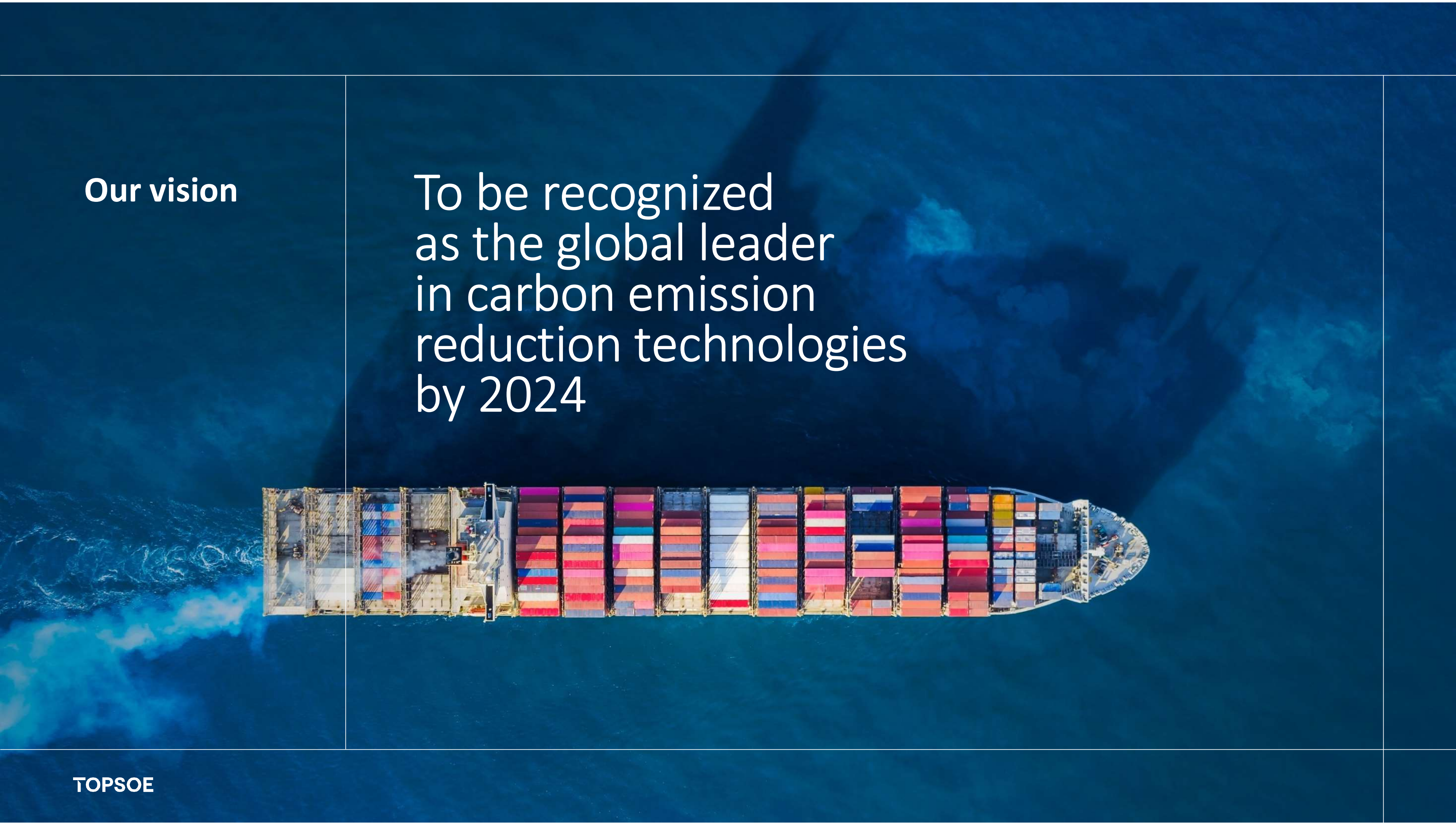
A SUSTAINABLE FUTURE FUELED BY SCIENCE

TOPSOE

Making the energy transition happen

Dinesh Kumar
Siddharth Singhroa

December 16, 2023


Our vision
To be recognized
as the global leader
in carbon emission
reduction technologies
by 2024
TOPSOE

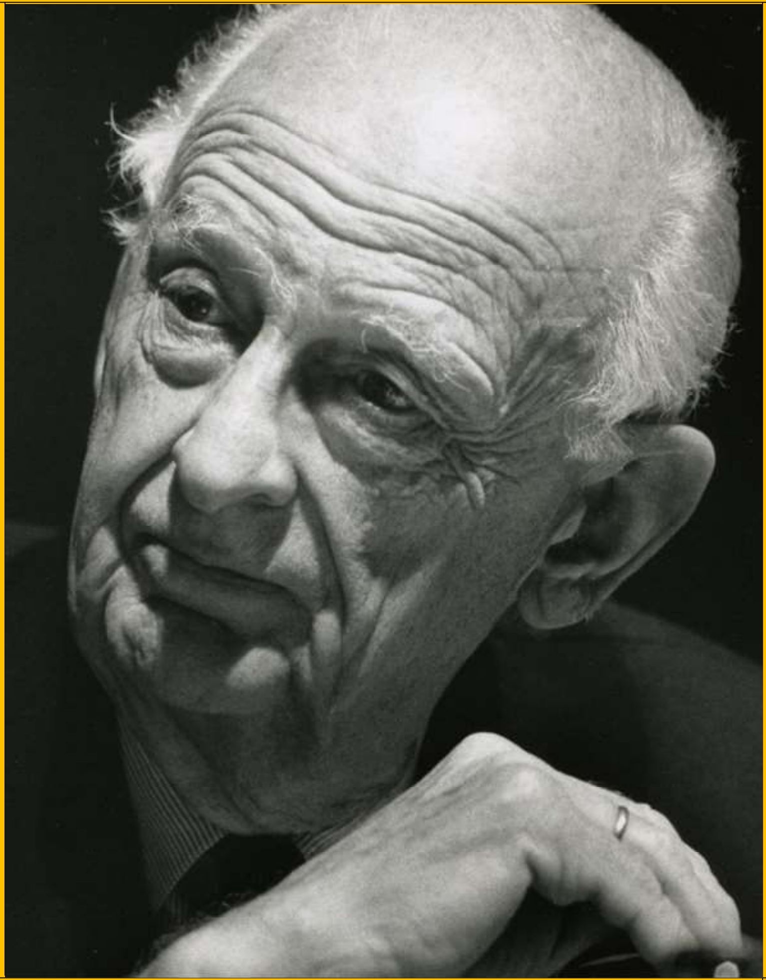
When Dr. Haldor Topsøe founded the company in 1940, he based it on two things:

A passion for science and a determination to make a positive difference to the world. We stay true to his legacy.

