CERES SOE TECHNOLOGY READINESS

ABOUT US

We are a world-class engineering services and nuclear organisation. We connect people, data and technology to transform the world's infrastructure and energy systems.

AtkinsRéalis has global expertise and capabilities in hydrogen across the full value chain, from production and storage to distribution and utilisation, including numerous studies in Europe, MENA and North America.

We have worked on the integration of hydrogen production into multiple end user cases including Direct Reduction Steel, Ammonia, Methanol, Semi-Conductor Long Duration Energy Storage and Sustainable Aviation Fuel.

AtkinsRéalis

Ceres is a leading developer of clean energy technology: electrolysis to produce green hydrogen and fuel cells for power generation.

Its technology licensing model has seen it establish partnerships with some of the world's largest companies. Ceres' solid oxide technology supports greater electrification of our energy systems and produces green hydrogen at high-efficiencies as a route to decarbonise emissions-intensive industries such as steelmaking, ammonia and future fuels.

ceres®

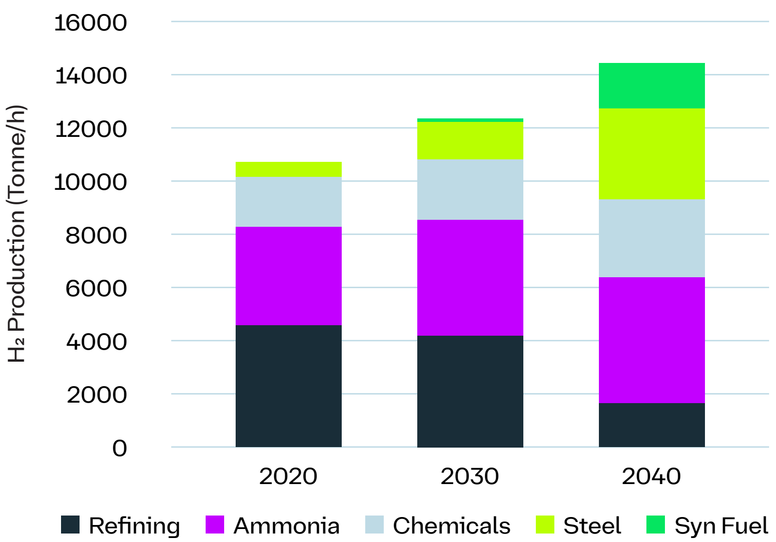
1.0 INTRODUCTION

AtkinsRealis were commissioned by Ceres Power to independently validate Ceres SOE technology readiness.

Green hydrogen offers a pathway in certain industries to decarbonisation, however cost will be the most pressing factor in the use.

Low operating temperature solid oxide steam electrolysis offers a pathway to achieve the cost of hydrogen required by industry to decarbonise. Ceres and AtkinsRéalis have developed the design for a scalable electrolyser module and balance of plant based on Ceres SteelCell™ Solid Oxide technology. The SteelCell™ technology has been proven in commercial fuel cell applications, and is ready for deployment. Ceres in partnership with Shell are demonstrating a 1MW scale electrolyser at its Bangalore R&D facility. The aim of this white paper is to show the scale of the industrial decarbonisation challenge, where Ceres solid oxide electrolyser fits and the readiness of the technology to have an impact on the market.

Global Hydrogen Production Forecast by Industry



2.0 THE CHALLENGE

Amid mounting pressure to achieve Net Zero targets, industrial companies require a clear roadmap to guide their commitments. Achieving Net Zero often entails significant engineering and infrastructure transformations, which will unfold over several years and necessitate access to both public and private funding. **In all scenarios, hydrogen from electrolysis is needed in huge volumes as a feedstock to decarbonise industry, and new or increased uses required to achieve net zero.**Hydrogen represents a major decarbonisation challenge for industrial firms, with 97 Mt (11,000 Tonne/h) of hydrogen demand, resulting in over 900 Mt of CO_2 emissions. Low emission sources of hydrogen account for less than 1% of production with electrolysis derived hydrogen at only 0.2%*.

The demand for hydrogen is projected to increase to between 100-150 Mt (11400-17,000 Tonne/h) in the coming years, based on AtkinsRealis internal analysis. The mix of use cases will evolve, with a decline in oil refining demand and a rise in steel demand. Our 2030 prediction for electrolysis production is based on announced projects moving toward final investment decisions. The estimated electrolysis share of production in 2050 aligns with the IEA Net Zero Energy (NZE) scenario.

