

# ELECTROLIZADORES DE ALTA TEMPERATURA: conceptos básicos y materiales

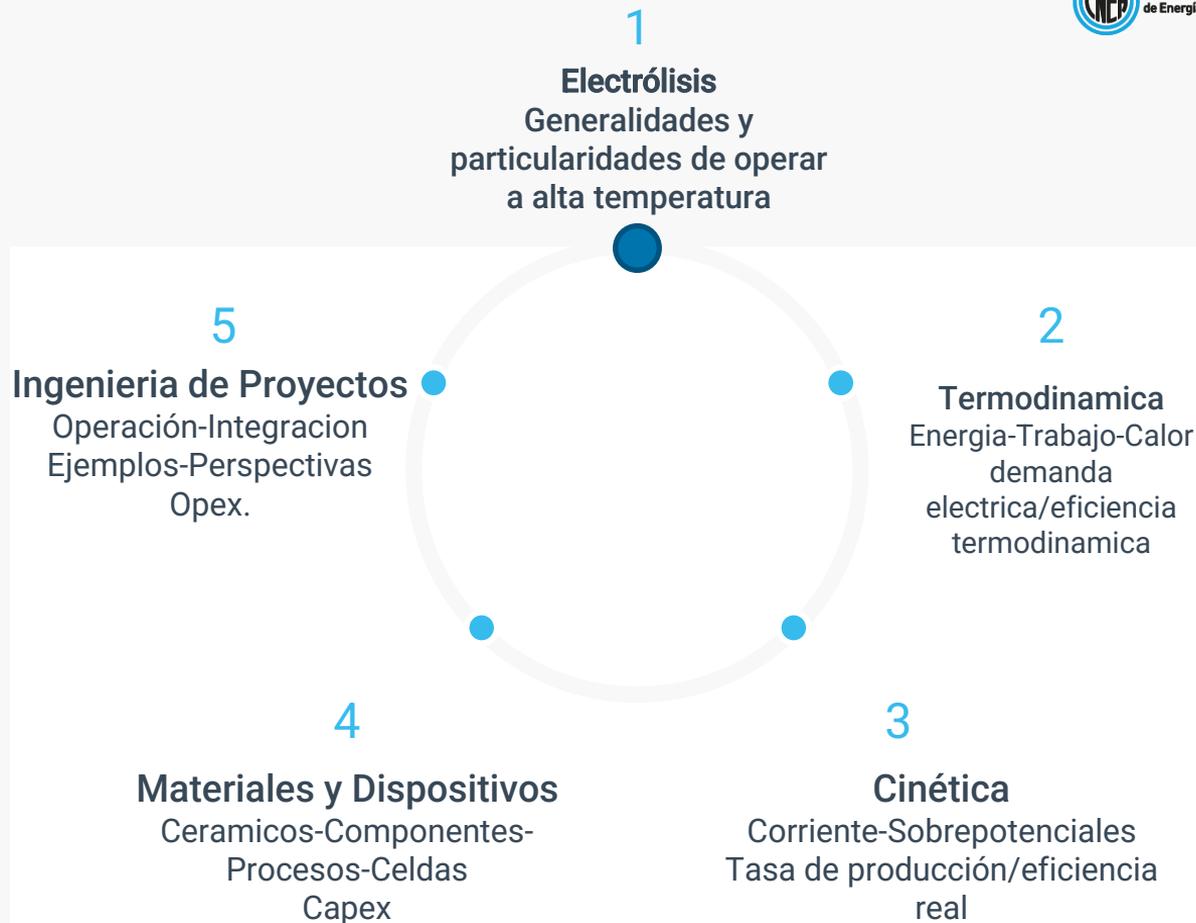
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Noviembre 2024

# Introducción

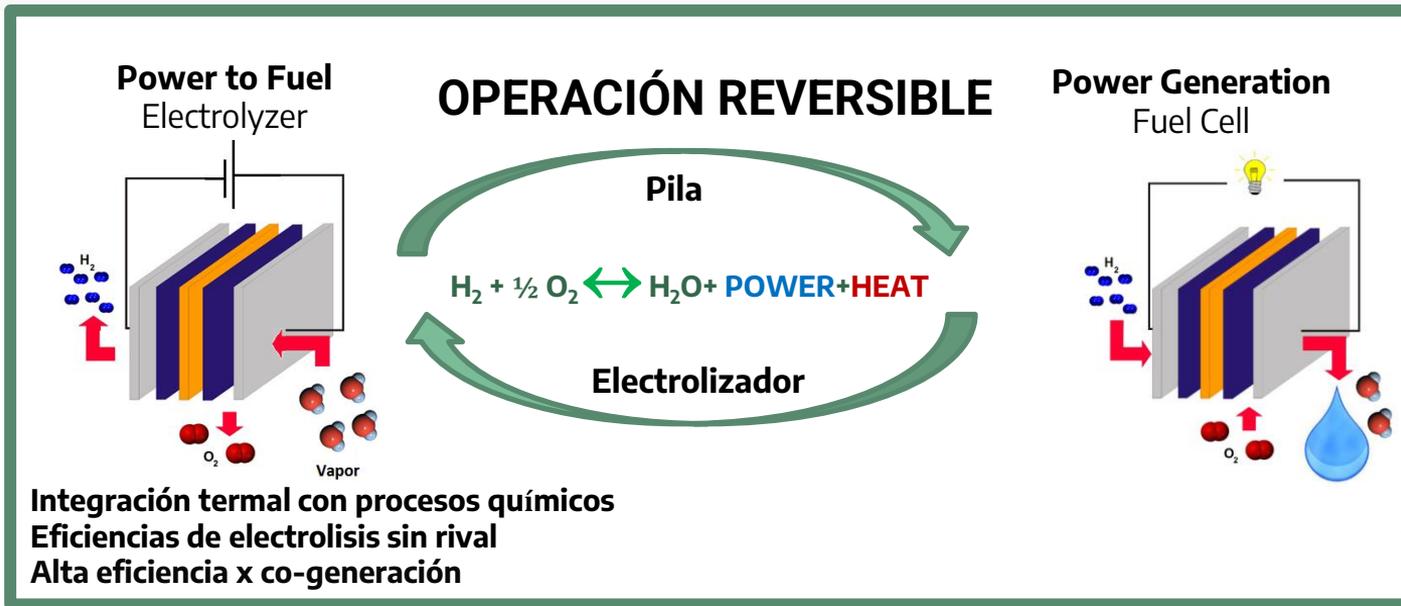
## Electrólisis de Vapor

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# Introducción

## Electrolisis de Vapor de Agua - Generalidades



**MATERIALES CERAMICOS**  
 Materia prima abundante, bajo costo, completamente solido,  
 $600\text{ }^\circ\text{C} < T_{op} < 1000\text{ }^\circ\text{C}$

**FLEXIBILIDAD COMBUSTIBLE**

Modo Fuel Cell:  
 H<sub>2</sub>, GN, Biofuel, NH<sub>3</sub>, methanol

Modo Electrolizador:  
 H<sub>2</sub>O → H<sub>2</sub>(+1/2O<sub>2</sub>), CO<sub>2</sub> → CO(+1/2O<sub>2</sub>)

**SOLID OXIDE ELECTROLYZER CELL (SOEC)- FUEL CELL (SOFC)**



# VENTAJAS

- 1) **Menor costo energético:** Aprovechamiento de la alta temperatura
- 2) **Mayor producción de H<sub>2</sub>:** Cinéticas favorecida → mayor densidad de corriente y producción de H<sub>2</sub>
- 3) **Alta eficiencia:** La eficiencia de la electrólisis puede ser mayor debido a la mayor conductividad iónica y menor resistencia del electrolito sólido.
- 4) **Menos corrosión y mayor durabilidad:** Los materiales de electrolito menos propensos a la corrosión en comparación con las membranas de electrolizadores PEM → mayor durabilidad a largo plazo.
- 5) **Menor necesidad de metales preciosos:** Requisitos de catalizadores menos exigentes por ejemplo que las PEM.
- 6) **Mayor tolerancia a impurezas en el agua de alimentación:** puede simplificar los requisitos de purificación del agua.

# DESVENTAJAS

- 1) **Materiales especiales, resistentes a altas temperaturas:** En especial en los módulos de stacks, requieren superaleaciones, cerámicos, aceros inoxidable especiales
- 2) **Degradación de la celda y stack por ciclados térmicos:** efectos de diferentes coeficientes de expansión térmico o ciclos redox.
- 3) **Degradación de la celda y stack por interdifusión y reacciones químicas entre componentes**
- 4) **Tiempo para inicio/apagado:** entrar en régimen, acondicionar sistema, etc.
- 5) **Procesamiento de cerámicos energéticamente intensivo**

# REQUERIMIENTOS ESPECÍFICOS

## •Electrolitos:

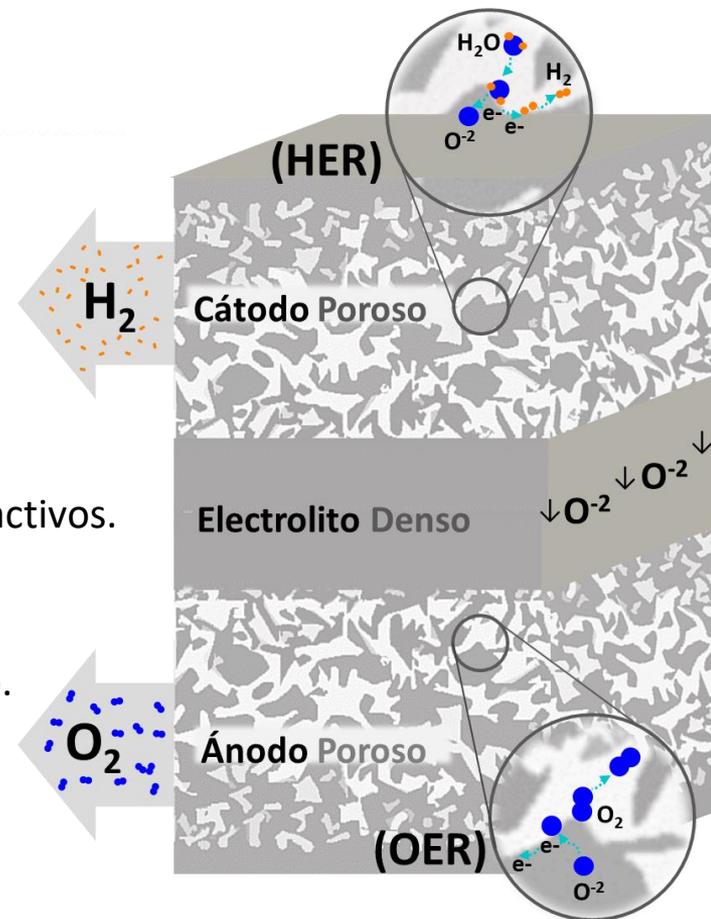
- Aislantes eléctricos, buenos conductores iónicos.
- Buena estabilidad química en atmósferas reductoras/oxidantes.
- Denso y delgado para reducir el sobrepotencial óhmico.

## •Electrodos:

- Porosos para garantizar transporte de gas y proporcionar sitios activos.
- Buena actividad para las reacciones.
- Coeficientes de expansión térmica compatibles con el electrolito.

• **Interconectores:** químicamente estables en ambientes redox.

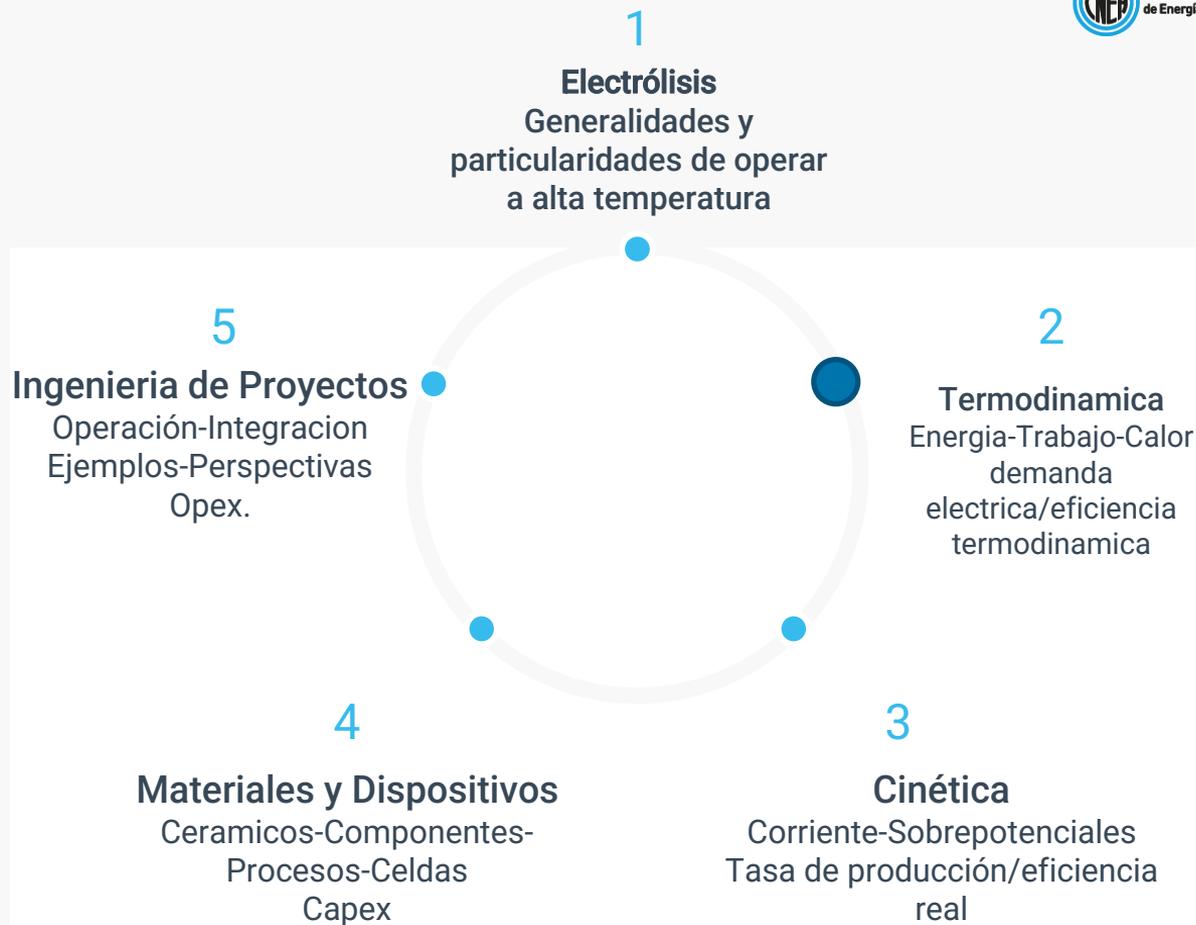
• **Selladores:** imposibiliten paso de gases entre ánodo y cátodo.



# Introducción

## Electrólisis de Vapor

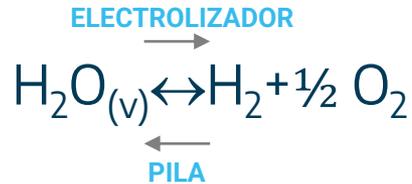
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# Electroquímica de estado sólido

## Termodinámica

### CONVERSION DE ENERGIA; POWER-to-X



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

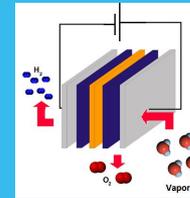
Energía = Trabajo + Calor

- $\Delta H$  entalpía (energía a  $p=\text{cte}$ ) almacenada en los químicos
- $T\Delta S$  término de “calor” asociado a pérdidas del sistema
- $\Delta G$  energía libre de Gibbs es el trabajo eléctrico MINIMO que demanda el Electrolizador o MAXIMO que puede hacer la Pila

$$\Delta G = -W_{\text{elec}} = \text{carga} \cdot \text{potencial} = -nFE$$

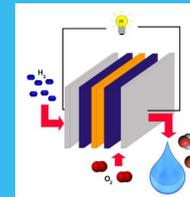
$n$  número de electrones intercambiados en la reacción redox;  $F$  = constante de Faraday 96500 C,  $E$  = potencial eléctrico.

