VOLTACERA White Paper Series

Chapter 2

The High-Temperature Electrolysis Advantage:

Why SOEC Is the Game-Changer in the Green Hydrogen Race

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Executive Summary

As net-zero 2050 targets translate into concrete industrial mandates, green hydrogen is emerging as the critical link in the decarbonization pathway for steel, chemicals, mobility, and power generation. Yet the key bottleneck to large-scale green hydrogen deployment remains the efficiency and cost of production technology. Alkaline (ALK) and Proton Exchange Membrane (PEM) electrolysis — the two commercially proven approaches — each face structural limitations in terms of electrical efficiency and the inability to utilize high-temperature waste heat.

Solid Oxide Electrolysis Cells (SOEC) overcome these limitations through thermodynamics. Operating at 600–900°C, SOEC substitutes a portion of the electrical energy required to split water molecules with thermal energy, and can directly accept waste heat from industrial processes, fundamentally raising overall system energy efficiency. Furthermore, the ability to co-electrolyze CO_2 and H_2O simultaneously — impossible in ALK or PEM systems — opens the pathway to next-generation e-fuels such as e-methanol and e-ammonia.

Key findings of this chapter:

- SOEC system efficiency reaches up to 85–90% when integrated with waste heat sources — structurally higher than ALK (65–75%) and PEM (70–80%).
- Direct synthesis gas (Syngas) production via co-electrolysis represents a unique competitive advantage that neither PEM nor ALK can provide.
- The technology roadmaps of leading global players — Sunfire, Topsøe, Bloom Energy, Ceres Power, and thyssenkrupp nucera — clearly demonstrate the path toward gigawatt-scale SOEC commercialization.
- By implementing SOEC on the same ceramic platform as SOFC, Voltacera aims for an integrated on-site energy hub model that combines power generation, hydrogen production, and heat supply on a single technology base.

1. Introduction: The Structural Shift in the Electrolysis Market — Why Green Hydrogen Now?

1.1 Hydrogen Demand Created by Net-Zero Targets

According to the IEA's 2023 Net Zero scenario, global hydrogen demand is projected to reach approximately 520 million tonnes per year by 2050. The share attributable to green hydrogen (renewable-powered electrolysis) must surge from virtually zero today to more than 40% of total demand by 2050. As of end-2023, globally installed electrolysis capacity stood at only approximately 1.4 GW, yet the IEA's Net Zero Emissions scenario requires roughly 560 GW by 2030. While announced projects total approximately 520 GW, the vast majority remain in early development stages.

Policy-driven pressure on the demand side is increasingly specific. The European Union's REPowerEU plan targets 10 Mt of domestically produced and 10 Mt of imported green hydrogen by 2030. South Korea has enshrined 250,000 tonnes of green hydrogen production by 2030 in its national hydrogen roadmap. The U.S. Inflation Reduction Act (IRA) creates conditions through a clean hydrogen production tax credit (§45V) of up to $3/kg that could bring green hydrogen production costs down to the $1.50–2.00/kg range.

1.2 Limitations of the Current Electrolysis Market — and the Opportunity

The global electrolysis market is expected to grow from approximately $2.5 billion in 2023 to $30 billion by 2030 and over $150 billion by 2040. However, the ALK and PEM technologies that currently dominate the market each carry structural constraints — creating the opening for high-temperature electrolysis (SOEC/AEM) to move in.

ALK's strengths lie in mature technology and low upfront capital cost, but its low current density and slow load-following response limit direct coupling with variable renewables. PEM offers fast response and high current density, but depends heavily on platinum-group metal catalysts and has shorter stack lifetimes compared with ALK. SOEC is currently at the early commercial stage, but its thermodynamic advantages at high temperature are widely viewed as the key to long-term cost competitiveness.