The nascent electrolysis market has several technologies all of which are not proven at the full scale required to decarbonise modern industry. A significant obstacle to achieving a world with decarbonised hydrogen production is the cost of production via electrolysis. Electrolytic hydrogen production costs are primarily driven by electricity prices, as it requires a minimum of 33.3 kWhe/kg to split water into hydrogen and oxygen. Therefore, developing and scaling new efficient electrolyser technologies that are competitive on a capital cost basis is critical for the successful decarbonisation of hydrogen consuming industries.

*IEA 2024 Global Hydrogen Review 2024

2.1 Industrial Hydrogen

Industrial chemicals such as ammonia and methanol alongside steel production form the primary demand for hydrogen now and into the future. **Green Hydrogen will be used to decarbonise ammonia, methanol, SAF and steel, all of which have processes able to be thermally integrated and generate steam for electrolysis. Hydrogen cost from electrolysis is dominated by electricity cost and so steam electrolysis will win, but scaling and capital cost of scaling is also critical to success.** Technologies that can integrate with these industries in the most efficient way in terms of capital cost and electricity consumption will be the market leaders in electrolysis technology.

Green Ammonia and Methanol

The production processes for ammonia and methanol involve exothermic reactions, which release energy. This significant heat generated during the reaction is typically extracted and recovered as steam at temperatures above 200°C.

In methanol plants the amount of steam produced depends on the gas composition feeding the reactor. Almost twice as much heat is released when a mol of CO is converted into methanol compared with a CO_2 rich feed. Steam raised by varying feed gas compositions is usually in the range of 0.6-1.5 kgSteam/kgMethanol. The generated steam is generally used for distillation increasing the purity of the methanol, however if low grade methanol (95%w/w) i.e. fuel quality is being produced, then a steam turbo generator is used to recover the reaction energy as electricity.

Ammonia and integrated fertiliser (ammonium nitrate) plants recover heat of reaction energy by steam raising which is then transformed into electricity via a turbo generator (approximately 8kWe/TPD of ammonia).

You can harness the steam generated from both methanol and ammonia as an energy source for Ceres Solid Oxide Electrolysers. A standard ammonia plant is capable of providing sufficient steam to a Ceres Solid Oxide Electrolyser, thereby producing the hydrogen needed for ammonia production.

In greenfield ammonia designs, the removal of the turbo generator from a typical plant is a significant CAPEX reduction of more than 5%. Additionally, the cooling requirement and hence the size of the cooling system are also reduced which adds to CAPEX savings.

Green Steel

Iron Ore can be reduced using Hydrogen to produce Direct Reduced Iron (DRI). DRI plants typically operate with 50-60 Vol% of H_2 in the feed, depending on the vendor and plant configuration. The DRI is then processed into steel using an Electric Arc Furnace (EAF). For green hydrogen's future growth, producing hydrogen efficiently is crucial for minimising the green premium required for clean steel. Ceres SOE can significantly contribute to the efficient production of green hydrogen, supporting the steel industry's decarbonisation initiatives.

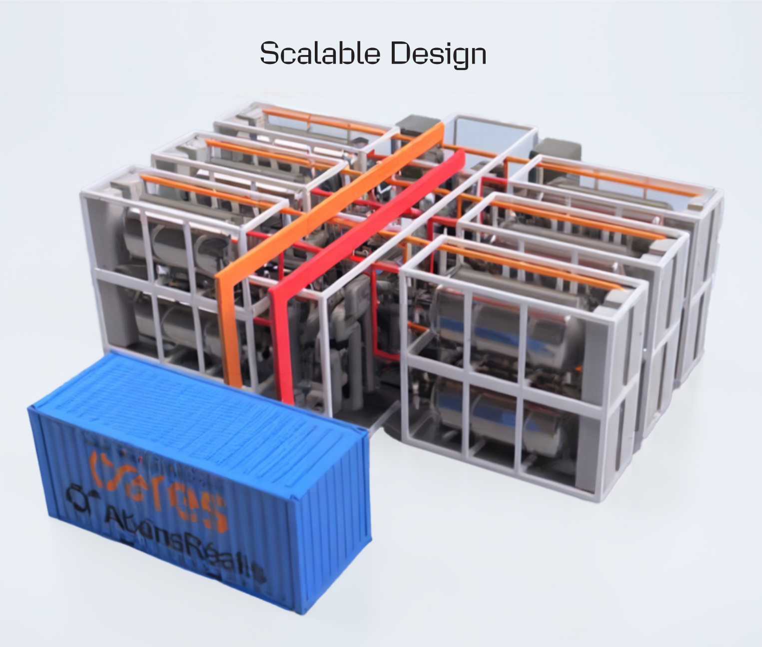
The production of steel using a combination of DRI and EAF generates significant waste heat in the off gas streams that can be used to raise steam for SOE. EAF off gas contains 36% of the input energy, a single 150-tonne EAF could supply approximately 51 tonne/h of steam at 5 bar, depending on operation. The Ceres SOE system can produce ~4000 kg/h of hydrogen from a single EAF. The hydrogen requirement for DRI production is between 47-68 kg H_2 / tonne DRI, assuming a value of 57 kg H_2 / tonne DRI, it is equivalent to approximately 70 tonne/h of DRI.