Para la reacción de arriba  $\rightarrow E \sim 1.2 \text{ V}$  (pila) o  $E \sim -1.2 \text{ V}$  (electrolizador)



**ELECTROLIZADOR**

$\Delta G > 0$ , proceso “forzado”



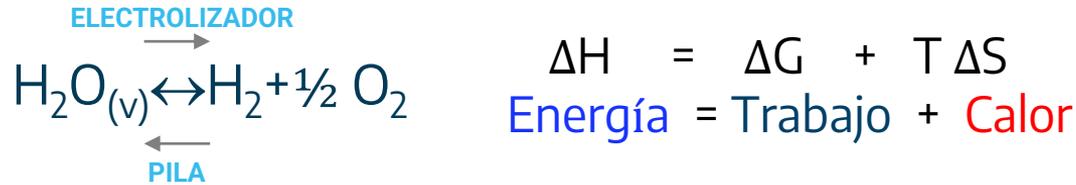
**PILA**

$\Delta G < 0$ , proceso espontáneo

# Electroquímica de estado sólido

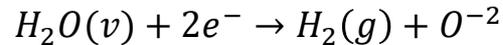
## Termodinámica

### CONVERSION DE ENERGIA; POWER-to-X

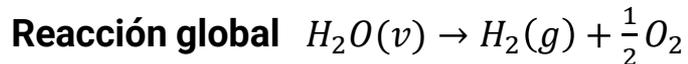
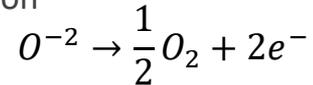


- Reacción Redox en electrolizador alta temperatura

**CÁTODO** → proceso de reducción



**ÁNODO** → Proceso de oxidación



**ELECTROLITO** transporta carga de un electrodo a otro como iones. En los electrolizadores de alta temperatura el electrolito es un **CERAMICO** (óxido sólido) que conduce **IONES O<sup>-2</sup>** dentro de la red cristalina

# Electroquímica de estado sólido

## Termodinámica

- En condiciones estándar (25 °C-1atm)  $\text{H}_2\text{O}_{(\text{liq})} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$

- $\Delta\text{H}^\circ = 285.84 \text{ kJ/mol}$  (**Higher Heating Value –HHV**)

$$E^\circ_{\text{HHV}} = -1.48 \text{ V}$$

Nota:  $\text{H}_2\text{O}(\text{vap}) \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$   $\Delta\text{H}^\circ = 241.83 \text{ kJ/mol}$  (**Lower Heating Value –LHV**)

- $\Delta\text{G}^\circ = 237 \text{ kJ/mol} \rightarrow$

$$E^\circ_{\text{LHV}} = -1.23 \text{ V}$$

**Potencial Estándar: VOLTAJE REVERSIBLE en condiciones estándar**

# Electroquímica de estado sólido

## Termodinámica

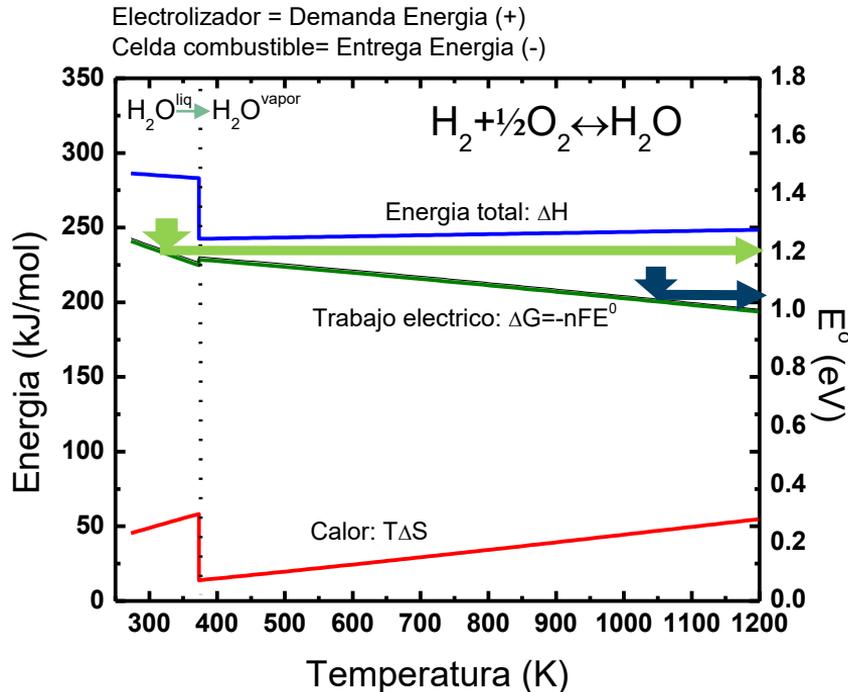
$$\Delta G = \Delta H - T \Delta S = -nFE$$

Efecto de la **TEMPERATURA**

PRESION

COMPOSICION

$$-nFE = \Delta G = -S\Delta T + V\Delta p + \sum_i^N \mu_i \Delta n_i$$



**HIDROGENO:  $H_2O(v) \rightarrow H_2 + \frac{1}{2} O_2$**

$$E^0 (25^\circ C) = -1.23 \text{ V}$$

$$E^0 (800^\circ C) = -1.03 \text{ V}$$

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

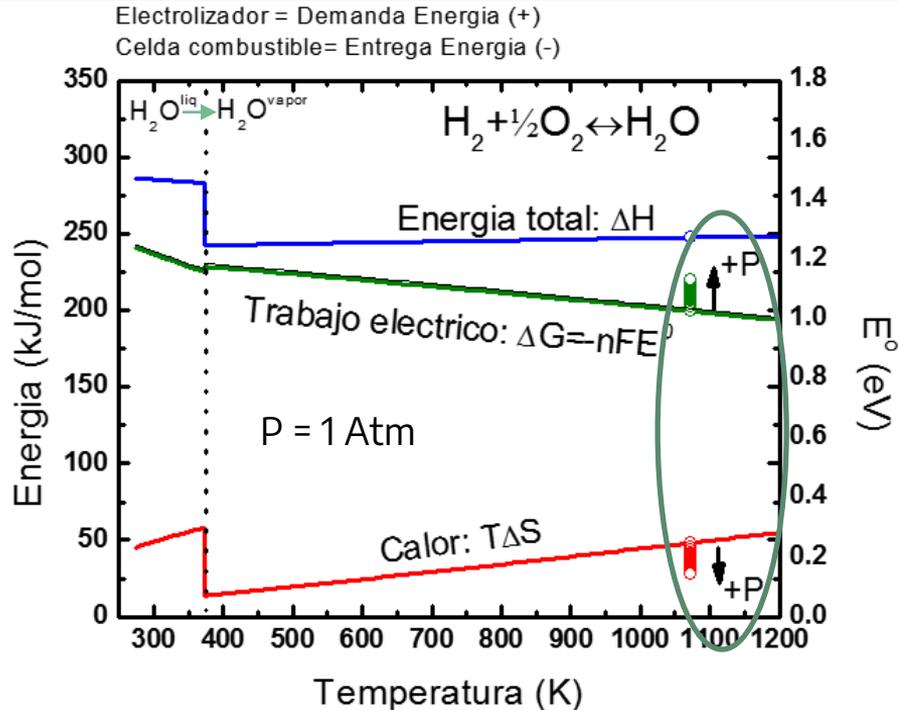
Entropía  $T\Delta S \rightarrow$  CALOR

DISIPADO en pila combustible

UTILIZADO en electrolizador

# Electroquímica de estado sólido

## Termodinámica



Efecto de la TEMPERATURA

**PRESION**

COMPOSICION

$$-nFE = \Delta G = -S\Delta T + V\Delta p + \sum_i^N \mu_i \Delta n_i$$

- *El efecto de la presión depende del cambio de número de moles gaseosas en la reacción*
- \* Aumento 3-5 atm aumenta algunas decenas de mV
- \* Los **electrolizadores cerámicos no son muy aptos para trabajar a muy altas presiones** (rupturas de membranas)

En la producción de  $H_2$  por electrolisis, el aumento de presión aumenta la demanda de energía, pero puede compensarse por el hecho de que se produce  $H_2$  comprimido y reduce el gasto de energía para la compresión del producto a la salida. En la electrolisis de líquido ayuda reducir tamaño de burbujas de gas

# Electroquímica de estado sólido

## Termodinámica

Efecto de la TEMPERATURA  
PRESION

COMPOSICION

Baja temperatura ( $T < 100^{\circ}\text{C}$ )



$$E = E^{\circ} - \frac{RT}{2F} \ln \frac{1}{p_{\text{H}_2} p_{\text{O}_2}^{1/2}}$$

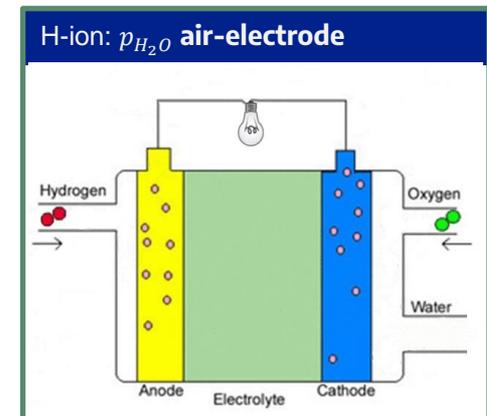
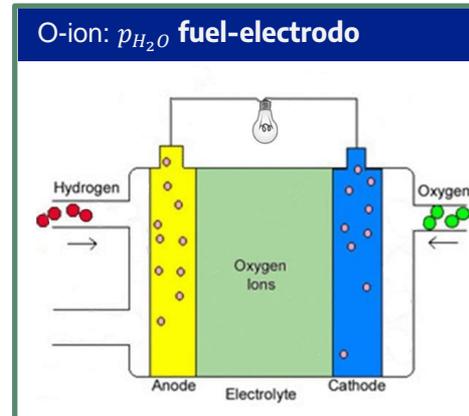
Alta temperatura ( $T > 100^{\circ}\text{C}$ )



$$E = E^{\circ} - \frac{RT}{2F} \ln \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2} p_{\text{O}_2}^{1/2}}$$

$$-nFE = \Delta G = -S\Delta T + V\Delta p + \sum_i^N \mu_i \Delta n_i$$

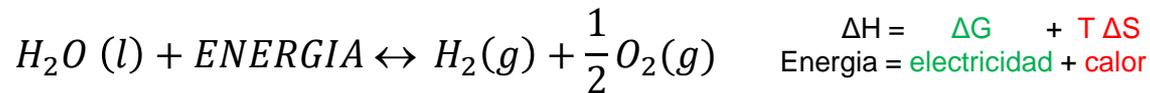
$p_{\text{H}_2}$  del lado del combustible  
 $p_{\text{O}_2}$  del lado de del aire  
 $p_{\text{H}_2\text{O}}$  en que electrodo se inyecta?



Electrólisis alta T con **electrolito conductor protónico**: vapor  $\text{H}_2\text{O}$  ingresa en electrodo de  $\text{O}_2$  → Se obtienen  $\text{H}_2$  puro (sin vapor)

# Electroquímica de estado sólido

## Termodinámica



Da cuenta de la **MINIMA** energía necesaria para producir  $H_2$  (cuando  $i \rightarrow 0$ )

$$\text{Demanda eléctrica para producir } H_2: \frac{\text{energía eléctrica}}{\text{energía total}} = \frac{\Delta G}{\Delta H} = \frac{E^0}{E^{tn}}$$

$E^{tn} = -1,48 \text{ V}$  (potencial termoneutral) =  $\Delta H/nF$

$E^0 \rightarrow$  depende de la temperatura

$$E^0(25^\circ\text{C}) = -1.23 \text{ V}$$

$$E^0(800^\circ\text{C}) = -1.03 \text{ V}$$

Demanda eléctrica para producir  $H_2$  con electrolizadores de:

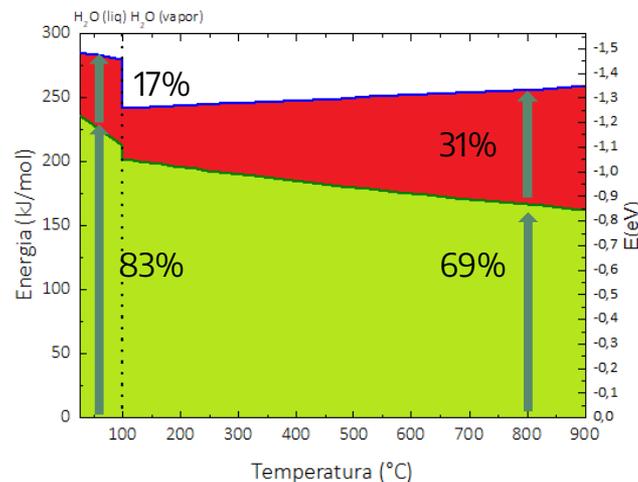
- BAJA TEMPERATURA ( $25^\circ\text{C}$ ) = **83%**      ALTA TEMPERATURA ( $800^\circ\text{C}$ ) = **69%**

Demanda eléctrica relativamente baja para electrólisis a alta T

## Demanda eléctrica

A temperatura ambiente

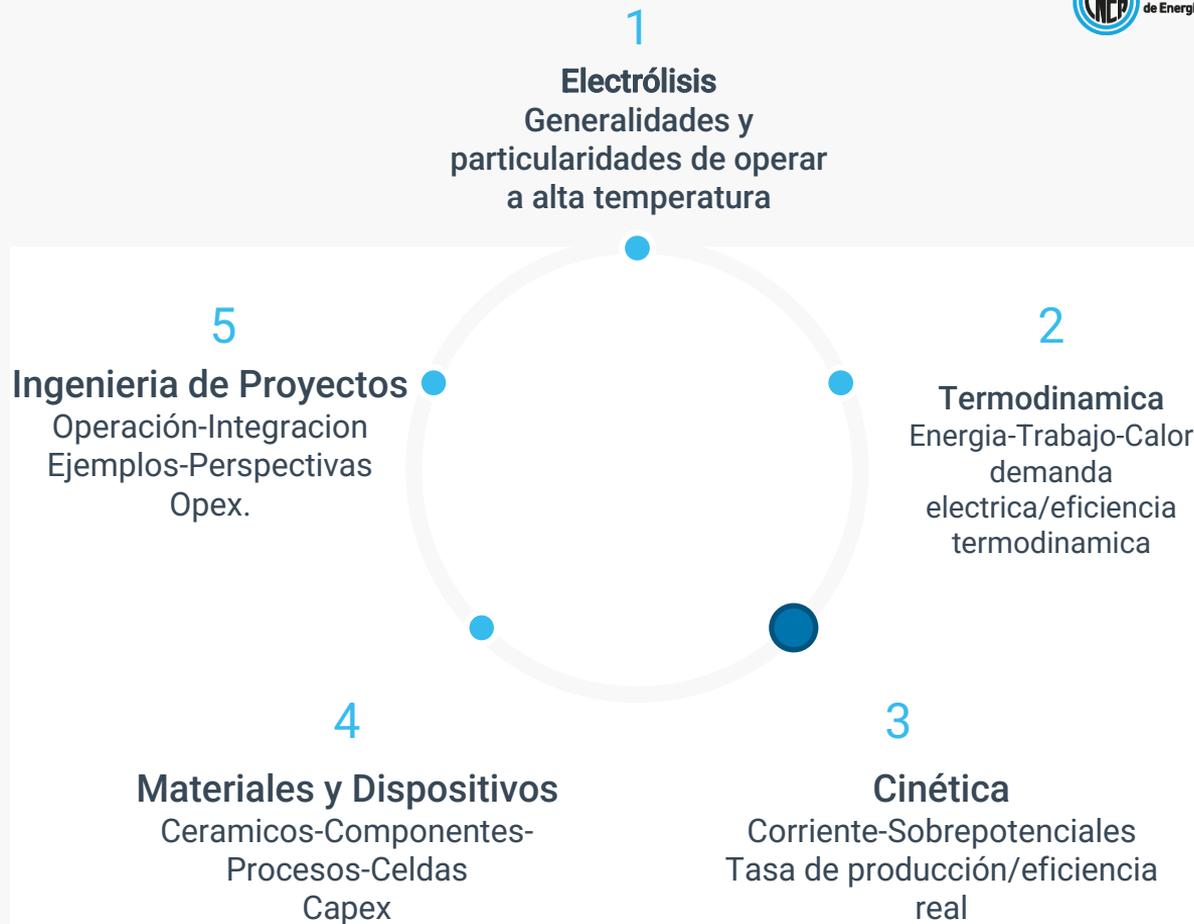
-285.8 kJ/mol	= -237.2 kJ/mol	-48.6 kJ/mol
-39.6 kWh/kg	= -32.8 kWh/kg	-6.7 kWh/kg
100 %	=	83%      17%



