelines between each production facility and a distribution or container port were assumed to be laid along existing roads. Therefore, the route and length of a pipeline have been calculated using the Google Directions API.[8] The routes of the pipeline are shown in Fig. 8.3. The pipelines used have been assumed to have a 10″ diameter with booster stations placed every 175 km, and a service life of 35 years, funded by a 25-year fixed repayment loan with an interest rate of 7% and an annual discount factor of 5%. For simplicity, only 25,000-tonne refrigerated storage tanks have been used at a cost of 0.549 USD/t/day.

Google Directions API was also used to estimate the distance and duration of an HGV journey, assuming that the roads in their current state can take the additional HGV traffic. Railway links have been used only where a railway line already exists, distances were found from TasRail[9] for Cape Grim to Port Burnie, Trainline Europe[10] for the European continent, and from IndiaRail[11] for Jodhpur to Kandla Port.

All other transport mode costs are assumed to be the same as in Table 8.9 for inland transport, and Table 8.8 for offshore transport, for flow rates from production facilities at 2100 tonnes per day and 75% of that capacity (1575 t/day).

Using a MILP optimization model it was found that it is most economical to supply ammonia to three container ports along the route: Singapore, Antwerp, and Malta, shown in Fig. 8.4. This allows the fleet of container vessels to complete their cycle with the lowest fuel costs. Demands from the container ports can be supplied using four production facilities in the network: Cape Grim, Australia; Sonnblick, Austria; List, Denmark; and Malin Head, Ireland.

It was also found that it would be optimal for the fleet to refuel 2100 tonnes per day of green ammonia at Singapore. This should be imported from Cape Grim, Australia requiring the use of both inland and offshore ammonia transportation methods. Inland, ammonia should be transported using a pipeline to Port Burnie; this has a levelized cost of 9.93 USD/t (Table 8.9). The pipeline can directly connect to a refrigeration tank at the distribution port (Port Burnie) saving costs associated with handling. Two refrigerated tanks are required at Port Burnie with a total capacity of 50,000 tonnes, 25% larger than the LGCs. The ammonia is then exported to Singapore once every 19.15 days (Table 8.10) costing 38.39 USD/t, requiring two LGCs.

It is also optimal for the fleet to refuel at Antwerp. The average demand is 4407 tonnes per day and therefore, three production facilities are needed to supply the ULCV's demand at Antwerp. These are Sonnblick, List, and Malin Head. Storage tanks would be required at the Malin Head, List and Sonnblick production facilities to act as buffers in case of operational problems at the

[8]https://developers.google.com/maps/documentation/directions/start (last checked 12/05/2020).
[9]https://www.tasrail.com.au/map (last checked (12/05/2020).
[10]https://www.thetrainline.com/en/train-times (last checked 12/05/2020).
[11]https://indiarailinfo.com/search/ju-jodhpur-junction-to-kand-kandla/126/0/8307 (last checked 12/05/2020).