3.0 PROCESS AND SYSTEM ARCHITECTURE

Ceres Solid Oxide Electrolyser process operates at low temperature and at pressure, which is a unique combination offering significant advantages over other high temperature SOE. System architecture is designed to be modular for the electrolyser with a scalable balance of plant.

Ceres technology supports equipment scaling due to their low operating temperature and durability, making both BoP and Ceres cells scalable for high-volume production with their innovative stack design.

Plant design is ready and achieves market leading efficiency at plant level, and significantly lower energy consumption compared to low temperature water electrolysis, even if steam is not available from the industrial process.



Ceres ©

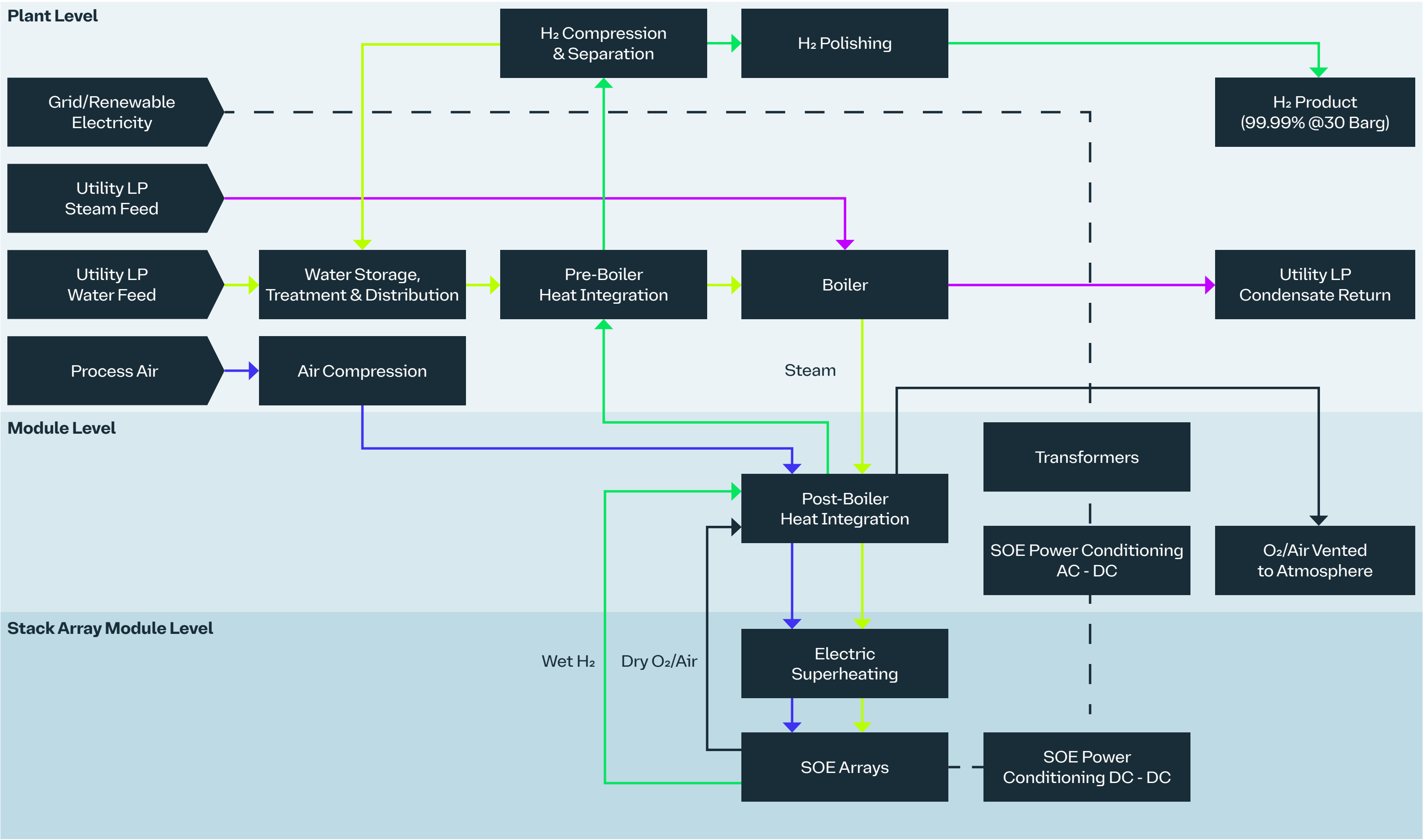
3.1 The Ceres SOE Process

The process starts with water purification to create deionised water which is then turned into saturated steam in a boiler through heat recovery with the balance of plant. The boiler may either be electric or use a thermal energy source from the partner facility (At least 175°C). Saturated steam at just over 2.7barg is then supplied to electrolyser modules (EMs).

Further heat integration occurs within the EM, which superheats the steam to near the stack operating temperature. Superheated steam is divided between Stack Array Modules (SAM) and the desired operating temperature of 500-600°C is achieved using electrical heating to add the small amount of additional heat required. A small air flow is also provided to the oxygen side of each SAM to help maintain a flow of gasses. The electrolysis step occurs within cells contained in each stack within the SAM.

