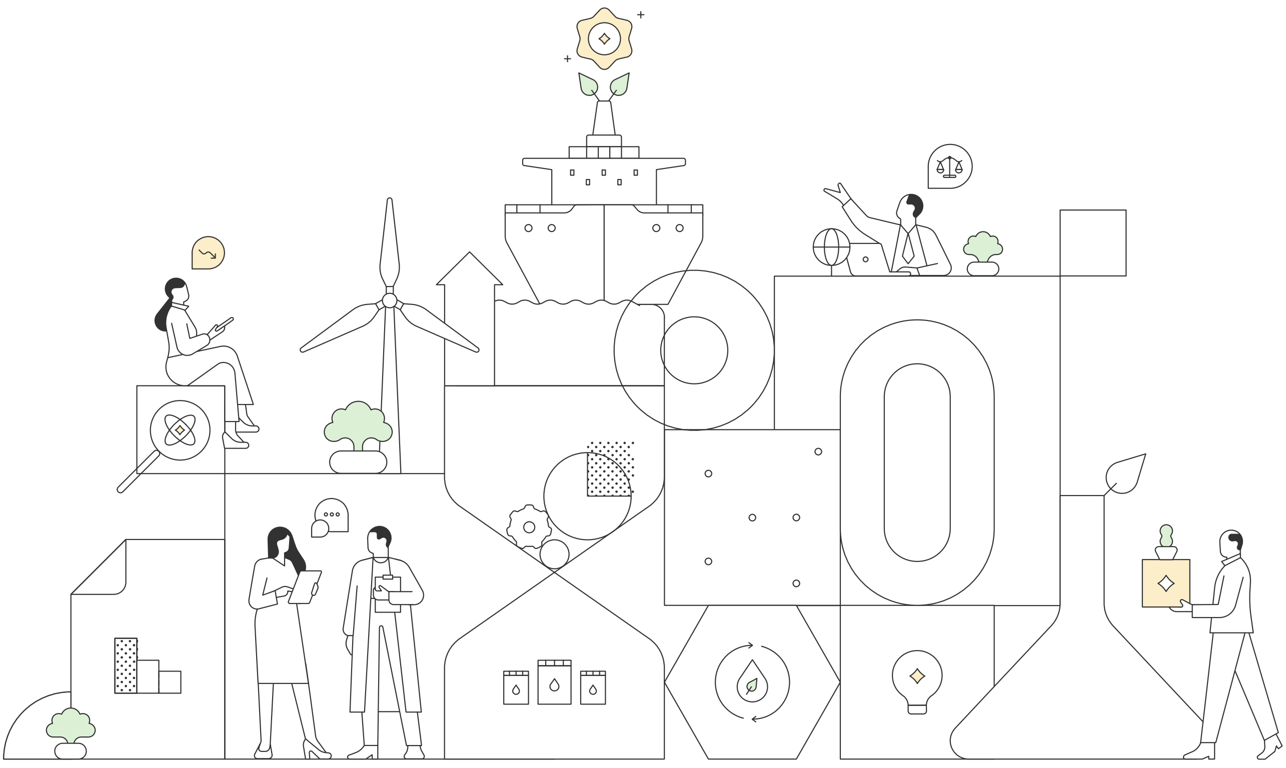
E-Ammonia Production from Nuclear Power

Techno-Economic Feasibility Study

November 2022



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

01 Executive Summary

This report presents the results of a study to evaluate the cost feasibility of a large scale nuclear fueled production facility for producing ammonia, which may have relevance. as a sustainable marine fuel. The primary aim of the project was to estimate the cost basis of producing ammonia using nuclear, in order to form a basis for cost comparison with solar/wind-based ammonia production plants. The scope of work entailed cost estimation based on process optimization, whereas other key assessments, e.g. regulatory risks and technological maturity, were not investigated in detail.

Electro-fuels are anticipated to play an important role in reaching global decarbonization targets. In the shipping industry, decarbonization will require substantial amounts of these e-fuels (such as e-ammonia and e-methanol), which in turn will require large capacities of electricity generated with low emissions.

However, solar and wind power still carry substantial investment costs, and e-fuels produced from them will cost 3x-4x higher than today's fossil alternatives, according to techno-economic modeling from the Mærsk Mc-Kinney Møller Centre for Zero Carbon Shipping.

Additional costs may depend on geographic constraints (such as transport to distant demand centers), and in some cases the land use might be prohibitive, since wind and solar bear significant installation footprints.

Considering these cost elements and implementation challenges, modern nuclear power may potentially provide a beneficial alternative. Molten salt reactors (MSRs) represent one potential opportunity for providing reliable and scalable energy supply, if the technological hurdles can be overcome within the timeframe of industry decarbonization.

MSRs may provide several advantages over other renewables: the base power output of MSRs is continuous instead of intermittent; the infrastructure occupies small footprints; and implementation is much less constrained by the natural resources of in a given geographical location – the main requirement being availability of cooling water for steam turbine operation. Additionally, the design of MSRs enables them to operate without the same control complexity that conventional nuclear reactors employ to address safety risks.

Therefore, MSRs may represent a viable alternative for producing sustainable electro-fuels— pending the technology's own challenges of commercial readiness and government regulation.

The costs of producing ammonia based on a proposed plant design were calculated for a large scale plant, to capture economies of scale: a total capacity of 10 million tons of ammonia product annually, corresponding to a total plant energy requirement of ~12 GWe.

Our analysis showed that nuclear fueled ammonia production could be economically feasible, having costs in the same range as future wind- and solar- powered ammonia production. As a result, nuclear fueled ammonia production could provide a viable alternative to wind and solar, especially in situations where land availability is constrained.

02 Introduction

2.1 Forecast Demand for Alternative Ammonia

According to the Industry Transition Strategy Report by Mærsk Mc-Kinney Møller Centre for Zero Carbon Shipping[1], "Ammonia may play a central role in meeting the maritime industry's overall energy demand during the transition on a Path to Zero. Ammonia's share in the fuel composition could steadily increase from ~16% in 2030 to just more than half in 2050." (Figure 1)

DNV (Det Norske Veritas-an international accredited registrar and classification society, headquartered in Norway), in their report "Energy Transition Outlook 2019: Maritime Forecast to 2050", suggests that the International Maritime Organization (IMO) could set emission reduction targets through innovative design, using ammonia as an alternative fuel. By their assessment, widespread commercial adoption of ammonia fuel would begin in 2037; it would be the dominant fuel choice for new ships by 2042; and it would represent 25% of the maritime fuel mix by 2050. Ammonia-fueled ships would represent almost 100% of new vessels (by fuel consumption) from 2044 onwards. The corresponding new demand for sustainable ammonia production is roughly equivalent to 120 million tons per year by 2050[2].

2.2 Scope of the report

2.2.1 Project Background

This project assesses the cost feasibility of a thorium molten salt energy based nuclear power plant, of approximately 12 GW electric, powering an ammonia synthesis facility to supply ammonia to the shipping industry. The electricity production from the nuclear power plant is based on a target