As a global energy technology company, Topsoe provides chemistry and science-based solutions that will make the green energy transition happen.

OUR PURPOSE:

PERFECTING CHEMISTRY FOR A BETTER WORLD

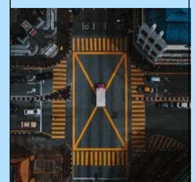


A HISTORY OF TAKING ON SOME OF THE WORLD'S TOUGHEST CHALLENGES

TODAY AND FOR THE FUTURE

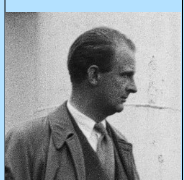
1950s

Topsoe ammonia technology to produce fertilizer helps feeding the growing world population



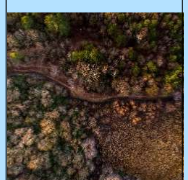
1990s

Topsoe clean air solutions remove hazardous particles, greenhouse gases, and smog from industrial emissions



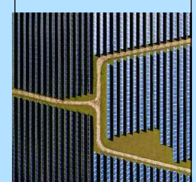
1940

Dr. Haldor Topsøe founds the company based on his passion for science and determination to make a positive difference in the world



1980s

Topsoe technology removes 18 million tons of sulfur oxides every year



2022

Topsoe solutions support all phases of the clean energy transition

TOPSOE AT A GLANCE: OVER 80 YEARS OF INNOVATION AND LEADERSHIP

For more than 80 years, we have been guided by our purpose, 'Perfecting chemistry for a better world'. We work to deliver solutions that will leave the world in better shape for future generations.

Today, it is our ambition to lead the global transition of hard-to-abate sectors to a net zero future.

Thanks to decades of exceptional R&D, Topsoe is in a **unique position** to accelerate the transition to sustainable technologies.

#1
In renewable fuels

#1
In low carbon hydrogen

+2,400
Employees

$1B
In revenue
(USD)

