Fission-to-X:

Flexibility, Affordability, and Grid Stability with Power-to-X and New Nuclear Technology

SEABORG

Contents

Introduction

In the International Energy Agency's (IEA) report titled "Net Zero by 2050 – A Roadmap to the Global Energy Sector", the rapid reduction of CO_2 emissions needed over the next 30 years is only deemed feasible through the adoption of bold policy approaches, innovative technologies, and widespread behavioral change. Within the field of decarbonization technologies, this means an unprecedented mobilization of all suitable alternatives to fossil fuels, and a systemic shift in how we share knowledge and collaborate across the industry.

Imbuing innovation with this responsibility to share, collaborate and push is vital. Decarbonizing the world's energy systems will require a multifaceted ecosystem of alternative energy solutions that can be easily integrated and work in tandem to quickly replace the conventional, carbon-intensive fuels that we currently rely on. The alternatives must be clean, scalable and cost-efficient.

Over the past two decades, the cost of renewables has plummeted, and in most cases, it is now more economically viable to deploy wind and solar solutions compared to fossil fuel alternatives in some parts of the world. Whilst the economic advantages are clear, both wind and solar face a number of challenges, predominantly related to variability and intermittency.

To achieve the scale needed for a global energy transition, we not only need access to renewable energy, but a consistent supply of renewable energy. Relying exclusively on variable renewable energy (VRE) solutions poses a significant risk to our net zero ambitions. Wind and solar are essential, but we need an expanded portfolio of clean, proven, and complimentary solutions for powering our journey to net zero and beyond.

In this paper, we explore the potential of two complementary technologies. First, we will introduce the Compact Molten Salt Reactor (CMSR) Power Barge, a modern nuclear technology platform. We then detail its synergy with the high temperature electrolyzer technology (SOEC) from Topsoe. Via the process known as Power-to-X, this combination can efficiently produce the necessary e-fuels and chemicals, overcoming the challenges of variability and intermittency associated with wind and solar powered feedstocks. This next generation of Power-to-X plants promises to deliver a more dependable base load of clean energy directly into the grid.

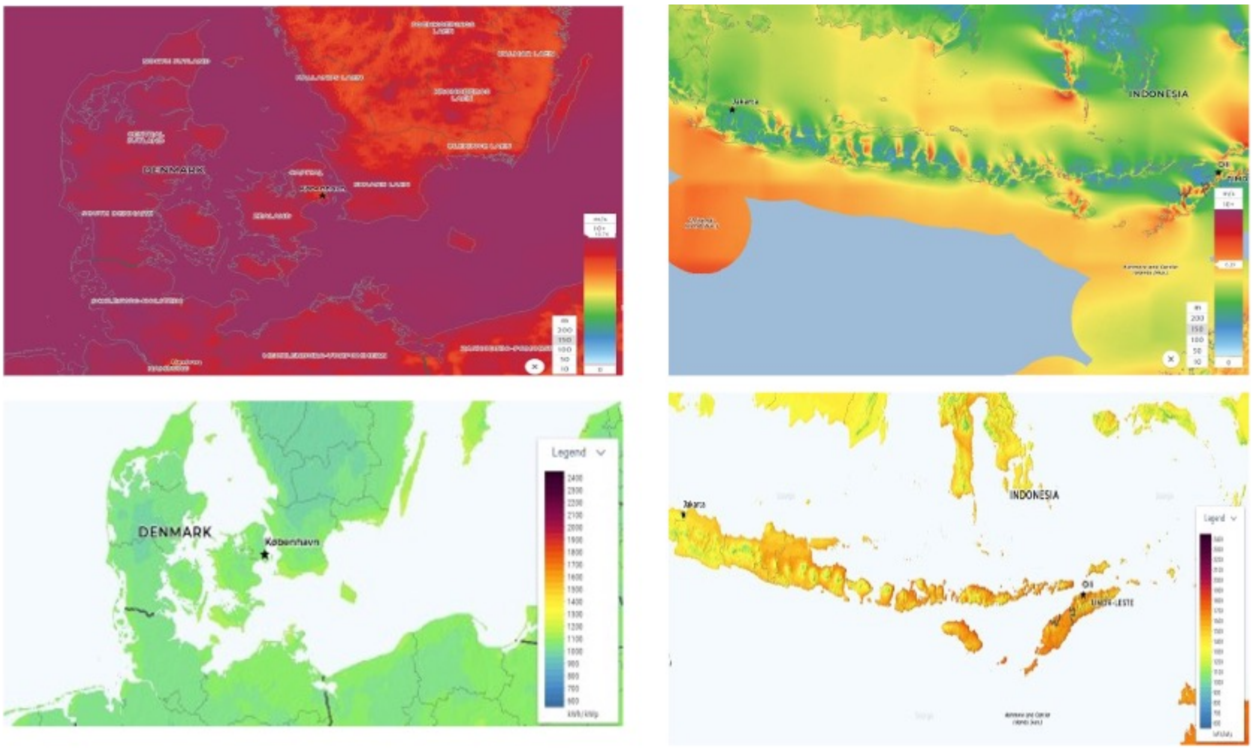
Challenges in low-emission electrification

