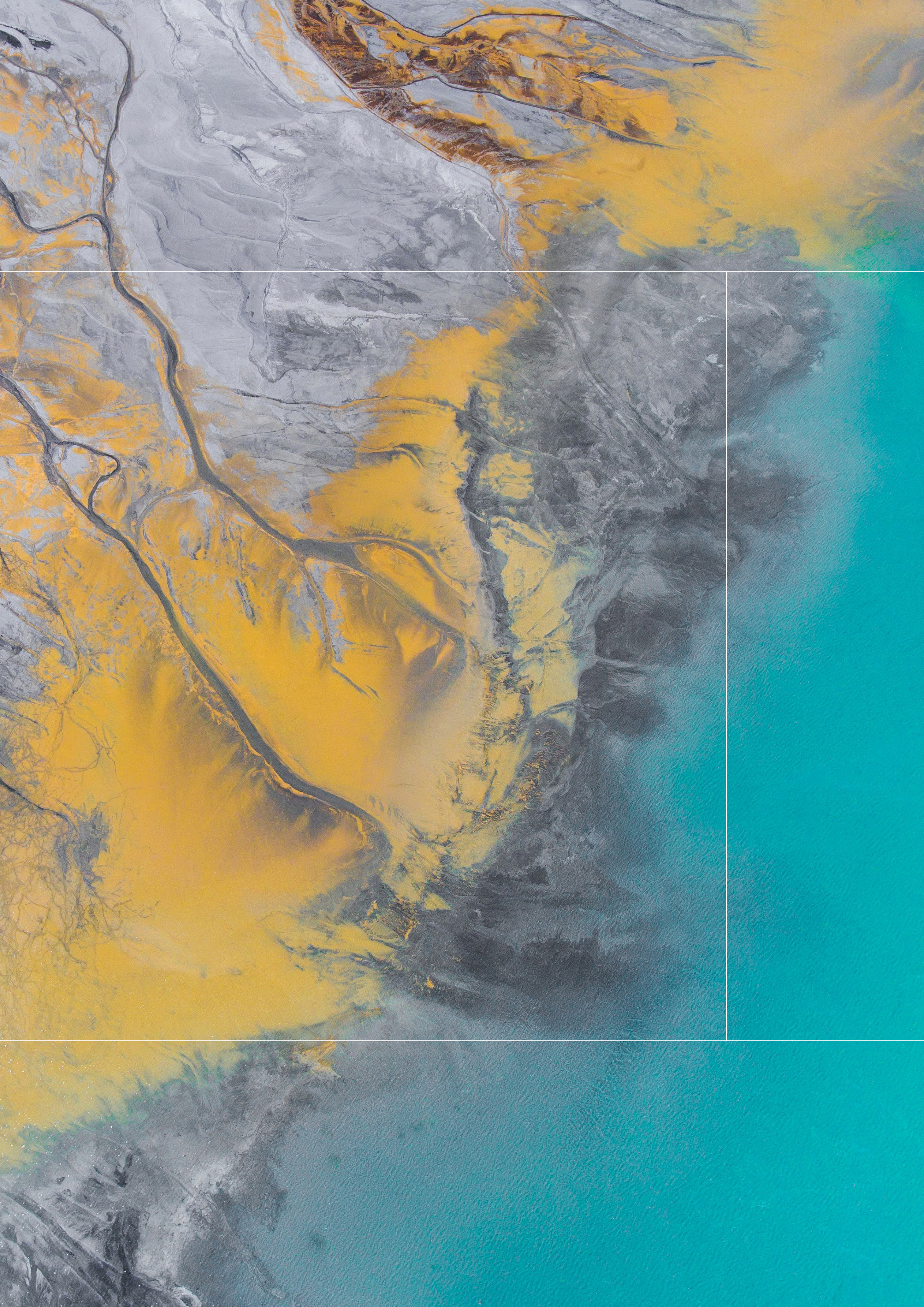
TOPSOE **PtX**

BRIDGING THE GAP

Transforming renewable energy and the net zero future of hard-to-abate sectors with Power-to-X

TOPSOE



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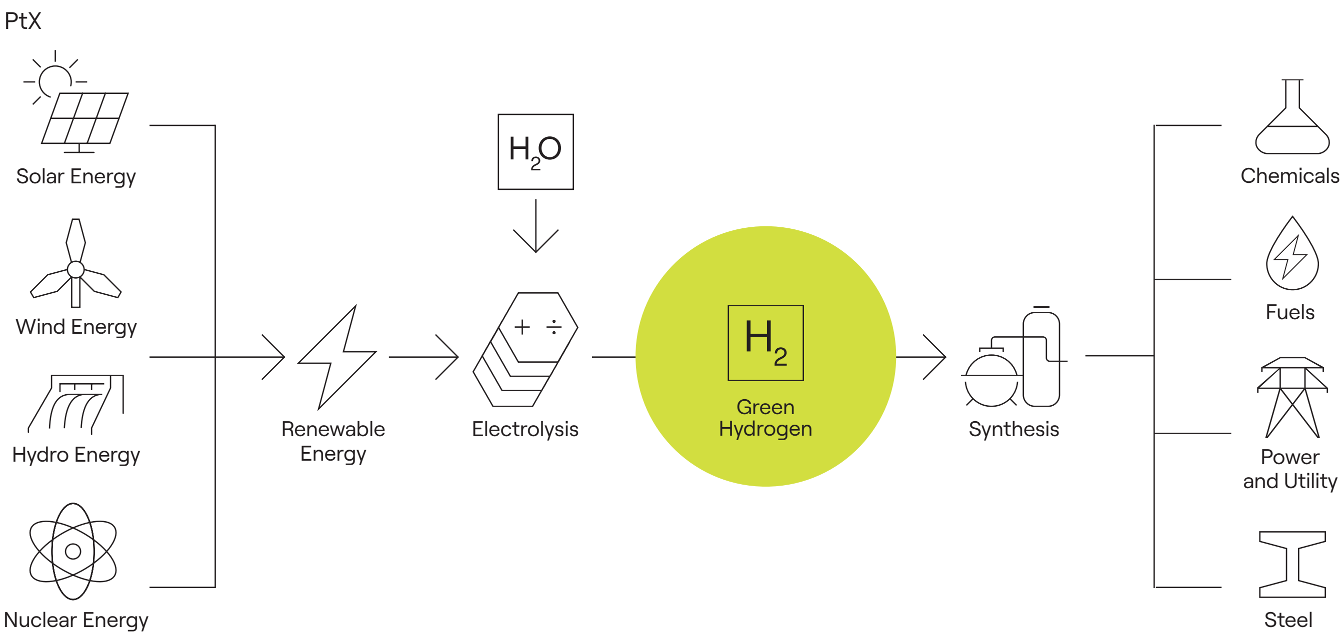


The road to net-zero by 2050 will not be paved by any one single idea or technology. Like most complex problems that need to be addressed at a global scale, the energy transition can only be enabled through an ecosystem of complementary solutions that prioritize equitable, sustainable, and scalable energy systems.

Power-to-X (PtX) is one of these key solutions.

To learn more about Topsoe's other PtX technologies and solutions, get in touch today with **PtXBD@topsoe.com**

Despite its massive potential, PtX is, at least on the surface, quite a simple idea. As a term, "PtX" covers a family 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). For example, this 'X' typically designates a variety of derivatives such as eMethanol, green ammonia and Sustainable Aviation Fuel (eSAF), as well as other chemicals and fuels that can be used across industries. By changing the form of renewable energy from electricity to molecules, we make it more fit for decarbonizing industries that cannot be directly electrified fully and at scale.