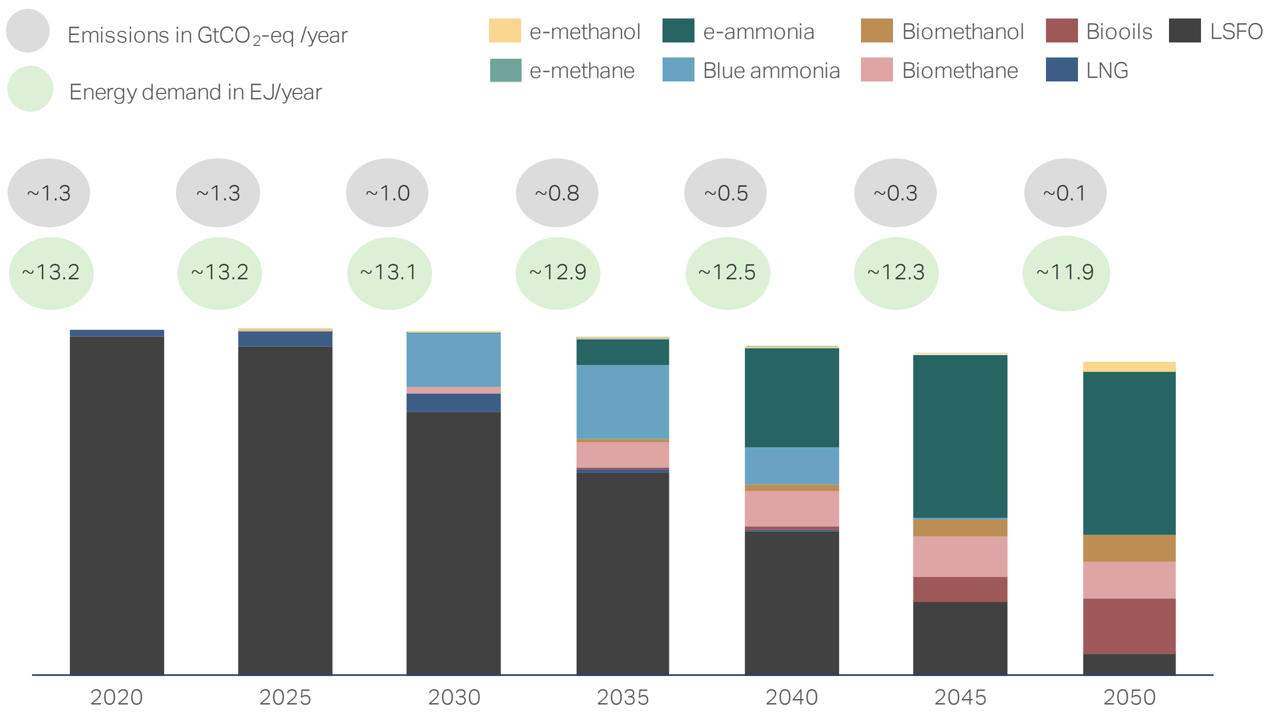


Figure 1 Total energy demand and fuel consumption on a path to zero.[1]
Ammonia is a principal component of the total maritime fuel mix, in this scenario.

[1] Industry Transition Strategy | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021

[2] Maritime fuel mix could be 25% ammonia by 2050 - Ammonia Energy Association

ammonia fuel production of 10 million MT per year, which is comparable to the scale of publicly announced renewable (solar & wind) energy source projects. The project partners included Copenhagen Atomics, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Topsoe, and Alfa Laval.

In this project, we considered plant design, site location, technology choice, production, and consumption. This process design then provided the basis for our techno-economic study which included the costs of building the plant and operational expenditures. Finally, we considered the risks and opportunities for producing ammonia using a thorium molten salt energy based nuclear power plant.

This project covered the complete ammonia value chain, from electricity generation to sustainable ammonia delivery. Some of the necessary yet unexplored considerations which were not included in this project are:

a. Impact of project scale on the delivered levelized cost of ammonia.
b. Impact of domestic transport, international export, semi-islanded operation using grid electricity, and
c. Details of project financing.

Further omissions are listed under "Exclusions" section 3.7.

2.2.2 Process Design Basis

The plant was designed for a capacity of 10 million tons per year ammonia as 100% NH_3, corresponding to 321.5 kg/s (360 days/year). All product ammonia is sent to storage and later transported to marine terminals.

Turndown capacities are not considered, so all subsequent calculations are based on 100% ammonia plant load.

For additional details of ammonia quality, storage, and feedstock, refer to Section 3.

Site information

According to a market intelligence report by Mordor Intelligence Analysis,[3] the market growth for ammonia is expected primarily in North America and in the Middle East.

The Middle East was selected as a representative location partly on the basis that the growth trend will extend beyond 2026, in addition to the following reasons:

a. Abundant availability of affordable land area away from population centers.
b. Easy access to the sea, therefore suitable for the transportation of water to the site and ammonia away from it by ship. Central geographical location could cater world-wide supply & demand.
c. Availability of less costly labor for construction.

Drawbacks of this region could include availability of qualified specialists (skilled labor), political stability. A more detailed geographical analysis, with site-specific information, may be covered in a follow-up project.

Due to the distant location and scale of the production, we assume no mixing with other electricity sources (i.e., no conventional power grid access). Therefore, the plant is designed to be self-sufficient, generating all the electricity consumed in the entire process.

[3] Ammonia Market | 2021 - 26 | Industry Share, Size, Growth - Mordor Intelligence

03 Process details

This section outlines our proposed molten salt reactor to ammonia plant design, including the technology choices and reasoning behind choices made as part of the project. Figure 2 shows the entire process as divided into multiple units and trains, which include well-proven technologies such as Haber-Bosch process etc. as well as not yet commercialized technologies such as MSRs. The fundamental feedstocks for any e-ammonia production plant are renewable electricity, water, and air. The main products are e-ammonia as well as pure or enriched oxygen.

3.1 Process Layout

The complete plant will consist of the following sections:

- Thorium-Molten Salt Reactor Section
- Boiler Steam Generation Section
- Steam Turbine-Generator Section
- High purity desalinated-demineralized water production section
- Electrolyzer system for hydrogen production
- Air separation unit for nitrogen production
- Ammonia synthesis loop with internal refrigeration system and steam generating system
- Ammonia refrigeration system for final product ammonia production

Refer to Figure 1 (Section 1) for a detailed block diagram depicting process flow. Figure 3 shows the plant layout diagram, for the overview of one way a plant could be arranged on land. An explanation of each section is given in the following section.

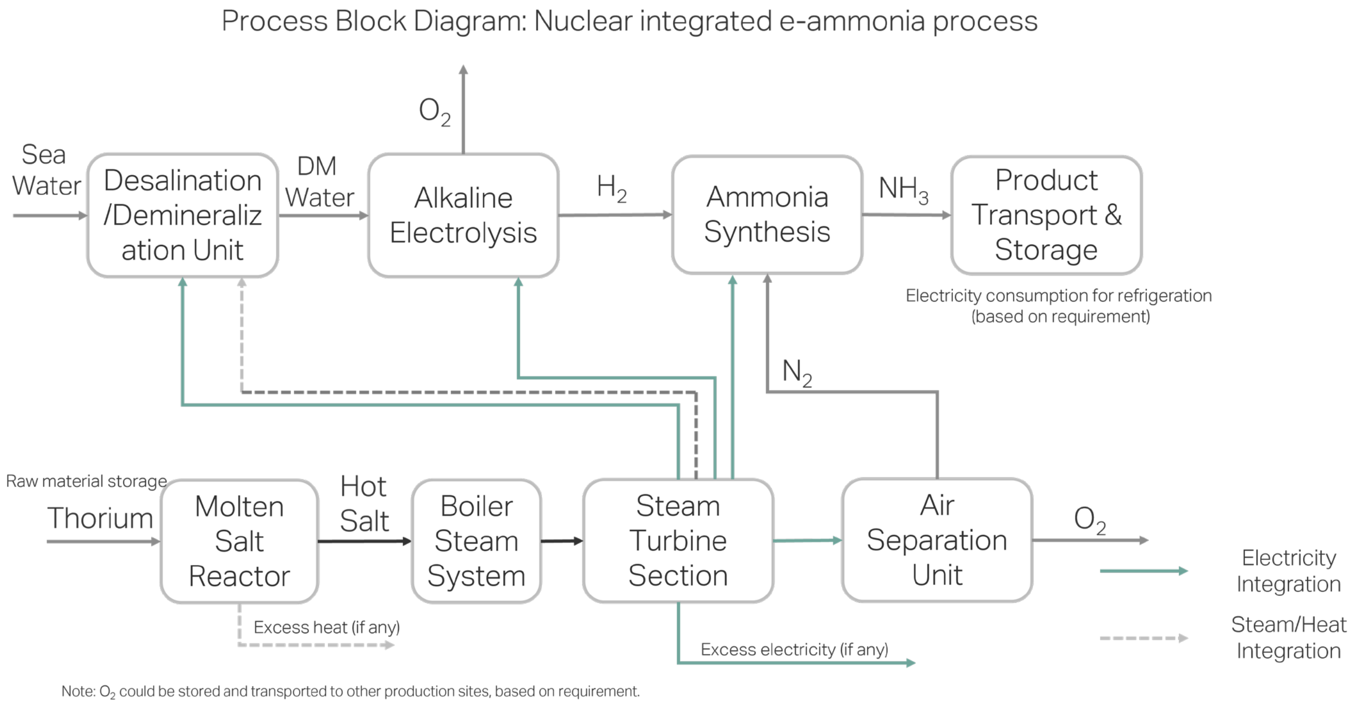


Figure 2 Block diagram representation of Nuclear based Ammonia production process