According to the IEA, "the direct use of low-emissions electricity in place of fossil fuels is one of the most important drivers of emissions reductions in the NZE, accounting for around 20% of the total reduction achieved by 2050."[1] While low-emission electrification will be central to a NZE by 2050 scenario, there are a number of challenges that should be considered when understanding how this market will scale and what technologies can meet the global demand needed.

Not all industries can be directly electrified.

The ongoing electrification of society necessitates an unparalleled expansion of renewable energy sources, especially wind and solar. While direct electrification remains the most efficient path to decarbonization, it is no t a viable solution for all sectors enroute to net-zero. Industries such as heavy transportation—including shipping and aviation—as well as heavy industries such as steel and chemical production, simply cannot currently rely on direct electrification as a feasible alternative to fossil fuels.

FIGURE 1 Wind and solar potential in Denmark and Indonesia[2]



1 https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf, p. 70

2 The source of information for the wind and solar potential illustration have been taken from Global Wind Atlas (https://globalwindatlas.info/en) and Global Solar Atlas (https://globalsolaratlas.info/map

These sectors are commonly referred to as the "hard-to-abate sectors" due to the absence of one-size-fits-all solutions. To reach our collective decarbonization goals, a diverse array of alternative fuels and chemicals is essential.

Engines designed to operate on eMethanol and green ammonia are now accessible, with pioneers already incorporating them into their shipping operations. Forward-thinking steel and chemical producers are leveraging green hydrogen and an assortment of other eco-friendly chemicals to power their operations. However, while many solutions are at hand, the energy required to produce these clean, cost-effective fossil fuel substitutes in necessary volumes is a significant barrier to broader adoption, hindering the transition to net zero.

Variable Renewable Energy (VRE) is highly dependent on local environments.

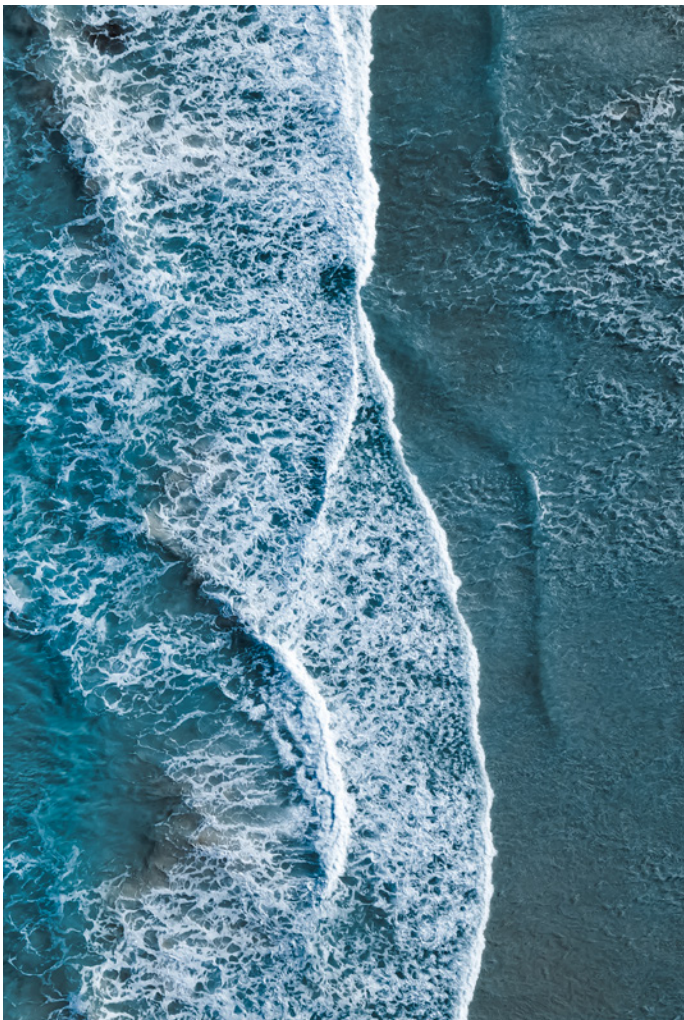
VRE build-out is shaped and oftentimes limited by local environmental conditions. Areas like Northern Europe, South America, Australia, and North Africa have already proven to be attractive locations for VRE sources, whereas large areas of Southeast Asia and other countries close to the equator have comparatively less favorable conditions. This is for a variety of reasons, from modest wind speeds to weaker solar intensity, poor site conditions such as deep-water close to shore or mountainous terrain.