2. The Thermodynamics of High-Temperature Electrolysis — Fundamental Advantages Over PEM and ALK

2.1 The Energetics of Water Splitting

The total energy required to split water (H_2O) into hydrogen and oxygen (ΔH) is approximately 286 kJ/mol — constant regardless of temperature. However, the allocation of this energy between electricity (ΔG, Gibbs free energy) and heat (TΔS, entropic contribution) changes dramatically with temperature. As temperature rises, the thermal contribution (TΔS) increases, and the electrical energy that must be supplied (ΔG) decreases correspondingly.

At 25°C (ambient), approximately 93% of the total energy must be supplied as electricity. At 800°C, this fraction falls to approximately 70%, with the remaining 30% supplied as heat. This is the structural reason why SOEC is advantaged on electrical consumption. At high temperatures, reaction kinetics also improve, reducing overpotential losses — so the actual efficiency advantage in operation is even greater than the thermodynamic gain alone.

2.2 Three-Way Comparison: ALK vs. PEM vs. SOEC

The table below compares the key performance parameters of the three most widely deployed electrolysis technologies.

Parameter	ALK	PEM	SOEC
Operating Temperature	60–80°C	50–80°C	600–900°C
Electrolyte	KOH aqueous solution	Nafion polymer membrane	ScSZ/YSZ/GDC ceramic
Electrical Efficiency (LHV)	65–75%	70–80%	**80–90%***
System Efficiency (incl. waste heat)	65–75%	70–80%	**85–95%***
Current Density	0.2–0.5 A/cm²	1.0–3.0 A/cm²	0.3–1.0 A/cm²
Stack Lifetime	80,000–100,000 h	50,000–80,000 h	Long-life validation ongoing (target: 80,000 h)
Load Following	Slow (minutes)	Fast (seconds)	Limited (thermal inertia)
PGM Catalyst Dependency	None	High (Pt, Ir)	None
Co-electrolysis	Not possible	Not possible	**Possible (CO_2+H_2O → Syngas)**

Parameter	ALK	PEM	SOEC
Commercialization Level	Mature (TRL 9)	Mature (TRL 8–9)	Early commercial (TRL 6–8)

* Based on operation integrated with industrial process waste heat or self-generated heat. Electrical efficiency alone is approximately 80–85%.

2.3 Additional Advantages of High-Temperature Operation

The benefits of SOEC's high-temperature operation extend well beyond improved electrical efficiency. At elevated temperatures, electrode reaction activation energies are reduced, enabling sufficient reaction rates without precious-metal catalysts — providing a fundamental advantage in materials cost structure compared with ALK and PEM. Additionally, the high-temperature waste heat generated by SOEC stacks (above 600°C) can be supplied directly to adjacent industrial processes without a separate heat exchanger, or conversely, industrial process waste heat can be fed directly into the SOEC. This bi-directional thermal integration is precisely what enables SOEC to function not merely as a standalone electrolyzer, but as a central node in an industrial energy system.

3. Co-electrolysis — CO_2+H_2O → Syngas and the e-Fuel Opportunity

3.1 What Is Co-electrolysis?

Co-electrolysis is the simultaneous electrochemical conversion of steam (H_2O) and carbon dioxide (CO_2) in SOEC's high-temperature environment to directly produce synthesis gas (Syngas: a mixture of H_2 and CO). This reaction is physically impossible in ALK or PEM systems. Both technologies operate at low temperatures and cannot meet the reaction kinetics conditions required for the electrochemical reduction of CO_2.

The co-electrolysis reaction is as follows:

$$H_2O + CO_2 \rightarrow H_2 + CO + O_2 \quad \text{(Syngas)}$$

The resulting Syngas (with H_2:CO ratio tunable by adjusting reaction conditions) can be converted via Fischer-Tropsch synthesis into a wide range of e-fuels, including e-methanol, e-ammonia, e-diesel, and e-kerosene (SAF — Sustainable Aviation Fuel).

3.2 Industrial Significance and Market Opportunity

The industrial significance of co-electrolysis lies in its simultaneous resolution of carbon capture and energy storage. CO_2 that is unavoidably emitted from steel, cement, and chemical plants can be captured and fed into SOEC — converting it into high-value fuel rather than simply venting or storing it (CCS). This approach is attracting growing attention as a core technology pathway for the Carbon Circular Economy.