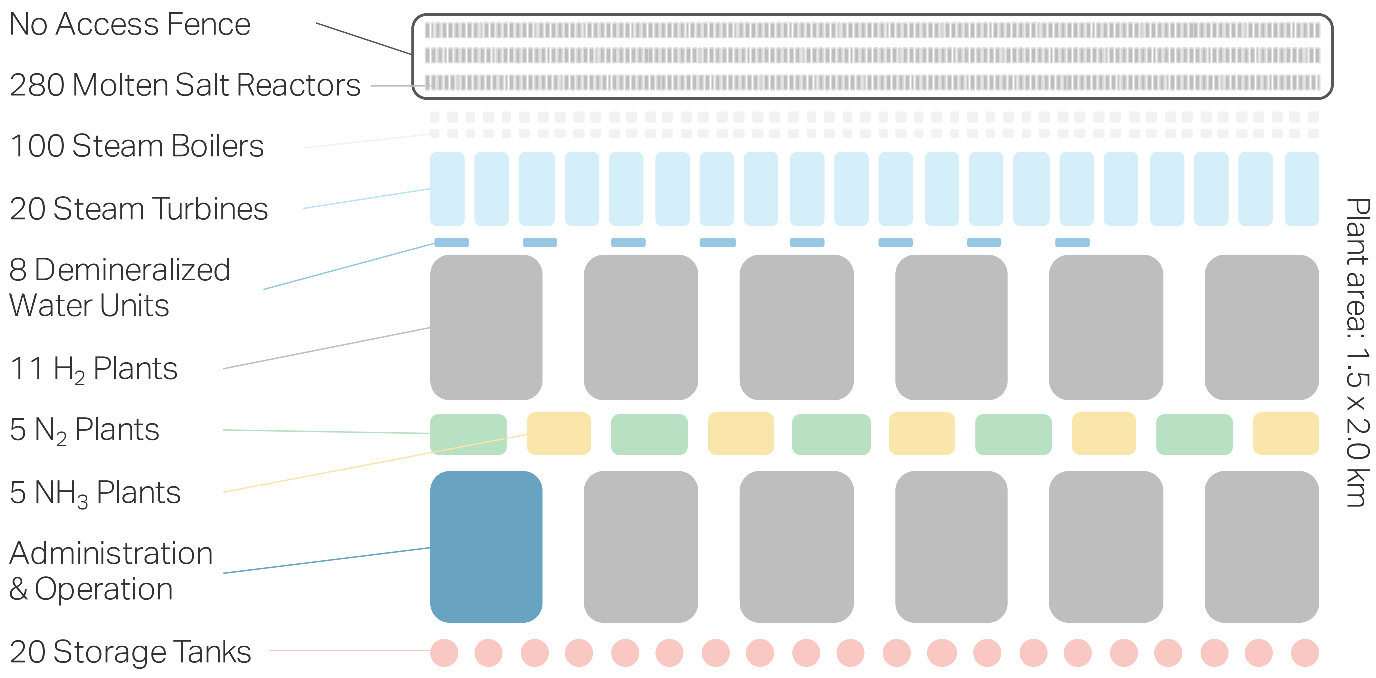


Figure 3 An indicative depiction of one potential plant layout, to indicate the size of plant components and the land use requirement.

3.2 Process Design Basis

Quantity & Quality:

Table 1 Quantity of ammonia produced and specifications for ammonia composition.

Capacity, Metric Tons Per Day	27,778
Metric Tons Per Year	10,000,000
Quality, Ammonia, %(w/w) (min)	99.5
Water, %(w/w) (min)	0.1
%(w/w) (max)	0.5
Oil Content, %(w/w) (max)	0.4
Nitrogen, %(w/w) (max)	0.3

Ammonia quality is as per the fuel specifications provided by MAN Energy Solutions.

Storage Conditions:

Table 2 Different storage conditions required for liquid ammonia.

Refrigeration, °C (max)	1 bar (-33°C (max))
Liquid under Pressure, bar g (max)	18 bar (45°C (max))

Feedstock Basis

Feedstock varies for different units:

Table 3 Overview of the various feedstocks that each plant unit consumes as input.

Molten Salt Nuclear Reactor	Fuel Salt (LiF-ThF_4) Coolant Moderator
Steam Turbine Electric Generator	Boiler Feed Water
Demineralization Unit	Raw Water (Sea Water)
Electrolysis Unit	Demineralized Water
Nitrogen Production Unit	Atmospheric Air
Ammonia Synthesis Unit	Hydrogen & Nitrogen

Utility Basis

Table 4 Specification of water utility requirements for plant operation.
Water source should be selected according to the plant site. In this project, we used sea water.

Temperature, °C, (min-max)	15-35
Pressure, bar g, min	Atmospheric

3.3 Process Description

Section I: Molten Salt Reactor

The Molten Salt Reactor (MSR) is used to generate the heat, which will provide the main source of energy to drive steam turbines to generate the electricity to run the rest of the plant components.

The input to the MSRs is electricity for control, internal cooling, and nuclear fuel—which is assumed to be provided by Copenhagen Atomics when the reactor is started. The reactor is replaced every 5 years, however the fuel salts and other salts and heavy water and building etc. is removed. Thus, only minimal components are replaced every 5 years.

The output from the reactors is in the form of a closed loop 565°C of nitrate salt. This energy is converted to steam in a boiler system. This boiler system will return the salt at 450°C. The salt output from the boiler is around 307°C, but a remixer is used to mix the 565°C salt with the 307°C salt to achieve the 450°C salt, which is needed to flow back into the MSR to close the loop. This closed nitrate salt loop is not radioactive. When the salt is loaded into this loop at start-up, it comes from a tank, which is placed next to the boiler system. The flow rate of the nitrate salt is nearly 573 kg/s per 100 MW reactor.

Each reactor uses approximately 1 MW of electricity, internal use.

The total output power of the MSR units is designed to match the 600 MW electric steam turbine unit. The boiler system located between the MSRs, and the steam turbines have 280 MW thermal output each. The design requires 5 steam boiler systems for every steam turbine. The thermal output of the Copenhagen Atomics waste burner is 100 MW thermal, thus 14 MSRs are needed per one steam turbine. Providing 12 GWe translates to about 280 reactors online and 6 in standby

Choice of Nuclear Reactor Technology

Due to historical public and political resistance towards nuclear technology, several plants built in the 80s and 90s remain un-operational; and since then, there has been an increasing demand of safety systems in the nuclear industry, especially following the Three Mile Island accident in 1979 Currently, it now takes 10 - 20 years in Europe and USA to build large classic nuclear reactors, whereas Rosatom can deliver in approximately 6 years and China has acquired the ability to build in 4 years.

USA-based NuScale is currently one of a few companies worldwide aiming to build small scale classic nuclear reactors. NuScale has invested close to $500 million in development but there has been no power plant or demonstration unit yet. Aside from NuScale, more than 20 start-up companies have been working to commercialize different types of molten salt reactors and small modular reactors before 2030.

The cost of MSR reactors is predicted to be much smaller than the cost of traditional nuclear power plants of same capacity. The lower cost for MSR reactors is mainly because they do not use water under high pressure as the cooling medium. MSRs thereby avoid the major accident scenario compared to a classic nuclear reactor sometimes referred to as 'nuclear meltdown' or loss of coolant water. In a general molten salt reactor (MSR), there is no water under pressure which can evaporate and cause a meltdown. However, the MSR designed by Copenhagen Atomics includes all safety aspects related to accident scenarios. Molten salt reactors also have potentially lower operating cost because they provide better fuel economy (output power per kg fissile inventory) than the classic nuclear reactors. It is also believed that standardized reactors manufactured on assembly lines will allow this new technology to achieve lower costs.

MSR technology also has beneficial safety characteristics. Even classic nuclear reactors have proven statistically over six decades to be the safest energy technology, in terms of deaths-per-MWh.[4] For molten salt reactors, experts generally agree that they can operate with more innate self-correction against accidents, compared against classic nuclear reactors; therefore, safety systems should be significantly less costly. And partly because molten salt reactors are smaller, any accident would likely be smaller in scope.