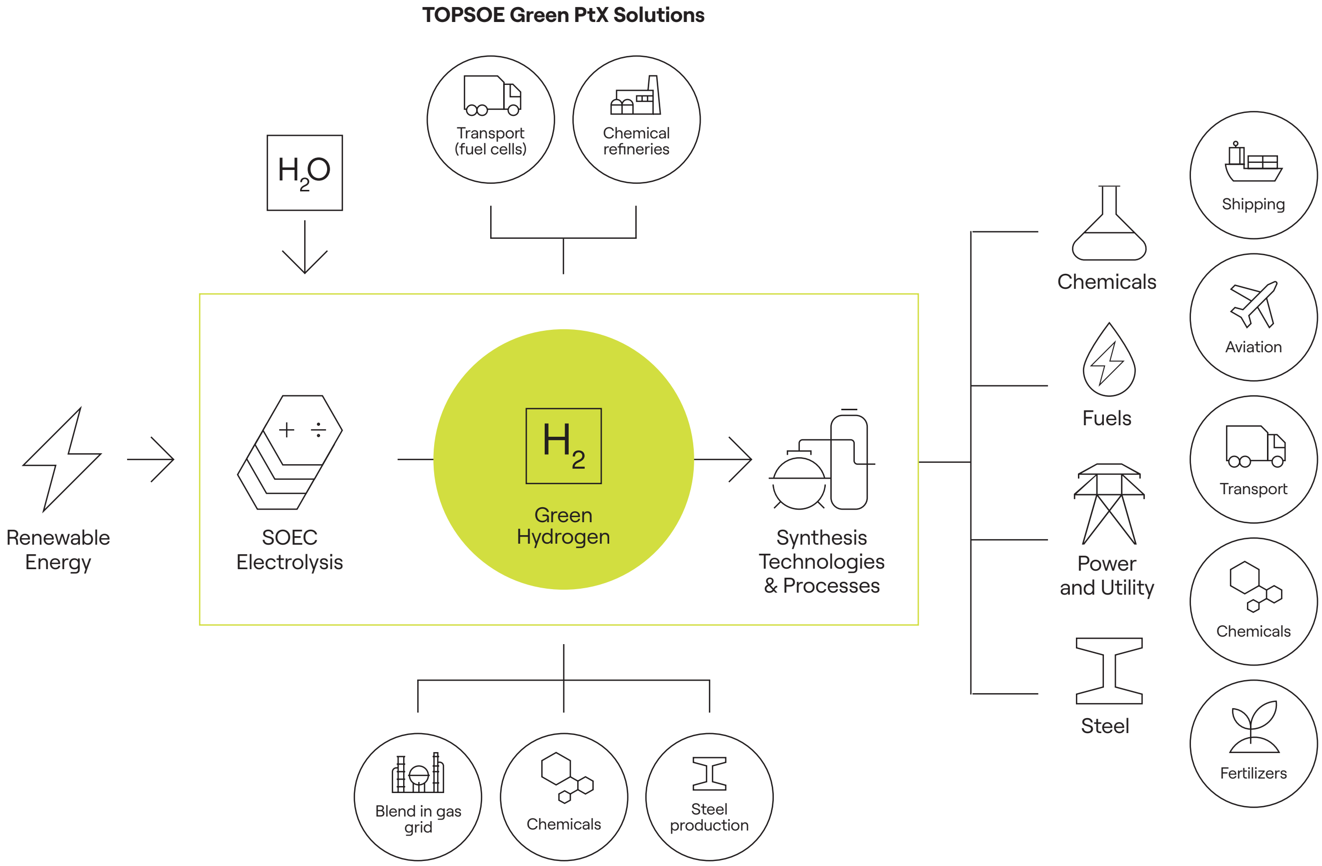
PtX is the bridge between a wind turbine and sustainable aviation fuel; a solar farm and carbon-free shipping; and the world's most carbon intensive industries and a net-zero future.

TOPSOE IN POWER-TO-X

To transition hard-to-abate industries away from carbon-intensive energy sources, the demand for sustainable alternatives such as green hydrogen and its derivatives are set to rise exponentially. At Topsoe, we know the path to decarbonization within these industries will operate differently depending on their own unique challenges. Because of this, we have leveraged over 80 years of scientific knowledge and innovation to deliver end-to-end PtX offerings that bring adaptable, tested and proven solutions to this dynamically evolving market.

This brochure offers an introduction to the heart of Topsoe's Power-to-X offering, the SOEC electrolyzer, and a detailed technical overview of the advantages its high temperature electrolysis exhibits when compared to the low-temperature alternatives of alkaline and PEM.

TOPSOE'S PTX OFFERINGS



UNDERSTANDING THE ELECTROLYSIS PROCESS

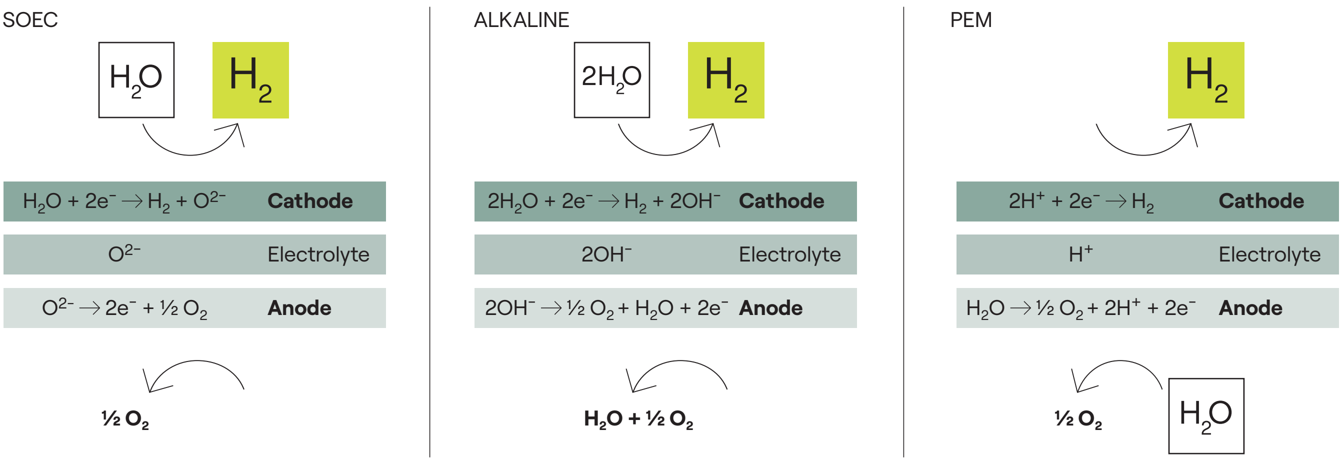
Electrolysis is commonly accomplished by using three different industrial technologies: high-temperature Solid-Oxide Electrolysis Cell (SOEC); low-temperature alkaline electrolysis; and low-temperature polymer electrolyte membrane (PEM) electrolysis. For alkaline and PEM electrolysis, water is supplied in a liquid state, whereas SOEC leverages steam.

The operation of the three technologies also differs. For SOEC, the breakdown of the steam takes place within the SOEC cell, with the steam being supplied at the cathode, where it is split via reduction into a green hydrogen molecule and oxide ions (O^{2-}). The oxide ions are then transported through the electrolyte to the anode and oxidized into oxygen molecules.

During alkaline electrolysis, liquid is supplied at the cathode, where hydrogen production occurs. Hydroxide ions (OH^-) are then transported over the electrolyte to produce oxygen molecules and water at the anode.