The illustrations in figure 1 of the wind and solar conditions for Indonesia and Denmark respectively compares the mix of VRE potential of both countries. Denmark boasts consistently high average wind speeds, approximately 10 m/s at 150 m elevation, making it favorable for wind turbines. However, its suitability for solar PV is compromised by significant seasonal variations due to its northern latitude. Conversely, Indonesia's geography is less conducive to wind turbines but is notably more advantageous for solar PV installations. While both countries face seasonal wind speed variations, combining wind and solar PV only partially counters the intermittency of VRE sources. To consistently meet each countries energy demand, a stable and clean alternative to fossil fuels is needed.

Incentives for achieving economies of scale in VRE are shaped by pre-existing energy infrastructures.

Another challenge facing the VRE build-out is its dependency on each country's pre-existing energy infrastructure and how this informs future policy. Most electrical grids are owned and operated by the Transmission System Operators (TSO) which is typically owned/controlled by a government entity with the objective to secure sufficient, reliable, and cheap electricity. The Independent Power Producers (IPP) on the other hand, supply electricity to the grids which are governed by a grid connection agreement with the TSO. Different countries have different potential for VRE in combination with their domestically available fossil resources – all of which greatly influence the optimal mix of power sources.

To scale VRE, it needs to become consistent and cost competitive. Unfortunately, increasing the installed VRE capacity to close the intermittency gap is not a cost-effective solution, given the correlation in the load profiles of existing and new grid capacity and the need to curtail it at high load hours. Storage in batteries or heat - as offered by Hyme, a Seaborg sister company - can only cover a limited range of production shortfalls (days or weeks at most) if we are dealing with large grid capacity systems.



Pairing VRE with Power-to-X

One popular proposal is to significantly increase VRE capacity and conversion of excess power through Power-to-X (PtX) – a series of processes that use an electrolyzer to convert renewable power (P) into green hydrogen, the base reactant that can be transformed into a whole spectrum of energy carriers (X). This 'X' is typically understood as chemicals such as green hydrogen, green ammonia, or eMethanol – derivatives which can enable longer term storage and decarbonization opportunities for hard-to-abate sectors.

To successfully scale PtX production facilities for energy carriers such as green hydrogen, green ammonia and eMethanol some of the general rules that apply to most large scale (commodity) productions should be considered:

- Productions facilities should operate with as high availability/on-stream factor and as close to or beyond nameplate capacity as possible.
- Production plants need to be as large as practically possible in order to benefit from economies of scale.
- The location of production facilities should preferably be close to consumers in order to limit energy loss when transporting less energy-dense products such as hydrogen, ammonia and methanol.

In order to minimize the current price gap between current fossil fuels and future e-fuels, it is required to prioritize high on-stream availability. In section 5 below, we have made some financial simulations to illustrate the impact of a reduced availability factor and the resulting inefficiency of the complete PtX train. We find that even at 0 (zero) LCOE the energy source needs to be available >30% to give a competitive return on the PtX train alone.

A CO_2 free energy source with high availability and predictability will give the best economic indicators for the PtX train and a higher (than zero) LCOE will still lead to the overall lowest cost of green ammonia or eMethanol.

The Seaborg CMSR Power Barge could be one such source of energy.