The produced wet hydrogen and oxygen are used as the energy source within the EM to superheat the electrolyser steam feed. The oxygen stream is vented but could also be recovered for industries such as steel. At the balance of plant level, the wet hydrogen streams are recombined, and then cooled, dried and compressed to produce a final hydrogen stream at the required purity and pressure. The water removed is recovered back to the start of the process such that nearly zero deionised water is wasted.

Block Flow Diagram of Ceres SOE system



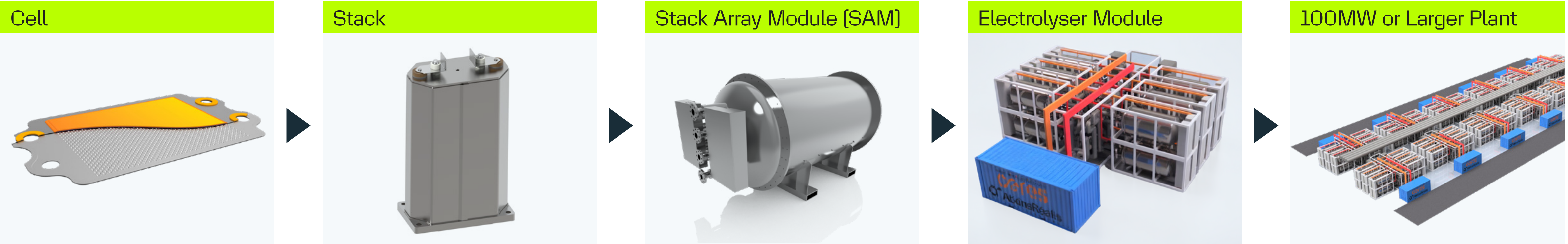
3.2 System Architecture

Ceres scalable Electrolyser Module (EM) is built up from Ceres' SteelCell™ technology into Stacks which are combined into a pressurised Stack Array Module (SAM). An EM is then formed of twelve SAMs which are stacked in pairs around a central piping and heat exchange module. The EM has a power draw of 8.6MW which is supplied from a dedicated transformer and rectifier package, generating 0.25 Tonne/h of hydrogen.

A full scale plant would then be built up of EM's linked to a centralised Balance of Plant (BoP) which supplies steam, recovers heat, and provides compression and purification to the hydrogen.

There is no reason why EMs cannot be assembled into large modules made up of multiple EMs, similar to how LNG has transitioned to constructing large mega plant modules weighing over 10,000 metric tonnes. The choice to do so would depend on various factors such as the project's location and on-site construction costs.

