VOLTACERA White Paper Series

Chapter 3

The Cell Determines the System:

Everything About SOFC/SOEC Cell Design — From Operating Conditions to System Economics

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Executive Summary

Why Does the Cell Determine the System?

The performance of SOFC and SOEC systems is not determined by the stack or the Balance of Plant (BOP) alone. The structure, materials, thickness, microstructure, and operating characteristics of the electrochemical cell — the smallest repeating unit of the system — are the starting point that determines system efficiency, power density, thermal management, durability, and economics.

The critical point here is that a high-performing cell is not necessarily a good cell.

Even with the same Solid Oxide Cell, the electrochemical and thermal operating conditions differ fundamentally between SOFC (power generation) and SOEC (hydrogen production). Moreover, even within the same SOFC application, the cell requirements differ entirely between a data center power system running continuously 24 hours a day and a mobility system experiencing repeated start-ups, shutdowns, and load fluctuations.

The central question in cell development must therefore shift:

▶ **'What is the highest-performing cell?' → 'What is the right cell for the system?'**

This white paper addresses the following key topics:

- SOFC and SOEC share the same platform but have different operating physics — and this difference determines cell requirements.
- Analysis of how the thermoneutral voltage concept in SOEC and external waste heat utilization strategies affect system economics.
- The trade-off between current density and degradation rate, and how this connects to LCOE/LCOH.
- How the duty cycle differences between stationary and mobility applications influence cell architecture choices such as ESC vs. ASC.
- The continuous manufacturing-performance chain from material composition through microstructure, electrochemical performance, and durability.
- How Voltacera's ESC platform integrates all of these elements to deliver cells optimized for the customer's system.

1. Introduction: From Cell to System

SOFC/SOEC systems are broadly structured in the sequence: Cell → Stack → Module → System. The characteristics of the cell accumulate as they move up through stack, module, and system levels, and their influence grows progressively larger. A performance difference in a single cell is magnified many times over at the stack level, and at the system level it has economic consequences across CAPEX, OPEX, maintenance costs, and the entire service lifetime.

As cell power output or hydrogen production per unit area increases, there is potential to reduce the number of cells and stack size required to achieve the same system output. However, high

current density operation increases electrode polarization and ohmic losses, and also affects the temperature distribution and degradation behavior within the cell. In this way, choices made at the cell level are closely linked to outcomes at the system level.

System design must therefore consider the following factors simultaneously, rather than simply maximizing output:

Design Factor	Impact on System Economics
Power / Hydrogen Production Density	Output or production per unit area — directly determines system size and CAPEX
Electrical Efficiency	The key lever for operating cost (OPEX) — translates directly into fuel or electricity cost
Operating Temperature	Directly influences material selection, thermal management complexity, and stack design
Degradation Rate	The lifetime metric that determines stack replacement intervals and maintenance costs
Thermal Management	Core to system efficiency optimization and ensuring temperature uniformity within the cell
Manufacturing Cost	The starting point for economics — links to mass producibility, yield, and material costs

For example, a cell with high power density may reduce the initial system size, but if a high degradation rate shortens the stack replacement interval, the long-term system economics may actually worsen. Conversely, operating at a low power density extends lifetime but may cause CAPEX to become excessively large. The economic optimum lies somewhere between these two extremes, and its location shifts with application and operating conditions.

Ultimately, the true performance of a cell must be evaluated not by a single I-V curve, but by the quantity and cost of power or hydrogen produced over the system's entire operating life. This is the central proposition of Chapter 3.

2. SOFC vs. SOEC - Same Cell, Different Operating Physics

SOFC and SOEC fundamentally perform electrochemical reactions in opposite directions on the same Solid Oxide Cell platform. This reversibility is a powerful technical advantage — a single ceramic platform can implement both power generation and electrolysis. However, reversibility does not mean identical operating physics.

2.1 Reaction Directionality and Energy Flow

In SOFC, the chemical energy of fuel is converted into electrical energy and heat. Hydrogen or hydrocarbon fuel is oxidized at the fuel electrode (Anode), while

oxygen ions (O^{2-}) supplied at the air electrode (Cathode) pass through the solid ceramic electrolyte and react with the fuel. This process produces current, heat, water, and carbon dioxide.