The Compact Molten Salt Reactor (CMSR) Power Barge in brief

The CMSR Power Barge comes in four sizes: 200, 400, 600, and 800 MW electrical output. Each CMSR Power Barge is comprised of a number of 200 MW modules and each module has four compartments for the nuclear reactors (as illustrated in figure 2). The total lifetime of the barge is twenty-four years – split into two twelve-year periods. For the first twelve-year period, power is supplied from two reactors, which are then replaced by two new reactors for the second period. The reactors from the first period are then taken out of service and left on the barge. After twenty-four years of operation, the barge is removed and towed for decommissioning. The modular design and shipyard construction ensure high quality and a flexible, cost-efficient power solution.

The nuclear reactor itself uses Uranium as fuel, however unlike most conventional reactors using Uranium in a solid form, in the Seaborg reactors the Uranium is contained in a molten salt operating at high temperatures (600-700 deg C.). Removal of the heat from the fission reaction is ensured by heat exchange with a secondary salt loop which delivers the heat into a steam system that drives a conventional steam turbine and a generator.

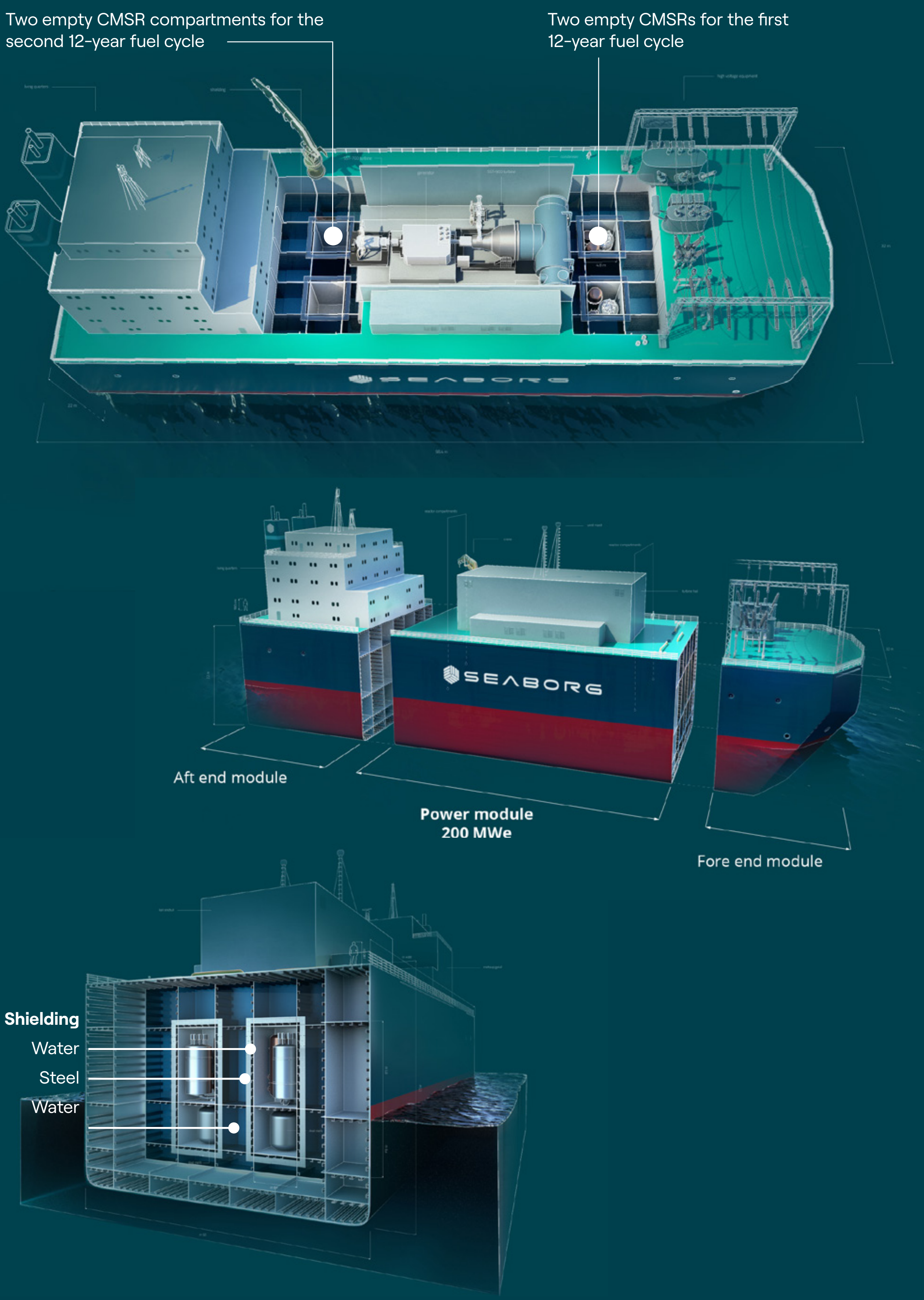
Like all other nuclear power plants, the Seaborg molten salt reactor will operate at a stable output and the plant is designed for high electrical availability in line with other nuclear power plants. The nuclear industry has a global average availability of close to 90% of the plants in operation — making these a very stable and predictable source of energy.