The overall approach to maintenance operations on a full-scale electrolyser plant is driven by the need to maintain or replace Stacks and SAMs, the stack has a lifetime of five years of continuous operation, which would mean the stack needs to be replaced five times during the expected 25-year lifespan of the main plant items. In the event of unplanned failures of stacks or equipment, the EM can be safely shutdown so a SAM can be replaced with spares whilst the incumbent SAM is refurbished. On a 15 Tonne/h plant this would represent a short-term reduction in plant production capacity of <2%.



Images © Ceres Power

4.0 COST OF HYDROGEN PRODUCTION

Hydrogen production cost is typically driven by the amount of electricity consumed accounting for approximately 70-80% of the Levelised Cost of Hydrogen (LCOH).

Electrical efficiency is therefore critical to getting the lowest LCOH. Capital costs and maintenance costs are also very important but account for 20-30% of the cost.

Image © Doosan

4.1 Capital Cost

Ceres Electrolyser capital costs have the ability to match or be lower than low temperature electrolysis technologies on a production rate basis (£/kg/day).

Hydrogen facility capital cost are made up of the direct construction costs such as equipment and indirect costs such as design & project management. The equipment costs form most of the overall facility direct costs with the electrolyser modules being the largest single cost.

4.1.1 Horizontal Scaling Cost Impacts

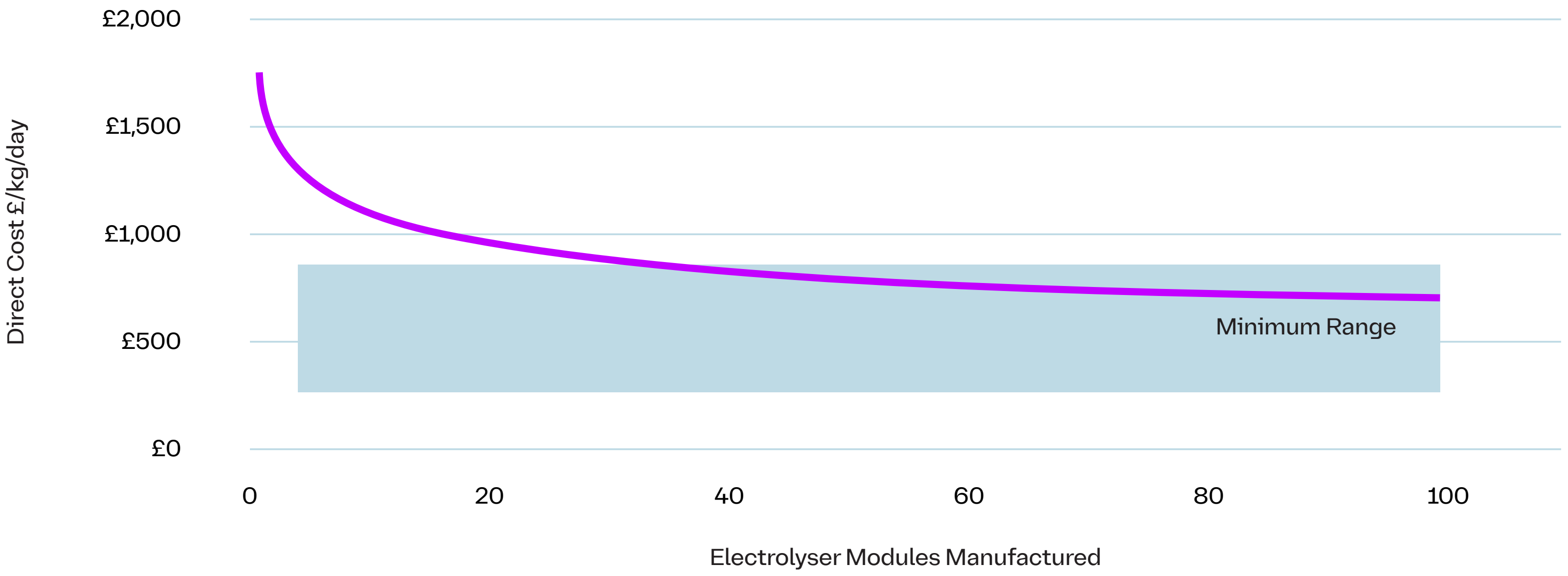
Scaling electrolysis to the size of a facility needed to supply ammonia or steel plants in a cost effective manner is challenging. SOE like other electrolysis technologies has some fundamental limitations on how big the stack can be made. Stacks and Stack Array Modules (SAM's) are numbered up from kg/h to Tonne/h, this is called horizontal scaling, where learning from each stack build is fed back into the design and manufacture to lower the cost, often called a learning curve.