In SOEC, by contrast, electrical energy and heat supplied from outside are used to decompose H_2O or CO_2. Steam is reduced at the fuel electrode (Cathode) to produce hydrogen, while oxygen is released at the air electrode (Anode). The direction of energy flow is completely reversed.

This difference in energy flow makes the electrochemical and thermal environments experienced by the cell fundamentally different.

Parameter	SOFC	SOEC
Energy Flow	Chemical energy → Electricity + Heat	Electricity + Heat → Chemical energy
Cell Voltage	Below OCV (generation losses)	Above Erev (applied overpotential)
Fuel Electrode Atmosphere	Reducing (H_2, CO present)	High steam conditions (high H_2O concentration)
Air Electrode Role	Receives O^{2-} (acts as Cathode)	Releases O^{2-} (acts as Anode)
Internal Heat Generation	Always exothermic (resistive + reaction heat)	Endothermic or exothermic depending on operating voltage
Primary Electrode Degradation Cause	Ni coarsening, oxidation, carbon deposition	Air electrode delamination, Ni re-oxidation risk
Thermal Management Direction	Remove excess heat	Supply external heat or balance internal heat
Operating Voltage Range	0.6–0.9 V (typical operating point)	1.0–1.5 V (above Erev)

▶ **The same electrochemical platform does not mean the same operating physics.**

2.2 Unique Technical Challenges in SOEC Operation

SOEC operation presents several unique technical challenges that distinguish it from SOFC. First, delamination of the air electrode (Oxygen Electrode) at high current density operation is reported as one of the primary causes of SOEC degradation. In SOEC mode, the air electrode functions as an Anode and releases O^{2-}; in this process, a local rise in oxygen partial pressure and mechanical stress can develop at the electrolyte/air electrode interface.

Second, the Ni-based fuel electrode is exposed to high steam partial pressure in SOEC mode. Under conditions where hydrogen partial pressure decreases during operation, the risk of partial Ni oxidation increases, which can lead to microstructure changes and performance degradation. For this reason, additional material design is required to suppress carbon deposition (coking) during co-electrolysis (simultaneous electrolysis of CO_2 and H_2O).

Third, during SOFC-SOEC switching (reversible operation), the combined electrochemical and thermomechanical stresses arising from changes in temperature, gas composition, and current direction between modes have complex effects on cell lifetime. For this reason, the selection of cell materials and structure must be approached far more carefully in systems targeting reversible operation than in unidirectional operation.

3. Thermoneutral Voltage — Where Is the Optimal SOEC Operating Point?

One of the most important characteristics of high-temperature electrolysis is that a portion of the total energy required for water splitting can be supplied as thermal energy rather than electricity. This is the starting point for the thermodynamic advantage that fundamentally differentiates SOEC from PEM or ALK.

3.1 Energy Partitioning and Key Voltages

The total energy ΔH required for the reaction can be divided into the Gibbs free energy (ΔG), corresponding to electrical energy, and the thermal energy contribution (TΔS):

$$\Delta H = \Delta G + T\Delta S$$

From this, two important reference voltages are defined:

Voltage	Definition	Significance
Reversible Voltage (Erev)	Erev = ΔG / nF	Thermodynamic minimum voltage. In actual operation, a higher voltage is required due to overpotentials.
Thermoneutral Voltage (VTN)	VTN = ΔH / nF	The voltage at which the total reaction enthalpy is supplied as electricity alone. Approximately 1.29 V for steam electrolysis near 800°C.

3.2 Three Operating Regimes and System Implications

Based on VTN, SOEC operation is divided into three distinct thermal regimes. This distinction is not merely a theoretical classification — it is the most important thermal balance design variable in system design.