During PEM electrolysis, liquid water is supplied at the anode, where oxygen production occurs. Protons (H^+) are then transported over the electrolyte to produce hydrogen at the cathode.

CONCEPTUAL DIAGRAM OF SOEC, ALKALINE, AND PEM ELECTROLYSIS, INCLUDING HALF-CELL REACTIONS (THE OXIDIZING AND REDUCTION REACTIONS)



TOPSOE'S SOEC TECHNOLOGY

Topsoe's SOEC technology is a modular design that leverages high-temperature electrolysis — a tested and proven process that enables industrial-scale production of green hydrogen using renewable electricity. Due to the nature of the intrinsic fast-reaction kinetics and optimized conductivity found in high-temperature electrolysis, **Topsoe's SOEC technology produces more hydrogen per total power input when compared to the alternatives of alkaline and PEM electrolysis.**

Additionally, when coupled with waste heat-producing technologies (such as those used in ammonia production, methanol production or steel production), SOEC allows for the lowest levelized hydrogen cost with the highest level of energy efficiency per megawatt or gigawatt volume, no matter the industry.

With Topsoe's SOEC, the value of a renewable electricity investment is utilized optimally to produce green hydrogen. This results in carbon-free, highly efficient processes for Power-to-X solutions.

WHAT IS WATER ELECTROLYSIS?

At the foundation of the PtX concept is the utilization of renewable power for water electrolysis. This is a process where an electric current is used to split water into gaseous hydrogen and oxygen:

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

This reaction is endothermic (heat-absorbent), so energy delivered in the form of electricity and heat must be supplied for the reaction to take place.

Electrolysis is accomplished by four key components:

- an anode (positive "oxidizing" electrode, which requires electrons from the external power source),
- a cathode (negative "reducing" electrode, which releases electrons to the external power source),
- an electrolyte,
- an external power source.

PROCESS & DESIGN

SAFETY & QUALITY

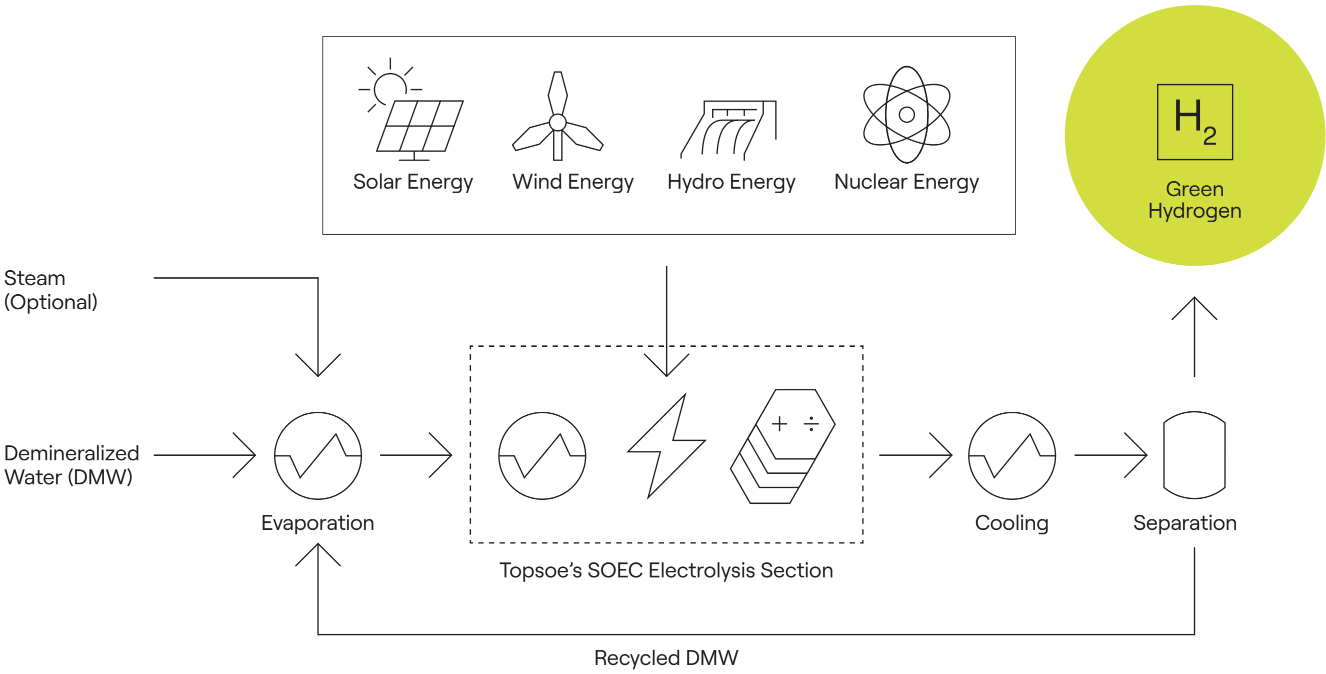
All of our SOEC electrolyzers are extensively tested before shipment, ensuring that you receive products of the highest quality and safety.

HOW IT WORKS

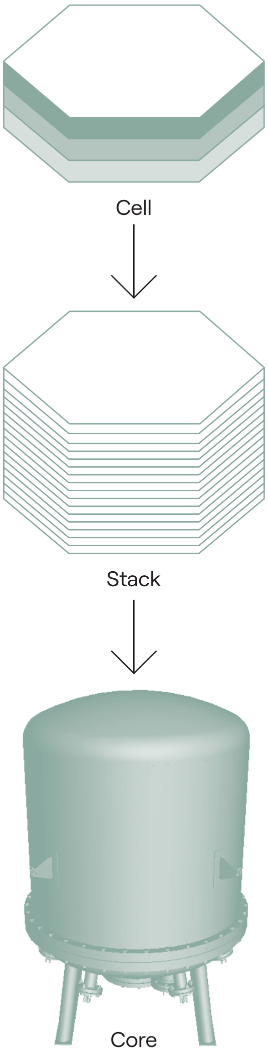
Demineralized water is evaporated, and then heated to the required temperature range from 675°C to 825°C at the entrance of the SOEC section; low-value steam can be imported to aid in the evaporation process. In the SOEC section, further heating takes place along with the reaction itself. SOEC has a wide operating range, which allows for mitigation against degradation of the stacks.

The SOEC cells are compact structures built primarily from abundant, low-cost ceramic materials. The steam flows in metal structures and is evenly distributed through microchannels into the cells. Within these cells, the electrolysis reaction splits the steam into hydrogen and oxygen, after which the latter leaves the electrolyzer while the hydrogen is cooled; excess water is then recycled via a separation process. The saturated, green hydrogen can then be compressed or purified to meet the clients' requirements.