The CMSR Power Barge has the potential to be a very meaningful power source for future PtX plants as it will deliver an on-stream factor and comes in sizes that allow for plants with economies of scale, similar to fossil-based facilities. Both of these factors will be important when trying to minimize the “green premium” or rather the price gap between e-fuels over fossil-based fuels.

In addition, the CMSR Power Barge has the advantage of not being dependent on local wind or solar resources and it can therefore be located close to the demand. This siting flexibility gives a further advantage – the less energy dense the fuel, the less feasible it will be to transport the fuel from the production site to the user sites, making a flexible selection of location critical for hydrogen and still relevant for ammonia and methanol.

A final and important consideration is that with the siting flexibility, power can be supplied practically independent of location, and therefore countries without oil and gas reserves will have numerous possibilities to become energy independent as the fossil free energy will be provided with the supply of hydrogen/ammonia or methanol.

FIGURE 2 Inside the Power Barge. 24 years operational life time



e-Ammonia production

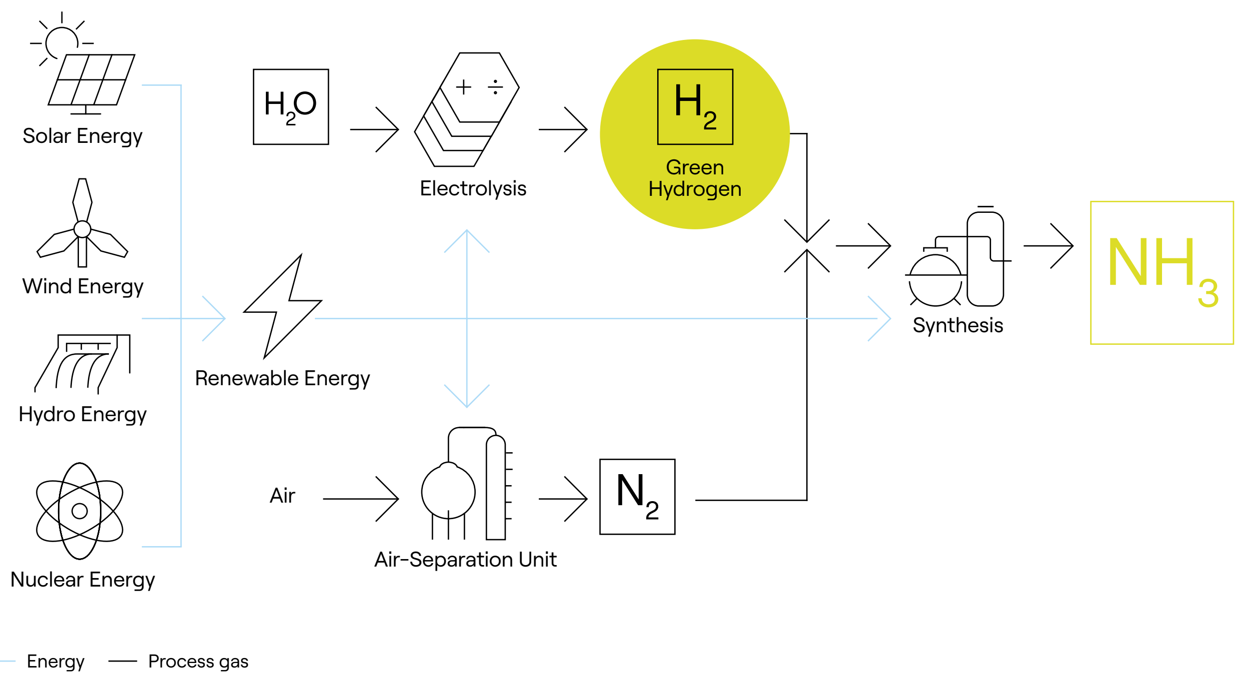
The largest Seaborg CMSR Power Barge delivers 800 MWe which, depending on the electrolyzer technology (Alkaline/PEM, SOEC), can be turned into 1900 – 2335 MTPD of ammonia respectively. This capacity range is within nameplate capacities of today's large conventional ammonia plants. The process lay-out for the Topsoe power to ammonia plant is shown below.