Operating Condition	Thermal Behavior	System Design Implication
Vcell < VTN	Endothermic	External heat must be supplied for the reaction to proceed. Can be strategically adopted in environments with abundant industrial waste heat. Minimizes electricity consumption.
Vcell ≈ VTN (~1.29 V @ 800°C)	Thermoneutral	Reaction heat and internal resistive heat are balanced, enabling isothermal operation without external heat exchange. Simplifies thermal management. Reference point for system design.
Vcell > VTN	Exothermic	Internal resistive heat exceeds reaction endotherm, generating surplus heat. Cooling system required. Temperature gradient risk increases at high current density operation.

In SOEC, operating voltage is thus not simply an electrical performance metric — it is a design variable that determines the system's thermal balance. Even with the same cell, the thermal management infrastructure required by the system changes completely depending on the operating voltage. This means that system thermal design must be established before cell selection.

4. Waste Heat Utilization - How Does an External Heat Source Shift the SOEC Operating Point?

One of the greatest potential advantages of SOEC is the ability to utilize high-temperature heat supplied from outside as part of the electrolysis energy. When usable heat sources exist — from industrial processes, nuclear power, or synthetic fuel production processes — the SOEC system does not need to supply all energy as electricity alone.

4.1 The Branching Point of Heat Source Utilization Strategy

Depending on the availability and cost of waste heat, the optimal SOEC operating strategy changes significantly. In industrial environments with abundant low-cost waste heat (e.g., near steel or chemical plants, or nuclear power stations), a strategy of intentionally operating at low cell voltage in the endothermic regime (Vcell < VTN) can be adopted. This reduces electricity consumption and can substantially lower LCOH in environments with high electricity costs. In Sunfire's Neste Rotterdam project, industrial waste steam was utilized as thermal input to the SOEC, achieving up to approximately 84% LHV electrical efficiency.

Conversely, in environments where usable external heat sources are scarce, thermoneutral or partially exothermic operation combined with internal heat recovery strategies is systemically advantageous. In this case, recovering the sensible heat of high-temperature exhaust gases from the stack for steam preheating or reactant heating becomes the core of the thermal integration design.

4.2 Impact of Thermal Integration on LCOH

The economic value of utilizing external heat sources varies significantly with the level of electricity prices. In markets with high electricity tariffs — South Korea, Japan, Europe — utilizing an additional 10–15 percentage points of waste heat can lower the Levelized Cost of Hydrogen (LCOH) by approximately $0.30–0.80/kg. This is a decisive lever for achieving the green hydrogen production cost target ($1.50–2.00/kg by 2030).

In the integrated SOFC-SOEC platform that Voltacera pursues, this thermal integration becomes even more sophisticated. Directly connecting the high-temperature exhaust heat generated during SOFC power generation (above 600°C) to SOEC thermal input improves overall system energy efficiency by an additional 5–10 percentage points compared with independent operation. This is the core system-economics rationale behind Voltacera's pursuit of a single SOFC-SOEC platform.

▶ **The optimum SOEC operating voltage depends not only on the cell, but also on the available heat source.**

5. Performance vs. Durability — What Do You Gain and What Do You Lose by Increasing Current Density?

One of the most direct ways to improve the economics of SOFC/SOEC systems is to increase power output or hydrogen production per unit area. At higher current densities, the same output can be achieved with a smaller cell area, creating the potential to reduce the number of cells, stack size, and overall system footprint.

5.1 Benefits and Trade-offs of High Current Density Operation

However, as current density increases, polarization and ohmic losses generally rise, and in SOEC, internal heat generation also increases. This directly leads to lower voltage efficiency. More importantly, the impact on long-term durability must be considered.