8.6%
Of revenues invested in R&D

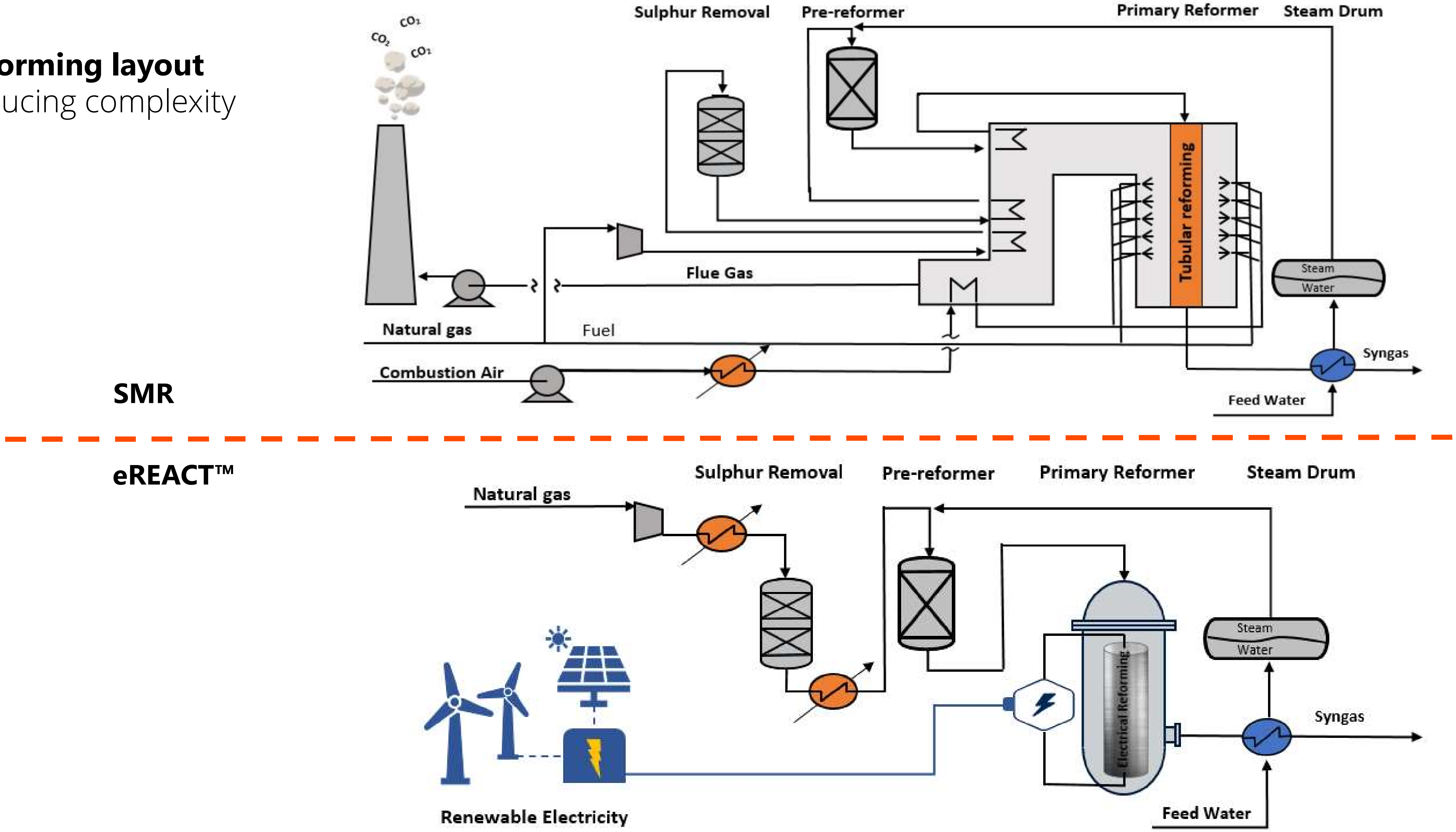
+500
Patent families


AGENDA
➢ eREACT™
➢ Green Ammonia
➢ Blue Ammonia
TOPSOE

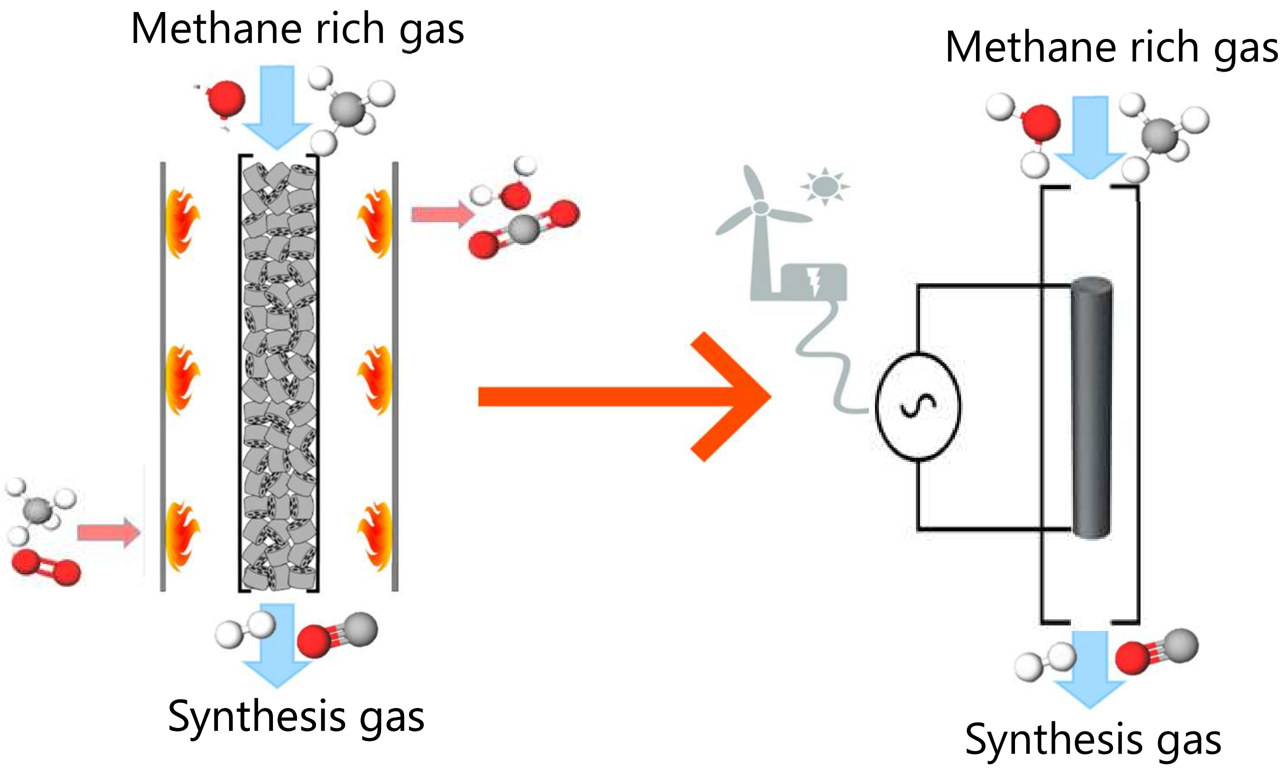
TOPSOE

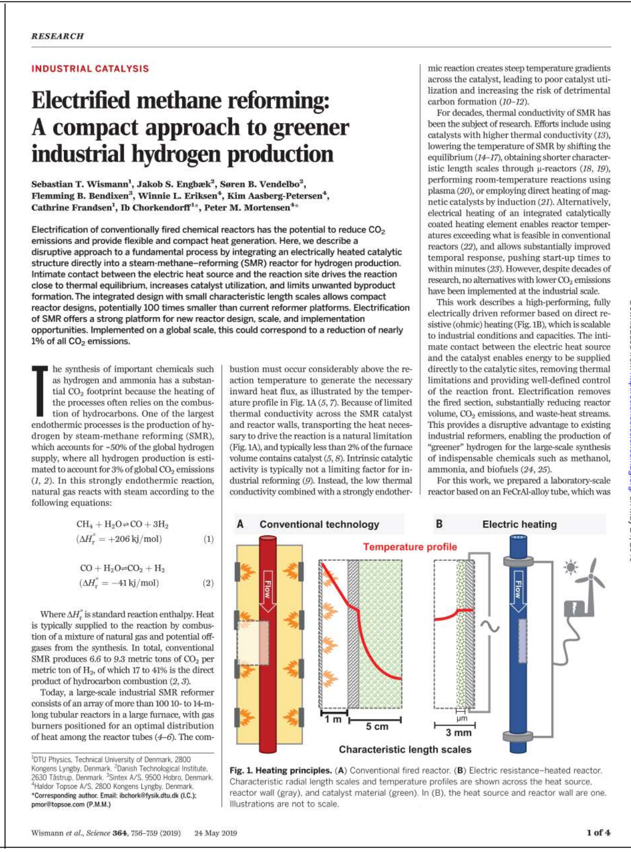
eREACT™
An initiative towards decarbonization

Reforming layout
Reducing complexity



WHAT IS eREACT™ ?





RESEARCH

INDUSTRIAL CATALYSIS

Electrified methane reforming: A compact approach to greener industrial hydrogen production

Sebastian T. Wismann[1], Jakob S. Engbæk[2], Søren B. Vendelbo[2], Flemming B. Bendixen[3], Winnie L. Eriksen[4], Kim Aasberg-Petersen[4], Cathrine Frandsen[1], Ib Chorkendorff[1]*, Peter M. Mortensen[4]*

Electrification of conventionally fired chemical reactors has the potential to reduce CO_2 emissions and provide flexible and compact heat generation. Here, we describe a disruptive approach to a fundamental process by integrating an electrically heated catalytic structure directly into a steam-methane–reforming (SMR) reactor for hydrogen production. Intimate contact between the electric heat source and the reaction site drives the reaction close to thermal equilibrium, increases catalyst utilization, and limits unwanted byproduct formation. The integrated design with small characteristic length scales allows compact reactor designs, potentially 100 times smaller than current reformer platforms. Electrification of SMR offers a strong platform for new reactor design, scale, and implementation opportunities. Implemented on a global scale, this could correspond to a reduction of nearly 1% of all CO_2 emissions.

The synthesis of important chemicals such as hydrogen and ammonia has a substantial CO_2 footprint because the heating of the processes often relies on the combustion of hydrocarbons. One of the largest endothermic processes is the production of hydrogen by steam-methane reforming (SMR), which accounts for ~50% of the global hydrogen supply, where all hydrogen production is estimated to account for 3% of global CO_2 emissions (*1*, *2*). In this strongly endothermic reaction, natural gas reacts with steam according to the following equations:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \quad (\Delta H_r^\circ = +206\ \mathrm{kj/mol}) \qquad (1)$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad (\Delta H_r^\circ = -41\ \mathrm{kj/mol}) \qquad (2)$$

Where ΔH_r° is standard reaction enthalpy. Heat is typically supplied to the reaction by combustion of a mixture of natural gas and potential off-gases from the synthesis. In total, conventional SMR produces 6.6 to 9.3 metric tons of CO_2 per metric ton of H_2, of which 17 to 41% is the direct product of hydrocarbon combustion (*2*, *3*).