In terms of market scale, co-electrolysis has potential that extends far beyond simple hydrogen production markets. The e-fuels market is projected to grow from approximately $14 billion in 2030 to over $350 billion by 2050, with demand from aviation and shipping — sectors where decarbonization is particularly challenging — as the primary driver. SOEC is currently the only technology capable of approaching co-electrolysis at commercial scale.

3.3 Technical Challenges

Co-electrolysis is SOEC's most powerful differentiator, but it also brings technical challenges. In a mixed CO_2/H_2O environment, carbon deposition (coking) can occur on the fuel electrode (Ni-YSZ cermet) surface, and this is a major cause of cell performance degradation. Materials improvements (Ru doping, A-site deficient perovskite electrodes, etc.) and operating condition optimization to suppress coking are among the central themes in global research today — and, notably, are areas in which Voltacera is actively engaged through its own R&D program.

4. SOEC Performance Metrics — Efficiency, Degradation, Durability, and the Economics of Waste Heat Integration

4.1 Current State of Key Performance Metrics

SOEC's commercial competitiveness is determined by three key performance parameters: electrical efficiency, degradation rate, and stack lifetime. The current technology status of leading developers and their medium-to-long-term targets are summarized below.

Parameter	Current Level	Medium/Long-term Target	Notes
Electrical Efficiency (LHV, standalone)	80–85% currently	Target: 85–90%	Additional 5–10 pp improvement possible with waste heat integration
Degradation Rate (cell level)	1–3%/1,000 h currently	Target: <0.5%/1,000 h	Key challenge for achieving lifetime targets
Stack Lifetime	10,000–20,000 h currently	Target: ≥80,000 h	Goal: approach ALK's long lifetime
H_2 Production Cost (LCOH)	$4–8/kg currently	Target: $1.5–2/kg (2030)	Achievable combined with IRA §45V
Stack Power Density	0.5–1.0 W/cm²	Target: ≥1.5 W/cm²	Lever for equipment miniaturization and cost reduction

4.2 Waste Heat Integration: SOEC's Hidden Economics

A factor often overlooked in SOEC economic analysis is waste heat utilization. SOEC continuously generates high-temperature waste heat above 600°C during operation, and can conversely accept external high-temperature heat sources directly. This bidirectionality creates special economic value when integrating SOEC into industrial energy systems.

Economics of Heat Input

When heat is supplied to SOEC in lieu of electricity, the electrical power consumption required for the same hydrogen output is reduced. For example, utilizing industrial plant waste heat above 300°C as thermal input to SOEC can improve hydrogen production efficiency on an electrical basis by an additional 10–15 percentage points. In markets with high electricity prices — Korea, Japan, Europe — this savings lever is decisive in lowering the Levelized Cost of Hydrogen (LCOH).

Utilization of Heat Output

High-temperature waste heat discharged from SOEC stacks can be supplied directly to adjacent processes — reactor heating in chemical plants, drying operations in food and paper industries, district heating systems, and more. In these cases, the SOEC operator can establish a dual revenue structure, capturing both hydrogen sales revenue and heat supply revenue.

Thermal Integration Synergy with SOFC

In the integrated SOFC-SOEC platform that Voltacera pursues, this thermal utilization becomes even more sophisticated. Directly connecting the high-temperature exhaust heat generated during SOFC power generation to SOEC thermal input improves overall system energy efficiency by an additional 5–10 percentage points versus independent operation. In other words, when SOFC (power generation) and SOEC (hydrogen production) operate simultaneously on the same site, the heat from each installation supports the other — forming a self-reinforcing structure.

5. Industry Applications — Data Centers, Steel, and Chemicals

5.1 Data Centers: A New Paradigm for On-Site Hydrogen Production

As discussed in Chapter 1, data center operators are actively deploying Behind-the-Meter (BTM) generation to reduce grid dependence. SOEC goes one step further, enabling a new value proposition: integrating on-site hydrogen production for energy storage with fuel cell backup power.