Parameter (as Current Density ↑)	Direction	System Impact
Production Density	↑ **Increases**	Reduced cell area needed for the same output → CAPEX reduction
Required Cell Area	↓	Stack size reduction, system miniaturization

Parameter (as Current Density ↑)	Direction	System Impact
	Decreases	possible
Polarization Loss	↑ **Increases**	Voltage efficiency decrease, higher electricity consumption (SOEC basis)
Heat Generation	↑ **Increases**	Higher cooling load, increased thermal management complexity
Temperature Gradient Risk	↑ **Increases**	Local overheating within cell → accelerated material degradation
Degradation Risk	↑ **Increases**	Accelerated electrode Ni coarsening, interfacial delamination

5.2 Connecting Degradation Rate to System Economics

In long-term SOEC operation research, degradation rate is treated as one of the most critical performance metrics. In ESC-based long-term steam electrolysis, cases have been reported of operation exceeding 23,000 hours with a voltage degradation of approximately 0.56%/1,000 h. Looking at the economic impact of degradation rate on this basis:

For example, if an SOEC stack has an initial electrical efficiency of 85% and a degradation rate of 1%/1,000 h, after 10,000 hours (approximately 14 months of continuous operation), efficiency falls to approximately 75%. To maintain the same hydrogen output, electricity input must be increased by approximately 13%. Assuming an electricity price of $0.05/kWh, this results in substantial additional electricity costs over the operating period. In contrast, if the degradation rate is halved to 0.5%/1,000 h, efficiency after the same 10,000 hours remains approximately 80%, significantly limiting the increase in additional electricity costs.

This is why Voltacera sets a low degradation rate as a core cell development objective equal in priority to high initial performance. The impact of a 0.5 percentage point improvement in degradation rate on LCOH can actually exceed the benefit of a 1–2 percentage point improvement in initial efficiency.

▶ **The highest-efficiency operating point is not necessarily the lowest-cost operating point.**

6. Duty Cycle Matters — Stationary vs. Mobility SOFC

Even with the same SOFC, the operating environment experienced by the cell varies significantly depending on the application. 'Duty cycle' refers to how often, how long, and under what conditions a system operates. These differences in duty cycle fundamentally reshape cell design requirements.

Application determines duty cycle, and duty cycle determines cell requirements.

6.1 Stationary vs. Mobility Requirements Comparison

Requirement	Stationary	Mobility	Notes
Continuous Operation Capability	★★★★★	★★★	Stationary: stable long-duration output is paramount
Low Degradation Rate	★★★★★	★★★★	Stationary: minimizing stack replacement cost takes priority
Power Density	★★★★	★★★★★	Mobility: lightweight and compact design critical
Start/Stop Durability	★★	★★★★★	Mobility: frequent start-up and shutdown cycles
Thermal Cycling Durability	★★	★★★★★	Mobility: repeated ambient-to-operating temperature cycles
Load Following	★★★	★★★★★	Mobility: rapid output variation response required
Weight / Volume	★★	★★★★★	Mobility: installation space constraints
Mechanical Robustness	★★★	★★★★★	Mobility: vibration and shock environment

A cell optimized for stationary SOFC is therefore not necessarily optimal for mobility SOFC. In stationary systems, low degradation rate and high electrical efficiency are most important, while in mobility systems, thermal cycling durability, start/stop durability, and high power density take priority. This difference in priorities is the fundamental reason why material composition, electrolyte thickness, electrode structure, and cell architecture choices differ.

7. Start/Stop, Thermal Cycling & Load Following — What Does Dynamic Operation Demand of the Cell?

When an SOFC system operates at constant conditions for long periods, the cell experiences a relatively stable temperature and electrochemical environment. However, when start/stop cycles repeat or load fluctuates significantly, the situation changes fundamentally.

7.1 Mechanical Impact of Thermal Cycling

In SOFC/SOEC operating at high temperature, different materials — electrolyte, fuel electrode, air electrode, bonding layers — are combined in layered structures. Each material has its own

Coefficient of Thermal Expansion (CTE), and expands and contracts at different rates during heating and cooling. Repeated thermal cycles continuously accumulate mechanical stress at interfaces due to this CTE mismatch, and can lead in the long term to interfacial delamination, cracking, or structural failure.

This is one reason why ESC architecture may be advantageous in terms of thermal cycling durability. The thick electrolyte substrate acting as a mechanical support has the effect of distributing interfacial stresses that occur during thermal cycling. Studies comparing thermal cycling durability between fuel-electrode-supported (ASC) and electrolyte-supported (ESC) cells have reported cases where ESC shows higher mechanical stability.