Challenges of Molten Salt Reactors

The project was focused primarily on cost feasibility rather comprehensively assessing risks. Therefore, only certain nuclear-specific issues were included, while others were kept out of scope.

Table 5 Overview of specific considerations for the design and implementation of MSR nuclear reactors. Some elements are already incorporated in the cost assessment by choice of reactor design, whereas other considerations were not scoped into this study and would require additional assessment to achieve more detailed costing.

Requirements addressed by this study's MSR design	Considerations not addressed in this study
- Radiation shielding is included, for reactor operation. - Cost advantage of no human reactor operators - Decay heat removal was modeled and deemed more than adequate for unexpected shutdown. - Reactor design avoids off-gas venting to the environment. - Kick-starter (reactor-grade plutonium) needs to be supplied only once (per salt load), and it lasts 50+ years. Delivery must occur in small batches. - Cost of decommissioning of MSR waste is included	- Local qualified specialists are required to maintain MSR plant infrastructure. - Clustering many such reactors could elevate the required level of physical protection and security measures on a per unit basis. - Low commercial readiness level, time/cost to develop - Total facility decommissioning, aside from MSR waste, was not included in the cost for any technology choice (for neither MSR, nor wind, nor solar).

[4] Nuclear Energy - Our World in Data

Section II: Steam Turbine System

The steam turbine output is mainly defined by the electricity need of the ammonia synthesis process. The scope of use as follows: The steam process takes the heat provided by the molten salt reactor (MSR) reactor, via a heat exchanger in a boiler system. The steam is then used in the steam turboset which contains the main components like steam turbine, generator and instrumentation and controls system.

The configuration / design and dimensions of the steam turboset is mainly defined by the temperature provided by the heat exchanger / boiler, the mass flow, and the pressure.

Due to the boundary conditions defined by small modular reactors (SMRs)/heat exchangers and overall power requirement (12 GWe), a steam turbine with large power output per unit was selected. The turbine leads to a power output of roughly 600 MW at a net efficiency of ~41% by using a reheat loop. Note that all components are standard products excepting the heat exchanger.

The main parameters are summarized as follow:

- Mass flow high temperature steam: approximately 530 kg/s @ 184 bar
- Mass flow reheat approximately 470 kg/s @ 50 bar reheat pressure
- Power Output: approximately 600 MW (therefore approx. 20 units necessary to provide 12 GW)
- Efficiency gross: approximately 47%
- Efficiency net: around 43% (depending on inherent power demand of plant and cooling conditions)

Section III: Electrolysis Unit

An alkaline electrolyzer system, consisting of 11 hydrogen plants, provides the total hydrogen required for the target ammonia production capacity of 10,000,000 MTPY.

The separate hydrogen plants can be shut down and isolated individually if required, without stopping the whole section.

High purity DM water and nuclear electricity is used in the electrolyzer system, to decompose water into hydrogen and oxygen. A non-pressurized system has been selected, and therefore downstream hydrogen compressors are required to lift the pressure to ~15 bar.

The pressurized hydrogen is mixed with nitrogen produced from the air separation unit. The oxygen rich stream is a potential financial asset, and its usage needs to be further investigated. Additionally, complete purge of the electrolyzer system will also require N_2 at 3 bar pressure.

Choice of Electrolyzer Technology

Keeping in mind the timescale for Molten Salt Reactor technology to emerge commercially, the representative plant is envisioned to be available after 2030. This delayed time point potentially makes Solid Oxide Electrolysis Cells (SOEC) a promising consideration for hydrogen production. However, this feasibility project was scoped to focus on technologies already commercially mature, and therefore alkaline electrolysis was selected for the present analysis: it is the most mature and commercialized system for green hydrogen production.

The project was also scoped to assess the more widely available non-pressurized alkaline electrolysis (at 15 bar), instead of pressurized alkaline electrolysis. Each of the two technologies has its own pros and cons. Developments are still ongoing on pressurized alkaline electrolysis, to reduce total energy consumption. A pressurized alkaline electrolyzer system can result in plot area savings, but at the expense of higher CAPEX: usually 20%-34% higher than for ambient systems (with and without installations and commissioning).

Section IV: Air Separation Unit

Atmospheric air is filtered before entering the air compressor. The compressed feed air is precooled and sent to a pre-purifying unit to remove moisture, CO_2, and most hydrocarbons. The clean, dry air is then sent to the cold box which comprises the cryogenic part of the air separation plant: the cryogenic heat exchangers, expansion turbine, distillation columns, related pumps, valves, and piping. Joule-Thomson expansion provides the required refrigeration to produce liquids in the distillation column system. Product compressors are then used to increase pressure of the nitrogen to the required pressure (~15 bar).

A liquid nitrogen storage tank is assumed, for handling any load variations. Instrument air and service air could also be supplied from the air separation unit (ASU) in normal operation (Subject to discussion with ASU vendor for a detailed study).

Pressurized nitrogen is mixed with hydrogen from the electrolyzers, and the use of oxygen rich stream is subjected to further investigation.

Section V: Ammonia Synthesis

Feed Mixing & Compression: At the suction of the synthesis gas compressor section, hydrogen and nitrogen are mixed in ratio 3:1 to maintain proper stoichiometry for ammonia synthesis reaction to occur.

Five sets of centrifugal compressors are required to compress and discharge the synthesis gas into the synthesis loop at the make-up point. The compressor system will be designed to operate at any load, along with an anti-surge system.

The condensate generated from the compressor stages is partly used for scrubbing the off gas and partly used as make-up water to the deaerator. In case of excess condensate, it is sent to wastewater treatment. Currently the process does not produce any excess condensate.

A Deoxo reactor is present at the discharge of each compressor section to absorb any oxygen by-product entering from the feed gases. Because oxygen acts as a poison to the ammonia conversion catalyst, thereby reducing its lifetime, it is necessary to eliminate even small traces of oxygen before the mixed compress gas enters the ammonia loop.

A steam turbine driven generator utilizes the steam produced by waste heat from the synthesis loop for power production. The steam turbine is a condenser type turbine, where the exhaust steam at 2 bar is condensed and cooled before entering the deaerator.

Ammonia Synthesis and Refrigeration Section: The ammonia loop is basically inert free since the hydrogen and nitrogen are of high purity. This permits the use of no or a very small purge stream from the loop, as compared to a conventional ammonia loop with high inert level.

The ammonia synthesis process takes place in the ammonia converter, according to the following reaction scheme:

$$3H_2 + N_2 \rightleftarrows 2NH_3 + \text{Heat}$$

The reaction is reversible and limited by chemical equilibrium. Only a part of the hydrogen and nitrogen is converted into ammonia when the gas passes through the catalyst bed. High pressure and low temperature favor a high equilibrium concentration of ammonia. Since the reaction rate is enhanced by increasing temperature, the choice of temperature should be based on a compromise between the reduced catalyst volume required at high temperature and the increased equilibrium conversion at lower temperature. The ammonia concentration is ~2.9 mol% at the inlet of the converter and ~20.4 mol% at the outlet. The unconverted hydrogen and nitrogen are recycled to the converter after separation of the liquid ammonia product.

The converter effluent gas is cooled stepwise in a train of heat exchangers. In this cooling process, both saturated as well as superheated steam is generated which can be further used in the boiler feed water (BFW) preparation section. The gas is finally cooled to -7°C using ammonia chillers and then separated into condensed ammonia stream sent for final refrigeration and the gases recirculated to the ammonia converter.

The ammonia converter is proposed as a series 300 Topsøe radial flow converter with three catalyst beds and two interbed heat exchangers placed in basket and a pressure shell.

The final refrigeration circuit is used for additional cooling and condensation of the ammonia produced in the synthesis loop. Here, liquid ammonia is flash cooled and compresses to obtain the product at –32°C and 1.96 bar, before being pumped into the tanks.

Section VI: Ammonia Storage & Transport

The product ammonia is intended to be stored in refrigerated storage tanks at the port area, to be later sent to the bunkering station for use as marine fuel. The refrigeration compressor system should be designed to accommodate the boiloff gases for recompression.

Fuel transport system including piping and the loading facility is not included in this project.