The Topsoe ammonia loop uses a highly efficient solid oxide electrolysis cell (SOEC) to split water into hydrogen and oxygen, and then combines the hydrogen with nitrogen from an air separation unit (ASU) to produce ammonia. The process is designed to be more energy-efficient and environmentally friendly than traditional ammonia production methods, which rely on fossil fuels.

One feature that makes this ammonia loop more efficient than a conventional ammonia loop is that the ammonia synthesis loop is "inert free" as the make-up gas (feed gas) to the ammonia synthesis is

FIGURE 3 The technology produces ammonia from energy sources such as wind, solar, hydroelectric, or nuclear power

GREEN AMMONIA PRODUCTION PROCESS THROUGH WATER ELECTROLYSIS



pure hydrogen and nitrogen. Only minor amounts of inert gases such as argon and helium from the ASU reach the ammonia loop via the nitrogen feed.

The biggest impact on the power consumption of the overall complex is the electrolyzer unit producing the hydrogen. Its' consumption accounts for approx. 88-92% of the available power as reflected in table 1 below. The Topsoe SOEC technology is inherently more efficient than alkaline and PEM technology. Furthermore, the ammonia loop from Topsoe benefits from heat integration with the solid oxide electrolyzer unit, thus lowering the power consumption. With a constant power supply from the Seaborg CMSR Power Barge of 800 MWe the above-described efficiency gains relate directly to more valuable ammonia product produced.

TABLE 1 Overview of distribution of electricity consumption

	AL/PEM	**SOEC**
Ammonia production capacity, %	100	123
Total power consumption, % (normalized)	100	100
Ammonia synthesis unit power of total *, %	5.8	8.3
Electrolyzer unit incl. water treatment power of total, %	91.5	88.4
Air separation unit (ASU) power of total, %	2.6	3.2
Off-sites & utilities power of total, %	0.1	0.1

*Ammonia loop produces power in AL/PEM case. Ammonia loop heat integration in SOEC case.

From a total complex perspective (i.e. power supply unit, electrolyzer unit, ammonia synthesis unit including ASU), the power supply unit, in this case the CMSR Power Barge, is the biggest cost item. Consequently, in line with any other production facility the highest possible on-stream factor for the power supply unit is therefore a goal in itself, to ensure the best possible economic feasibility of the entire operation.

Similar feasibility consideration is valid when it comes to the hydrogen/ammonia/methanol production in question – once the investment is made in the production facility, the lowest specific production cost is achieved with as high on-steam factor, at full capacity, as possible.

Baseload in combination with PtX

In order to consider the criteria in section 5, a potential solution could be that a number of production facilities are established with the purpose of producing the transportation fuel required and as a secondary objective to provide the necessary back-up power for the grid. Such a facility would have several advantages both technically and economically.

As described above, nuclear power in the form of a CMSR Power Barge in combination with already established technologies for PtX conversion, offers an attractive and sustainable CO_2-free production of hydrogen, ammonia, or methanol. It seems credible that a large portion of the future e-fuels will be powered from electricity coming from nuclear power as this will, due to its availability, increase the speed converting from a fossil to non-fossil based society. Building dedicated e-fuels plants, however, is not the only application for such a "production train".

The availability of renewable sources such as wind turbines, solar PV, geothermal and hydropower are very much dependent on the location and therefore any country will have to develop a mix of power sources based on availability and demand for power.

There are two major challenges to address:

a) the gap-filling when VRE sources fall short due to the lack of wind or solar, and
b) the ramping up to load during peak demand hours.

These can, to some extent, be mitigated by grid scale storage, but it can be observed in the IEA APS scenario that natural gas is expected to be a large part of the solution[3]. Another possibility to close this gap is to allocate a certain percentage – f.inst. 10 to 20% – of the power output from the CMSR Power Barge serving the PtX plant, to the grid. In this case, the plant owner will be compensated with a power price that guarantees at minimum the same project return (10% IRR) as in the case with full PtX production.