7.2 Redox Tolerance

Ni-based fuel electrodes are the most common fuel electrode material in SOFC, but they are sensitive to changes in oxidizing and reducing conditions. If the fuel supply is cut off during shutdown, the fuel electrode can be exposed to an oxidizing atmosphere, at which point Ni oxidizes to NiO, causing volume expansion. On restart in a reducing atmosphere, reduction back to Ni causes volume contraction. When this oxidation-reduction cycle repeats, irreversible changes to the fuel electrode microstructure and mechanical damage accumulate.

Approaches being researched to mitigate this problem include redox-stable material development (GDC-based composite fuel electrodes, perovskite-based fuel electrodes), shutdown protocol optimization (inert gas purging), and maintaining a minimum reducing atmosphere.

7.3 Load Change and Thermo-mechanical Stress Within the Cell

Rapid load changes (Load Change) trigger a cascade of effects at the cell level. When current changes abruptly, current distribution within the cell is redistributed, causing local heat generation to change accordingly. This change in local heat generation creates temperature gradients within the cell, and temperature gradients in turn induce thermomechanical stresses.

In systems with frequent dynamic operation, the following characteristics therefore become important cell design objectives equal to initial maximum output and electrical efficiency:

▶ **Thermal Cycling Durability / Redox Tolerance / Mechanical Integrity / Transient Response**

8. Cell Architecture — ESC vs. ASC: Application-Specific Design

Solid Oxide Cells are broadly classified by mechanical support structure into ESC (Electrolyte-Supported Cell) and ASC (Anode/Fuel-Electrode-Supported Cell). The two structures each have unique advantages and constraints, and the appropriate applications differ.

8.1 Structural Differences and Characteristics of ESC and ASC

Parameter	ESC	ASC
Electrolyte Thickness	100–250 μm (thick support)	5–20 μm (thin dense layer)

Parameter	ESC	ASC
Mechanical Support	Electrolyte itself	Fuel electrode (Ni-YSZ cermet)
Ohmic Resistance	Higher (thick electrolyte)	Lower (thin electrolyte)
Operating Temperature	800–1,000°C (requires high ionic conductivity)	650–800°C possible
Power Density	Relatively lower	Relatively higher
Thermal Cycling Durability	Excellent (mechanical stability of thick electrolyte)	Limited (interfacial stress vulnerability)
Redox Tolerance	Relatively good	Ni-based fuel electrode vulnerable
SOEC Suitability	Excellent (especially for reversible operation)	Delamination risk at high current density in SOEC
Manufacturing Complexity	Relatively simple	Multi-layer thin-film processing required
Mass Production Cost	Relatively favorable	Process optimization required

8.2 Criteria for Architecture Selection

The key question in cell architecture selection is therefore not 'Is ESC superior to ASC?'

▶ **Which architecture best matches the required operating conditions?**

ESC is advantageous for systems targeting long-duration high-temperature operation, repeated thermal cycling, SOFC/SOEC reversible operation, and emphasizing manufacturing cost and mass producibility. Conversely, large-scale stationary power generation systems where maximum power density and low operating temperature are the priority and thermal cycling frequency is low may select ASC.

Rather than applying a specific cell structure to all applications, Voltacera's approach is to design materials, thickness, electrodes, and cell structure together in accordance with the target operating conditions. This is the core of 'Application-Specific Design.'

9. Materials and Microstructure — Materials Determine Cell Characteristics

Even within the same cell architecture, electrochemical performance and durability can vary greatly depending on material composition and microstructure. Material selection is the starting point of cell development and the most fundamental lever for system economics.

9.1 Electrolyte Materials

The electrolyte simultaneously requires high ionic conductivity, gas-tightness, and mechanical stability. The most widely used electrolyte material today is yttria-stabilized zirconia (YSZ, 8 mol% Y_2O_3). Scandia-stabilized zirconia (ScSZ) has higher ionic conductivity than YSZ, making it advantageous for reducing ohmic losses in low-temperature operation or ESC structures. Gadolinium-doped ceria (GDC) shows high ionic conductivity at intermediate-to-low temperatures (500–700°C), but can exhibit electronic conductivity when used as a standalone electrolyte, so it is sometimes used in a bilayer structure with YSZ.