# Introducción

## Electrólisis de Vapor

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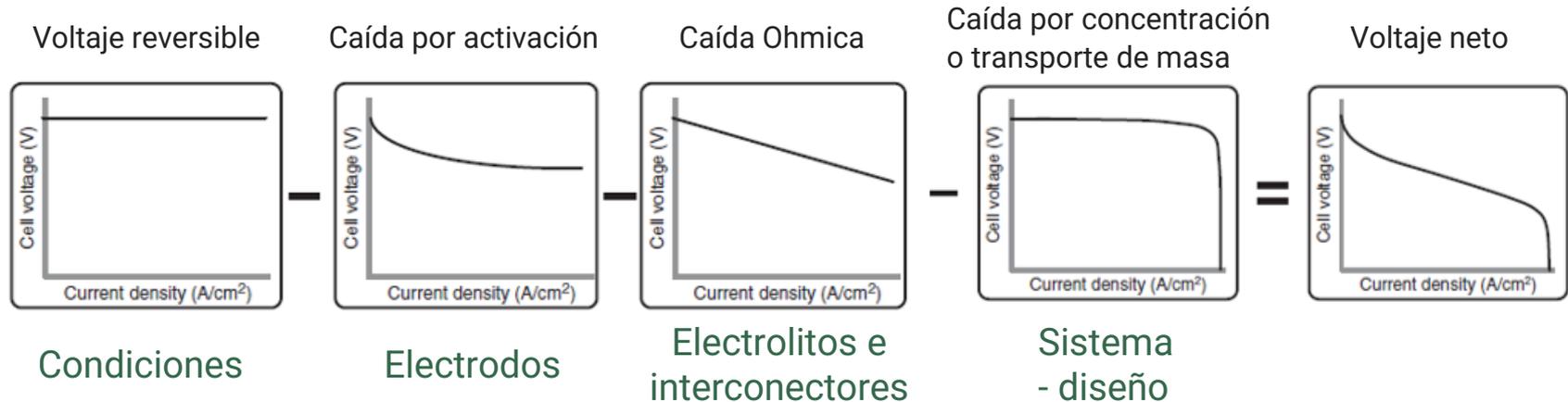


# Electroquímica de estado sólido

## Efectos de Cinética y transporte de carga y masa

Sobrepotenciales ( $\eta$ )

$$E^{th} - \eta_{act} - \eta_{ohm} - \eta_{conc} = V(i)$$



# Electroquímica de estado sólido

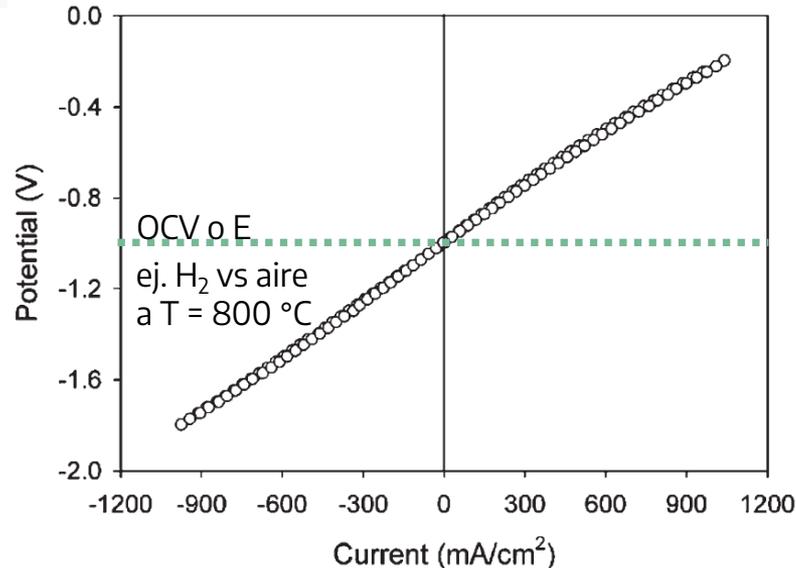
## Efectos de Cinética y transporte de carga y masa

Sobrepotenciales =  $\eta$



OCV: Open Circuit Voltage o  
POTENCIAL REVERSIBLE (E)

→ Potencial a circuito abierto,  
corriente  $i = 0$



Cuando circula corriente el  
potencial eléctrico cambia

Ley de Faraday (tasa de producción de H<sub>2</sub>)

$$m_{\text{H}_2} = \frac{m_{\text{eq}} I t}{F}$$

Donde  $m$  = masa de sustancia generada por electrólisis,  $I$  intensidad de corriente;  $t$  tiempo que circula corriente,  $F = 96500$  C cte de Faraday  $m_{\text{eq}}$  = masa molecular/ $n$  de electrones ( $m_{\text{eq}} \text{H}_2 = 1$ )

# Electroquímica de estado sólido

## Cinética y transporte de carga y masa

### Sobrepotenciales

El electrolizador necesita mas energía de la esperada para producir H<sub>2</sub> por los sobrepotenciales  
 La producción de H<sub>2</sub> es proporcional a la corriente  
 Buscamos obtener mayor corriente a menor V



#### Electrolizador

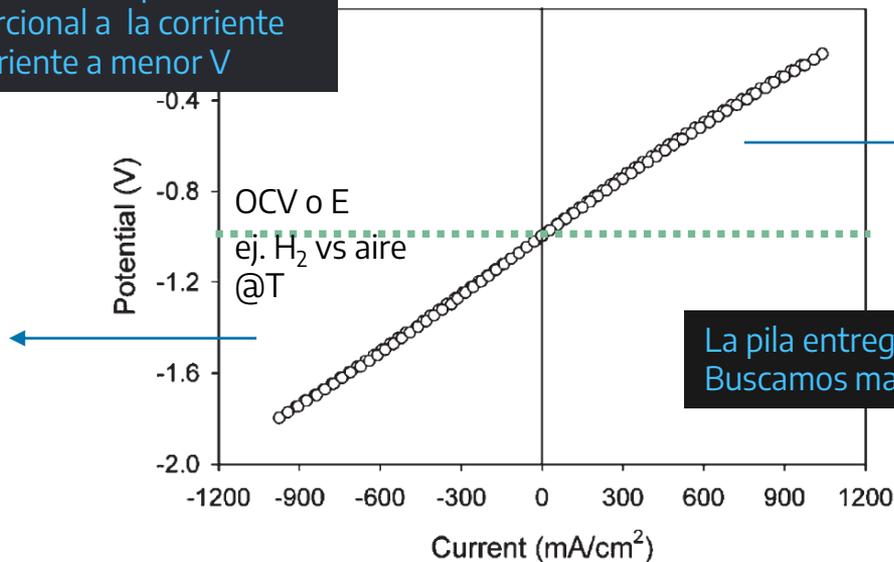
Energía eléctrica → energía química

$$|V| = |E| + \eta(i) + |iR|$$

$i$  = corriente

$R$  = resistencia de la celda (conductividad iónica)

$\eta(i)$  = sobrepotenciales de electrodos (cinética de reacciones)



#### Pila de combustible

Energía química → energía eléctrica

$$|V| = |E| - \eta(i) - |iR|$$

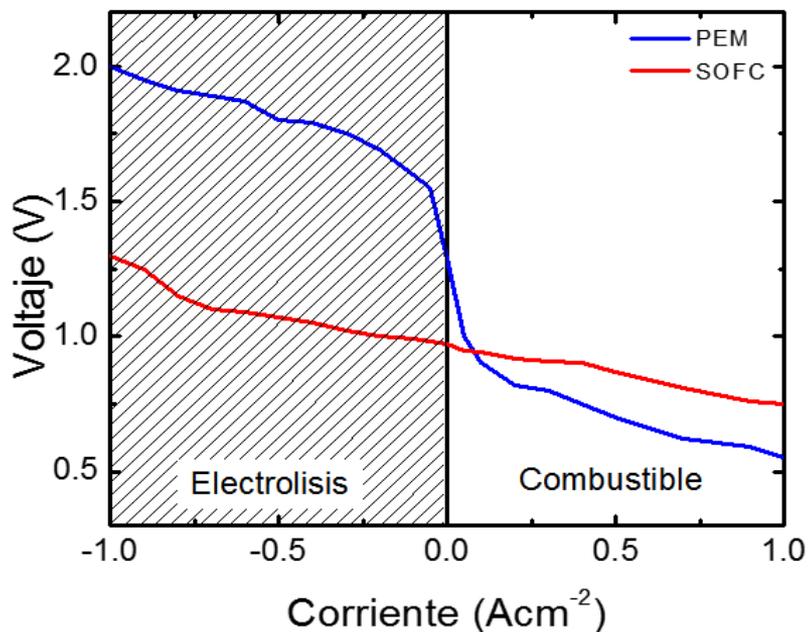
La pila entrega menos potencia de la esperada  
 Buscamos mayor potencia  $P=iV$  (en general máximo)

# Electroquímica de estado sólido

## Cinética y transporte de carga y masa

### Sobrepotenciales

Curva Voltaje-Corriente Real de distintos tipos de electrolizador/pila combustible



Voltaje  $V$  aplicado o de operación

Si  $V \leq E^0 \rightarrow$  NO HAY CORRIENTE ( $I = 0$  A)

Si  $V > E^0 \rightarrow$  corriente  $I_{H_2} \rightarrow (V - E^0) = I_{H_2} R$

$$R_{total} = R_{electric} + R_{anode} + R_{bubble,O_2} + R_{ions} + R_{membrane} + R_{bubble,H_2} + R_{cathode}$$

Las diferencias se deben principalmente a los **sobrepotenciales** o **resistencias de electrodos** (cinética de las reacciones) y **transporte de cargas** (conductividad iónica)

**$\rightarrow$  DISMINUYEN con la TEMPERATURA**

# Electroquímica de estado sólido

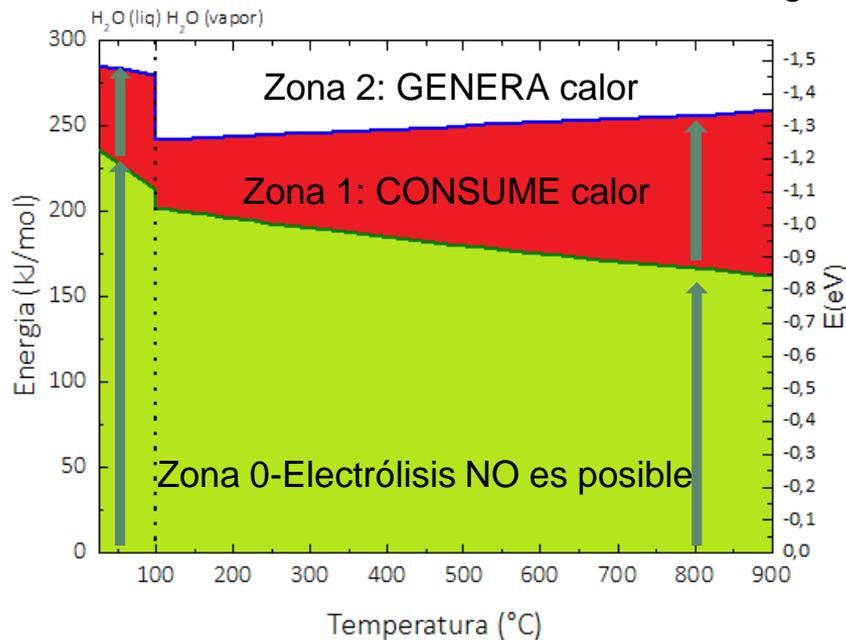


$$\Delta H = \Delta G + T \Delta S$$

Energía = electricidad + calor

## Eficiencia de termodinámica conversión

$$\varepsilon_{th} = -\frac{\Delta H}{W_{el}} = \frac{E^{tn}}{V_{aplicado}}$$



$\Delta G$  es el MINIMO trabajo que se necesita para empezar a producir  $\text{H}_2$  (cuando la corriente es "0")

- **Zona 0:**  $V < E^0 \rightarrow$  El potencial o trabajo eléctrico no es suficiente para producir  $\text{H}_2$
- **Zona 1:**  $E^0 < V_{aplicado} < E^{tn} \rightarrow$  **Modo endotérmico:** Se empieza a producir  $\text{H}_2$  pero el proceso también consume calor (podría ocurrir que baje la temperatura de la celda), si se inyecta calor ese calor también produce  $\text{H}_2$ :  $\varepsilon_{th} > 100\%$
- **Equilibrio térmico:**  $V_{aplicado} = E^{tn} \rightarrow$  celda opera teóricamente en condiciones de equilibrio térmico con  $\varepsilon_{th} = 100\%$  **Modo termoneutral**
- **Zona 2:**  $V_{aplicado} > E^{tn} \rightarrow$  **Modo Exotérmico:** extraer calor para mantener la celda a T constante, en este caso  $\varepsilon_{th} < 100\%$

## Actividad – Electrolisis T ambiente vs Alta T

Si se tienen dos electrolizadores basados en distintas tecnologías:

- Electrolizador A opera a temperatura ambiente
- Electrolizador B opera a 800 °C.

Si ambos tienen igual resistencia interna  $R = 1\Omega$ , y a ambos se le aplica el mismo potencial

$$V = E^{tn} = 1.48 \text{ V}$$

Cuál produce mayor cantidad de  $H_2$ ? Cuánto más?

*Cuanto es la eficiencia de conversión?*

$$(V - E^0) = I_{H_2} R$$

Voltaje  $V$  aplicado o de operación

Si  $V \leq E^0 \rightarrow$  NO HAY CORRIENTE ( $I = 0 \text{ A}$ )

Si  $V > E^0 \rightarrow$  corriente  $I_{H_2} \rightarrow (V - E^0) = I_{H_2} R$

$$E^0 (25 \text{ °C}) = -1.23 \text{ V}$$

$$E^0 (800 \text{ °C}) = -1.03 \text{ V}$$

$$I_{H_2} = 0,25 \text{ A}$$

$$I_{H_2} = 0,45 \text{ A}$$

Es decir, que la producción de  $H_2$  es prácticamente el doble

## Eficiencia de termodinámica conversión

$$\varepsilon_{th} = -\frac{\Delta H}{W_{el}} = \frac{E^{tn}}{V_{aplicado}}$$

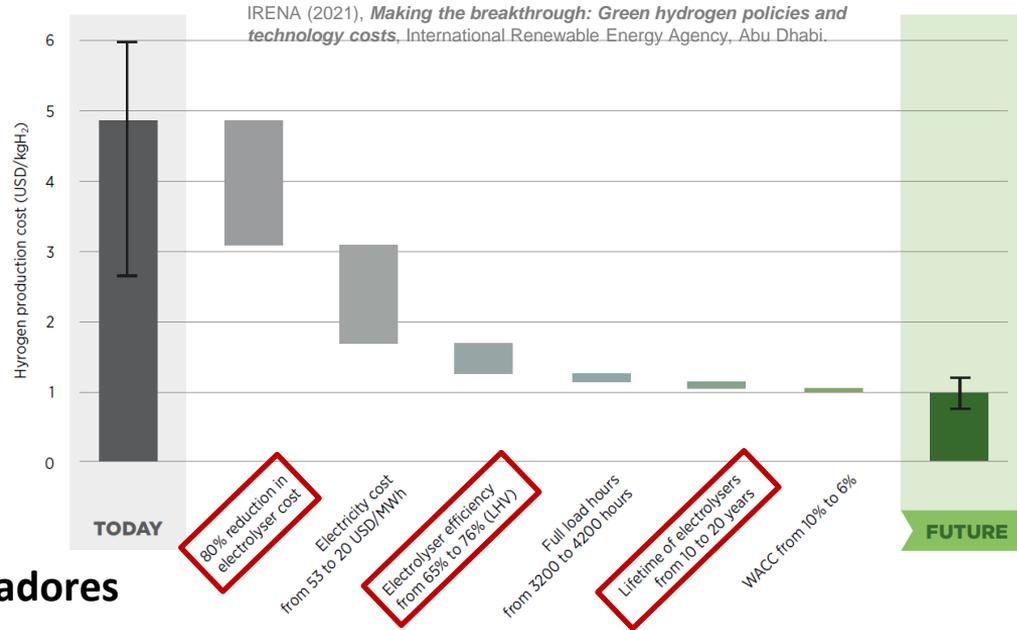
$E^{tn} = -\frac{\Delta H}{nF}$  es el voltaje “termoneutral”,  $E^{tn} \approx 1.48 \text{ V}$  para el  $H_2$  a T ambiente.

# ELECTROLIZADORES & CIENCIA DE MATERIALES

1 USD/kg H<sub>2</sub>

TARGET PARA COSTO DE PRODUCCION DE H<sub>2</sub>

- Produccion 1 USD/kg H<sub>2</sub>
- Transporte 2 USD/kg H<sub>2</sub>
- Almacenamiento 9 USD/kWh



## TARGETs Electrolizadores

150 USD/kW → 70 % eficiencia → 80.000 h duración

Comprender que mecanismos controlan el rendimiento y durabilidad, teniendo en consideración los costos



- Reducir los costos de capital (CAPEX)
- Mejorar eficiencia (OPEX).
- Aumentar la vida media.

DESAFIOS PARA LA CIENCIA E INGENIERIA DE MATERIALES

# DESAFIOS PARA LA CIENCIA E INGENIERIA DE MATERIALES

Comprender que mecanismos controlan el **rendimiento** y **durabilidad**, teniendo en consideración los **costos**.



**-REDUCIR LOS COSTOS DE CAPITAL DE EQUIPOS**

**-Mejorar eficiencia**

**-Aumentar la vida media.**

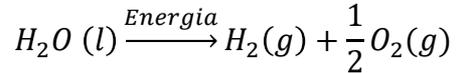


# DESAFIOS PARA LA CIENCIA E INGENIERIA DE MATERIALES

Comprender que mecanismos controlan el **rendimiento y durabilidad**, teniendo en consideración los costos.