Today, a large-scale industrial SMR reformer consists of an array of more than 100 10- to 14-m-long tubular reactors in a large furnace, with gas burners positioned for an optimal distribution of heat among the reactor tubes (*4*–*6*). The combustion must occur considerably above the reaction temperature to generate the necessary inward heat flux, as illustrated by the temperature profile in Fig. 1A (*5*, *7*). Because of limited thermal conductivity across the SMR catalyst and reactor walls, transporting the heat necessary to drive the reaction is a natural limitation (Fig. 1A), and typically less than 2% of the furnace volume contains catalyst (*5*, *8*). Intrinsic catalytic activity is typically not a limiting factor for industrial reforming (*9*). Instead, the low thermal conductivity combined with a strongly endothermic reaction creates steep temperature gradients across the catalyst, leading to poor catalyst utilization and increasing the risk of detrimental carbon formation (*10*–*12*).

For decades, thermal conductivity of SMR has been the subject of research. Efforts include using catalysts with higher thermal conductivity (*13*), lowering the temperature of SMR by shifting the equilibrium (*14*–*17*), obtaining shorter characteristic length scales through μ-reactors (*18*, *19*), performing room-temperature reactions using plasma (*20*), or employing direct heating of magnetic catalysts by induction (*21*). Alternatively, electrical heating of an integrated catalytically coated heating element enables reactor temperatures exceeding what is feasible in conventional reactors (*22*), and allows substantially improved temporal response, pushing start-up times to within minutes (*23*). However, despite decades of research, no alternatives with lower CO_2 emissions have been implemented at the industrial scale.

This work describes a high-performing, fully electrically driven reformer based on direct resistive (ohmic) heating (Fig. 1B), which is scalable to industrial conditions and capacities. The intimate contact between the electric heat source and the catalyst enables energy to be supplied directly to the catalytic sites, removing thermal limitations and providing well-defined control of the reaction front. Electrification removes the fired section, substantially reducing reactor volume, CO_2 emissions, and waste-heat streams. This provides a disruptive advantage to existing industrial reformers, enabling the production of "greener" hydrogen for the large-scale synthesis of indispensable chemicals such as methanol, ammonia, and biofuels (*24*, *25*).

For this work, we prepared a laboratory-scale reactor based on an FeCrAl-alloy tube, which was

Fig. 1. Heating principles. (**A**) Conventional fired reactor. (**B**) Electric resistance–heated reactor. Characteristic radial length scales and temperature profiles are shown across the heat source, reactor wall (gray), and catalyst material (green). In (B), the heat source and reactor wall are one. Illustrations are not to scale.

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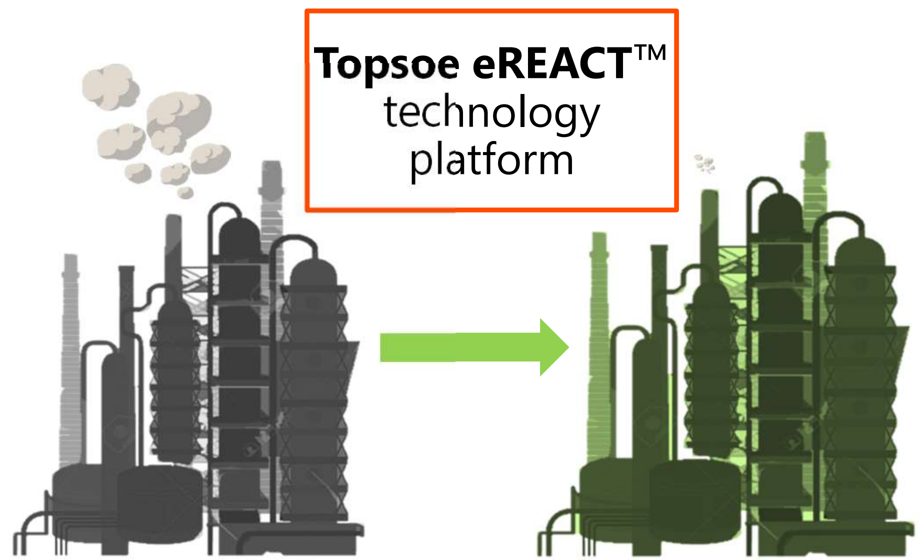
WHY eREACT™ ?
A GOOD FIT TO ENERGY TRANSITION AND FUTURE DEMAND

Demand for GHG emission reduction

Improved cost of renewable energy

Increased focus on Power-2-X

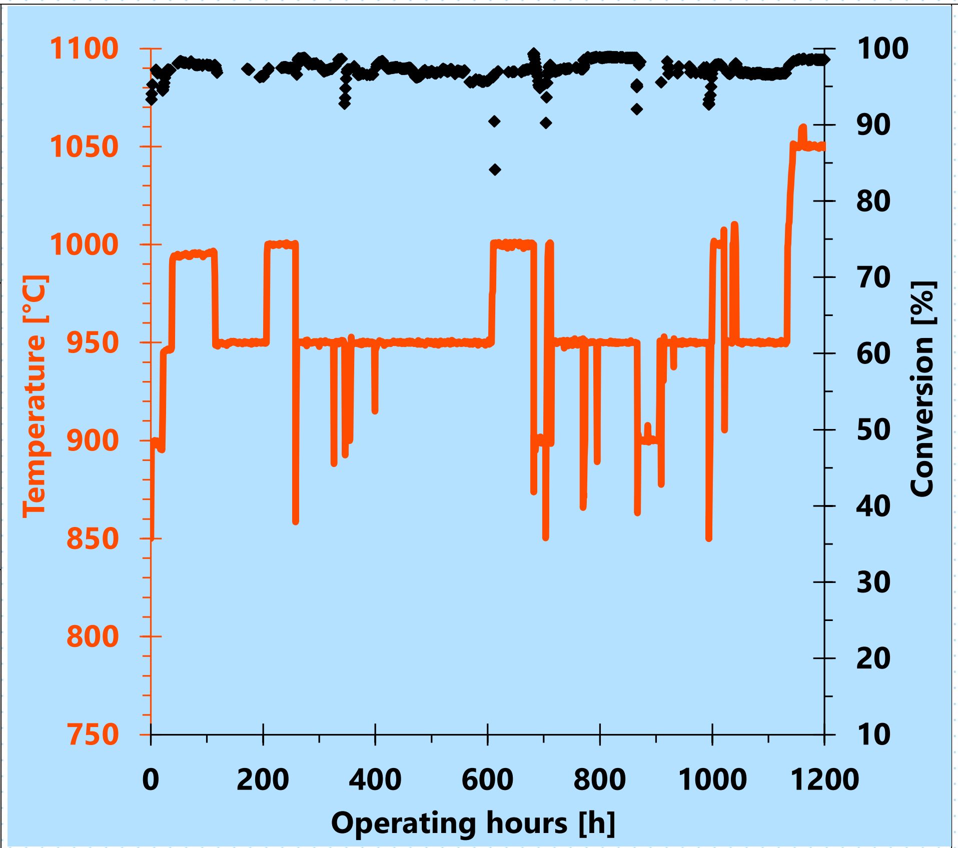
Solutions for both blue and green chemicals and fuels