Voltacera is developing its own tape casting process for ScSZ-based electrolyte substrates, with a focus on optimizing post-sintering density and mechanical strength.

9.2 Fuel Electrode Materials

In the fuel electrode, electrical conductivity, ionic pathways, gas diffusion, and electrochemical reaction sites (TPB: Triple Phase Boundary) must be balanced. The mainstream material is the Ni-YSZ cermet, a composite combining the electronic conductivity of Ni with the ionic conductivity of YSZ.

However, Ni-YSZ cermet can experience accelerated Ni particle coarsening when exposed to high steam conditions in SOEC mode, and is also vulnerable to redox cycling. To address this, NiO-GDC composite fuel electrodes based on GDC are being actively researched, and perovskite-based mixed ionic-electronic conductors (MIEC) are also receiving attention as next-generation fuel electrode materials.

9.3 Air Electrode Materials

The air electrode requires high ORR (oxygen reduction reaction)/OER (oxygen evolution reaction) activity, together with chemical and microstructural stability during long-term high-temperature operation. LSCF ($La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$) has high mixed ionic-electronic conductivity and is currently the most widely used air electrode material. However, delamination can occur at the electrolyte interface during high current density SOEC mode operation, making the role of the GDC buffer layer important.

Voltacera is developing co-precipitation processes for LSCF powder synthesis that control particle size distribution and sintering activity as a core capability. This is being continuously refined through collaborative research with Professor Sim, referenced in Chapter 2.

9.4 The Continuous Manufacturing-Performance Chain

Real cell development is therefore not simply a matter of material selection. The entire process from material composition to final cell performance must be understood as one continuous chain.

Stage	Role and Impact
Powder Composition	Particle size, compositional uniformity, and surface area are the foundation for all subsequent processes
Particle Size & Dispersion	Directly influences slurry/ink rheology and forming uniformity
Slurry / Ink Rheology	Determines tape casting thickness uniformity and screen printing resolution
Green Body Formation	Starting point for pore structure and shrinkage rate uniformity

Stage	Role and Impact
Sintering	Determines final density, grain size, and interfacial bonding quality
Porosity & Microstructure	Gas diffusion pathways, TPB density, effective ionic and electronic conductivity
Electrochemical Performance	ASR (area-specific resistance), activation energy, operating voltage characteristics
Durability	Degradation rate, thermal cycling stability, operating lifetime

10. Voltacera ESC Platform — From Ceramic Materials to Electrochemical Cells

Rather than approaching Solid Oxide Cells as finished products, Voltacera is developing them as a ceramic platform that connects materials, processes, microstructure, and electrochemical performance. The core of this approach is jointly optimizing Materials → Cell Architecture → Electrochemical Performance according to the customer's system and operating conditions.

10.1 Core Technical Capabilities

Capability Area	Details
Ceramic Powder Synthesis and Formulation	Co-precipitation synthesis of LSCF air electrode powder; optimization of ScSZ/YSZ electrolyte powder composition
Electrolyte Substrate Manufacturing via Tape Casting	Achieving thin, uniform ESC substrates; controlling post-sintering density and mechanical strength
Electrode Ink Design for Screen Printing	Ink rheology optimization for air electrode, fuel electrode, and functional layers
Functional Layer and Electrode Structure Design	GDC buffer layer, functional cathode layer, graded electrode structure design
Sintering Profile and Ceramic Co-processing	Co-sintering condition optimization for multilayer ceramic structures; interfacial quality management
ESC-based SOFC/SOEC Cell Manufacturing	Single cell completion; development of cells capable of bidirectional SOFC/SOEC operation
Single-Cell Electrochemical Evaluation	Electrochemical impedance spectroscopy (EIS), I-V characteristics, long-term degradation testing, performance evaluation by gas composition