The electrolyser module around the SAM's will also come down a learning curve however not as steep as the Stacks and SAMs simply due to the number to be manufactured and the types of equipment. For example, there is not a huge amount to be learned about the design and welding of pipes however the manufacture of stacks is relatively new and only recently coming down the learning curve.

Wright's Law states that every time cumulative production volume doubles, manufacturing costs drop by a consistent percentage. Ceres benefit from companies like Bosch and Doosan mass-producing their stack design, thus beginning the learning curve.

AtkinsRéalis found through experience and research that an 11-13% learning rate for the Electrolyser Module, including SAM's and Stacks, is possible, as shown in the graph below. However, material costs set a minimum limit.

Electrolyser Module Learning Curve



4.1.2 Vertical Scaling Cost Impacts

Outside of the electrolyser module in the Balance of Plant (BoP) the equipment has typically been manufactured for many years and has already come down the learning curve however, the ability to vertically scale the equipment is possible which allows for significant capex savings.

AtkinsRéalis and Ceres have maximised this in the electrolyser module and the Balance of Plant to drive down cost but also to minimise as much as possible the amount of equipment to be monitored and maintained.

The balance of plant is unlikely to benefit significantly from learning rates but can benefit from vertical scaling which has been used in industries such as Oil & Gas to great effect, in driving down the marginal cost of production. The nonlinear scaling relationship between the production capacity of the hydrogen facility balance of plant cost can be expressed as $C1/C2 = (Q1/Q2)^{\alpha}$ where α varies between 0.45 to 1 with a typical value for chemical plants of ranges between 0.6-0.8, C is the Cost, Q can be the hydrogen production capacity or the power draw of the electrolyser.

4.1.3 Overall Cost

AtkinsRéalis have estimated that after the First of a kind (FOAK) at scale facility i.e. over 40TPD capacity, direct costs of less than **1900 £/kg/day** of hydrogen for an Electrolyser module and BoP can be achieved with room to decrease further at Nth of A kind Facilities (NOAK).

Electrolyser and hydrogen production facility costs are usually expressed based on power draw, but it's more useful to measure costs by production capacity to account for efficiency. Lower capital costs are achieved by optimising vertical scaling of the balance of plant and leveraging the manufacturing advantages Ceres partners have in stack production.

Vertical Scaling Cost Example

If a small ~3 Ton/h BoP cost is ~£10m and we want to scale this to 60 TPD by adding the same balance of plant 20 times then the cost would be £200m. If the BoP is vertically scaled the cost will be closer to £60m as it's now a nonlinear relationship.

4.2 Operating Cost

Ceres SOE is significantly more efficient than competing low temperature electrolysis technologies. Competing low temperature technologies such as Alkaline and PEM must operate at voltages above the thermoneutral point due to slower reaction kinetics and lower conductivities within the stack. Operation above the thermoneutral point results in electrical energy being converted to thermal energy via joule heating of the stack. In an SOE system, the stack is able to operate at the thermal neutral point, therefore it has almost no loss of electrical energy within the stack to thermal energy. Ceres SOE can achieve a stack energy consumption of approximately 34 kWhe/kgH_2 or 98% electrical efficiency on a hydrogen Lower Heating Value basis (LHV).

Operators and Developers of hydrogen plants care about average electrolyser efficiency throughout the operating life of the plant. It is difficult to understand what is included and what is not when looking at publicly available data.