**-REDUCIR LOS COSTOS DE CAPITAL DE EQUIPOS**  
**-MEJORAR EFICIENCIA**  
**-Aumentar la vida media.**



$$(V - E^{\text{rev}}) = I_{H_2} \times (R_{\text{electrolito}} + R_{\text{ohmic}} + R_{\text{anodo}} + R_{\text{catodo}})$$

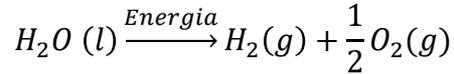
(DEMANDA ELECTRICA) = (TASA DE PRODUCCION DE H<sub>2</sub>) x (TECNOLOGIA DEL ELECTROLIZADOR)

# DESAFIOS PARA LA CIENCIA E INGENIERIA DE MATERIALES

Comprender que mecanismos controlan el **rendimiento** y **durabilidad**, teniendo en **consideración los costos**.

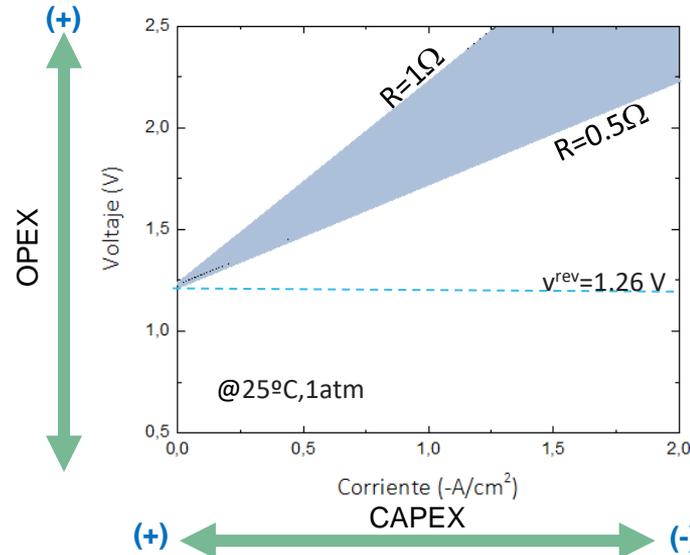


- REDUCIR LOS COSTOS DE CAPITAL DE EQUIPOS
- MEJORAR EFICIENCIA
- Aumentar la vida media.



$$(V - E^{rev}) = I_{H_2} \times (R_{\text{electrolito}} + R_{\text{ohmic}} + R_{\text{anodo}} + R_{\text{catodo}})$$

(DEMANDA ELECTRICA) = (TASA DE PRODUCCION DE H<sub>2</sub>) x (TECNOLOGIA DEL ELECTROLIZADOR)



# DESAFIOS PARA LA CIENCIA E INGENIERIA DE MATERIALES

Comprender que mecanismos controla el **rendimiento, costo, y durabilidad**



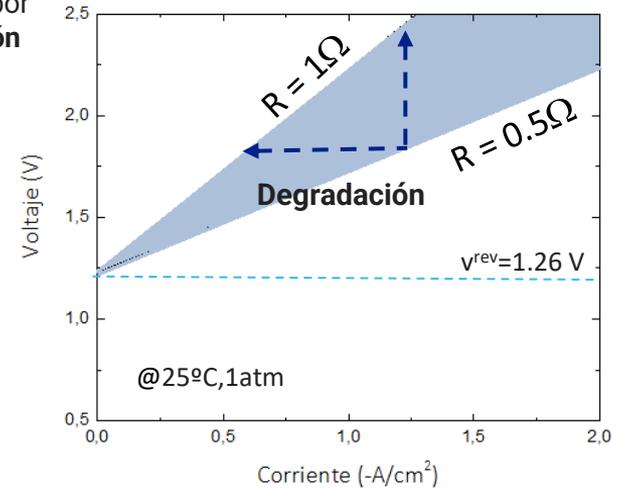
- REDUCIR LOS COSTOS DE CAPITAL DE EQUIPOS
- MEJORAR EFICIENCIA
- AUMENTAR LA VIDA MEDIA.

$$(V - V^{rev}) = I_{H_2} \times (R_{\text{electrolyte}} + R_{\text{ohmic}} + R_{\text{anode}} + R_{\text{cathode}})$$



Aumentan con el tiempo por fenómenos de **degradación**

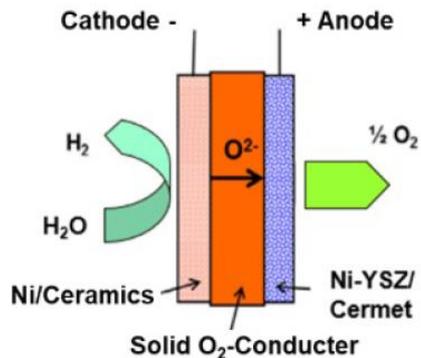
**DESARROLLO**



**ENTENDIMIENTO**

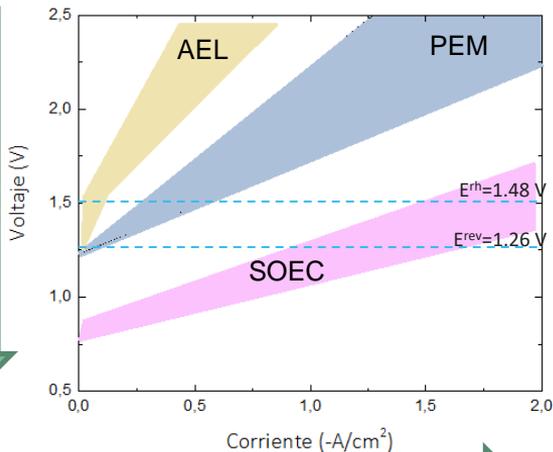


# El estado del arte: ELECTROLIZADORES SOEC



- Materiales mas robustos
- Aumentar escala de producción
- Integración con otras tecnologías

(-) \$ operación



(-) \$ capital

- Madurez Prototipo/T&D
- No requiere mantenimiento regular
- Alta densidad de potencia
- Costo de materiales
- No usa sust. corrosivas
- Alta eficiencia
- Posibilidad de integración (calor)
- Co-electrolisis CO<sub>2</sub>
- Vida útil < 10.000 h
- Etapa R&D
- Estabilidad a largo plazo / ciclados
- Respuesta lenta

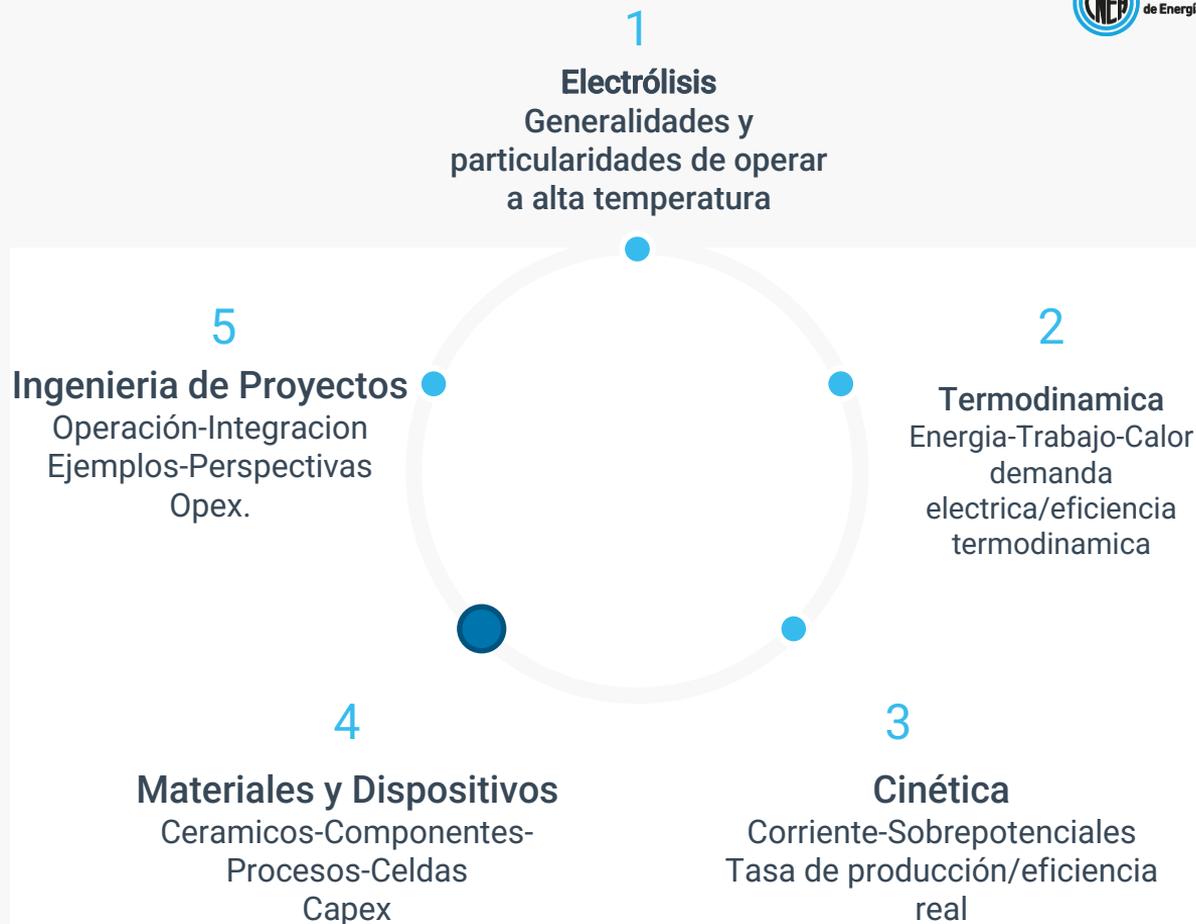
**\$ operación bajo (aprovecha calor)**

**\$ capital medio (materiales económicos, pero se degradan)**

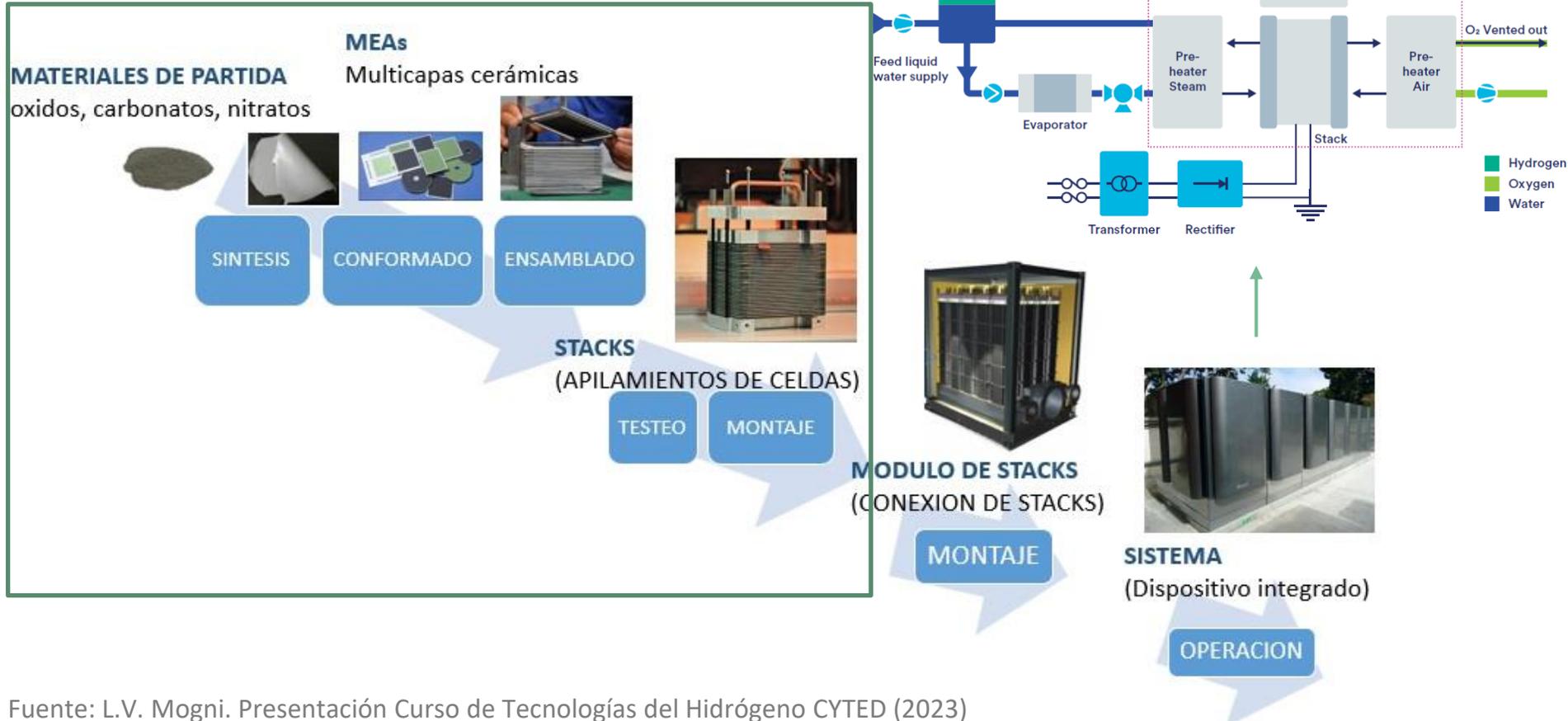
# Introducción

## Electrólisis de Vapor

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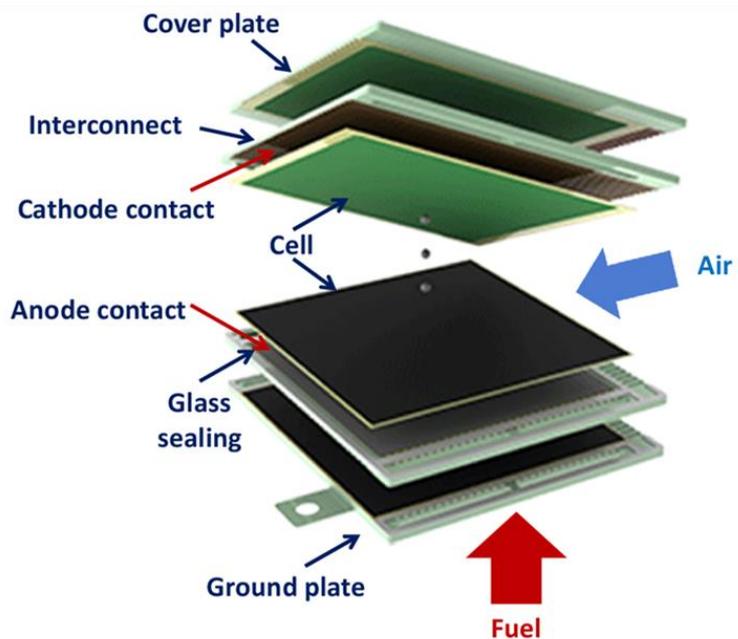