10.2 Cell Design Flexibility by Application

Voltacera's ESC platform does not provide a single fixed cell specification. The following design

parameters can be adjusted according to the customer's application and priorities:

- Electrolyte material and thickness: ScSZ-based (high ionic conductivity) vs. YSZ-based (high mechanical strength); balancing ohmic resistance and mechanical stability through thickness adjustment
- Air electrode structure: LSCF single-layer vs. LSC/LSCF bilayer; functional layer thickness and composition
- Fuel electrode composition: Ni-YSZ vs. Ni-GDC; application of redox-stable compositions
- GDC buffer layer: electrolyte-air electrode interface optimization through thickness and density adjustment
- Cell size and geometry: customization to match customer stack design

11. From Cell to System Economics — How Do Cell Differences Translate into LCOE and LCOH?

Ultimately, the value of cell technology must connect to system economics. Understanding how performance improvements at the cell level affect system LCOE (Levelized Cost of Electricity) or LCOH (Levelized Cost of Hydrogen) determines the direction of cell development.

11.1 The Relationship Between Cell Area and CAPEX

As cell power density or hydrogen production density increases, the active cell area required to achieve the same system output can be reduced. Conceptually, for SOFC:

Required Cell Area ≈ Target Output / Power Density (W/cm²)

Similarly for SOEC:

Required Cell Area ≈ Target H_2 Production / H_2 Production Density (mol/cm²/s)

For example, if power density improves 25% from 0.4 W/cm² to 0.5 W/cm², the cell area required to implement the same 1 MW system decreases by 2,500 cm². This translates directly into stack CAPEX reduction. However, this is not the whole picture.

11.2 Linking Degradation Rate, Lifetime, and OPEX

If higher current density accelerates degradation, the stack replacement interval shortens and replacement costs (OPEX) increase. Conversely, operating at excessively low current density to maximize lifetime may cause required cell area and stack CAPEX to become excessively large.

Actual system economics must be understood as a complex function of the following factors:

Economic Factor	Cell-Level Lever	System-Level Impact
Electrical Efficiency	Material ASR, operating temperature	Fuel / electricity consumption (OPEX)
Degradation	Electrode microstructure stability	Stack lifetime, replacement interval

Economic Factor	Cell-Level Lever	System-Level Impact
Rate		(OPEX)
Manufacturing Cost	Material cost, process yield	Stack unit price (CAPEX)
Stack Lifetime	Thermal cycling durability, Redox tolerance	Total CAPEX depreciation
Thermal Integration	Operating temperature, waste heat temperature	External heat source utilization, power savings (OPEX)
Power Density	I-V characteristics, active area	System miniaturization, CAPEX reduction

▶ **The engineering objective is to find the operating point that minimizes the cost of useful energy over the system lifetime.**

12. Conclusion — There Is No Universal Best Cell

In the SOFC/SOEC industry, cell performance is often compared using a single number: power density, current density, or efficiency. But what determines a 'good cell' in a real system is far more complex.

In SOEC, the cell moves from endothermic to thermoneutral to exothermic regimes depending on operating voltage, and the optimal operating strategy changes depending on the presence of external waste heat. In SOFC, even the same cell faces different duty cycles in stationary versus mobility applications, and accordingly the relative importance of long-term degradation, thermal cycling, start/stop, and power density all change. And these requirements in turn connect back to cell architecture choices such as ESC/ASC, electrolyte thickness, electrode composition, microstructure, and manufacturing process.

Cell development cannot therefore be thought of separately from system development.

▶ **There is no universally 'best' SOFC/SOEC cell. The best cell is the one engineered for the system it serves.**

Based on a technology platform connecting ceramic materials and electrolyte substrates through electrodes, functional layers, and completed cells, Voltacera's goal is to develop Solid Oxide Cells suited to the customer's system and operating conditions.

From ceramic materials to electrochemical cells — engineered for the system.

▶ **Preview: Chapter 4**

Chapter 4 presents, with concrete data, what specific performance metrics Voltacera's ESC-based cells achieve relative to competing products, and how that performance is being validated

in actual customer systems.

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