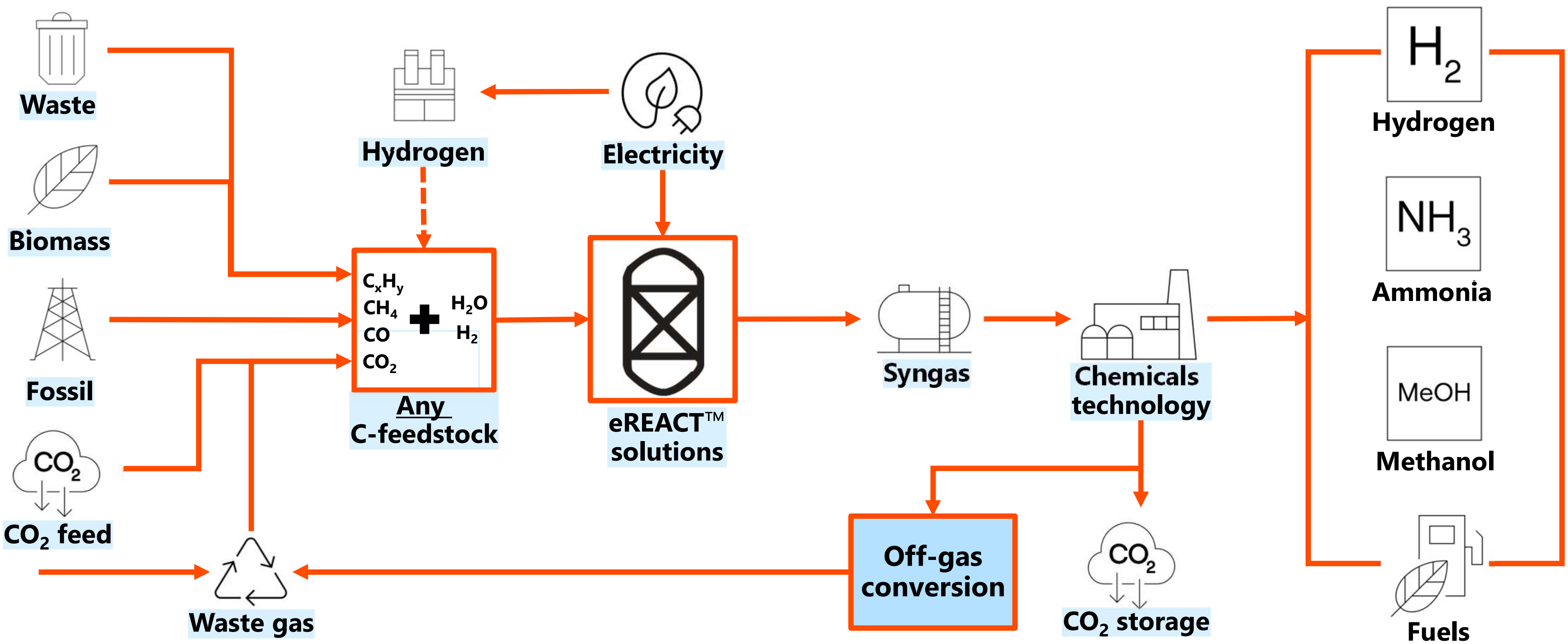
eREACT™ PILOT SITE FOULUM
CENTRAL JUTLAND, DENMARK

SELECTED OPERATING DATA FROM eREACT™ PILOT

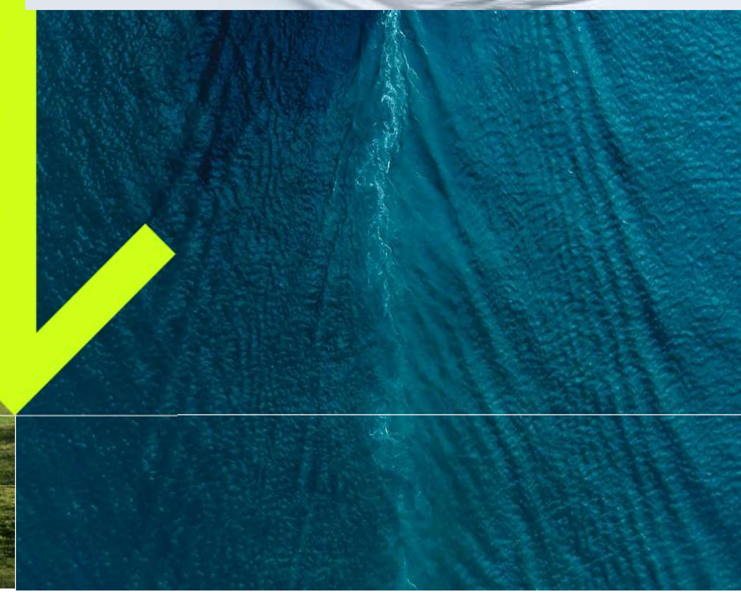
Stable Operation for several thousands' hours	**> 95%** Conversion
SOR = EOR eREACT™ performance	**900 – 1050°C** Exit temperature
Fast Start-up & turn down	**0** trips due to eREACT™



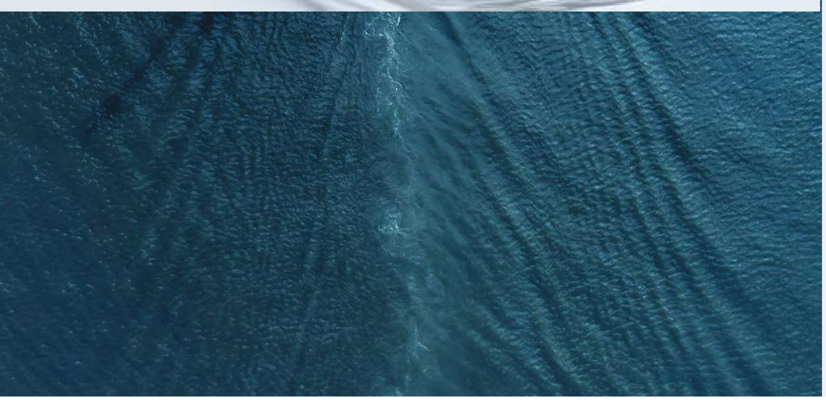
PLATFORM' TECHNOLOGY
APPLICATIONS




GREEN AMMONIA
TOPSOE



Green Ammonia to deliver a greener future



Green ammonia produced using renewable energy – is crucial to a low-carbon future. It can serve as a carbon-free fuel for industry and shipping, as well as stored energy to support renewable power grids. It's also easier and safer to transport than the hydrogen it derives from.