# SOEC. Componentes y procesamiento



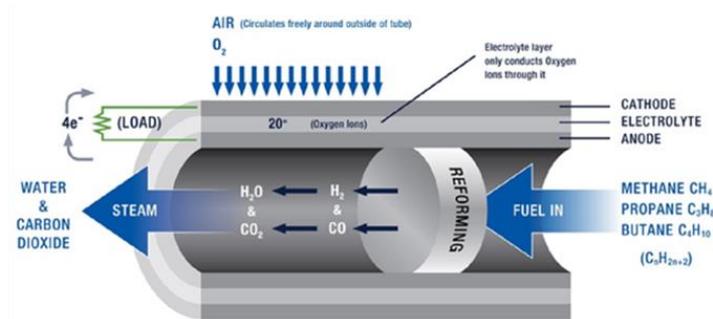
# SOEC. Configuraciones de Stacks

## Diseño planar (Frankhoufer IKTS)



M. Kusnezoff *et al*, Proceedings of the 12th European Fuel Cell Forum, (2016) A0601

## Diseño tubular (Acumentrics)

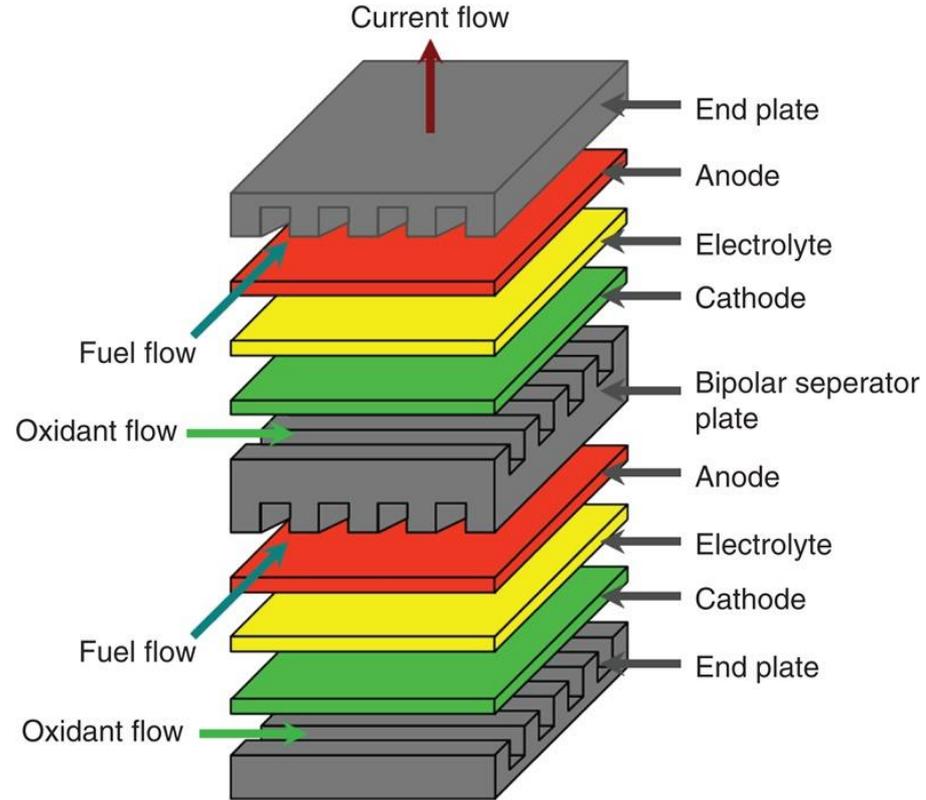
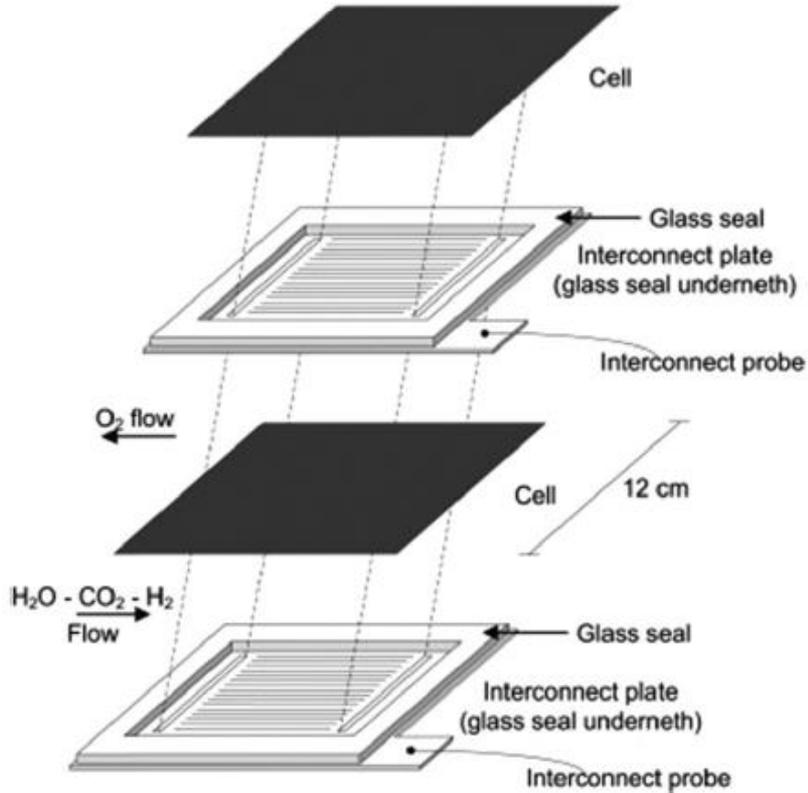


Fuente: Technical White Paper: Solid Oxide Fuel Cell ("SOFC") Generators vs Thermoelectric Generators ("TEGs"); a Technical Comparison, Acumentrics  
Boigues-Muñoz *et al*, Int. J. Hydrogen Energy 39 (2014) 21714-21723

# SOEC. Configuraciones de Stacks

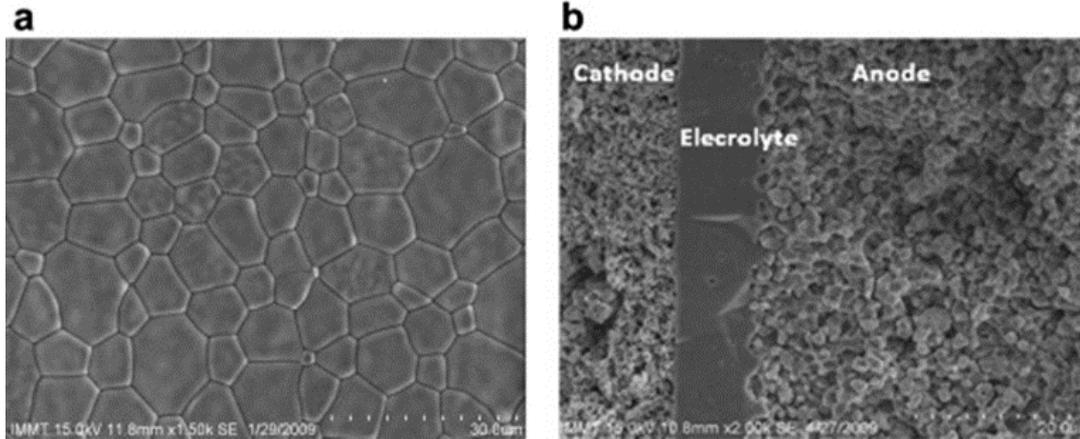
TIPO DE DISEÑO	VENTAJAS	DESVENTAJAS
<b>TUBULAR</b>	<ul style="list-style-type: none"> <li>- Menos problemas con las tensiones de origen térmico.</li> <li>- Sellado más sencillo o ausencia de sellado</li> </ul>	<ul style="list-style-type: none"> <li>- Largo recorrido para la corriente</li> <li>- Menor densidad de potencia</li> </ul>
<b>PLANAR</b>	<ul style="list-style-type: none"> <li>- Flexibilidad en la geometría, la configuración del flujo de gas y el colector de gas.</li> <li>- Flexibilidad en la fabricación, especialmente para el caso de celdas separadas que se interconectan</li> </ul>	<ul style="list-style-type: none"> <li>- Posible límite de escalamiento a tamaños grandes, especialmente para las autosoportadas.</li> <li>- Exigencias rigurosas de planitud y sellado.</li> <li>- Potenciales contactos entre celdas e interconexiones</li> </ul>

# Electrolizador SOEC



Apliamientos de MEAs

# Electrolito SOEC



## REQUISITOS

- **Conductividad iónica**, nula o casi nula conductividad electronica
- Compatibilidad química y física con ánodo y cátodo
- **Estabilidad** en atmosfera reductora y oxidante
- Capacidad de **sinterizado** (altamente denso)

# Electrolito SOEC

## MATERIALES

### Conductores de iones óxido ( $O^{2-}$ )

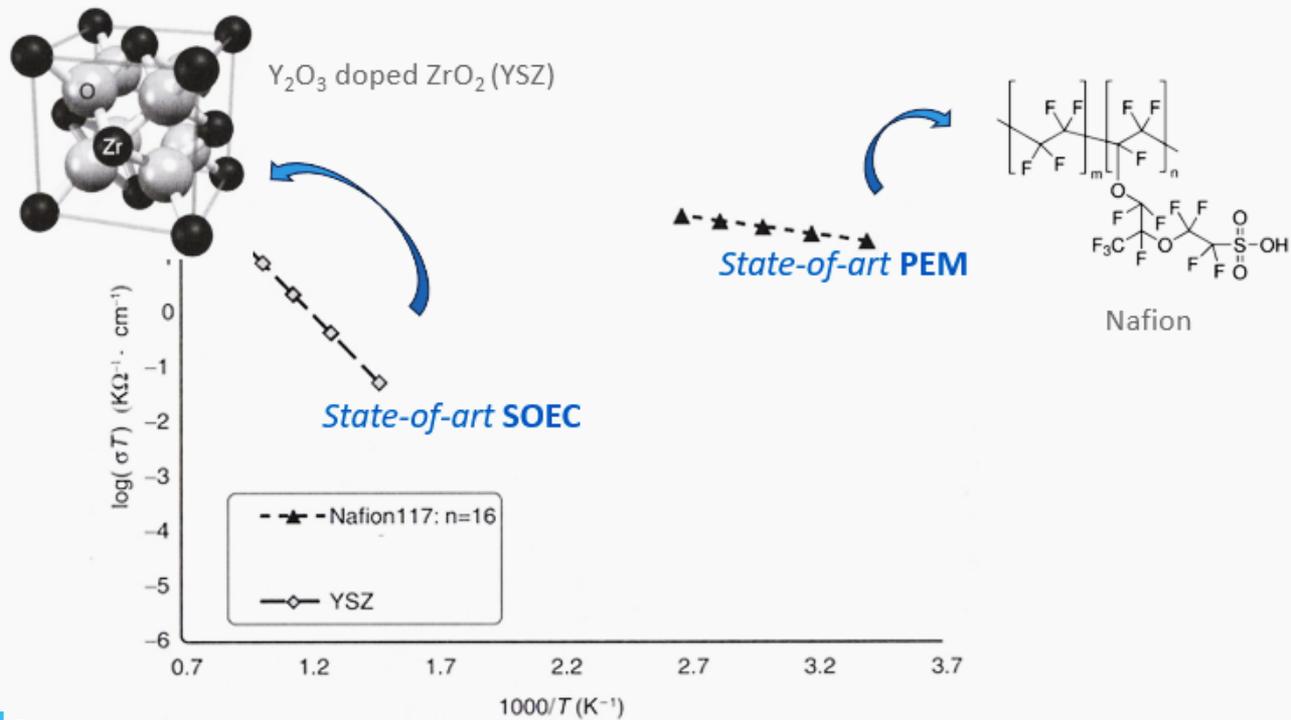
- Óxidos con estructura tipo fluorita (YSZ, ScSZ, GDC, SDC)
- Perovskitas (LSGM)
- Otros

### Conductores protónicos ( $H^+$ )

- Perovskitas (BCZO, BCZYO)

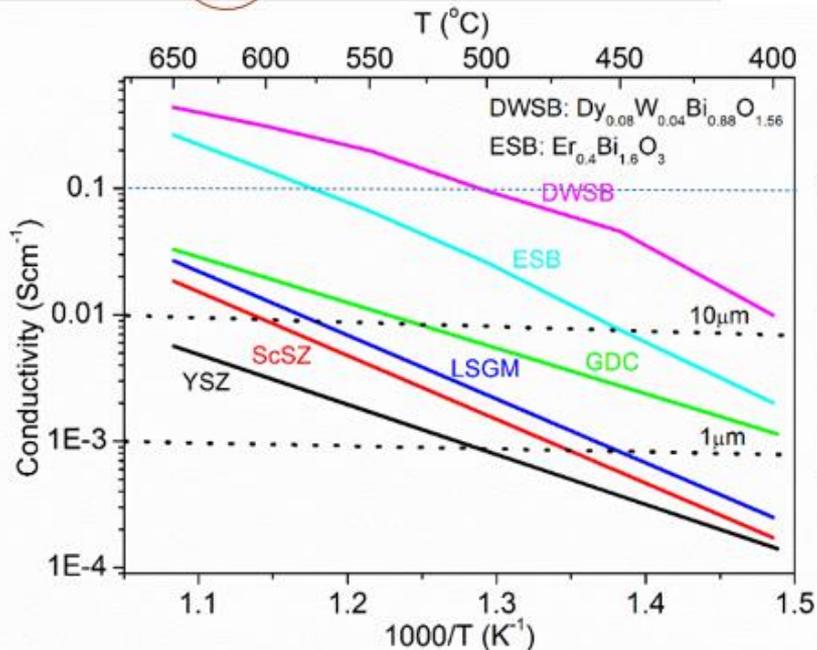
$\sigma$ : conductividad iónica

GDC: gadolinia doped ceria  
óxido de cerio dopado con óxido  
de gadolinio  $CeO_2-Gd_2O_3$



# Electrolito SOEC

$$V(j) = E^{th} + \eta_{ohm} + \eta_a^{Act+TM} + \eta_c^{Act+TM} - \eta_{leak}$$



ESPESOR

$t \sim 100 \mu m$

$t \sim 10 \mu m$

$t \sim 1 \mu m$

**OBJETIVO** → Minimizar las pérdidas óhmicas

- Aumentar conductividad
- Disminuir espesor

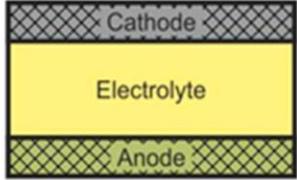
$$\rho = \frac{e}{\sigma}$$



Target: resistividad x espesor  $\lesssim 0.1 \Omega cm^2$

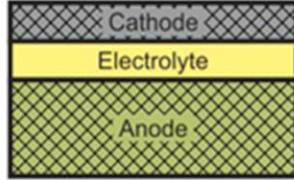
Si el espesor  $\sim 100 \mu m$  (0.01 cm):  $\rho_i \lesssim 10 \Omega cm$  or  $\sigma_i \gtrsim 0.1 S cm^{-1}$

# Electrolito SOEC - CONFIGURACIONES MEAs



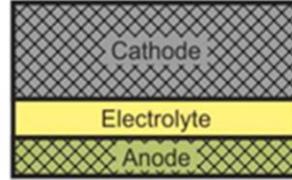
**Electrolyte supported (ES)**

1ra Generación

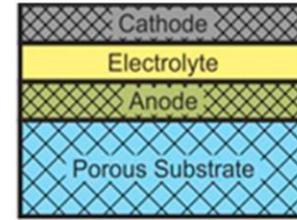


**Anode supported (AS)**

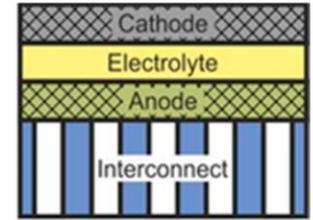
2da Generación



**Cathode supported (CS)**



**Substrate supported (SS)**

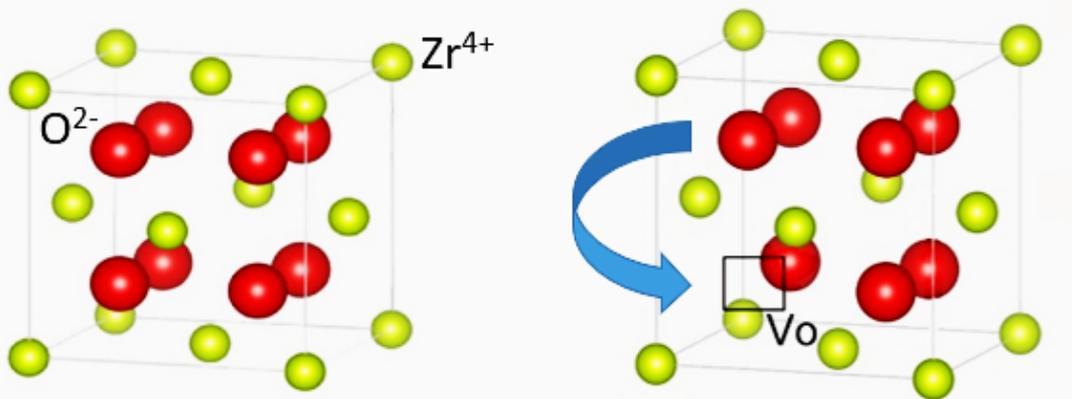


**Metal supported (MS)**

3ra Generación

# Electrolito SOEC

## ÓXIDOS CON ESTRUCTURA TIPO FLUORITA



Vacancias de oxígeno intrínsecas

Ej.  $ZrO_2$

### CONDUCCIÓN IÓNICA

- A  $T > 0K$  óxidos presentan vacancias de oxígeno (intrínsecas) x entropía
- Proceso **térmicamente activado**, baja movilidad de vacancias a  $T_{amb}$

movilidad de los iones:

$$\mu_{ion} = \frac{\mu_0}{T} \exp\left(-\frac{E_a}{RT}\right) \quad (1)$$

conductividad iónica:

$$\sigma_{ion} = n q \mu_{ion} \quad (2)$$

$n$ : #portadores (vacancias),  $q$ : carga

$$\sigma_{ion} = \frac{\sigma_0}{T} \exp\left(-\frac{E_a}{RT}\right)$$

$$\sigma_{ion} \propto n$$

$$\sigma \propto [V_o] \text{ bajas concentraciones de } V_o$$

**Vacancias extrínsecas:**

son por agregado de un dopante con carga diferente, ej  $Y^{3+}$

# Electrodos SOEC

## Objetivo

Desarrollar **cátodos** de celdas de temperatura intermedia (IT-SOFC):  $500^{\circ}\text{C} < T_{\text{op}} < 750^{\circ}\text{C}$

### *Desafíos*

1 ↑ Transporte de carga <sub>1</sub>

2 ↑ Actividad catalítica

### *Diseño de nuevos materiales*

Buenos **conductores mixtos** iónicos-electrónicos (MIECs) a Toperación

**porosidad:** mejora la transferencia de masa  
**nanoestructuración:** + defectos, + sitios activos  
**funcionalización:** dopado