GREEN HYDROGEN PRODUCTION PROCESS THROUGH SOEC SECTION

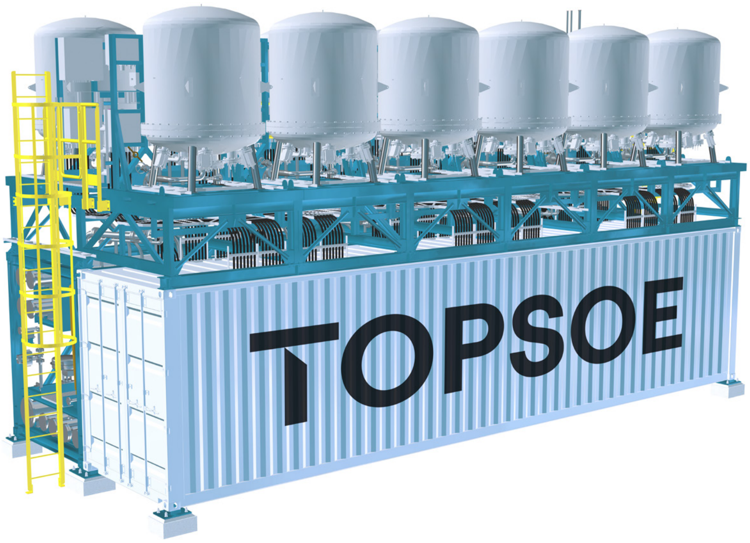


SOEC CELL, STACK AND CORE



The design of Topsoe's SOEC is based on three main components: cells, stacks and cores. Each core is made up of an array of stacks, which in turn are composed of a series of cells placed on top of each other. A sequence of these cores makes up a full SOEC section. Each SOEC section is specifically designed to facilitate easy service and maximize plant uptime. For example, every SOEC stack can easily be replaced without the need to replace the entirety of the core – prolonging the longevity of the technology, avoiding unnecessary material waste and maximizing plant efficiency.

3D MODEL OF A SOEC HYDROGEN SECTION WITH APPLICABLE UTILITIES AND EQUIPMENT



IN THE DETAILS

THE ADVANTAGES OF SOEC OVER ALKALINE & PEM

The higher efficiency of Topsoe's SOEC technology over alkaline and PEM is driven by the fact that SOEC operates at a higher temperature, benefitting from faster kinetics and higher conductivity. As a result, Topsoe's SOEC solution runs at a lower voltage, which translates into a lower power consumption per unit of hydrogen produced.

Higher temperatures make it easier to drive the electrolysis reaction, allowing for more efficient hydrogen production

The availability of electricity is an essential factor in the electrolysis reaction and it is supplied in the form of a voltage that drives the reaction.

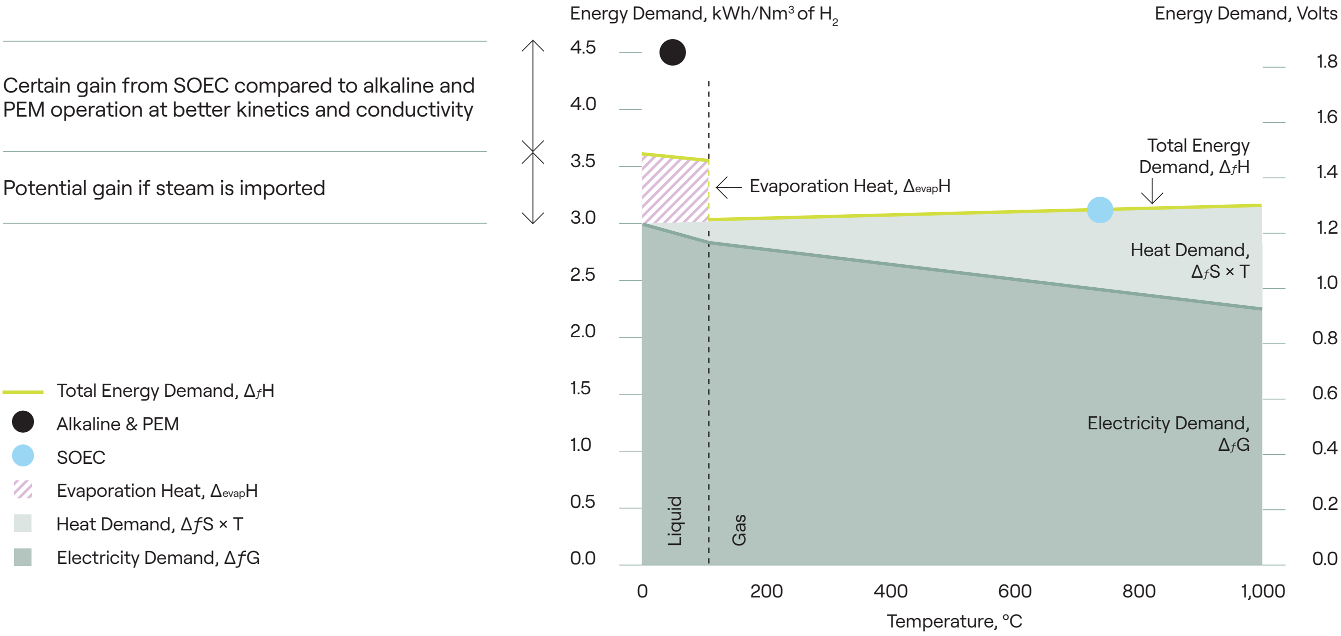
The electrical demand, known as Gibbs Free Energy (amount of available energy of a substance that can be used in a chemical reaction), $\Delta f G$, decreases as temperature increases. Furthermore, **kinetics and conductivity both increase at higher temperatures. Higher temperatures make it easier to drive the electrolysis reaction, allowing for more efficient hydrogen production** per area of electrolyzer cell.

However, operation at a voltage covering the exact electricity demand will result in insufficient current density, resulting in unsatisfactory hydrogen-product flow. This is due to the reaction's heat demand, which is the product of the reaction temperature, and Entropy (amount of energy which is unavailable to do work), $\Delta f S \times T$. Heat demand increases with the temperature since energy is required to heat steam or liquid water to a desired temperature.

The total energy demand, known as Reaction Enthalpy (amount of energy in a system), $\Delta f H$, is the sum of the Gibbs Free Energy and the product of the temperature and Entropy, as defined in the equation below:

$$\Delta f H = \Delta f G + (T \times \Delta f S)$$

ENERGY DEMAND FOR WATER ELECTROLYSIS



1. SOEC electrolysis benefits from operation at a lower voltage

SOEC is more efficient than both alkaline and PEM technologies since it operates at a lower voltage. SOEC operates at a voltage covering exactly the sum of the electricity and heat demand, while alkaline and PEM processes both operate above the sum of these two. The reason for this is that **SOEC operates at the thermo-neutral voltage**, which is the point at which the heat demand is balanced out by the Joule Heat. Joule Heat is produced from resistance that occurs when an electric current is applied to the electrolysis cells. This, in turn, means that temperature gradients do not occur within the SOEC, as the temperature of the steam supplied is equivalent to the temperature of the resulting green hydrogen product.

On the other hand, when operating at the thermo-neutral voltage at lower temperatures, the same current densities are not achieved, since the kinetics and conductivity are not as fast or as high, respectively. Therefore, in order to achieve competitive current densities, alkaline and PEM technologies must operate at voltages above the thermo-neutral voltage. This results in the production of excess heat, which is lost energy that is then removed, for instance in the form of cooling water. As a result, alkaline and PEM systems both require constant auxiliary cooling to prevent temperature increases, which is expensive and inefficient.