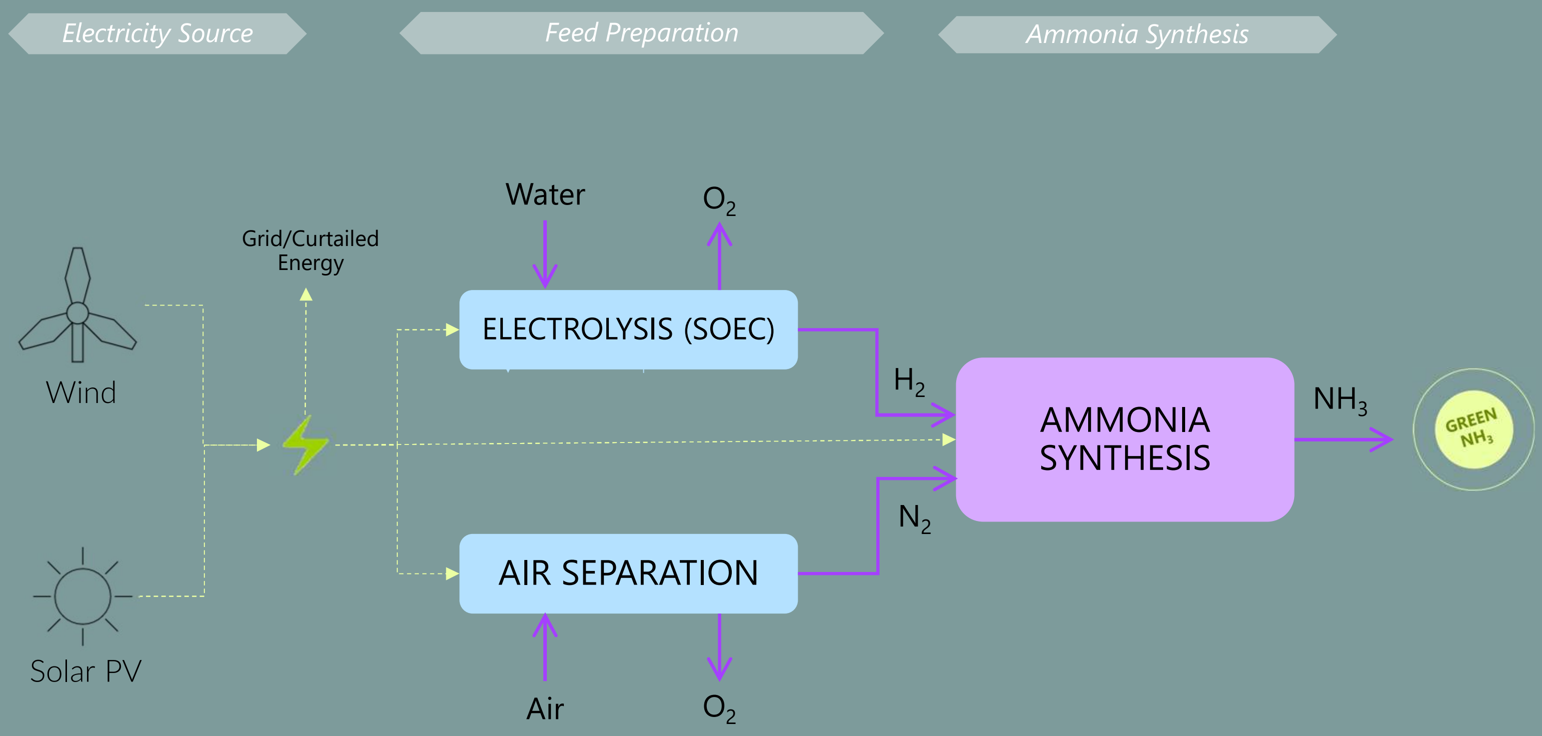
Producing green ammonia demands electrolysis on a huge scale. Topsoe's solid oxide electrolyzer cell (SOEC) technology promises to provide exactly that. Our new facility in Denmark will produce electrolyzers.

> To produce enough ammonia, we need companies like Topsoe. They're uniquely positioned to get it right and help us demonstrate to the world that this works.

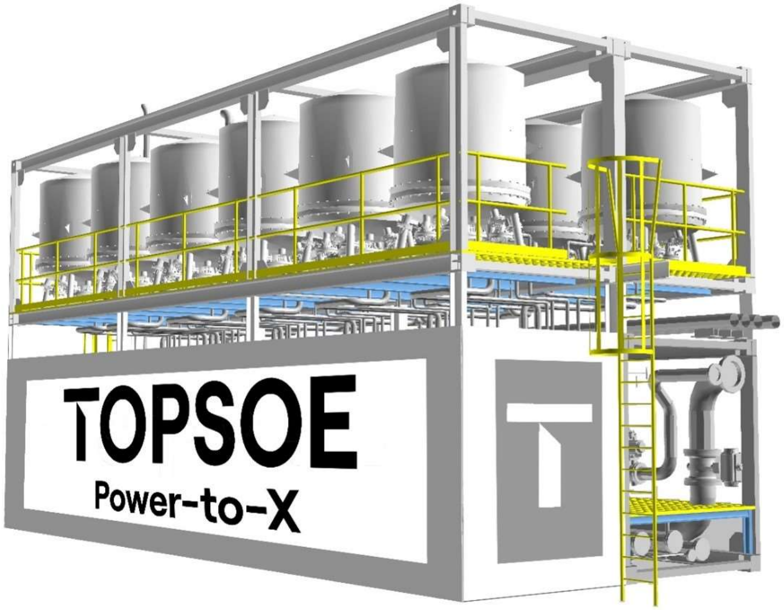
JOEL MOSER
CEO, First Ammonia

POWER TO AMMONIA : DYNAMIC OPERATION

RENEWABLE ENERGY ➔ ELECTROLYSIS ➔ SYNTHESIS

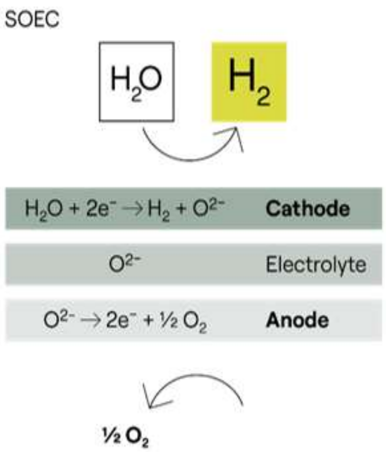


HOW DOES TOPSOE'S SOEC WORK?