# Cátodos SOEC

## ↑ Actividad catalítica

**Problema:** Disminuir la temperatura de operación de las celdas



Reduce la cinética de los procesos de electrodos (térmicamente activados)

### POROSIDAD

Mejora la transferencia de masa

### NANOESTRUCTURACIÓN

Aumenta el número de **sitios activos** para la reacción

### FUNCIONALIZACIÓN

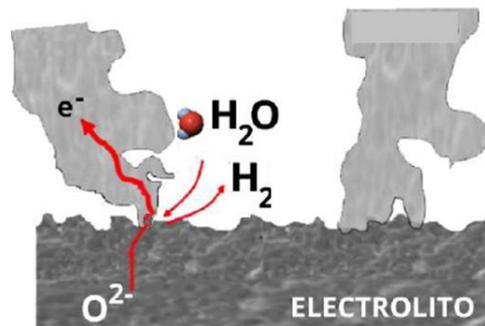
- Dopado con otros cationes**
- Mejora la **movilidad del oxígeno** en la red
  - Mejora la **interacción del soporte** cerámico con la fase metálica

# Electrodos SOEC: Cátodo

↑ Transferencia de carga: Conductores mixtos iónicos-electrónicos

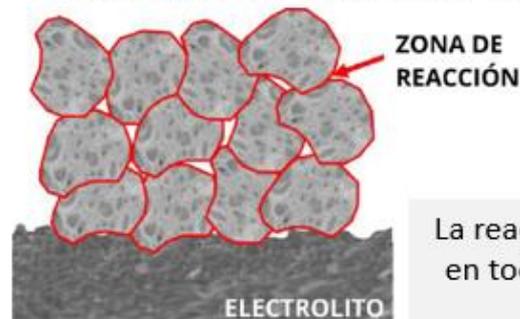
MIECs

Cátodo poroso conductor simple:



La reacción sólo ocurre en los puntos triples (TPB)

Cátodo poroso conductor mixto:



La reacción puede ocurrir en toda la superficie del material

**Objetivo:** desarrollar cátodos porosos conductores mixtos

**Metal-cerámicos**

**Soporte:** óxido cerámico basado en  $\text{CeO}_2$   
**Metal:** NiO, CuO, NiO-CuO (en atmósfera reductora del ánodo pasan a metales)

**Perovskitas**

**Única fase:**  $(\text{La,Sr})(\text{Cr,Mn})\text{O}_3$ ,  
 $(\text{Sr,L a})(\text{Ti,Fe})\text{O}_3$ ,  $\text{Sr}_2\text{MgMoO}_6$ ,  $(\text{La,Sr})_2\text{MnO}_4$

# Cátodos SOEC

## Fase metálica:

- conductora electrónica

## Fase cerámica:

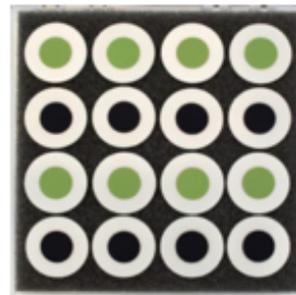
- mejora la adherencia al material de electrolito
- Agrega conductividad iónica al material de ánodo

## Desventajas

- **Operación a  $T > 900^{\circ}\text{C}$**  (limita: conductividad iónica del YSZ)
- Baja área útil del electrodo (sinterizado)
- Cambios bruscos de volumen y rotura mecánica

## Cátodos tradicionales

Fase metálica (Ni) + Fase cerámica ( $\text{ZrO}_2\text{-Y}_2\text{O}_3$ )



-  Electrolito de  $\text{ZrO}_2$  dopado con  $\text{Y}_2\text{O}_3$  (YSZ)
-  Cátodo de Ni/YSZ
-  Ánodo de  $\text{La}_{1-x}\text{Sr}_x\text{MnO}_{3-\delta}$

Típicamente cermet de Ni/YSZ o Ni/GDC (dependiendo necesidad de resistir carbono)

# Cátodos SOEC

Estrategias de optimización:

- DOPADO** con otros cationes que brinden mayor actividad
- INFILTRACIÓN/SOPORTE** sobre una superficie altamente porosa
- EXSOLUCIÓN** de nanopartículas metálicas

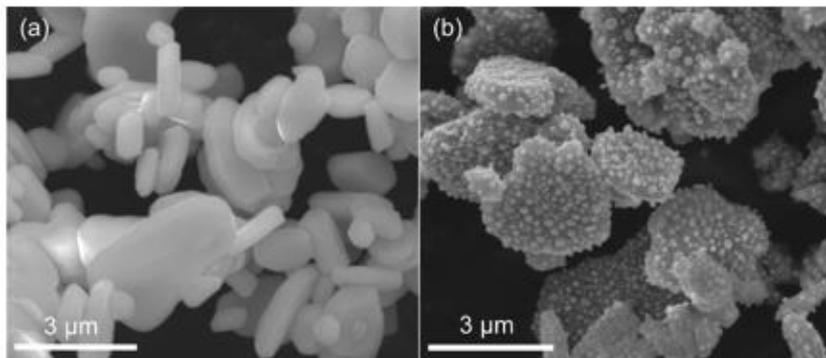
# Cátodos SOEC

**EXSOLUCIÓN.** Las partículas son dispersadas en la superficie a partir de la exsolución de las mismas de la propia estructura cristalina

## Ventajas:

Alta dispersión, excelente interacción con soporte (están ancladas), evita coarsening, posibilidades de regeneración con ciclados redox

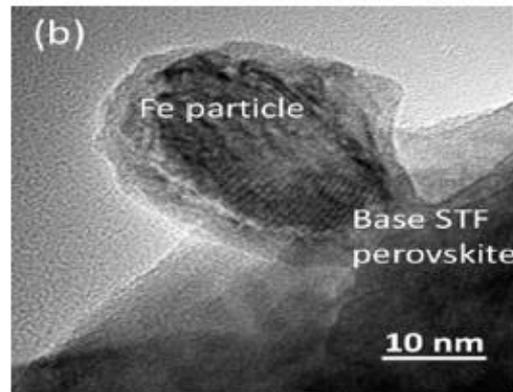
Con ruptura de la estructura:  $\text{NiTiO}_3$



$\text{NiTiO}_3$

$\text{Ni} + \text{TiO}_{2-\delta}$

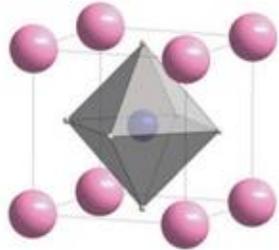
Sin ruptura de la estructura:  $\text{SrTiFeO}_{3-\delta}$



$\text{Fe} + \text{SrTiFeO}_{3-\delta}$

# Ánodos SOEC

Ocurre la evolución de  $O_2$ . Similitudes con requerimientos del cátodo, como porosidad, actividad, etc. Típicamente se buscan materiales resistentes a oxidación, por lo que los conductores mixtos (MIEC) son los más usados.

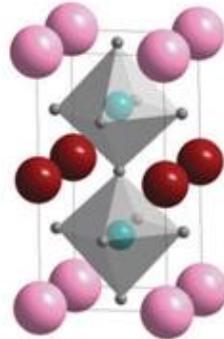


## Perovskite $ABO_{3-d}$

A = alkaline earth or lanthanide metal

B = Transition metal

O-vacancy randomly distributed



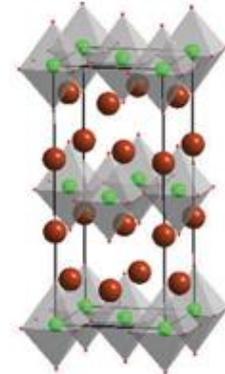
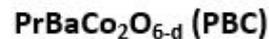
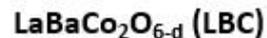
## Double Perovskite $AA'B_2O_{6-d}$

A = high radii alkaline earth (i.e. Ba)

A' = low radii lanthanide metal

B = Transition metal (i.e. Co)

O-vacancy located on A'O layer

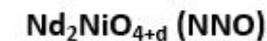
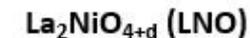


## Ruddlesden –Popper $A_2BO_{4+d}$

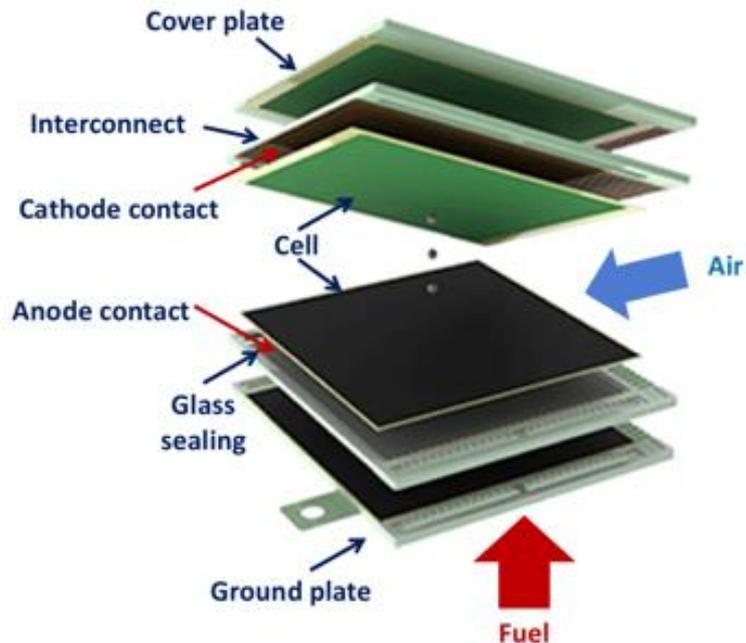
A = lanthanide or alkaline earth

B = Transition metal (i.e. Ni)

O-interstitial located on AO layer



# Interconectores SOEC



Plansee

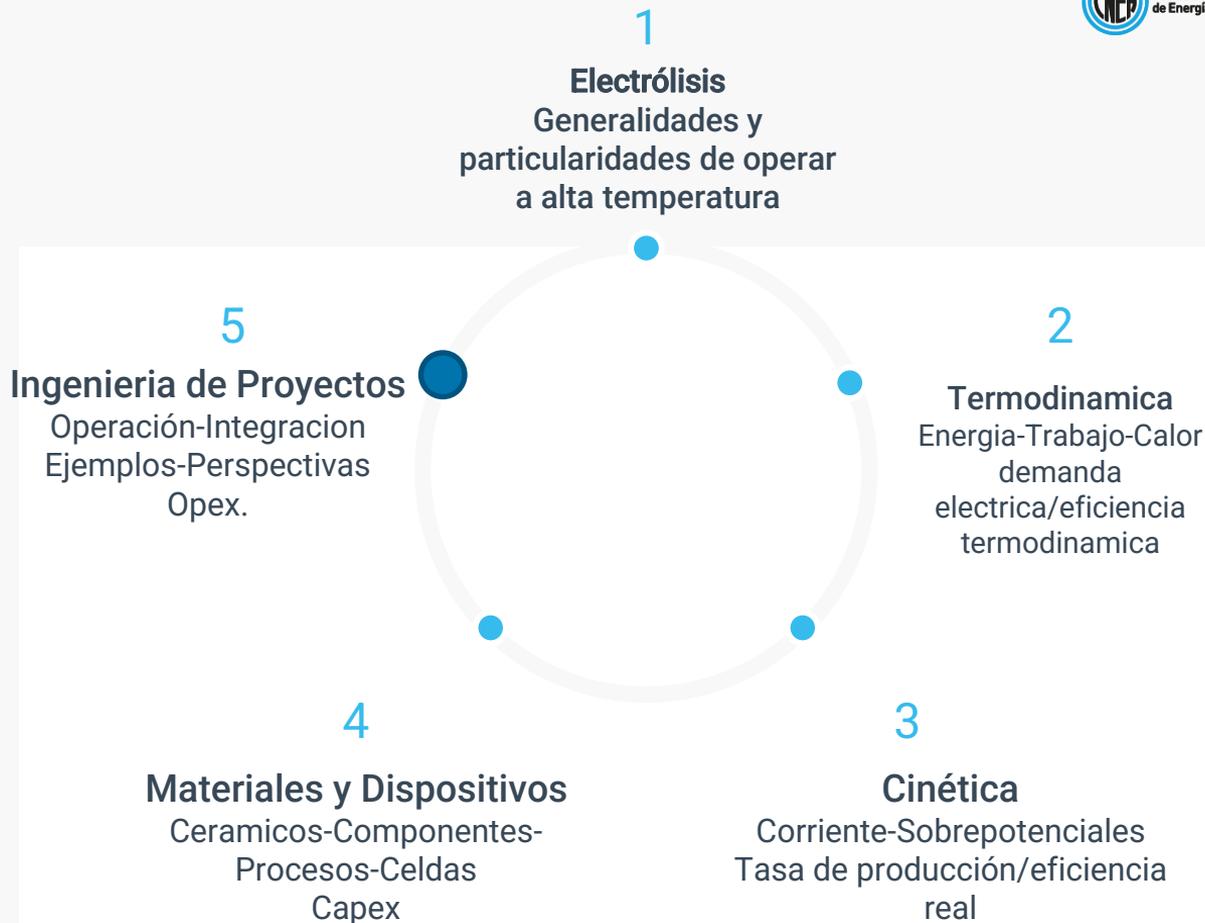
## REQUISITOS

- **Coeficiente de expansión térmica (TEC) compatible** con el electrolito
- **Alta conductividad electrónica** y baja conductividad iónica
- **Estabilidad** en atmósferas oxidantes y reductoras
- **Compatibilidad química** con electrodos y sellos
- **Resistencia mecánica**

# Introducción

## Electrólisis de Vapor

---



# SOEC. Operación e Integración

**MATERIALES DE PARTIDA**  
óxidos, carbonatos, nitratos

**MEAs**

Multicapas cerámicas



SINTESIS

CONFORMADO

ENSAMBLADO

**STACKS**  
(APILAMIENTOS DE CELDAS)

TESTEO

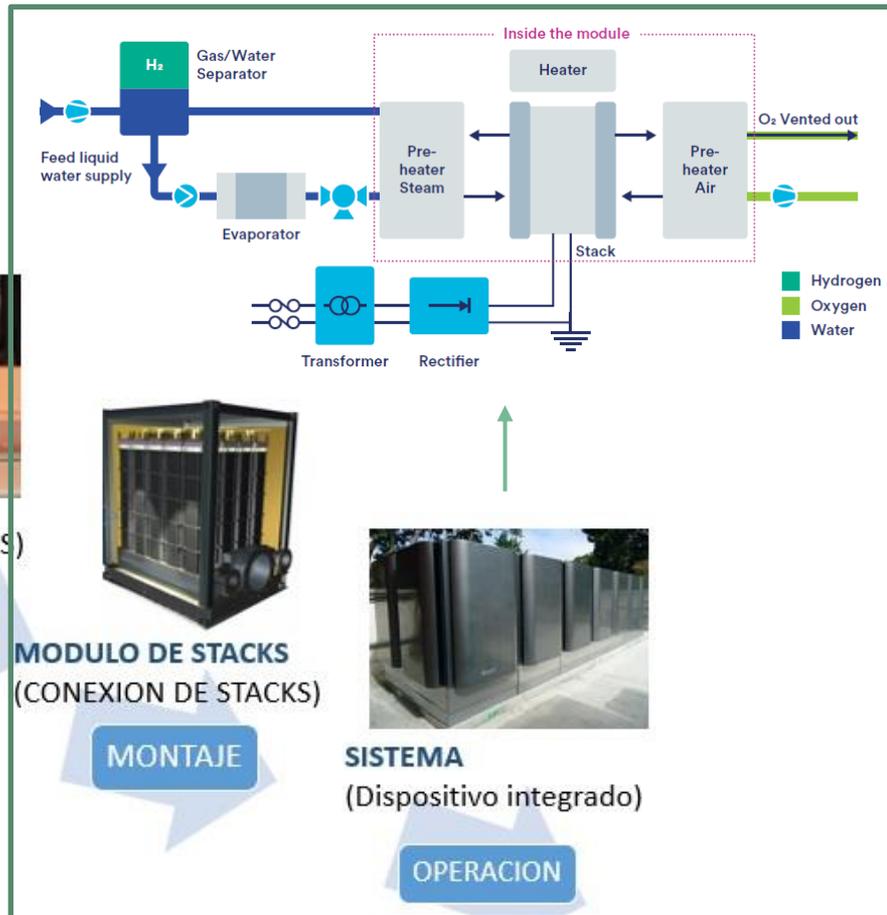
MONTAJE

**MODULO DE STACKS**  
(CONEXION DE STACKS)

MONTAJE

**SISTEMA**  
(Dispositivo integrado)

OPERACION



## Requerimiento de calidad y cantidad de agua para electrolizadores de baja temperatura:

**1. Agua ultrapura:** materia prima para electrólisis. Conductividad  $<1 \mu\text{S}/\text{cm}$  para estandar AEL y  $<0.1 \mu\text{S}/\text{cm}$  para PEM o AEL avanzados.