Specifically, a Power-to-X-to-Power cycle — producing and storing hydrogen via SOEC during periods of abundant renewable electricity, then converting hydrogen back to electricity via SOFC during peak demand — provides long-duration energy storage solutions that Battery Energy Storage Systems (BESS) cannot deliver. The interest that hyperscale data center operators such as Microsoft, Amazon, and Google are showing in hydrogen-based energy systems can be understood in precisely this context.

5.2 Steel Industry: A Critical Hydrogen Source for DRI-H_2

The steel industry accounts for approximately 7–9% of global CO_2 emissions and represents one of the most challenging sectors for decarbonization. Direct Reduction of Iron with Hydrogen (DRI-H_2) uses hydrogen as the reducing agent in place of coke (coal) in the blast furnace, theoretically reducing CO_2 emissions from steelmaking by more than 90%. Major steelmakers including SSAB (Sweden), thyssenkrupp (Germany), and POSCO (South Korea) have adopted this pathway as their primary decarbonization strategy for the 2030s.

In the DRI-H_2 process, SOEC plays two critical roles. First, as a large-scale high-temperature hydrogen source, it can directly accept high-temperature waste heat from the steelmaking process to maximize energy efficiency. Second, by capturing the CO_2 in the steel plant's exhaust gas and feeding it into co-electrolysis, SOEC can complete a carbon circular cycle — converting carbon into e-fuel feedstock.

5.3 Chemical Industry: Green Ammonia and e-Methanol

The largest SOEC market in the chemical industry lies in green ammonia and e-methanol production. More than 98% of the approximately 180 million tonnes of ammonia produced annually is made via natural-gas-based Steam Methane Reforming (SMR), emitting approximately 2.4 tonnes of CO_2 per tonne of ammonia. Feeding green hydrogen produced by SOEC into the Haber-Bosch process can reduce these emissions to near zero.

For e-methanol, the strength of co-electrolysis is even more directly expressed. Feeding CO_2 captured from chemical plants or biomass installations together with steam into SOEC directly yields synthesis gas, and integrating this with a methanol synthesis process reduces process steps and raises overall system efficiency. The pathway that Topsøe is demonstrating through the Triskelion project in Spain is precisely this approach.

6. Global Competitive Landscape — Sunfire, thyssenkrupp nucera, Bloom Energy, Ceres Power, Topsøe

The SOEC market is currently in early commercialization, with a small number of leading companies establishing first-mover advantages in technology and reference projects. Understanding the technological positioning and strategy of these key players is a critical starting point for Voltacera in designing its role within the supply chain.

6.1 Sunfire GmbH (Germany)

- The leading SOEC commercialization company, holding the most accumulated MW-scale SOEC system demonstration operating experience to date.
- Has demonstrated co-electrolysis technology through multiple industrial pilot projects, including collaboration with Danish energy company Ørsted. The MultiPLHY/Neste project at the Rotterdam refinery demonstrated a 2.6 MW SOEC system producing over 60 kg-H_2/h utilizing industrial waste steam, achieving up to approximately 84% LHV electrical efficiency.
- As of 2023, has released a single-module 2.6 MW SOEC system, with the goal of achieving systems of 100 MW and above through module stacking.
- Strengths: most mature SOEC commercialization track record. Key challenges: improving stack degradation rate and reducing mass production costs.

6.2 thyssenkrupp nucera (Germany)

- Traditionally the global ALK electrolysis leader (over 20 GW of cumulative installations), now expanding its portfolio toward next-generation electrolysis technologies including SOEC.
- Developing ESC (Electrolyte-Supported Cell)-based SOEC stacks in collaboration with Fraunhofer IKTS — technically the approach most similar to Voltacera's. In 2025, the two organizations opened the first SOEC pilot production plant for stacks (approximately 8 MW annual capacity), demonstrating long-term stability and thermal cycling performance.
- Vertical integration with the parent group's (thyssenkrupp Steel) hydrogen-based direct reduction steelmaking project provides a powerful internal demand anchor.
- Strengths: ability to leverage ALK mass production infrastructure and customer base. Key challenges: SOEC technology maturity currently lower than Sunfire.