Section VII: Cooling Water Section

The cooling water circuit in the production section will use sea water as the cooling medium. Cooling of all related heat exchangers takes place in 2 steps. In the first step, all compressor inter-stage coolers, loop water cooler and ammonia condenser streams are cooled using sea water supplied at 25°C. The heated seawater at 33°C will further be used to cool the electrolyzers and the steam condenser, to obtain an overall temperature of approximately 40°C. This heated seawater will further be sent to the desalination-demineralization unit for purification and subsequent use in production.

Section VIII: Desalinated Seawater-Desalination and Management of Water (DSW-DMW) Preparation Unit

The Alfa Laval MEP desalination process consists of a series of evaporation and condensation chambers known as “effects”. In the plate channels on one side of an effect, the seawater is heated up and partially evaporated into distillate vapor, which is used in the next effect. On the other side of each effect, the distillate vapor from the previous effect is condensed, giving up its latent heat, into pure distillate.

Seawater is pumped into the system via a seawater pump to a condenser. Here, the seawater acts as a coolant, removing the heat supplied to the system and thereby maintaining the proper energy balance. In the condenser, the vapor produced in the last effect is condensed into pure distillate.

On the evaporation side of the plate stack, the seawater is partially evaporated by the heat from the condensation side of the plate stack. The vapor produced is passed through a demister, to separate salt from the water droplets, before it enters the condensation side of the subsequent heat exchanger plates. Here, the vapor condenses into distilled water, while transferring its latent heat through the plates to the evaporation side. The process is repeated in all effects.

Finally, distillate and brine are extracted from the last effect. The evaporation takes place at sub-atmospheric conditions, and vacuum conditions are created and maintained by a venting system. The venting system is a water-driven ejector and removes air from the plant at start-up, while extracting non-condensable gases during operation of the plant.

Section IX: Subsidiary Units

Waste-water treatment: The waste-water treatment unit is required for handling all liquid streams that cannot directly be reused or those that require treatment before they are sent into the sewer. E.g.:

- Waste effluents,
- Oil sludge,
- Storm water etc.

Instrument & Service Air System

Flare/Vent System

The requirement for these systems has been noted, but these were deemed out of scope for this cost feasibility assessment.

3.4 Production and Consumption Summary

The below table summarizes the mass flow for raw materials and products in each section for the complete process.

Table 6 Summary of various material flows in the different plant units, including feedstocks, products, and heat.

Section	Raw Material	Product	Unit	Mass Flow(1Unit)	Mass Flow (Total)
Thorium Molten Salt Reactor	Thorium		kg/yr	33	9900
		Molten Nitrate Salt	kg/s	572.50	160,300
Steam Boiler System	Molten Nitrate Salt		kg/s	715	71,500
	Boiler Feed Water		kg/s	107.18	10,718
		Process Steam	kg/s	106.12	10,612
Steam Turbine System	Process Steam		kg/s	530	10,600
		Exhaust Steam	kg/s	530	10,600
Desalination Unit	Sea Water		kg/s	391	3,124
	Motive Steam		kg/s	15	124
		Demineralized Water	kg/s	81	647
Electrolysis Unit	DM Water		kg/s	115	573
	Sea Water (Cooling)		kg/s	3,575	17,876
		e-Hydrogen (Saturated)	kg/s	20	98
		e-Oxygen (Saturated)	kg/s	95	475
Ammonia Synthesis	e-H_2 (pressurized)		kg/s	12	60
	DM Water		kg/s	0.06	0.28
	Sea Water		kg/s	8,061	40,303
	Nitrogen (pressurized)		kg/s	53	265
		Liq. Ammonia	kg/s	64	322
Air Separation Unit	Air		kg/s	69	347
		Nitrogen	kg/s	59	265

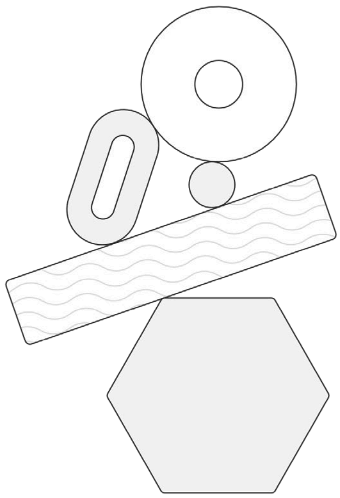
3.5 Power Consumption

Power Consumption for all units are following:

Table 7 Summary of the electrical power demanded by the various plant components.
The electrolyzer consumes the majority fraction of the total electricity consumption.

Section	Total Power (MW)
Thorium Molten Salt reactor	280
Steam Turbines & Buildings	0
DS-DM Unit	25
Electrolyzer **	10,100
H_2 Compressor	320
Ammonia Synthesis & Refrigeration	480
Air Separation Unit	300
N_2 Compressor	20
Feed water Pump(s) (Cooling)	30
Feed water Pump(s) (Boiler)	235
	11,790 Mwe#
Total Electric Power Consumed	12 GWe
Total Thermal Power Requirement ##	29 GWt

* All values are inclusive of the losses for each unit in its respective section.
** For the electrolyzer plant an End of Life (EOL) power consumption has been used.
# After deducting electrical energy generated within ammonia production section
Based on 41% conversion efficiency
¤ Net power treated as 0 assuming net turbine efficiency, i.e., accounting for own minor electrical consumption.



The overall plant efficiency and the energy content of the final product are calculated based on the conversion losses from each section, as depicted in Figure 4.

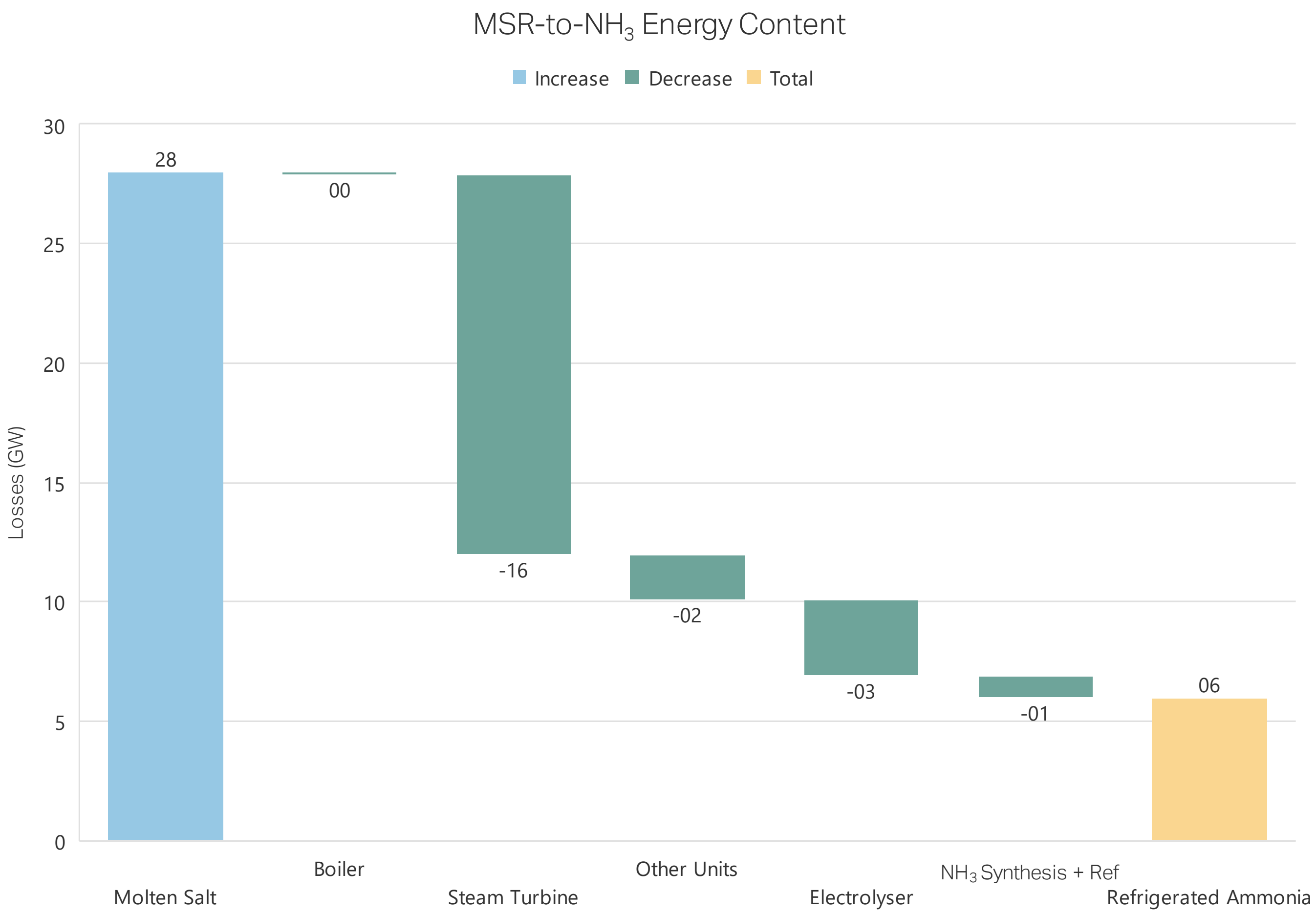


Figure 4 Overview of energy losses at various conversion steps, starting from molten salt heat power and finishing with ammonia as a fuel pre-combustion.