Consumo  $9 \text{ kg H}_2\text{O}/\text{kg H}_2$  (100% eficiencia Faradaica)

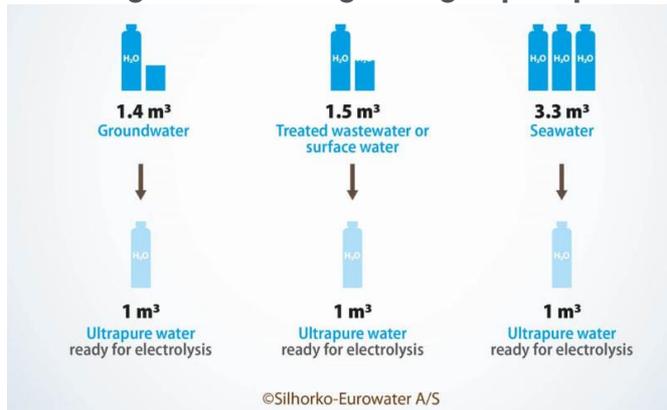
Si  $45\text{--}55 \text{ kWh}/\text{kg H}_2$  o  $0.16\text{--}0.2 \text{ L}/\text{kWh}$ , o electrolizador de **1 MW  $\rightarrow$  163-200 L/h.**

**2. Agua para circuitos de refrigeración:** si electrolizador opera en modo exotérmico  $\rightarrow$  calor “desperdiciado”. Circuito de refrigeración  $\rightarrow$  aprovechar el calor o usar agua de mar.

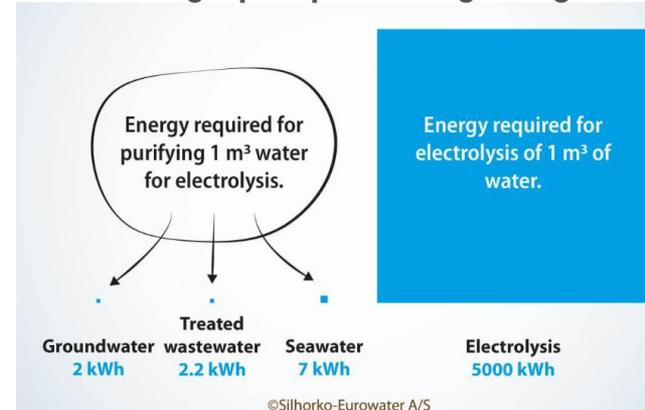
En general 2-3 veces respecto del consumo de agua ultrapura electrolizador de **1 MW  $\rightarrow$  400-600 L/h.**

**3. Agua “cruda”:** cuanta agua se necesita para generar el agua “ultrapura”?

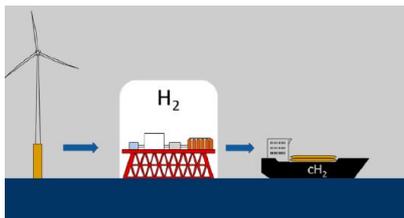
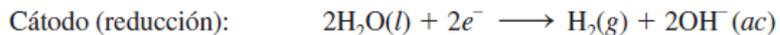
### Demanda de agua “cruda” según origen para purificar $1 \text{ m}^3$



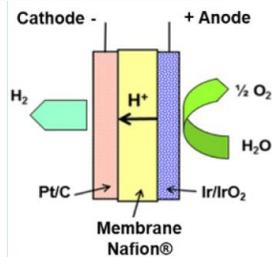
### Demanda de energía para purificar agua según origen



## Electrólisis de una disolución acuosa de cloruro de sodio:

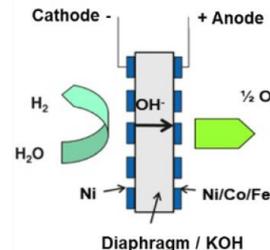


1. Electrólisis directa: Evolución de  $\text{Cl}_2$  ( $2\text{Cl}^- \rightarrow \text{Cl}_2 + 2e^-$ ) compete con OER
2. Pre-purificación (requiere energía)



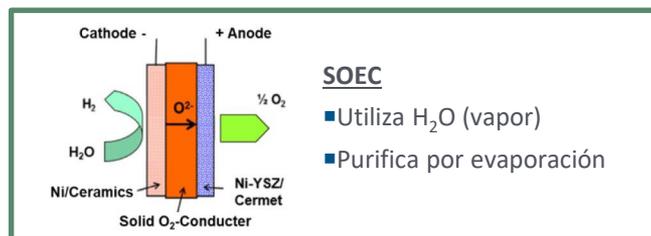
### PEM

- Desalinizar
- Impurezas dañinas
- Depósito  $\text{Mg}(\text{OH})_2$



### AEL

- Reemplazar KOH por agua de mar (NaCl)
- Conductividad agua de mar << salmuera
- Corrosión por formación de  $\text{Cl}_2$
- Reemplazo electrodos (++)

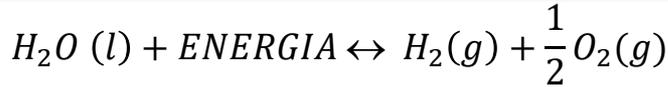


### SOEC

- Utiliza  $\text{H}_2\text{O}$  (vapor)
- Purifica por evaporación

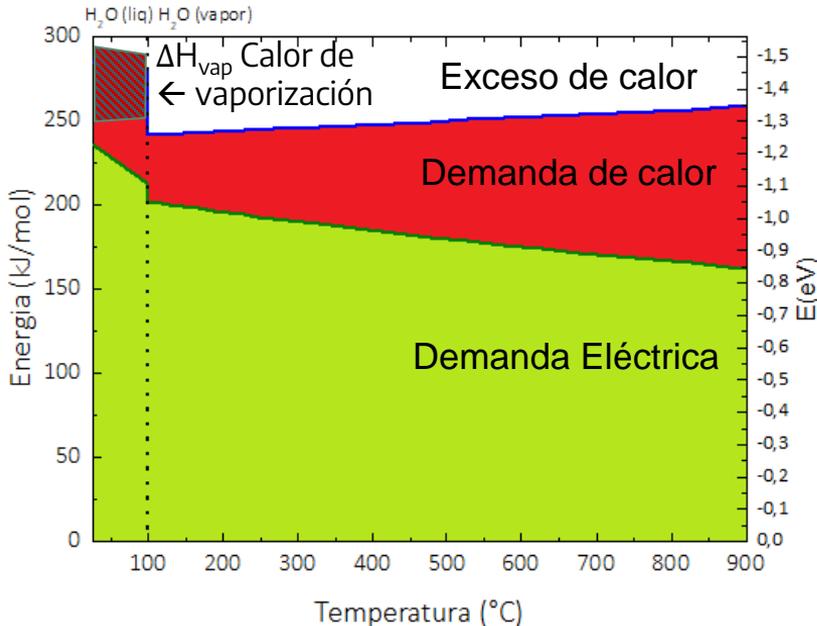
# SOEC: Aprovechamiento de calor de procesos industriales

REPASANDO...



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

Energía = electricidad + calor



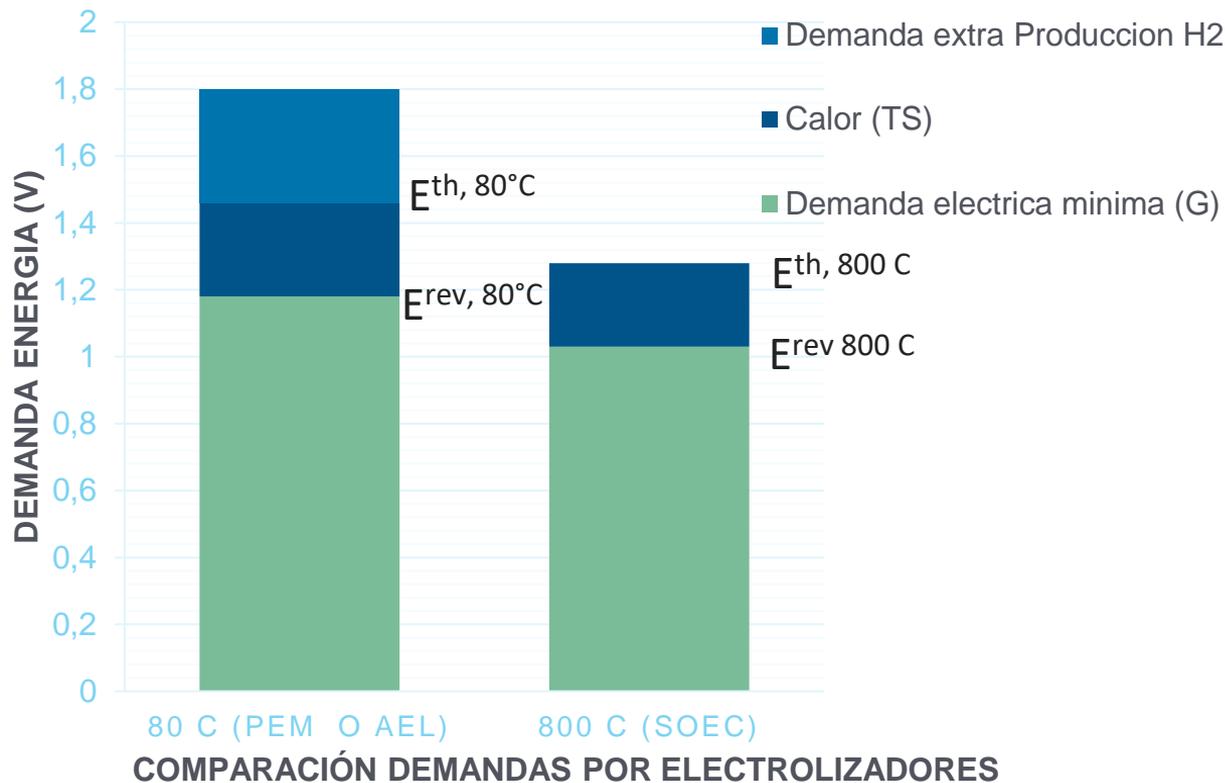
- $\Delta G$  es el MINIMO trabajo que se necesita para empezar a producir  $H_2$  (cuando la corriente es "0") y  $\Delta G = -nFE$

**Demanda Producción Neta =**  

$$= (V - E^{rev}) = I_{H_2} \times (R_{electrolito} + R_{ohmic} + R_{anodo} + R_{catodo})$$

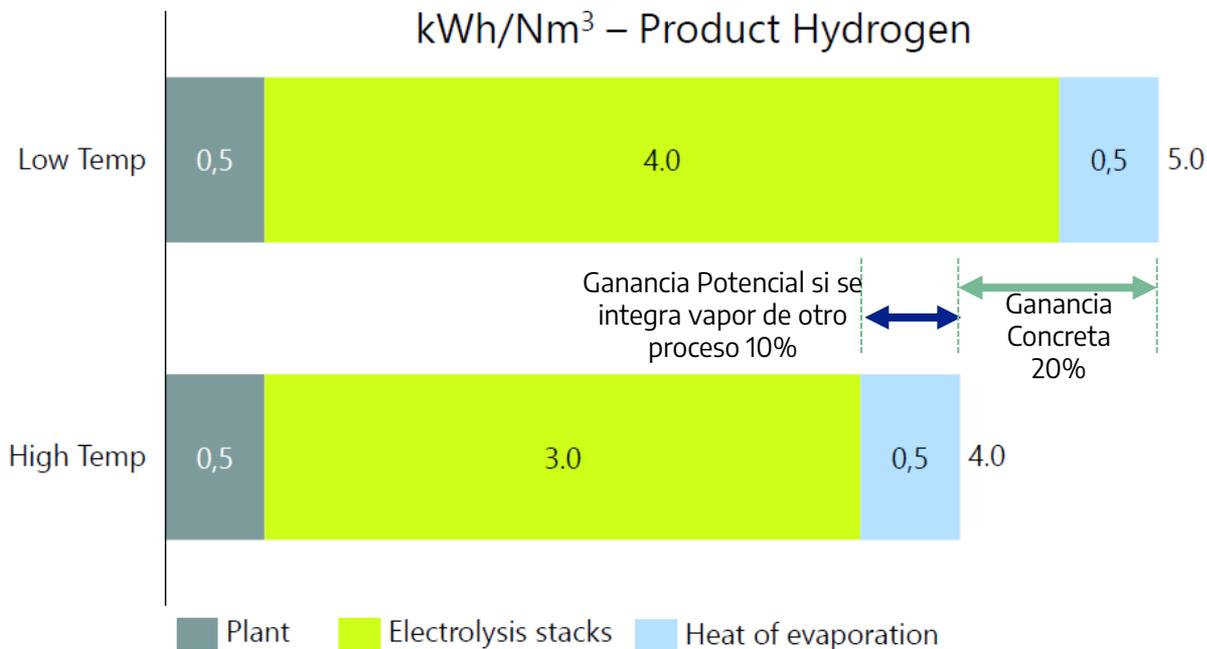
- En general  $R_{(PEM/AEL)} > 1.2 R_{SOEC}$
- PEM/AEL tienen que operar en modo Exo para tener una buena producción (necesitan si o si sistema de refrigeración)  
 $\rightarrow V_{op} \gg E^{th,80^\circ C}$  (ej.  $V_{op} = 1.8-2.2 V$ )
- SOEC puede operar en modo termoneutral teniendo una buena  $I_{H_2}$   
 $\rightarrow V_{op} = E^{th,800^\circ C}$  (ej.  $V_{op} = 1.3 V$ )

# SOEC: Aprovechamiento de calor de procesos industriales

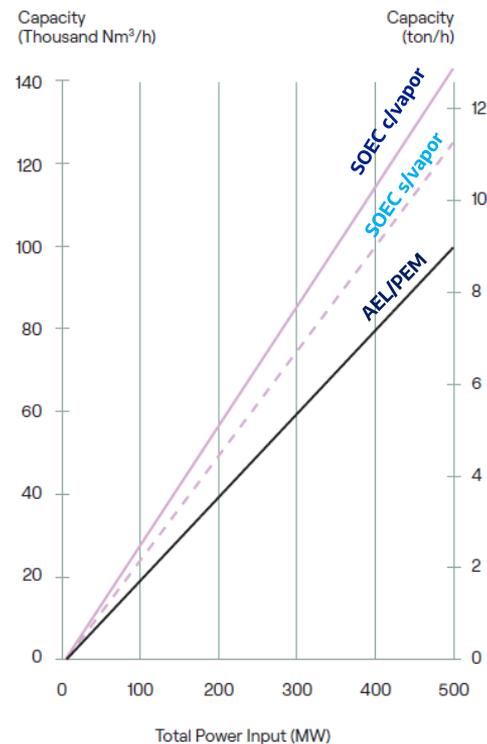


# SOEC: Aprovechamiento de calor de procesos industriales

Traducido a Demanda eléctrica de una Planta y su Capacidad de producción de H<sub>2</sub>

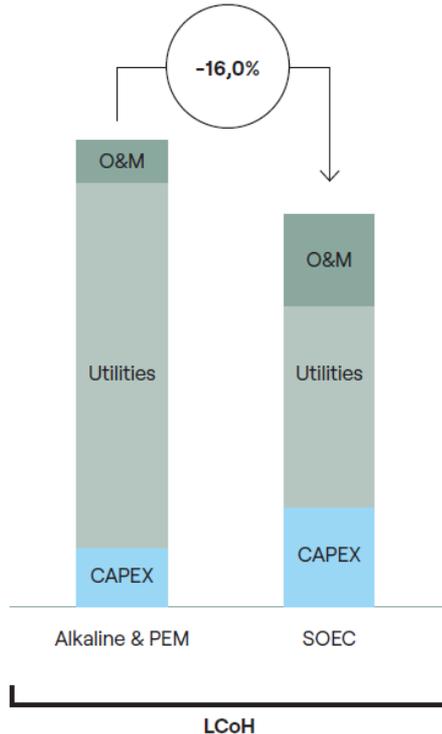


Capacidad de planta vs Potencia



# SOEC: Aprovechamiento de calor de procesos industriales

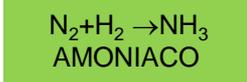
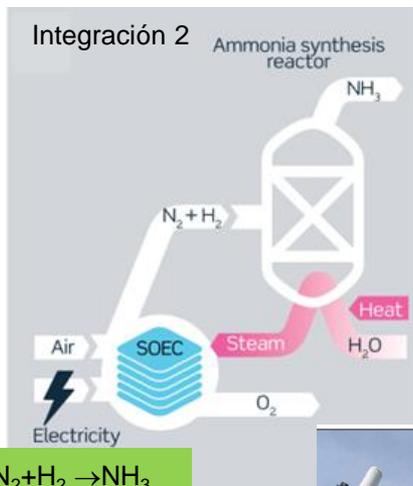
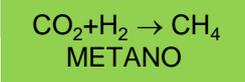
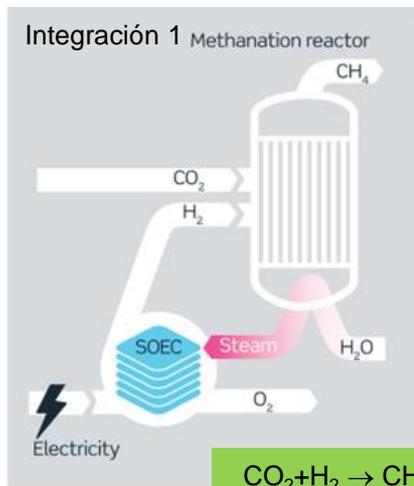
Traducido a Costo nivelado de producción de H<sub>2</sub> (LCoH): Costo promedio por kg H<sub>2</sub> producido (incluye CAPEX, OPEX y costos de energía)



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 <sup>1</sup>	Years	0%	10% / 8 years
Power Consumption	kWh/Nm <sup>3</sup> of H <sub>2</sub>	W. Steam = 3.5 Wo. Steam = 4.0	5.0
H <sub>2</sub> Production	Nm <sup>3</sup> /h	W. Steam = 28.600 Wo. Steam = 25.000	20.000

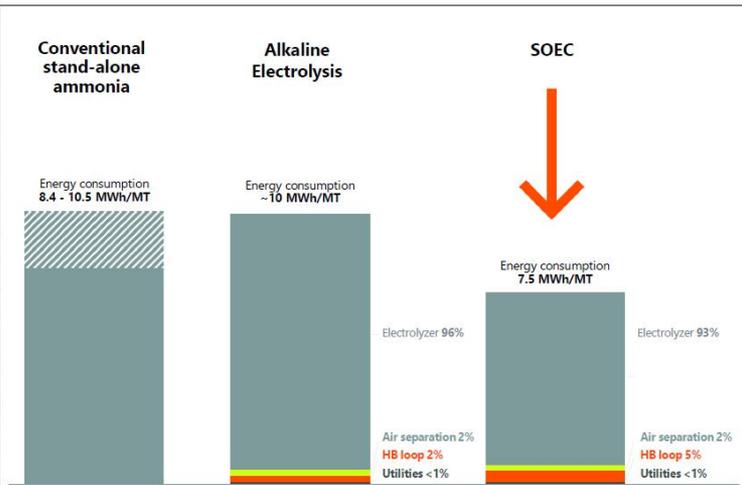
1) No electricity penalty of degradation.