6.3 Bloom Energy (USA)

- The world's largest commercial SOFC manufacturer, which has commercialized SOEC technology (Bloom Electrolyzer) by operating the same ceramic cell platform in reverse.
- Received SOEC technology development support from the U.S. Department of Energy (DOE) in 2023, and is applying electrolysis technology to space applications through collaboration with NASA.
- The identical SOFC-SOEC platform strategy is precisely aligned with Voltacera's direction, providing a commercially validated precedent.

- Strengths: leveraging SOFC mass production infrastructure and customer network; proven business blueprint for the BTM model. Key challenges: current SOEC business scale remains early-stage relative to SOFC.

6.4 Ceres Power (UK)

- Developing a next-generation SOEC platform based on Metal-Supported Cells (MSC), with lower operating temperatures (500–600°C) and faster start-up/shutdown as advantages over conventional ceramic-supported cells. A MW-scale SOEC demonstrator developed in collaboration with Shell produced its first hydrogen in 2025, validating the commercial pathway.
- Has adopted a 'platform company' model, deploying technology through licensing to multiple global partners including Bosch, Weichai Power (China), and Doosan (South Korea). Partnerships with Denso, Delta Electronics, Shell, and others continue to expand.
- Following Bosch's exit from SOFC/SOEC business in March 2025, there has been some impact on Ceres's licensing partner ecosystem, though collaboration with Doosan and others continues.
- Strengths: materials and sealing advantages from lower operating temperatures; capital efficiency of licensing model. Key challenges: gigawatt-scale commercial deployment still years away.

6.5 Haldor Topsøe (Denmark)

- A global leader in catalysis and process technology, focused on integrating SOEC into e-fuel (e-methanol, e-ammonia, SAF) production processes.
- Topsøe is set to supply 55 MW of SOEC technology to the Triskelion e-methanol project by Forestal del Atlántico in Spain, pursuing a large-scale Power-to-X commercialization model combining SOEC with downstream methanol synthesis. Topsøe operates an SOEC manufacturing facility in Herning, Denmark with annual production capacity of approximately 500 MW, with roadmap to GW-scale manufacturing expansion.
- Combines in-house SOEC stack production with downstream chemical process integration system engineering — occupying a 'Process Integrator' position.
- Strengths: unrivaled in co-electrolysis and e-fuel process integration. Key challenges: business centered on large-scale process projects rather than unit cell/stack sales, creating distance from the component supply chain market.

6.6 Competitive Landscape Summary and Voltacera's Position

Synthesizing the strategies of the leading companies reviewed above, competitive strength in the SOEC market is coalescing around three primary axes: ① cell and stack performance and durability, ② manufacturing cost and mass production capability, and ③ downstream process integration capability.

Global industry leaders are building differentiated competitiveness in these areas based on their respective technology foundations and business strategies. Some companies are strengthening their cell and stack technology alongside large-scale manufacturing capability, while others are expanding their market footprint through integration with downstream processes such as hydrogen and e-fuel production.

In this industry structure, rather than a single company internalizing all technology and manufacturing capabilities, the importance of collaboration among specialized companies across the **materials–cell–stack–system–plant** value chain is expected to grow further.

Voltacera aims to position itself as a specialized technology partner providing high-performance ceramic materials and ESC-based cell technology within this value chain. Based on proprietary capabilities in **materials synthesis, electrode ink production, tape casting, cell fabrication, and electrochemical evaluation**, Voltacera's goal is to respond flexibly to the development needs of cell, stack, and system companies.

Rather than competing with large-scale system operators, Voltacera's core strategy is to support the global SOFC/SOEC ecosystem through customized cell development, rapid prototyping, small-to-medium volume production, and co-development.

7. Voltacera's SOEC Strategy — The Significance of a Shared Platform with SOFC

7.1 Technical Rationale for the Single-Platform Strategy

Voltacera's core technology strategy is to implement bidirectional operation — SOFC (fuel cell power generation) and SOEC (electrolysis) — on a single ceramic cell platform. This is not merely a technical choice; it is a strategic decision that fundamentally redesigns the business model and capital efficiency.