3.6 Emissions and Effluents Summary

The mass flows of the effluents and byproducts for the individual sections are as follows:

Table 8 Summary of effluents for the different plant components.

Section	Effluent/By-product	Total Mass Flow (kg/s)
Thorium Molten Salt Reactor	N.A.*	-
Steam Boiler System	Blow Down (Evaporator)	0.03
Steam Turbine System	N.A.	-
DS-DM Unit	Brine	2,476
Electrolysis Unit	e-Oxygen	475
Air Separation Unit	Oxygen	80
Ammonia Synthesis Section	Gas-Loss (SG Compressor)	0.324
	Off-Gases (Off-gas Scrubber)	0.285
	Water Vapor (Deaerator Vent)	0.06
	Condensate (H_2 Compressor)	7.6
	Blow Down (Blow Down Drum)	0.5

N.A.: Not Applicable. Currently, no significant effluents/by-products are generated in these sections.
* Off gas handling is incorporated into the reactor design selected.

3.7 Cost Estimation

Capital Expenditure (CAPEX)

The cost estimates for different sections of the nuclear based ammonia production plant include the following components:

The overall estimated capital expenditure for the above-mentioned sections is about 50 billion USD, where the major cost contributors are molten salt reactors, steam turbine-generator system and ammonia production section (incl. electrolysis). CAPEX and OPEX for individual sections are as mentioned in Table 9.

The total net present value for the complete process is calculated to be approximately 64 billion USD (considering 7% discounted OPEX, without any inflation).

Based on the level of engineering design, the pricing method and the cost estimate details, the reliability of this estimate is stated to be +60/-20% for total plant cost, within an 80% confidence interval.

Turnkey costs were used to represent the CAPEX of all plant components, representing the total cost to deliver and install a unit that is ready for operation.

Table 9 Summary of numerical investment costs and operating costs for the different plant components

Description	CAPEX (Billion USD)	OPEX (Billion USD)
Molten Salt Reactor System	11.6	5.8
Boiler Steam System	3.4	0.8
Steam Turbine System	13.8	0.3
Ammonia Production Section (Electrolysis+ASU+NH_3 Syn.)	17.7	9.9
Desalination Section	0.2	0.3
Total	46.7	17.1

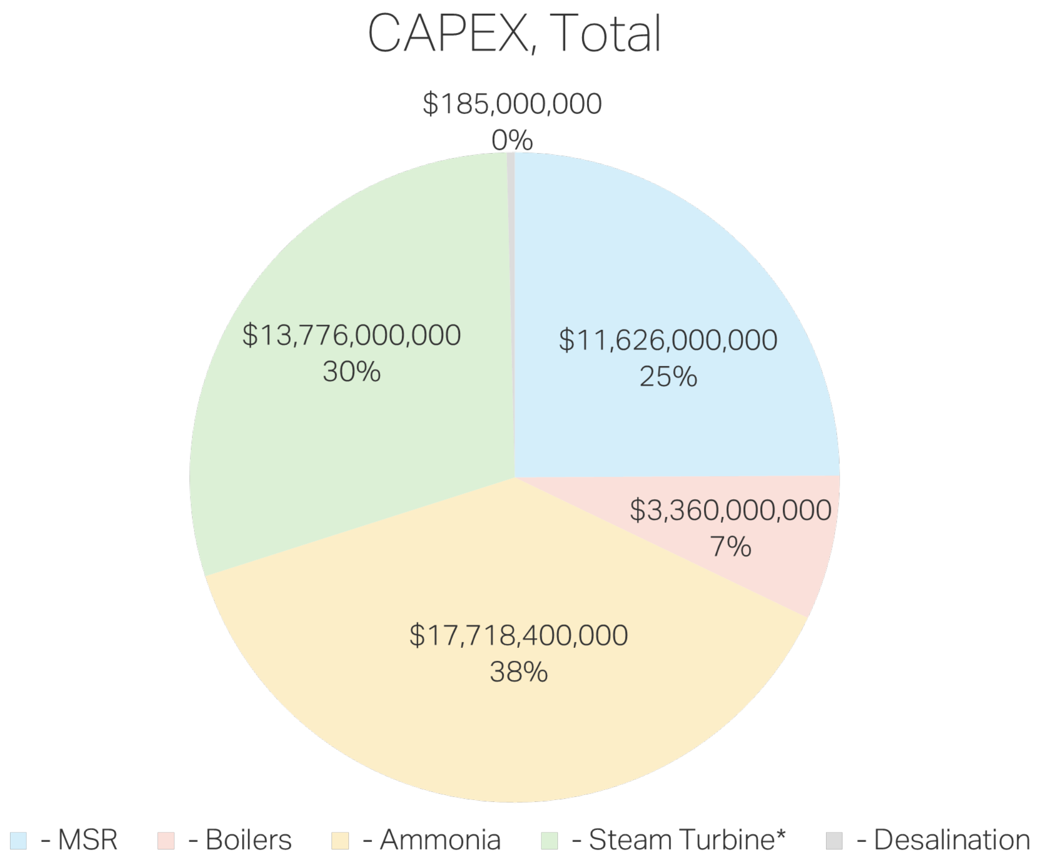


Figure 5 Overview of total installed cost contributions from the different components of the plant. The MSRs represent a similar contribution to overall cost (approximately 30%) as steam turbines and ammonia plants.

The cost for individual section as a percentage of total CAPEX is shown in Figure 5.

The following components are common for all sections of the process for CAPEX estimation:

- Equipment Cost (All Units-inclusive of material cost, internal piping, and electrical installations)
- First charge of raw materials (molten salt, thorium fuel, catalysts and electrolyzer stacks)
- Civil work (excavation, backfill, de-watering, surfacing, foundations, etc.)
- Construction costs (incl. construction overheads)
- Construction contractor personnel for commissioning and start-up
- Professional services (licenses, basic & detailed engineering, procurement, expediting, main contractors project management including site management)
- Contingency and contractor margin

Operating Expenditure (OPEX)

Fixed OPEX for the complete process (all sections) are approximate, and they amount to **17.1 billion USD** for a lifetime of 30 years.

This is assumed to be around 37% of the total CAPEX cost, and is inclusive of the following:

I. General Maintenance costs
II. Inspections
III. MSR and electrolytic stack replacements (every 5 and 10 years respectively)
IV. Cost of Operators and Engineering Team
V. Insurances

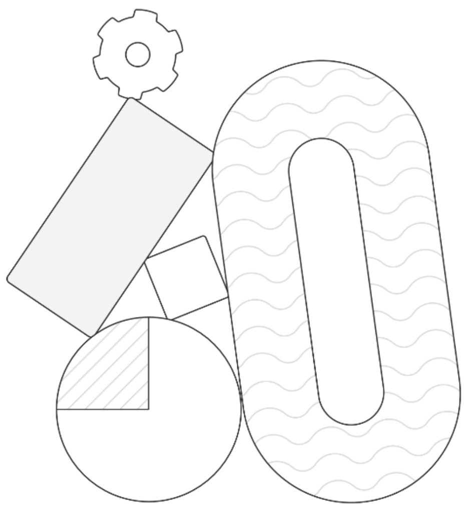
Exclusions

The cost estimate excludes the following components:

- Cost of land for all sections
- Owner's costs for all units (excl. ammonia synthesis section)
- Interconnection piping and instrumentation costs between all the sections.
- Adders for all units (excl. ammonia synthesis section)
- Taxes and duties for all units (excl. ammonia synthesis section)
- Decommissioning costs (of infrastructure)
    - Note: Cost of recycling reactors is included, and cost of sending fission products to country of origin are contracted.