In table 2 below we have made some economic calculation examples comparing the different technologies/e-fuels based on the scenario of having electrical power from one 800 MWe CMSR Power Barge available. The availability is to be understood as % of hours in a full year at full capacity (24/7/365). Levelized cost of ammonia or methanol (LCO-A/M) has only been calculated when fully converted into ammonia/methanol and not in the cases where power is also supplied to the grid.

3 https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

TABLE 2 Overview of economical modelling results

Case description	Electro-lyzer type	Availability factor, %	Ammonia/ MeOH sales price, USD/t	LCO-A/M, USD/t	IRR, %	NPV, mill USD	Electricy price, USD/MWh
1900 MTPD Ammonia case	PEM	90	850	594	10.3%	532	
1900 MTPD Ammonia – 10% of power output to grid	PEM	90	850	–	10.5%	560	95
2335 MTPD Ammonia case	SOEC	90	850	518	12.8%	1281	
2335 MTPD Ammonia – 10% of power output to grid	SOEC	90	850	–	12.6%	1228	95
2230 MTPD Methanol	SOEC	90	750	593	8.1%	19	
2230 MTPD Methanol – 10% of power output to grid	SOEC	90	750	–	8.2%	60	95
2335 MTPD Ammonia case – Free electricity from grid	SOEC	30	850	477	13.1%	477	
2335 MTPD Ammonia case – Free electricity from grid	SOEC	15	850	1014	1.7%	-465	

Basis: One Seaborg 800 MWe CMSR Power Barge – WACC = 8%

Some of the most interesting observations from the table are the following:

1) The electrolyzer technology has significant impact on the production capacity and thereby the derived results (LCO-A/M).
2) The ammonia or methanol sales price of 850 USD/t and 750USD/t respectively is within the price range that have been traded already on the spot market with conventional methods, although it is on the high side and for shorter periods. Natural gas prices are expected to increase and that will naturally also impact the ammonia and methanol prices produced conventionally, so the gap will become smaller. Furthermore, a potential CO_2 tax on fossil natural gas will also contribute to minimizing the gap.
3) Electricity break-even prices of 95 USD/MWh are very competitive if the alternative is to build additional dedicated peak capacity to the grid. In addition, this also represents the most credible answer to a price cap on the electricity markets as the logical prioritization of the electricity will be to the highest value application. If the electricity market can pay a higher price than the inferred value from the PtX plant (including the cost of plant inefficiencies) the plant operator will increase the share of power to the electricity market.
4) It seems evident that even with free electricity, any PtX facility should be connected to a power supply source/grid allowing for a higher availability than the 30% in order to be feasible.

Although difficult to quantify economically, stable operations of large PtX facilities operating with large size rotating equipment (compressors, pumps), control of catalytic processes, operation at elevated temperatures and pressures are from an operational and maintenance point of view highly desirable. Which is another reason for seeking a high availability factor.

Concluding remarks

While the path to achieving net zero by 2050 might appear daunting, the necessary technologies already exist, as we have discussed in this paper. There is not a one-size-fits-all solution; the ideal blend of clean energy alternatives to fossil fuels will differ significantly among sectors and countries. Decisions will be influenced by a myriad of factors, including local market dynamics, capital availability, legislative frameworks, and political will.

In our analysis, we have the limitations of wind power and solar PV and addressed the obstacles to direct electrification for decarbonizing heavy transportation and industry. Furthermore, we have highlighted the potential of integrating two complementary clean energy technologies: Seaborg's CMSR Power Barge and Topsoe's SOEC electrolysis-driven PtX production facilities. We have presented various use-cases that underscore the synergy between 4th generation nuclear and PtX facilities, illustrating how this duo can offer competitive e-fuel production costs while offsetting the intermittency issues of VRE sources. This combination promises both a swift departure from fossil fuels and a reliable energy feed to the grid.

About Seaborg

Seaborg is a Danish nuclear energy company that delivers a new, safe nuclear technology based on a molten salt reactor design. The company's mission is to provide clean, safe, and reliable power generation to meet the growing demand for sustainable energy worldwide.

About Topsoe

This paper is co-authored by Topsoe, a global leader in developing solutions for a decarbonized world, including hydrogen, ammonia, methanol and e-fuel production technologies, catalysts, and other services for enabling the worldwide energy transition.

Topsoe has contributed to this paper by providing key data points and technical validation in relation to their SOEC electrolysis and ammonia loop technology.
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