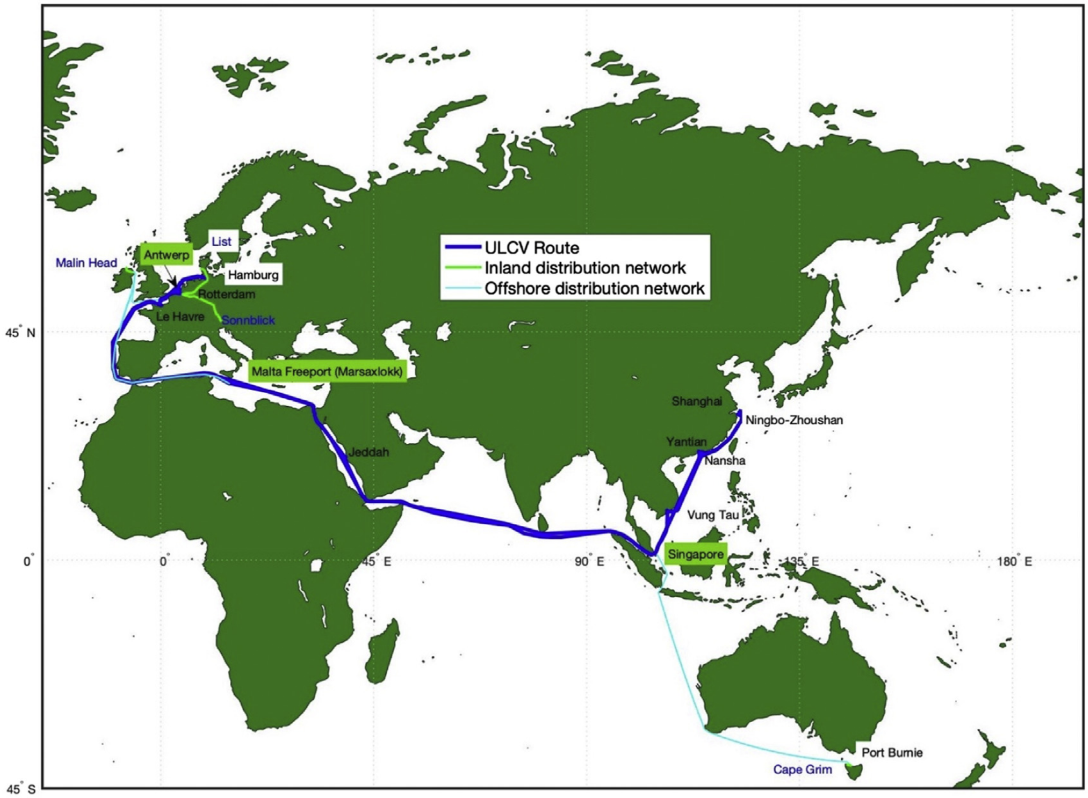

FIG. 8.4 Optimized global distribution network for green ammonia supplying the FA3 container service.

production facility or the next mode of transport. 2100 tonnes of ammonia are imported from Sonnblick which are transported directly to Antwerp once every 5.24 days (Table 8.10) using a freight train carrying liquid ammonia in 100 chemical rail tanks. This would cost 12.26 USD/t. An average of 2100 tonnes per day should also be imported from List once every 5.24 days (Table 8.10), costing 11.28 USD/t. The remaining green ammonia is the cheapest imported from Malin Head, Ireland; this is transported via pipeline to Belfast Harbor where it is stored in refrigeration tanks in the harbor. Given the relatively short distance between Belfast Harbor and Antwerp, it is cheaper to export the ammonia using an MGC rather than an LGC. This demand is very low thus ammonia shipments are required only once every 111 days (Table 8.10); exporting ammonia via LGC would cost 13.38 USD/t (Table 8.8).

Ammonia is also exported from Ireland to Malta as the latter is the next best port for the vessel to refuel at on its eastbound journey giving it sufficient fuel levels to complete its full cycle. Exporting ammonia to Malta from Belfast Harbor is more economical by LGC because of the longer distance involved and it would cost 26.25 USD/t (Table 8.8). The demand for ammonia in Malta is low, and the LGC would be required only once every 80.3 days (Table 8.10). Two 25,000 tonnes of refrigerated storage tanks at Belfast Harbor and Malta would be required at each port. A storage tank would be required at Malin Head acting as a buffer in case of operational problems at the production facility or port.

Overall, results from this model have a fleet operating cost of 8,012,925 USD per ULCV-cycle, or 580.65 USD per container-cycle; the overall green ammonia demand from the FA3 service is an average of 7008.22 tonnes per day (Table 8.10) and would save a total of 807,466 tonnes of CO_2 for a cycle completed by the fleet of 36 vessels.

TABLE 8.10
Results of the Supply Chain Requirements for the Case Study.

Production Facility - Container Port	Australia —Singapore	Austria —Antwerp	Denmark —Antwerp	Ireland —Antwerp	Ireland —Malta	Total
Demand [t/day]	2100.00	2100.00	2100.00	207.48	500.74	7008.22
Number of storage tanks	5	3	3	3	5	19
Pipeline [t/day]	2100	—	—	207.48	500.74	2808.22
Number of freight trains	—	1	1	—	—	2
Rail frequency [days]	—	5.24	5.24	—	—	—
Number of LGCs	2	—	—	—	1	3
LGC frequency [days]	19.15	—	—	—	80.30	—
Number of MGCs	—	—	—	1	—	1
MGC frequency [days]	—	—	—	110.85	—	—