$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

- An anode, "oxidizing" electrode, which requires electrons from the external power source
- A cathode, "reducing" electrode, which releases electrons to the external power source
- An electrolyte



Blue Ammonia

NH_3

TOMORROW'S FUEL.
READY TODAY.

PATHWAY
BLUE

TOPSOE

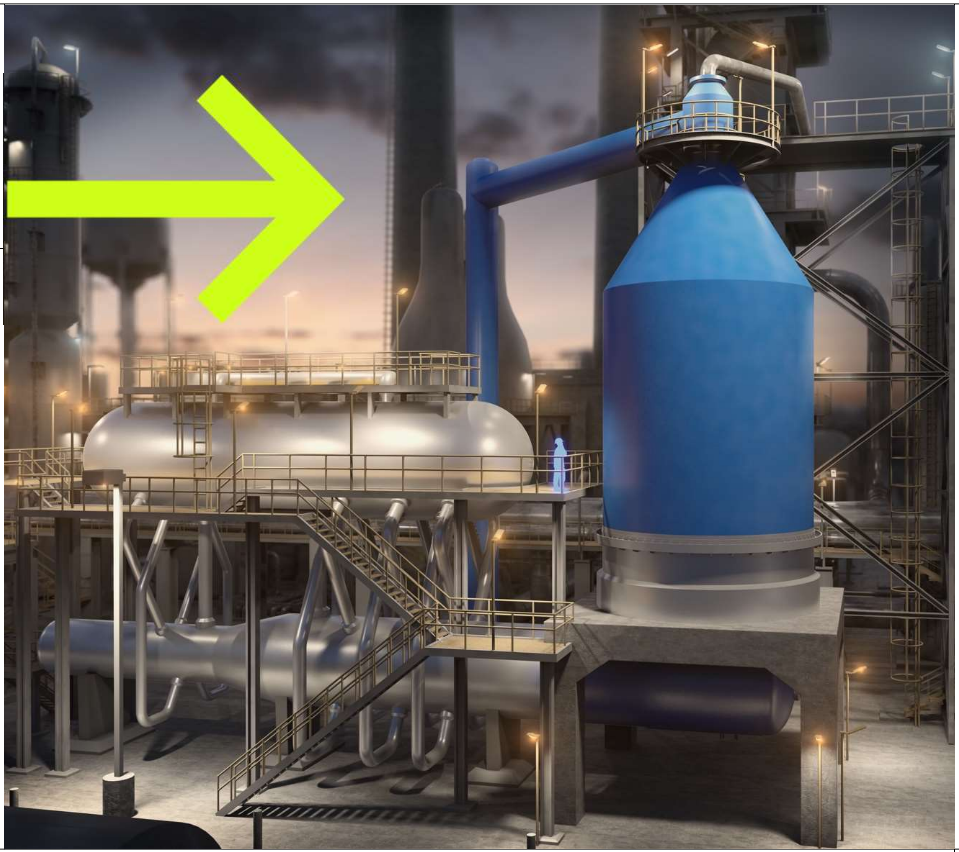
BLUE AMMONIA

The Blue Ammonia process

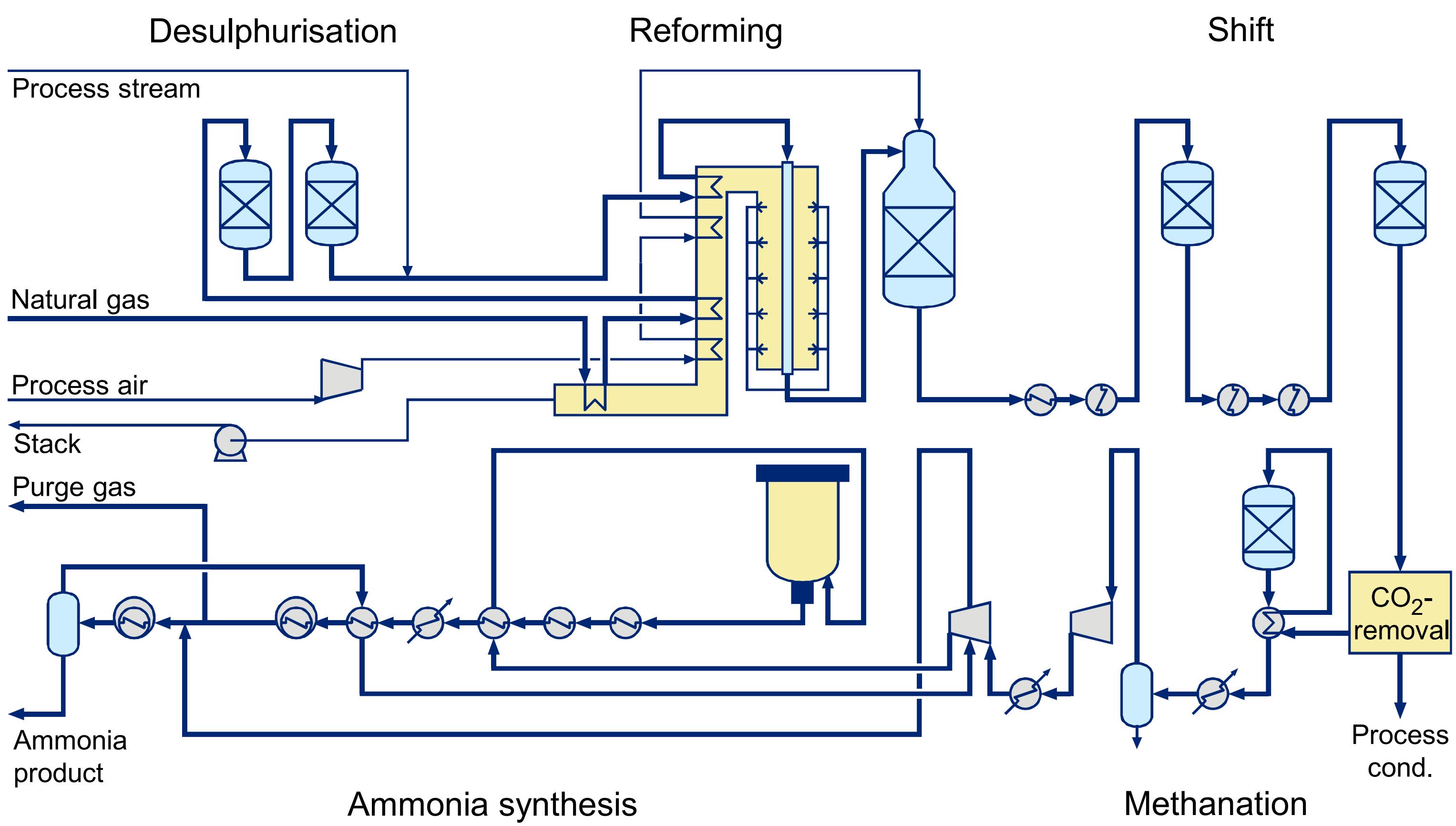
- Blue ammonia is an environmentally friendly way of producing NH3 through integrated carbon capture (CC).