Levelized Costs

The levelized cost of electricity (LCoE) as well as levelized cost of ammonia (LCoA) are strongly affected by the total CAPEX. The total levelized cost of electricity and ammonia are calculated to be **$27.78 per MWh** (USD/MWh) and **$27.65 per GJ** (USD/GJ) respectively. On the basis of the ammonia production capacity for the entire plant, the LCoA can also be considered equivalent to **$514 per ton** (USD/$ton_{NH3}$).



Cost Sensitivity Analysis

It should be kept in mind that various cost components (as mentioned in the exclusion section) will have a big impact on the levelized cost calculations.

Variations in the Levelized cost of electricity (LCoE), and Levelized cost of ammonia (LCoA), can be observed from the sensitivity analysis graphs in Figure 6 and 7.

Among our selected sensitivities, the discount rate parameter could account for the highest potential impact on LCoE & LCoA. This parameter would depend partly on the economy with geographical dependence, regarding local attractiveness for investment. The LCOA is least sensitive to OPEX variation, reflecting the highly CAPEX-intensive nature of the business case.

The CAPEX uncertainty could be interpreted as forecast error of MSR, since it is the main technology not yet-commercialized in this feasibility study. However, possible CAPEX deviations may easily result from other plant components, which are even today subject to significant variation. Note that MSR does not represent the greatest CAPEX in the pie chart shown earlier.

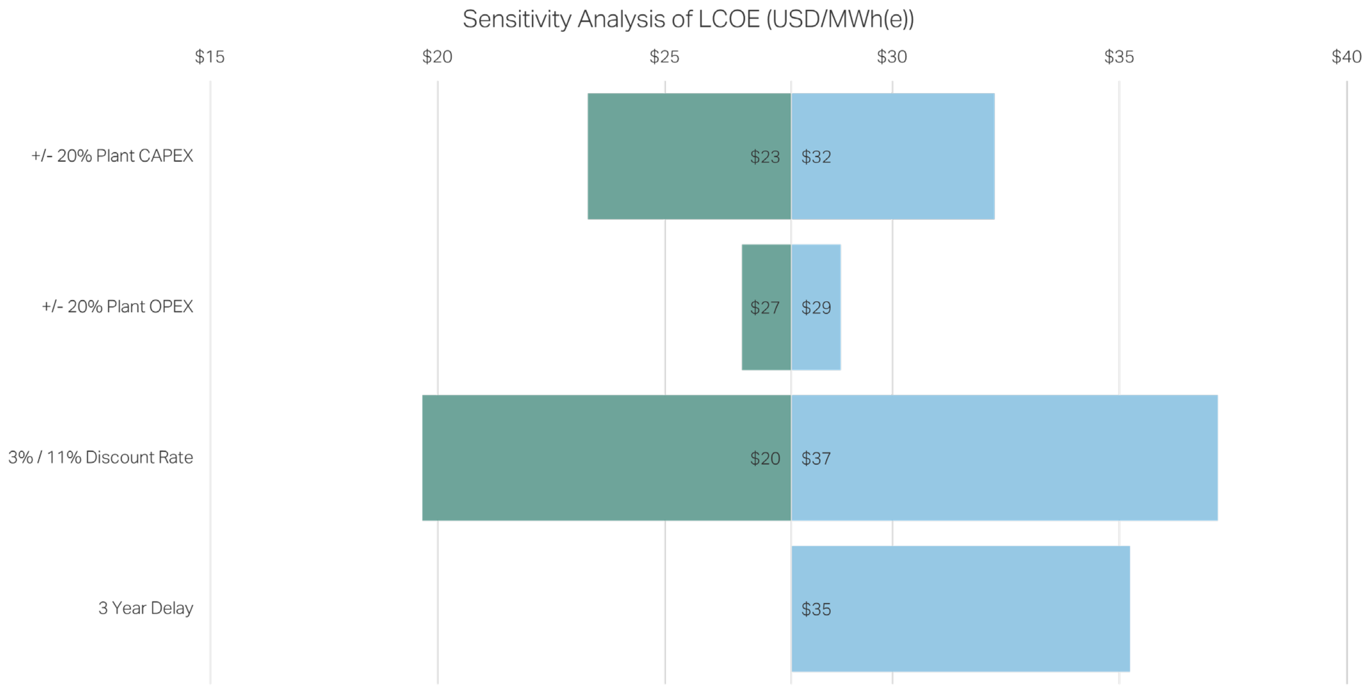


Figure 6 Sensitivity analysis of the effect of techno-economic inputs on the Levelized Cost of Electricity. The lower- and upper- bounds of electricity cost are shown centered around the LCoE calculated in the present study, indicating how the range of outcomes depends on assumptions used.

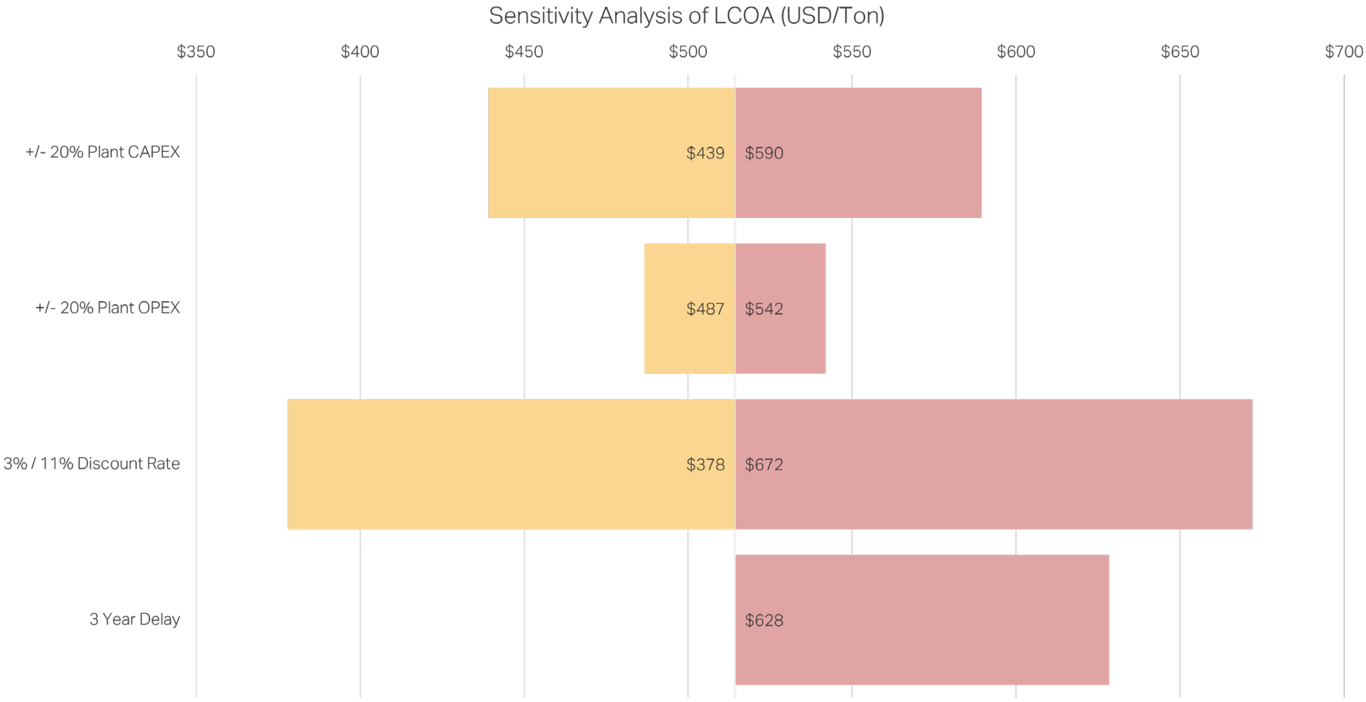


Figure 7 Sensitivity analysis of the effect of techno-economic inputs on the Levelized Cost of Ammonia. The lower- and upper- bounds of electricity cost are shown centered around the LCoA calculated in the present study, indicating how the range of outcomes depends on assumptions used.