SOEC'S ADVANTAGE OVER ALKALINE AND PEM TECHNOLOGIES

2. SOEC electrolysis benefits from optimal design and plant integration

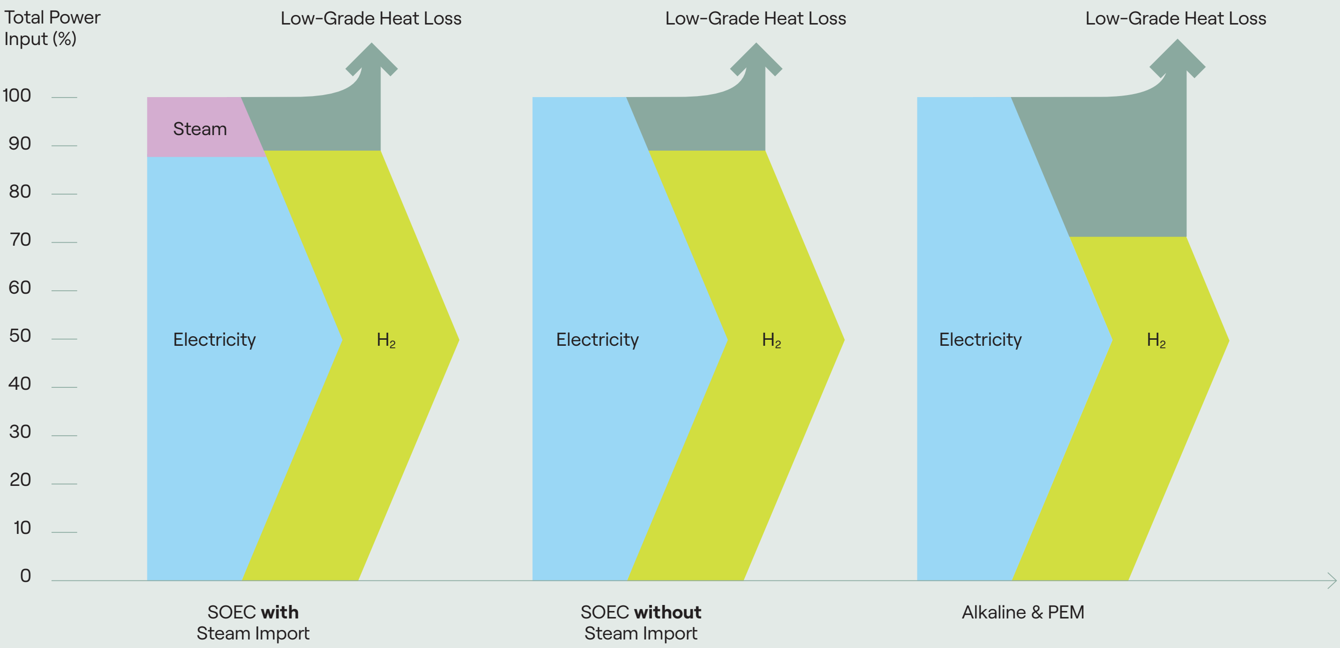
When compared to alkaline and PEM alternatives, the SOEC electrolysis process requires less power overall. Additionally, with the integration of a steam feed, the SOEC process becomes even more efficient.

Since the hydrogen product is in a gaseous state, extra energy is required to evaporate any water needed for alkaline or PEM processes. In the case of SOEC, steam is utilized, resulting in further reduction of the total energy demand.

Bear in mind though, that the steam used in SOEC electrolysis must be produced through the evaporation of water, which requires energy. This is in part provided with heat recovered from the SOEC setup. **With Topsoe's SOEC solution, 30% of this heat is recovered and used for heating process streams, such as steam, to the SOEC itself. The vast majority of the remaining 70% is obtained through heat integration**, which involves coupling the SOEC with other downstream and waste heat-producing processes, such as ammonia, Fischer-Tropsch, or steel production.

In contrast, heat recovered from alkaline and PEM processes exhibits a low temperature, which is unsuitable for heat integration and is expelled as low-grade heat. As such, the low-temperature waste heat from the alkaline and PEM technologies must be removed by water, or air coolers, which further enhances the advantage of SOEC. This is emphasized by considering the Higher Heating Value for hydrogen, expressing the energy content, which is 39.4 kWh/kg. By using this value, it is clear that alkaline and PEM technologies have a larger loss of low-grade heat compared to SOEC.

ILLUSTRATING THE ENERGY FLOWS FOR EACH TECHNOLOGY BASED ON THE HIGHER HEATING VALUE OF GREEN HYDROGEN



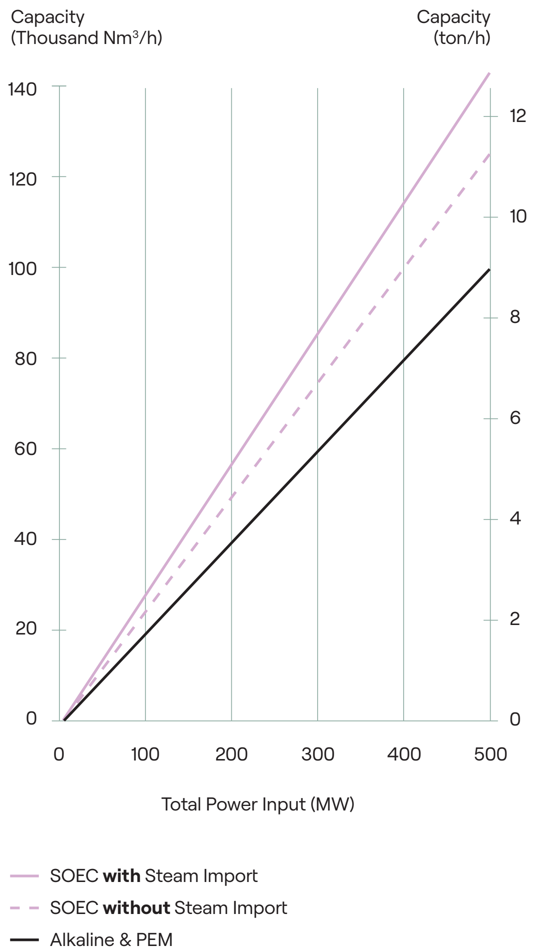
These diagrams give a comparison of the efficiency of the technologies, to illustrate how much of the total energy input is converted into green hydrogen and how much is lost as low-grade heat. Here it is evident, that alkaline and PEM both have a significant low-grade heat loss from the total energy input, further emphasizing the advantage of SOEC.

3. SOEC electrolysis produces more hydrogen per unit of power consumed

More hydrogen is produced, per total power input, by SOEC technology compared to alkaline and PEM, **making SOEC a more efficient solution.** This efficiency is further improved when steam is imported, whereby **SOEC's hydrogen-production capacity per total power input increases compared with that of alkaline or PEM.**

By comparing the three technologies' energy flows, it is evident, that SOEC is significantly more efficient. The advantage of operating a SOEC comes from its highly optimized design, which produces more green hydrogen while exhibiting only minor low-grade heat losses from the total heat input.

CAPACITY AS A FUNCTION OF TOTAL POWER INPUT



Additional technical information available by scanning the QR-code

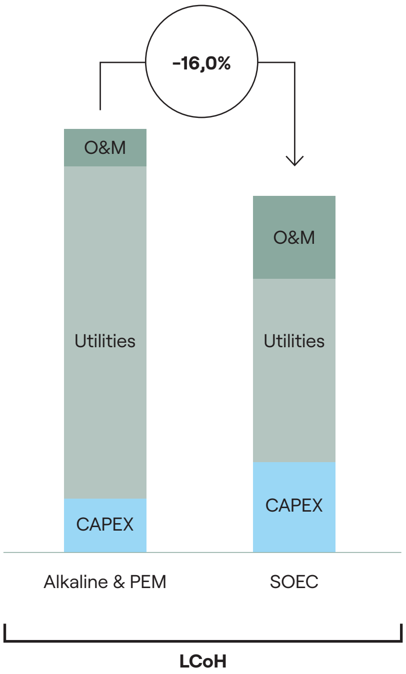
OPTIMIZING THE LEVELIZED COST OF HYDROGEN

Having seen the operational advantages of SOEC over alkaline and PEM, it is important to understand how this translates into overall plant economics. Levelized Cost of Hydrogen (LCoH) provides an estimated price per unit of hydrogen considering capital (CAPEX) and operational expenditures through a project's life-cycle. By accounting for efficiency and benefits during the expected duration of a project, this metric enables an equal comparison of electrolyzer technologies.