Proven & reliable blue ammonia technologies

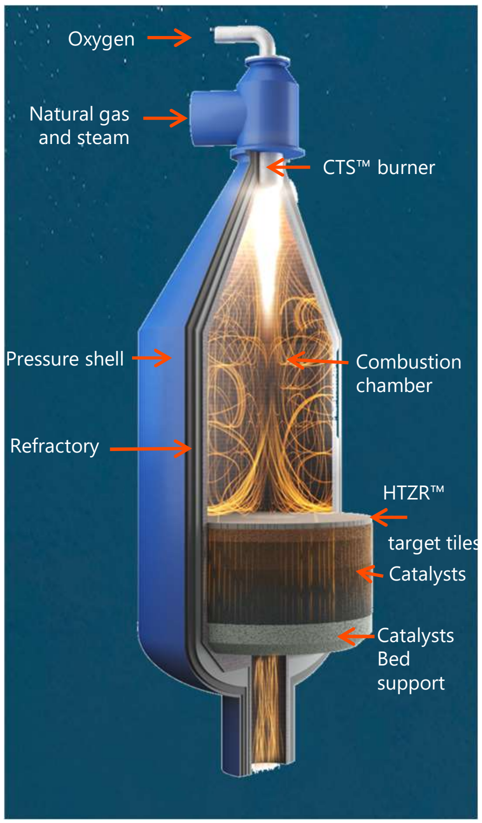
- Carbon-free
- High energy density – nearly 3x more than compressed hydrogen
- Easy to liquefy, store, and transport
- Production and transportation infrastructure already in place
- Blue ammonia checks all the boxes as the market's most viable and cost-effective low carbon intensity fuel.

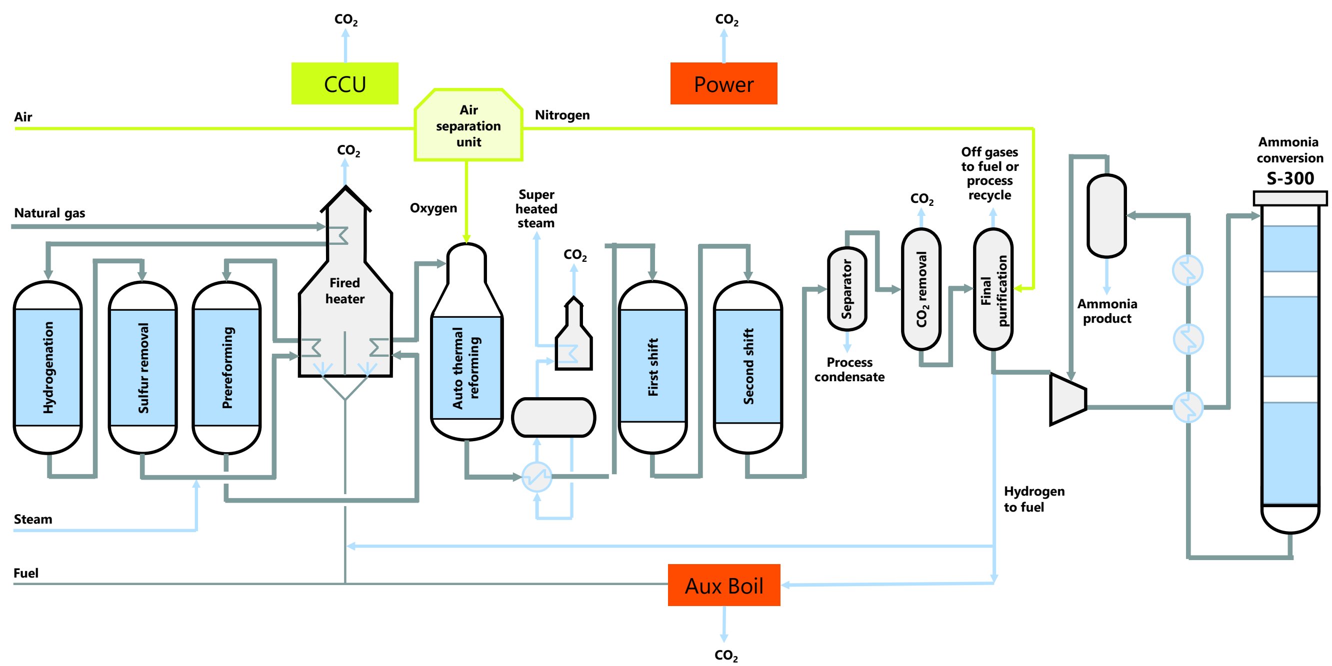


STEAM METHANE REFORMING



THE SynCOR™ AMMONIA PROCESS LAYOUT

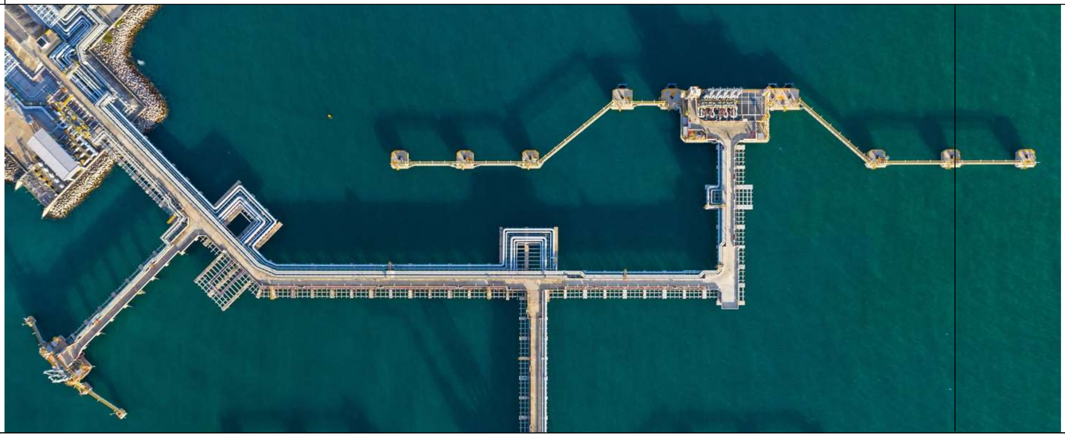




BEST-IN-CLASS TECHNOLOGIES

SynCOR™

- Unparalleled economy of scale
- Capacity: Up to 6000 MTPD single train




Thank you
“Understanding Is The Basis Of Development.”
Dr. Haldor Topsøe
TOPSOE

QUESTIONS?

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TOPSOE