The following table provides a comparison of levelized costs for ammonia production. The molten salt reactor powered ammonia production process is compared against production from renewables (wind and solar), and the calculations from two different sources are shown[5,6].

A representative grey ammonia marked price (not cost) is also included for reference.

The effective MSR electricity cost was also analyzed from this study, evaluated to be $28/MWh$_e$. This level falls within range to MMMCZCS's NavigaTE model value of $31/ MWh$_e$ for load-balanced wind and solar power in the year 2030.

Table 10 An overview of different ammonia costs, from different production routes and different points in time. For comparison, a representative price (not cost) of grey ammonia price (fossil-based) is shown, indicating the large fluctuations over the last 20 years - in particular with sensitivities to natural gas prices and changing market demand for ammonia.

	LCoA	
	USD/GJ	USD/MT $_{NH3}$
MSR-to-NH_3	$28	$514
NavigaTE Model Electro-ammonia costs (MMMCZCS)		
- Global (2030)	$32	$610
- Global (2050)	$18	$329
Ammonfuel Report Electro-ammonia costs (Topsoe)		
- Green Ammonia (2030)	$22	$500
- Green Ammonia (2050)	$15	$275
Representative Grey Ammonia Market Price	$18 +/- 10	$350 +/- 200

[5] MMMCZCS Center knowledge based on NavigaTE TCO Model

[6] Ammonfuel Whitepaper- Haldor Topsoe

3.8 Risks and Opportunities

For the process design described so far, there are potential technology variations that may improve the business case, and there are also a few design elements that have not been proven to have commercial maturity—and therefore could require additional development or incur higher costs than assumed. The following describes some of the key uncertainties encountered, representing either opportunities or risks that require further research to assess readiness levels.

1. **Molten Salt Reactor:** MSRs are not a new concept and have been known in the scientific world even during the 20th century. But Molten salt reactors are an emerging technology, and a few advancements could promote its value as an energy solution: The MSR only operates for intervals of 5 years in the current proposed design.

   This should be optimized to extend the lifetime to 10 years. This could reduce the total cost of MSR heat by 10%. Better heat utilization could improve efficiency by 3-4 percentage points. There is potential to reach 650 ºC temperature instead of the 565 ºC utilized from the nitrate based molten salt in this design. Two technologies could be applied to achieve this: supercritical steam turbines (SST: ~47% efficient) or supercritical CO_2 closed Brayton cycle turbines (BCT: ~45%-50% efficient). Finally, there is possibility to gain revenue from utilizing nuclear waste. Disposal of existing nuclear stockpiles represents a large expense, so there is value in utilizing it.

   Three plants, at the scale of this study, could relieve the UK of £73 million per year that it spends to maintain storage of our potential kick-starter (separated reactor-grade plutonium). UK expects a cumulative discounted expense of £10.0 billion for disposal of these stockpiles.[7] Alleviating this public cost burden could represent an opportunity to decrease the net cost of MSR power.

2. **Steam Generating Unit (Boiler):** The use of molten salts with steam generator technology is rare at present. The only existing references have used molten salt for concentrated solar power technology, i.e., none with nuclear equipment. The MSR process of this study would be among the first to adapt such boilers.

   Another distinguishing feature of these boilers is the pressure of generated steam. Today's boilers have been optimized for performing at stable load with steam generation below 140 bar. But in the nuclear based ammonia production, steam is required at even higher pressure (184 bar). For simplicity, we have assumed that boilers generating this higher-pressure steam can be made available in the future years. But at the same time, higher pressure will result in more expensive metallurgy for construction-- thereby increasing the overall CAPEX.

   Lastly, this study has not assumed a higher temperature operation by the use of chlorine salts. If chlorine salts are used as heat transfer medium for steam generation, steam temperature at the boiler outlet can increase up to 700 ºC, thereby increasing efficiency by a few percentage points.

[7] Progress_on_Plutonium.pdf (publishing.service.gov.uk)

3. **Electrolyzer:** The present feasibility study has assumed the use of alkaline electrolyzers for hydrogen production. PEM electrolyzers, though commercially available, have not been utilized for large scale hydrogen production due to higher cost. It is also well known that Solid Oxide Electrolytic Cells (SOECs) offer better overall efficiencies (about 20% higher) and heat integration (with operating temp. of ~ 700 ºC), compared to alkaline electrolysis. However, SOECs were not considered in this project, due to their lower technology readiness level and lack of commercial references. Considering its advantages over Alkaline & PEM electrolyzers, SOECs would be the best option to optimize plant economics, in future scenarios.

4. **Ammonia Synthesis & Refrigeration:** If the ammonia section can be optimized by decreasing the cooling water consumption, there is potential for power saving-- as well as pump and piping costs.

5. **Desalination Unit:** Traditional thermal techniques (such as Multi flash distillation and Vapor Compressed Distillation) and membrane technologies (such as Reverse Osmosis, Electrodialysis and Electrodialysis Reverse) are not considered in this process, due to process constraints. Several small-scale references are available for RO type desalination plants in Middle East, but due to requirement of ultra-pure demineralized water for electrolysis at this large scale, MED technology was selected.

   Multi effect distillation (or MED) is also a thermal technique and the most preferential to handle large amount of steam and waste heat efficiently in the process. The main advantage of this technology is its ease of operation (lower temperature and higher efficiency compared to MSF, no water pretreatment needed and less chemicals compared to RO) resulting in lower OPEX and lower maintenance requirements. Other technical benefits are as follows:

   I. Low temperature requirement
   II. Higher efficiency compared to MSF
   III. No need for water pre-treatment
   IV. Less chemicals compared to RO process.

   An existing reference for such a large-scale desalination unit is in Pakistan using 2x MEP-7-7000 (14,000 m^3/day, 2006).

   In future, if SSTs and BCTs are implemented with reheaters, there is a large scope of heat utilization from SOECs. This layout can be optimized for around 5% savings on efficiency if the condenser/waste heat handling is coupled efficiently with Alfa Laval desalination units. Quantification and costs for these units are still unknown and need to be explored.

6. **Other general plant improvements**:
   The steam turbine and electrolyzer buildings in the current design can likely be optimized to take up half (or even a quarter) of the space. MSRs, boilers and demineralized water units, include their own weather shields, which is not a classic building, but a weather structure. Thus, no concrete floor and no classic building foundation is needed, which helps to save cost and construction time.

   Finally, it may be possible to reduce the number of salt pipes, steam pipes and electrical cables.

04 Conclusions

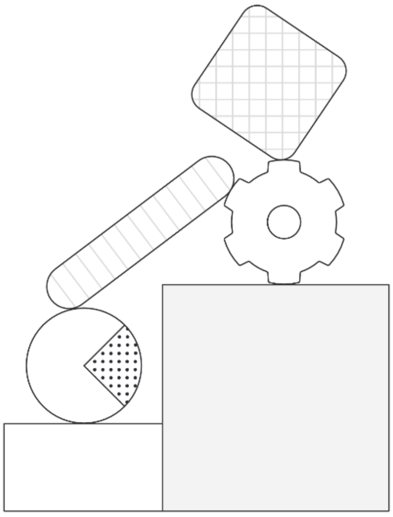
Our analysis, as outlined above, confirms that a thorium molten salt energy based nuclear power plant is a cost-feasible option for ammonia production for the shipping industry.

The levelized cost of ammonia from the molten salt reactor plant falls within range of the production costs compared to other renewables (wind and solar). Furthermore, although it is not substantially cheaper than other renewable energy sources, a molten salt reactor powered ammonia production could provide a viable alternative to meet the global energy demands if land availability is constrained.

Producing energy using molten salt reactors has several benefits compared to wind and solar energy, such as the potential for closer proximity to demand centers, as cost-competitive production is not as constrained to location like wind and solar is.

Additionally, approximately 2 000 times less area is needed for a molten salt reactor powered ammonia plant in comparison to production plants based on wind and solar. Moreover, our sensitivity analysis showed that varying assumptions did not make molten salt reactor powered ammonia production costs vary significantly from NavigaTE Model costs, indicating the robustness of the implementation of such technology.

Thus, the development of molten salt reactor powered ammonia plants should be considered for future fuel production, as they provide a cost feasible alternative to other renewable energy sources and could aid in supplementing the global energy demand.



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