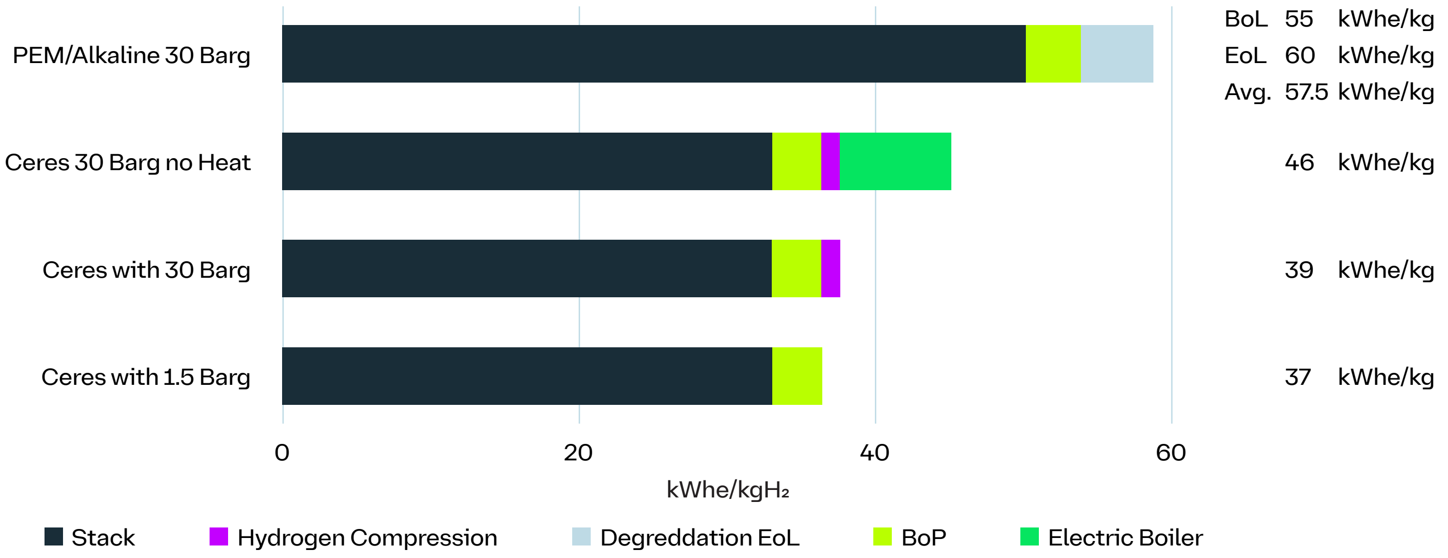
AtkinsRéalis with Ceres have defined the boundary of the facility consumption as everything downstream of an electrical grid Distribution Network Operator (DNO) or incoming site transformer. Our design is capable of a market leading electrical efficiency of 37 kWhe/kgH_2 with a hydrogen discharge pressure of 1.5 Barg, when integrated with a source of heat.

To achieve 30 Barg hydrogen discharge pressure this increases the overall energy consumption to 39 kWhe/kgH_2.

PEM and Alkaline electrolyser stacks degrade from Beginning of Life (BoL) to End of Life (EoL) leading to increased electrical resistance.

SOE systems also have stack degradation however the SOE systems can increase the operating temperature of the stack which reduces the electrical resistance such that the system electrical consumption stays constant over the plant life.

Specific Electrical Consumption



4.3 Levelised Cost of Hydrogen using SOE

Primary drivers for the Levelised Cost Of Hydrogen (LCOH) are Electricity Cost, OPEX and Capital Costs (depreciation and cost of capital). A simple LCOH calculation can help demonstrate the financial benefits of Ceres SOE relative to competing technologies such as PEM, Alkaline (AWE) and High Temperature (HT) SOE. LCOH is presented showing the breakdown of costs based on the assumptions shown in the table below.

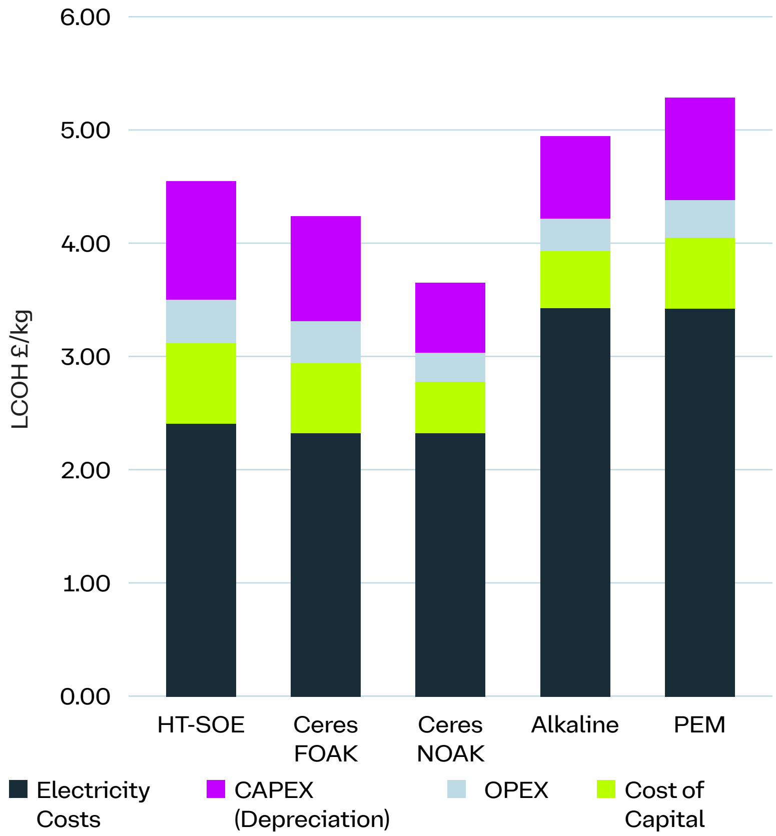
Ceres SOE Electrolyser deployed at scales >40TPD is expected to have a greater than 20% reduction in LCOH when integrated with industrial processes vs. competing technologies.