REFERENCES

[1] IEA. The Future of Hydrogen: seizing today's opportunities. International Energy Agency; 2019.
[2] Ikäheimo J, Kiviluoma J, Weiss R, Holttinen H. Power-to-ammonia in future North-European 100% renewable power and heat system. Int J Hyd Energy 2018;43:17295—308.
[3] Philibert C. Renewable energy for industry: offshore wind in northern Europe. Rotterdam. 2018.
[4] Nayak-Luke R, Bañares-Alcántara R. Techno-economic viability of the islanded-production of ammonia from renewable power. 2020.
[5] Morgan E, Manwell J, McGowan J. Sustainable ammonia production from U.S. offshore wind farms: a techno-economic review. ACS Sust Chem Eng 2017;5:9554—67.
[6] Allman A, Daoutidis P. Optimal scheduling for wind-powered ammonia generation: effects of key design parameters. Chem Eng Res Des 2018;131:5—15.
[7] Nayak-Luke R. Green ammonia: AI optimised decarbonised ammonia production for conventional use and as a viable renewable energy storage solution. DPhil thesis. Department of Engineering Science, University of Oxford; 2020.
[8] Armijo J, Philibert C. Flexible production of green hydrogen and ammonia from variable solar and wind energy: case study of Chile and Argentina. Int J Hyd Energy 2020;45:1541—58.
[9] Palys M, Daoutidis P. Using hydrogen and ammonia for renewable energy storage: a geographically comprehensive techno-economic study. Comput Chem Eng 2020:106785.
[10] Allman A, Palys M, Daoutidis P. Scheduling-informed optimal design of systems with time-varying operation: a wind-powered ammonia case study. AIChE J 2019;65:e16434.
[11] Arora P, Hoadley A, Mahajani S, Ganesh A. Multiobjective optimization of biomass based ammonia production - potential and perspective in different countries. J Clean Prod 2017;148:363—74.
[12] Morgan E. Techno-economic feasibility study of ammonia plants powered by offshore wind. University of Massachussetts Amherst, Dept of Mechanical and Industrial Engineering; 2013.
[13] Appl M. Ammonia : principles and industrial practice. Wiley-VCH; 1999.
[14] Bañares-Alcántara R, Dericks III G, Fiaschetti M, Grünewald JLP, Yang A, Ye L, Zhao S. Analysis of islanded ammoniabased energy storage systems. 2015.
[15] Sánchez A, Martín M. Scale up and scale down issues of renewable ammonia plants: towards modular design. Sust Prod Consump 2018;16:176—92.
[16] Vrijenhoef J. Opportunities for small scale ammonia production. 2017.
[17] Reese M. Ammonia from wind, an update. San Franciso. 2007.
[18] Morgan E, Manwell J, McGowan J. Wind-powered ammonia fuel production for remote islands: a case study. Renew Energy 2014;72:51—61.
[19] Tunå P, Hulteberg C, Ahlgren S. Techno-economic assessment of nonfossil ammonia production. Environ Prog Sustain Energy 2014;33:1290—7.
[20] ISPT. Power to Ammonia: feasibility study for the value chains and business cases to produce CO_2-free ammonia suitable for various market applications. Institute for Sustainable Process Technology (ISPT); 2017.
[21] Nayak-Luke R, Bañares-Alcántara R, Wilkinson I. "Green" ammonia: impact of renewable energy intermittency on plant sizing and levelized cost of ammonia. Ind Eng Chem Res 2018;57:14607—16.
[22] Eichhammer W, Oberle S, Händel M, Boie I, Gnann T, Wietschel M, Lux B. Study on the opportunities of "Power-to-X" in Morocco: 10 hypotheses for discussion. Karlsruhe: Fraunhofer ISI; 2019.
[23] Beerbühl S, Fröhling M, Schultmann F. Combined scheduling and capacity planning of electricity-based ammonia