The LCoH for a 100 MW hydrogen plant is presented, where the upfront capital expenditure, utilities and maintenance have been considered, based on the assumptions given in the table.

It is clear, that **the LCoH of a SOEC operation is substantially more attractive than that of either alkaline or PEM. This is a result of SOEC's significantly lower electricity demand.**

SOEC & ALKALINE/PEM LCoH ESTIMATES



SOEC is with steam integration with electricity price set at EUR50/MWh. Further assumptions detailed in table below.

ASSUMPTIONS FOR ESTIMATION OF LEVELIZED COST OF HYDROGEN

Assumption	**Units**	**SOEC**	**Alkaline & PEM**
Capacity of Hydrogen Plant	MW	100	
Plant Operating Hours	Hours/Year	8,000	
Frequency of Stack Replacement	Years	4	8
Degradation of Stack Efficiency[1]	Years	0%	10% / 8 years
Power Consumption	kWh/Nm^3 of H_2	W. Steam = 3.5 Wo. Steam = 4.0	5.0
H_2 Production	Nm^3/h	W. Steam = 28.600 Wo. Steam = 25.000	20.000

1) No electricity penalty of degradation.

THE FINANCIAL BENEFIT OF SOEC

Because of this enhanced LCoH, SOEC technology can offer further benefits for any downstream process and additional derivative production. While SOEC's price of electricity can actually be higher than corresponding alkaline or PEM set ups, this technology's ability to produce more green hydrogen per MWh or kWh still makes this process result in positive earnings. This is illustrated through a so-called "break-even price" — meaning the maximum electricity price at which a plant can still show positive earnings.

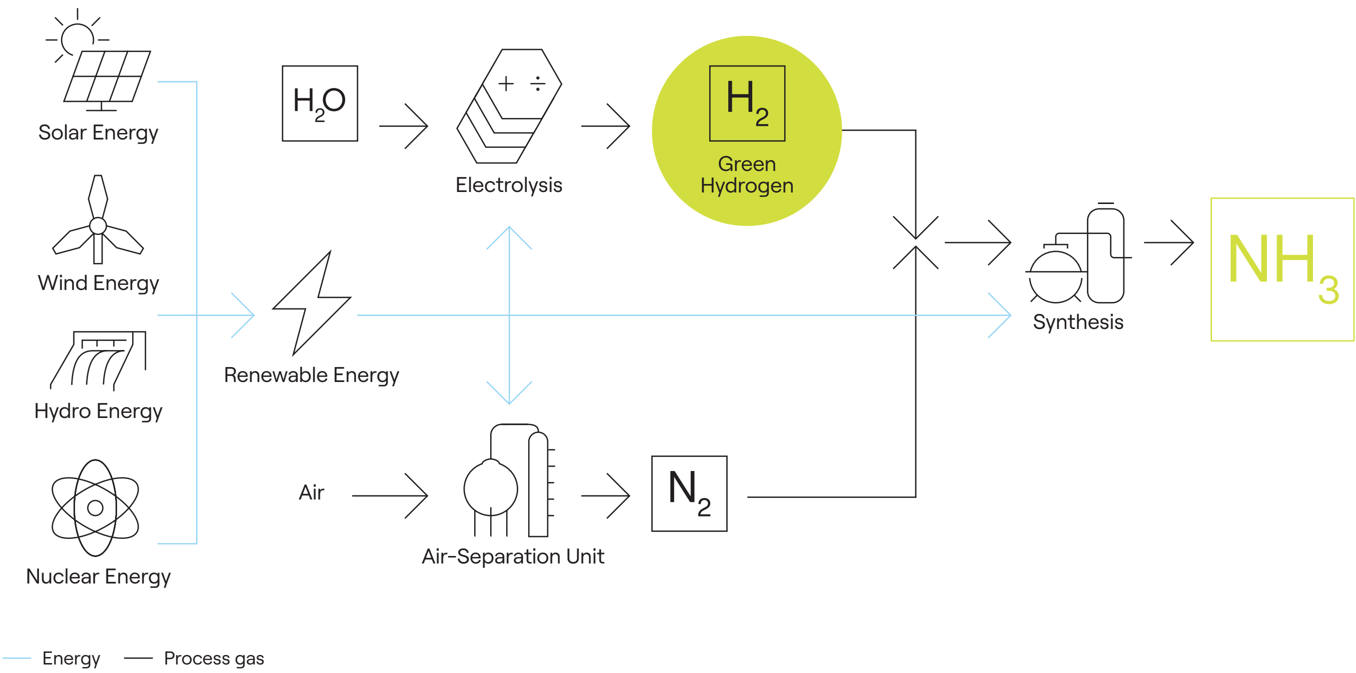
The following use case illustrates SOEC's higher "break-even price" when compared to alkaline and PEM →

CASE

SOEC IN A GREEN AMMONIA PLANT

This estimation is based on an ammonia plant, rather than a hydrogen plant, since the price of ammonia is a globally applicable value (approximately USD 750/ton in 2021), while the price of hydrogen varies regionally. Additionally, the estimation assumes the use of a 100 MW electrolyzer, and that the air-separation unit (which obtains the required nitrogen) and the ammonia synthesis exhibit power consumptions of 3% and 5% of the total energy input to the whole plant, respectively, compared to the electrolyzer. Based on these conditions, the break-even price can be estimated.

GREEN AMMONIA PRODUCTION PROCESS THROUGH WATER ELECTROLYSIS



ESTIMATION OF BREAK-EVEN PRICES

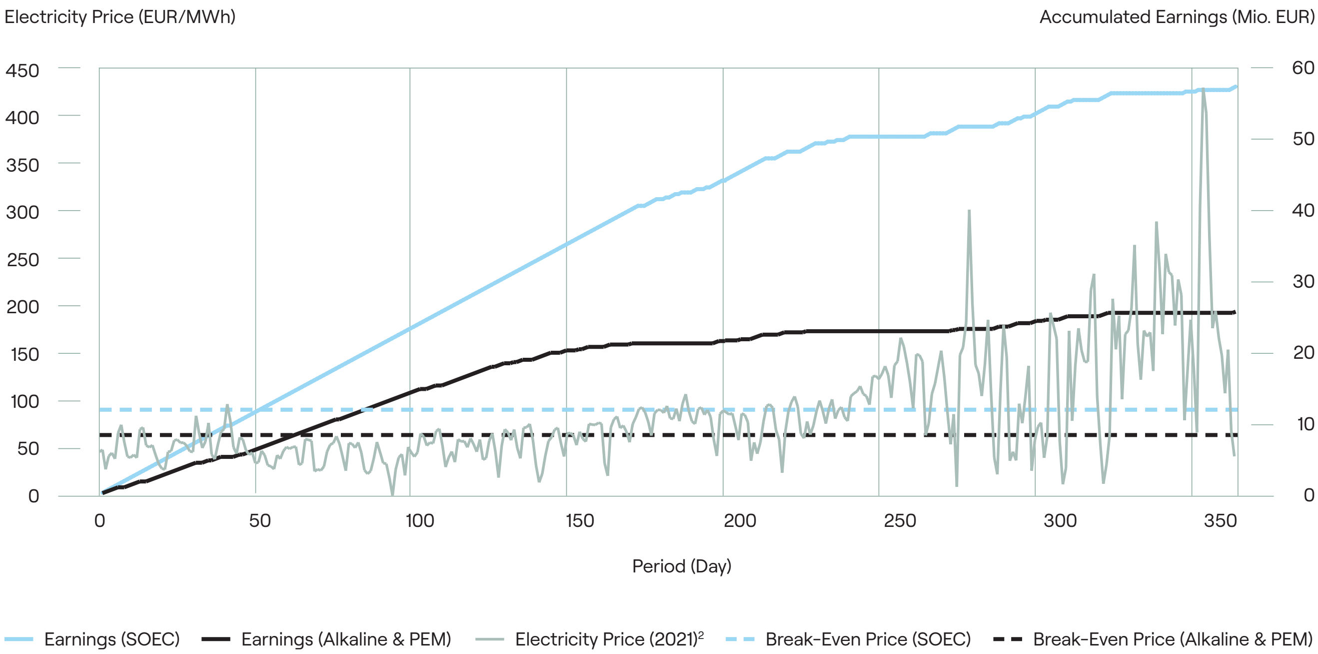
	Units	SOEC	Alkaline & PEM
Power Consumption of Electrolysis	MW	100	
Power Consumption of Ammonia Synthesis	MW	5.43	
Power Consumption of Air-Seperation Unit	MW	3.26	
Price of Ammonia	USD/Ton	712.5	
Production Capacity of Ammonia	MTPD	330	231
Break-Even Price	EUR/MWh	90	63