There are several additional benefits of Ceres SOE technology that are not accounted for in the LCOH. Ceres steelcell™ technology means the stack is almost entirely made of steel which can be recycled easily making it one of the most environmentally sustainable electrolyser stacks available.

Steelcell™ technology also improves the durability of the stacks during transportation and construction reducing the likelihood of stack failure during commissioning and operation.

The compact and scalable modular design has a lower footprint than PEM systems with a specific electrolyser module footprint greater than PEM, 1.85 Vs 1.3 kg/h/m² depending on what is accounted for in the area.

Levilised Cost of Hydrogen (LCOH)



Input Data for Levilised Cost of Hydrogen

		HT-SOE*	Ceres FOAK	Ceres NOAK	AWE	PEM
Discount Rate	%			8		
Design Life	Years			25		
OPEX	%			2.5		
Capacity Factor	%			97		
Indirect Project Costs	%			40		
Electricity Cost	£/MWh			59		
Stack Lifetime	Kilo Hours	40	50		80	
Electrolyser & BoP Direct Costs**	£/kg/day	2151	2460	1899	2788	3302
Specific power consumption***	kWhe/kg	39	37		57.5	57.5
Battery Limit H2 Pressure	Barg	2	1.5		13	30

*HT = High Temperature >700°C stack operating temperature

** AWE and PEM costs from BNEF 2024 Electrolyser Price Survey Data and AtkinsRéalis internal data for western electrolysers

***Accounts for stack degradation over life

5.0 KEY TAKEAWAYS

The Challenge: Achieving Net Zero targets requires significant engineering and infrastructure transformations. Hydrogen from electrolysis is needed in huge volumes to decarbonise industry. Currently, low emission sources of hydrogen account for less than 1% of production.

Technology Readiness: Ceres and AtkinsRéalis have developed a scalable electrolyser module and balance of plant based on Ceres SteelCell™ Solid Oxide technology. This technology has been proven in commercial fuel cell applications and is ready for deployment.

System Architecture: The Ceres Solid Oxide Electrolyser process operates at low temperature and pressure, offering significant advantages over other high-temperature SOE. The system architecture is modular and scalable.

Capital Cost: Capital costs can match or be lower than low-temperature electrolysis technologies through scale-up of stack and SAM manufacture. Vertical scaling of system component enabled by Ceres low operating temperature has significant cost saving benefits.

Cost of Hydrogen Production: Hydrogen production cost is primarily driven by electricity consumption, accounting for approximately 70-80% of the Levelised Cost of Hydrogen (LCOH). Ceres SOE is significantly more efficient than competing low-temperature electrolysis technologies, and is best in class for Solid Oxide Electrolysers.

Levelised Cost of Hydrogen: Ceres SOE Electrolyser deployed at scales greater than 40 TPD is expected to have a greater than 15% reduction in LCOH when integrated with industrial processes such as Fertiliser production in comparison to Alkaline and PEM systems.

AtkinsRéalis UK Limited

Nova North
11 Bressenden Place
Westminster
London
SW1E 5BY

Tel: +44 (0)20 7121 2000
Fax: +44 (0)20 7121 2111
Gareth.Richardson@AtkinsRealis.com

Ceres Power Limited

Viking House
Foundry Lane
Horsham
West Sussex
RH13 5PX

Tel: +44 (0)1403273463

marketing@cerespower.com