production to integrate renewable energies. Eur J Oper Res 2014;241:851—62.
[24] Wang G, Mitsos A, Marquardt W. Conceptual design of ammonia-based energy storage system: system design and time-invariant performance. AIChE J 2017:1620—37.
[25] Sánchez A, Martín M. Optimal renewable production of ammonia from water and air. J Clean Prod 2018;178: 325—42.
[26] Palys M, McCormick A, Cussler E, Daoutidis P. Modeling and optimal design of absorbent enhanced ammonia synthesis. Processes 2018;6:91.
[27] Brown T. Midwest BioEnergy - monmouth, IL,. 2020 [Online]. Available: https://ammoniaindustry.com/monmouth-il-midwest-bioenergy-2/# [Accessed 2019].
[28] Buttler A, Spliethoff H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review. Renew Sustain Energy Rev 2018;82:2440—54.
[29] Schmidt O, Gambhir A, Staffel AHI, Nelson J, Few S. Future cost and performance of water electrolysis: an expert elicitation study. Int J Hydrog. Energy 2017:30470—92.
[30] Mathis W, Thornhill J. Hydrogen's plunging price boosts role as climate solution. Bloomberg; 2019.
[31] Demirhan C, Tso W, Powell J, Pistikopoulos E. Sustainable ammonia production through process synthesis and global optimization. AIChE J 2019;65:e16498.
[32] Böcker N, Grahl M, Tota A, Häussinger P, Leitgeb P, Schmücker B. Nitrogen. In: Ullmann's encyclopedia of industrial chemistry; 2013.
[33] Hardenburger T, Ennis M. Nitrogen. In: Kirk-othmer Encyclopedia of chemical technology; 2005.
[34] Olson N. Sustainable ammonia for food and power. Rotterdam. 2018.
[35] Parks G, Boyd R, Cornish J, Remick R. Hydrogen station compression, storage, and dispensing technical status and costs: systems integration. Golden, CO: National Renewable Energy Lab.(NREL); 2014.
[36] Schoenung S. Economic analysis of large-scale hydrogen storage for renewable utility applications. 2011.
[37] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P. National hydrogen roadmap. CSIRO; 2018.
[38] Danish Energy Agency and Energinet. Technology data for energy storage. 2019 [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.pdf.
[39] NFUEL. Sustainable ammonia for food and power. Nitrogen 2018:1—10.
[40] Pfromm P. Towards sustainable agriculture: fossil-free ammonia. J Renew Sustain Energy 2017;9.
[41] Hansen J, Han P. The SOC4NH3 project in Denmark. Rotterdamm. 2019.
[42] IRENA. Renewable power generation costs in 2018. Abu Dhabi: International Renewable Energy Agency; 2018.
[43] Andersson J, Lundgren J. Techno-economic analysis of ammonia production via integrated biomass gasification. Appl Energy 2014;130:484—90.
[44] Sánchez A, Martín M, Vega P. Biomass based sustainable ammonia production: digestion vs gasification. ACS Sust Chem Eng 2019;7:9995—10007.
[45] Arora P, Hoadley A, Mahajani S, Ganesh A. Small-scale ammonia production from biomass: a techno-enviro-economic perspective. Ind Eng Chem Res 2016;55:6422—34.
[46] Paixão V, Secchi A, Melo P. Preliminary design of a municipal solid waste biorefinery for environmentally friendly NH3 production. Ind Eng Chem Res 2018;57:15437—49.
[47] Bartels J. A feasibility study of implementing an Ammonia Economy. 2008.
[48] Hale CC. 1983 Survey of refrigerated ammonia storage in the United States and Canada. Plant Oper Progr July 1984;3(3):147—59.
[49] UN Industrial Development Organization. Fertilizer manual. 3rd ed. ed. Springer; 2010.
[50] Leighty B. Energy storage with anhydrous ammonia: comparison with other energy storage. In: Annual NH3 fuel conference: ammonia — the Key to energy independence, NH3 fuel association (2008); 2008.
[51] Jawad D, Ozbay K. The discount rate in life cycle cost analysis of transportation projects. In: 85th annual Meeting of the transportation research board, Washington D.C.; 2006.
[52] Lloyd's Register (LR) and University Maritime Advisory Services (UMAS). Techno-economic assessment of zero-carbon fuels. 2020.
[53] Herben E, Laursen R, de Vries N, Valera-Medina A. Ammonia as marine fuel. In: NH3 fuel conference. Pittsburgh, PA: Maritime Panel Discussion; 2018.
[54] Leighty B. Costs of delivered energy from large-scale, diverse, stranded, renewable resources, transmitted and firmed as electricity, gaseous hydrogen, and ammonia. In: Ammonia: Key to US energy independence, Denver; 2006.
[55] Leighty B. Ammonia renewable energy fuel systems at continental scale: transmission, storage, and integration for deep decarbonization of world's largest industry at lower cost than as electricity. In: NH3 fuel association. Minneapolis, MN, USA: American Institute of Chemical Engineering; 2017.
[56] Barkan C. Introduction to North American rail transportation. In: Railroad engineering education symposium; 2014.
[57] Boergert SR, Nyquist G. Super-safe large anhydrous ammonia tanks. In: 2008 annual NH3 fuel conference, Minneapolis, MN; 2008.
[58] Song S, Demirel YK, Atlar M. Penalty of hull and propeller fouling on ship self-propulsion performance. Appl Ocean Res 2020;94.
[59] Tolliver D, Lu P, Benson D. Comparing rail fuel efficiency with truck and waterway. Transport Res Transport Environ 2013;24:69—75.
[60] Almansoori A, Shah N. Design and operation of a future hydrogen supply chain: snapshot model. Chem Eng Res Des 2006;84(6):423—38.
[61] Wärtsilä. "Wärtsilä encyclopedia of marine technology," [Online]. Available: https://www.wartsila.com/encyclopedia/term/gas-carrier-types. [Accessed 2020].

[62] BW LPG Limited. BW LPG's Q3 2019 financial results presentation to be held on 21 November 2019. Bloomberg; 2019.
[63] Forbes CWR. Zero emission vessels for shipping: optimising a green ammonia production, distribution and port bunkering network. MEng thesis. Department of Engineering Science, University of Oxford; 2020.
[64] Leighty WC, Holbrook JH. Alternatives to electricity for transmission, firming storage, and supply integration for diverse, stranded, renewable energy resources: gaseous hydrogen and anhydrous ammonia fuels via underground pipelines. Energy Proc 2012;29:332—46.