Under the aforementioned conditions, if the price of electricity exceeds 90 EUR/MWh, earnings for a SOEC-equipped ammonia plant will be negative. Under the same conditions, an alkaline or PEM-equipped ammonia plant will yield negative earnings at an electricity price above 63 EUR/MWh.

In order to optimize earnings, the plant should be put on standby when the break-even price is exceeded. Since SOEC's break-even price is higher than both alkaline and PEM, operations would not have to be put on standby until a comparatively much later point, meaning that viable operational hours would increase and allow for greater earnings and overall financial benefit.

Greater uptime with SOEC compared to alkaline and PEM electrolysis

SOEC GRANTS AN ENHANCED ECONOMY



2) https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/DK/Daily/?dd=DK2&view=table

TECHNICAL DATA OF A 100 MW HYDROGEN SOEC ELECTROLYZER

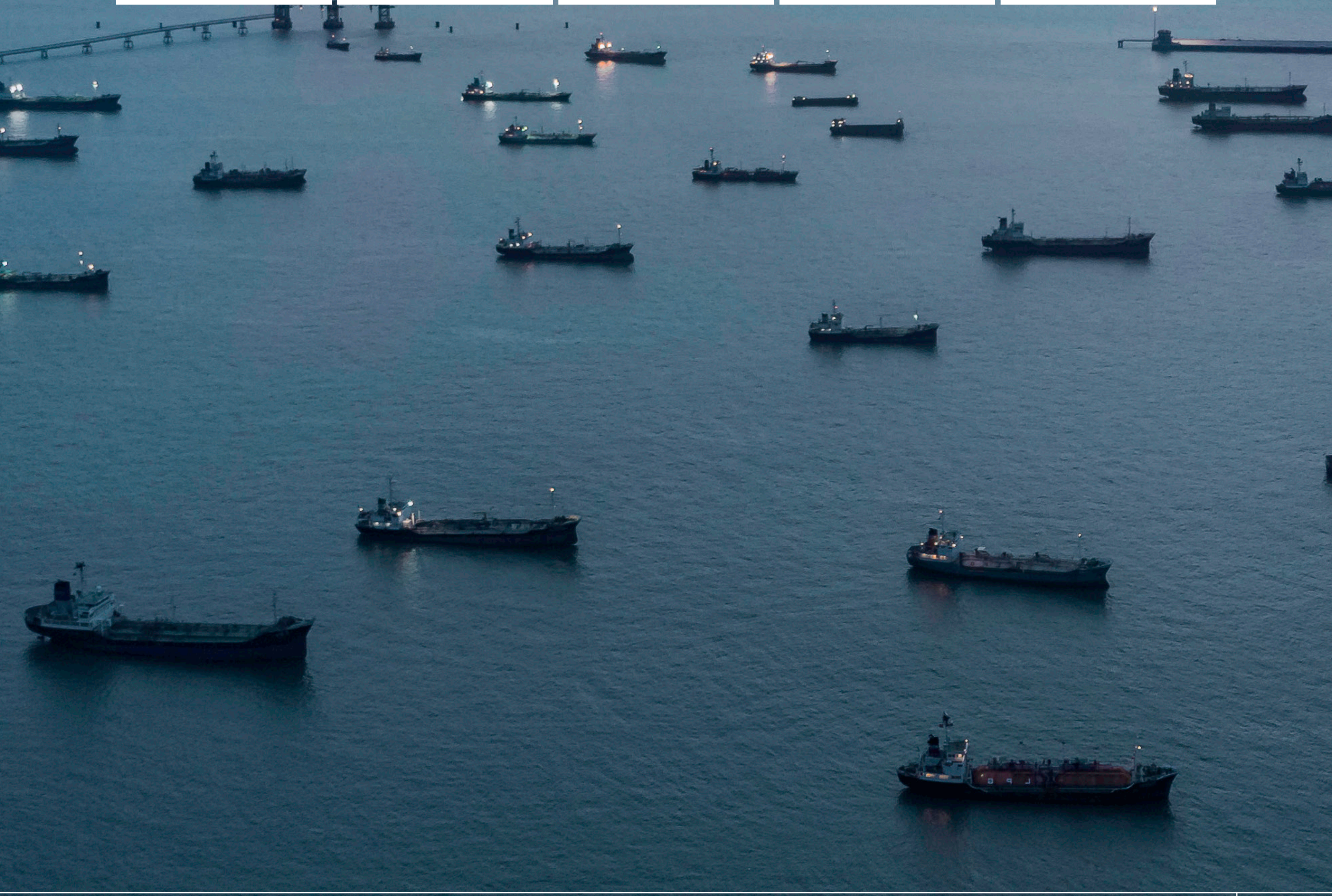
TECHNICAL DATA OF A 100 MW HYDROGEN SOEC ELECTROLYZER

	Units	Without Steam Import	With Steam Import
PLANT PRODUCTION			
Hydrogen Production	**Nm³/h**	**25,000**	**28,600**
Hydrogen Production	**kg/h**	**2,250**	**2,570**
PRODUCT CONDITIONS			
Pressure Battery Limits	bar g	2	
Temperature at Battery Limits	°C	AMBIENT	
Purity on Dry Basis	%	99,8	
FEED STOCKS			
Demineralized Water (DMW)	t/h	21	24
Steam (> 5 bar g)	t/h	0	23
POWER SUPPLY			
Power Consumption	**MW**	**100**	
Electricity Supply	kV	6-24 (preferable 20-24)	
OTHER SPECIFICATIONS			
Ramping Up from 0 to 100% from Hot Stand-By	min	10	
Turn-Down Ratio at Plant Level	%	10-100	

THE KEY PIECE OF THE NET-ZERO PUZZLE

PRODUCTION DATA FOR DOWNSTREAM PROCESSES OF A 100 MW HYDROGEN SOEC ELECTROLYZER
(THE ENERGY CONSUMPTION OF CO_2-CAPTURE IS NOT INCLUDED FOR THIS EVALUATION)

Ammonia (MTPD)	Methanol (MTPD)	Renewable Natural Gas (Nm^3/h)	Jet Fuel (BPD)	Naphtha (BPD)
330	270	7,100	940	230



At Topsoe we follow the solution all the way from production to end customer, ensuring a safe start-up and fully optimized, scalable plant performance that we guarantee from initial electricity intake to the final product molecule.