Technically, SOFC and SOEC represent the forward direction (fuel cell) and reverse direction (electrolysis) of the same electrochemical reaction. Developing a high-performance SOFC cell therefore enables simultaneous improvement of SOEC performance through fine adjustment of material compositions and optimization of operating conditions. Bloom Energy and Sunfire have already demonstrated the commercial viability of this approach; Voltacera implements it within the ESC (Electrolyte-Supported Cell) architecture.

7.2 Advantages of ESC Architecture for SOEC Applications

Although SOEC shares the same solid oxide cell platform as SOFC, the operating environment is not identical. Unlike SOFC, SOEC operation involves high-temperature steam electrolysis under applied external voltage at high current density, with high-temperature, high-steam conditions and strong electrochemical driving forces at electrodes and interfaces acting simultaneously. Particularly at high current density operation, factors affecting long-term durability — electrode degradation, interfacial delamination, localized thermo-mechanical stresses — can become more significant.

SOEC cells therefore require not only high performance but structural stability against electrochemical, thermal, and mechanical stresses. From this perspective, the ESC (Electrolyte-Supported Cell) architecture adopted by Voltacera provides several unique advantages for SOEC applications:

- Mechanical Stability: With the electrolyte serving as the mechanical support structure, cell structural integrity is maintained even under alternating exposure to high-temperature oxidizing and reducing atmospheres during SOEC operation.
- Thermal Cycle Durability: In the data center BTM model, SOEC may undergo frequent start-up and shutdown cycles depending on renewable energy availability. The electrolyte thickness in ESC architecture provides greater resistance to this thermal cycling stress.
- Materials Development Synergy: The materials stack that Voltacera is independently developing — LSCF cathode, GDC buffer layer, NiO-GDC fuel electrode — can be optimized for both SOFC and SOEC directions, yielding high R&D investment efficiency.

7.3 Business Model: The Evolutionary Path Toward an On-Site Energy Hub

Voltacera's single-platform strategy provides customers with a phased application expansion pathway.

In Stage 1, high-efficiency on-site power generation using SOFC; in Stage 2, expansion into hydrogen production via SOEC; in Stage 3, broadening the application scope into Syngas production through H_2O and CO_2 co-electrolysis, and further into e-fuel and chemical feedstock production.

In particular, SOEC's co-electrolysis capability enables simultaneous conversion of H_2O and CO_2 into Syngas composed of H_2 and CO, which can be utilized as an intermediate feedstock for various Power-to-X processes — including methanol, synthetic fuel, and SAF (Sustainable Aviation Fuel) production.

Through this phased approach, Voltacera aims to expand its role beyond simple cell supply to become a technology partner for a high-temperature electrochemical platform that scales across Power → Hydrogen → Syngas/e-Fuels.

8. Conclusion and Preview of Chapter 3

SOEC is not a 'future technology.' Sunfire's MW-scale commercial systems, Topsøe's industrial-scale co-electrolysis demonstrations, and Bloom Energy's commercialization of an integrated SOFC-SOEC platform are all unfolding realities at this very moment. At the same time, the domains that ALK and PEM cannot fill — high-temperature waste heat utilization, co-electrolysis, integrated operation with SOFC — represent unique value that structurally only SOEC can provide.

As the green hydrogen market scales toward gigawatts by 2030, the strategic value within the supply chain of companies possessing high-performance SOEC cell and stack technology will continue to rise. In this technology cycle, companies that systematically reduce SOEC cell manufacturing costs through materials innovation and process development will be the greatest beneficiaries of market diffusion.

Voltacera is building its technology and capabilities aimed precisely at this position.

▶ Preview: Chapter 3

Chapter 3 answers the question: 'Why does the cell determine the system?' We will show in detail — with concrete figures — what performance advantages Voltacera's ESC-based SOFC/SOEC cells hold relative to competing cells, and how those advantages translate into LCOE and fuel cost at the system level.

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