We consider it our responsibility to alleviate as much customer risk as possible. We do this through long-term production, optimization and maintenance, and by providing comprehensive optimization across the entire plant, facilitated by decades of troubleshooting experience within the petrochemical and refinery sectors. By managing the development of the full SOEC electrolyzer system, we give our customers the certainty they need to manage their energy consumption and production costs.

ABOUT TOPSOE

WHY TOPSOE?

3

TOPSOE PTX PROJECTS

1. USA

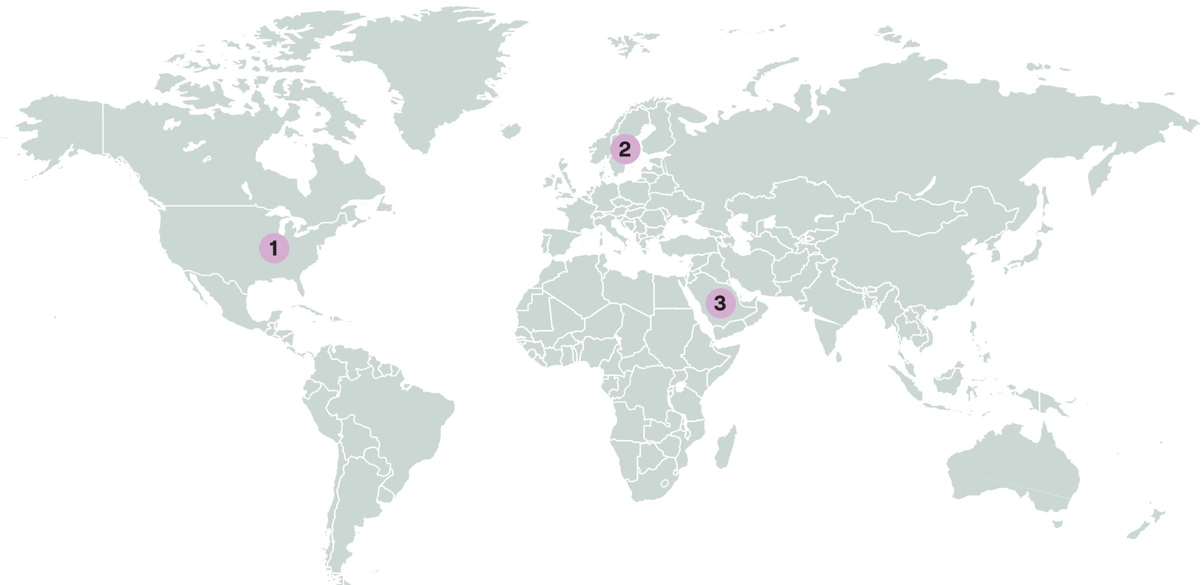
First Ammonia signs 5 GW agreement with Topsoe for solid oxide electrolyzer cells (SOEC) to produce green ammonia, fuel for transportation, power storage and generation, and fertilizer.

2. Sweden

Topsoe provides eMethanol ModuLite™ technology to Ørsted's first commercial-scale Power-to-X facility, **FlagshipONE** – creating the largest eMethanol facility in Europe.

3. Saudi Arabia

World's largest green hydrogen project **(NEOM)** uses Topsoe's green ammonia technology to produce 650 tons per day of carbon-free hydrogen to power buses and trucks.



TOPSOE CLIENT CASES

FIRST AMMONIA

KEY FACTS

Client	First Ammonia
Technology	SOEC Electrolyzer, Dynamic Ammonia Loop
Reserved Capacity	500MW
Impact	Potential to eliminate 13m tons of CO_2 — equivalent of taking 9m petrol cars off the road.

Launching zero emission ammonia production with Topsoe's SOEC electrolyzers

About the Project
First Ammonia is a pioneering integrated green ammonia producer developing modular, commercial scale plants utilizing SOEC electrolysis technology. Based in New York, First Ammonia is developing a global network of dynamic plants designed to convert intermittent renewable energy into ammonia — a highly transportable and storable fuel and hydrogen carrier that can enable the rise and success of the hydrogen economy.

First Ammonia's first plants under development in the United States are expected to be fully operational in 2025 and will be the world's first commercial scale green ammonia production facilities. First Ammonia has established an initial plan for 500MW of electrolyzer capacity for the production of up to 5 million metric tons of green ammonia per year.

Topsoe's Role
Topsoe's SOEC technology will be installed in First Ammonia's green ammonia plants around the world in the coming years. Because of SOEC's ability to integrate waste heat into its electrolysis process — allowing for the lowest levelized hydrogen cost at the highest level of energy efficiency at megawatt or gigawatt volume — Topsoe was the natural choice to be the sole ammonia tech supplier for First Ammonia's ammonia plants.

Topsoe's SOEC manufacturing plant is being built in Herning, Denmark, and will open its doors in 2025.

FlagshipONE

Enabling eMethanol production in Europe's largest green eMethanol facility

KEY FACTS

Client	Ørsted
Technology	eMethanol ModuLite™
Capacity	Producing up to 50,000 tonnes/year of eMethanol
Impact	Renewable methanol can reduce greenhouse gas emissions by 95% for CO_2 and up to 80% for NOX

About the Project
FlagshipONE is a groundbreaking project situated in Örnskjoldvik in Northern Sweden. FlagshipONE is Ørsted's first commercial-scale Power-to-X facility and is set to be the largest green eMethanol facility in Europe — estimated to produce around 50,000 tonnes of eMethanol annually.

This project marks an exciting new commitment to scaling up green fuel production and investing in energy alternatives that can offer clean transitions across industries. Green eMethanol is a versatile, liquid fuel that is also carbon neutral and easy to store, transport and use. The process of upcycling biogenic waste carbon dioxide for use as a renewable fuel to replace fossil fuels can offer new opportunities in powering our industries while actively cleaning up the waste they currently produce.

Topsoe's Role
Topsoe will be supplying the FlagshipONE project with our eMethanol ModuLite™ technology to enable the synthesis of the feedstocks green hydrogen and carbon dioxide. Intended for use in PtX applications, Topsoe's ModuLite™ systems are complete plants built from prefabricated, truckable modules. The benefits of a ModuLite™ plant include rapid deployment, a plug-and-play architecture, and less work on site – features that pose a particularly high advantage on remote sites like FlagshipONE.

3D illustration of Topsoe's SOEC electrolyzer manufacturing facility.

TOPSOE'S HERNING SOEC FACTORY

In 2023, we took the first steps towards building our SOEC manufacturing facility at Haldor Topsøes Vej 2 in Herning, and in 2025, we expect to be ready for production.

The manufacturing facility is is one of the largest of its kind in the world and will be able to produce electrolysis technology with a capacity of 500 megawatts per year. To put this in perspective, this is equivalent to the annual energy consumption of nearly one million Danish households.

To learn more about our SOEC factory in Herning as well as its over 150 job opportunities, please visit:

topsoe.com/herning

Get in touch today
PtXBD@topsoe.com

Founded in 1940, Topsoe is a global leader in developing solutions for a decarbonized world, supplying technology, catalysts, and services for the worldwide energy transition.

Our mission is to combat climate change by helping our partners and customers achieve their decarbonization and emission-reduction targets, including those in challenging sectors: aviation, shipping, and production of crucial raw materials.

From low-carbon or zero-carbon chemicals to renewable fuels and plastic upcycling, we are uniquely positioned to aid humanity in realizing a sustainable future.

Topsoe is headquartered in Denmark, with 2,100 employees serving customers all around the globe.
To learn more, visit topsoe.com

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