# SOEC: Aprovechamiento de calor de procesos industriales

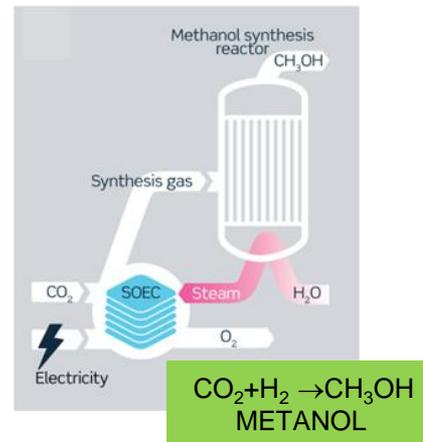
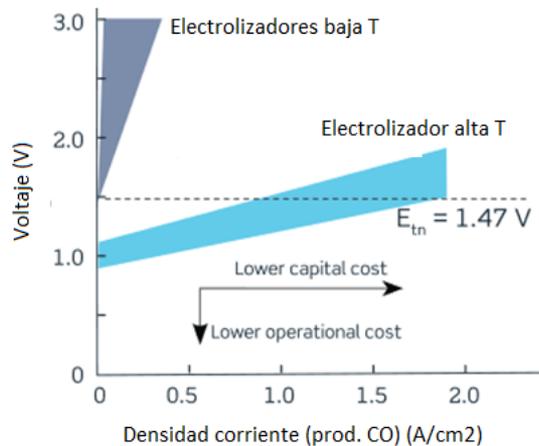
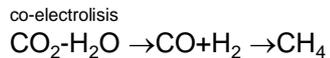


Ejemplo de la ganancia de eficiencia en una planta de amoniaco (**Topsoe**)

Hauchet et al., Science370, (2020).



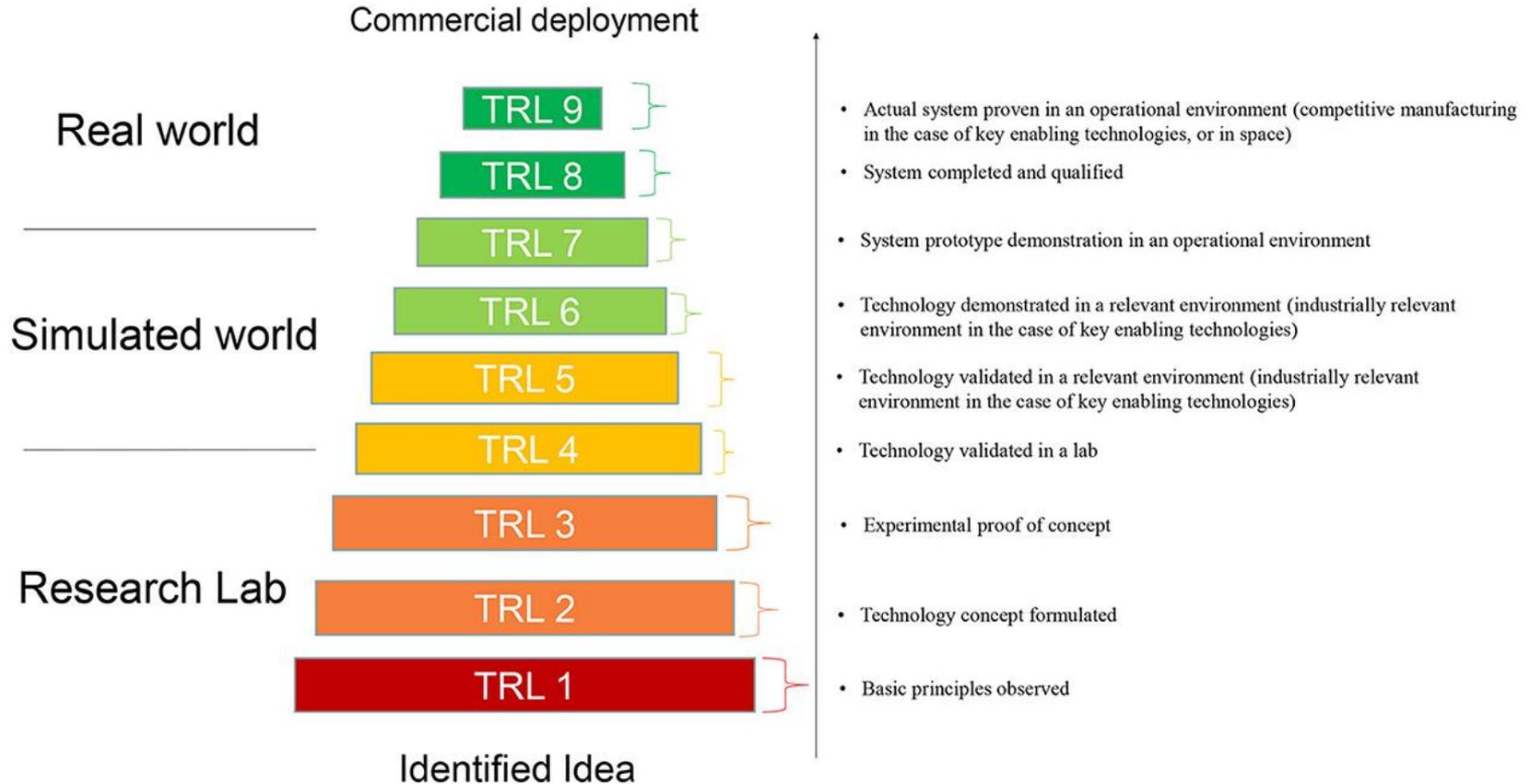
## SOEC: CO-ELECTRÓLISIS DE DIOXIDO DE CARBONO (CO<sub>2</sub>)



Hauchet al., Science370, (2020).

# EJEMPLOS DE PLANTAS ELECTROLIZADORAS SOEC

# TRL (TECHNOLOGY READINESS LEVELS)



## Chemical Industry – Carbon Monoxide Production TRL: 8

Since 2020, U.S.-based DeLille Oxygen Company has used two commercially available, 750-kW Topsoe eCOs™ units for the on-site production of ‘clean’ carbon monoxide via solid oxide electrolysis.

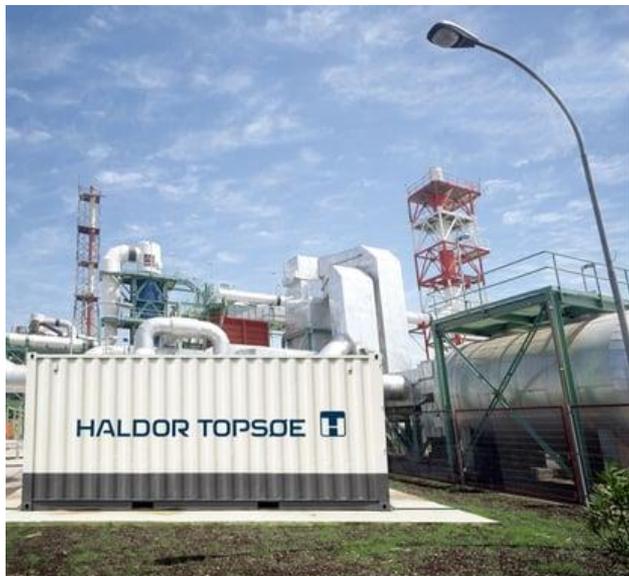


Figure 21: Topsoe eCOs™ Electrolyzers at a DeLille Oxygen Co. Site<sup>42,43</sup>



Topsoe- 750 kW- Síntesis CO- DeLille Oxygen Co  
(Francia)

## Chemical Industry – Hydrogen Production TRL: 7

Sunfire began testing a 1-MW electrolyzer for use in methanol synthesis at the Hydrogen Lab Leuna, in Germany, in 2021. Various operational studies were carried out at the lab, in close cooperation with Sunfire, to evaluate likely system performance when connected to an intermittent renewable electricity supply.<sup>44</sup>

Another MW-scale Sunfire project, MultiPLHY, involves the first commercial-scale use of high temperature solid oxide electrolyzers at Neste's biofuel refinery in Rotterdam. A 2.6-MW electrolyzer was installed in April 2023 and was scheduled to start operations by the end of 2023. If this project meets performance targets by the time it concludes (expected by end of 2024), the Sunfire technology should reach TRL 8.

Sunfire Síntesis H<sub>2</sub> p/:

1. **CH<sub>3</sub>OH** -1 MW, Hydrogen Lab Leuna, Alemania
2. Refinería Biofuel – 2.6 MW , Neste, Rotterdam

Figure 22: One of Sunfire's SOEC Modules at the MultiPLHY Site<sup>45</sup>



Topsoe Planta de Metanación  
Foulum Dinamarca- 50kW SOEC:  
H<sub>2</sub>+Biogas-> SNG

### Steelmaking

#### TRL: 7

The benefits of coupling SOEC with a steel plant are similar to those of coupling SOEC with a nuclear plant, in that industrial process heat can be reused in the SOEC to increase the overall electrical efficiency of hydrogen production. In this configuration, a SOEC system will require less low-carbon electricity than PEM or alkaline electrolyzers to produce the same quantity of hydrogen.

In the first large-scale project to test this concept, called GrinHy 1.0, the German company Salzgitter AG installed a 140-kW Sunfire SOEC system at one of its steelmaking plants. The project proved that heat from a steel plant could be used with a solid oxide electrolyzer to produce hydrogen at the purity required for low-carbon steelmaking. In the first phase of the GrinHy project, however, hydrogen was turned back to electricity using the reversibility of solid oxide technology, rather than being used in steelmaking.<sup>46</sup>

GrinHy 1.0 was succeeded by GrinHy 2.0, which involves a substantially larger, 720-kW SOEC system. This prototype also recycles process heat from steelmaking

Figure 23: The GrinHy 2.0 720-kW Sunfire Electrolyzer at Salzgitter's Site<sup>47</sup>



but has been further integrated into Salzgitter's steelmaking operations in that it supplies hydrogen for the annealing process. By the end of 2022, stack performance had been proved for 20,000 hours of operation, producing a total of around 100 tons of high purity 'green' hydrogen at an electrical efficiency of minimum 84% (measured at the lower heating value (LHV) of hydrogen), and proving the technology at TRL level 7. In the next phase, the electrolyzer will supply hydrogen for the reduction of iron ore, which will reduce CO<sub>2</sub> emissions from this step of the steelmaking process by 95% and prove the technology at TRL 8.

Sunfire, Producción de H<sub>2</sub> con integración de calor de Aceros:

1. 140 kW, Salzgitter, Alemania
2. 720 kW

## Synthetic Fuels

### TRL: 5 – 6

Because a solid oxide electrolyte can conduct oxygen ions, SOEC technology can be used to electrolyze molecules such as CO<sub>2</sub>. The resulting product in this case would be carbon monoxide (CO).

When carbonated water is fed to a solid oxide electrolyzer, both water and CO<sub>2</sub> can be electrolyzed simultaneously – this process is called co-electrolysis. Co-electrolysis produces a mixture of carbon monoxide and hydrogen, also known as synthetic gas or 'syngas', alongside steam and CO<sub>2</sub>. Syngas can be used to produce a range of synthetic hydrocarbons, including fuels and materials.

Sunfire has demonstrated a 150-kW co-electrolyzer for methanol production through its SynLink project, putting the technology at TLR 6.<sup>48</sup> In parallel, Sunfire has also validated a 10-kW module to produce synthetic fuels through its Kopernikus PtX project.

Another solid oxide cell manufacturer, Estonia-based Elcogen, has partnered with French energy company Engie SA on a pilot project to produce dimethyl ether (DME), a synthetic alternative to diesel fuel for transport

Figure 24: Sunfire Co-Electrolyzer Module as Part of the Kopernikus PtX Project



applications. The project, called C2 Fuels is deploying a small solid oxide system, with electrical capacity in the single-digit kW, in Dunkirk, France.<sup>49</sup>

The next challenge for co-electrolysis technology is demonstration on a MW scale. To that end, the European Union is co-funding an ongoing project, called MegaSyn, to demonstrate syngas production by co-electrolysis in an industrial environment. The aim is to lift the solid oxide co-electrolysis technology to TRL 7 by 2025.<sup>50</sup>

Sunfire- 150 kW- Co-electrolysis -Síntesis CH<sub>3</sub>OH // 10 kW PtX  
Elcogen – kW – DME síntesis (Francia)

## Energy Storage

TRL: 5 – 6

Another practical application of reversible SOEC technology would be clean energy storage: water could be electrolyzed at times when clean sources of power are abundant, the resulting clean hydrogen could then be stored and turned back to electricity using the same device at times when clean power supply is low. This approach would benefit from lower capital expenditures and reduced space requirements because it avoids the need to purchase and install electrolyzers and fuel cells separately.

Reversible SOEC/SOFC technology has already been demonstrated in large-area stacks. For instance, FuelCell Energy (FCE) has a reversible SOFC (rSOFC) technology that is currently at TRL 5 and expected to reach TRL 6 due to concurrent work supported by DOE's National Energy Technology Laboratory (NETL) (project award number DE-FE0031974). The aim of this work is to validate and verify engineering/pilot-scale rSOFC technology in a relevant environment. FCE has been open about the outstanding challenges that need to be solved before its rSOEC technology is commercial, including challenges with respect to stack-module size, durability, and number of cycles. In fact, improvements in these three areas are recurring themes for most SOEC manufacturers.

European firms are also conducting trials of reversible SOEC: for example, Elcogen is currently testing its rSOEC technology at Finland's VTT Technical Research Centre. This project is due to wrap up in the summer of 2023, with the aim of reaching TRL 6.<sup>52</sup> Sunfire has already validated a small, 140-kW rSOEC system through its GrinHy project at the Salzgitter steel plant, which puts its technology at TRL level 6.<sup>53,54</sup>

Celdas reversibles:

Figure 25: FCE rSOFC Targets and Current Capability<sup>51</sup>



Figure 26: Sunfire's GrinHy 1.0 Reversible SOEC<sup>55</sup>



FuelCell Energy- rSOFC- SOFC 6kW/SOEC 32 kW  
 Elcogen – rSOFC  
 Sunfire 140-kW rSOEC

## Nuclear

### TRL: 3 – 4

The benefits of pairing SOEC with a nuclear plant go both ways: the electrolyzer gets access to high-grade process heat (300°C–500°C) while the nuclear plant gains the option to switch between feeding electricity to the grid or using it to produce hydrogen. In a system with high penetration of wind and solar generators, this optionality would allow the nuclear plant to keep a steady electricity generation profile, without having to ramp up and down in response to fluctuating output from low-cost renewable generation. This could be particularly important for integrating nuclear with high-renewable-energy systems.

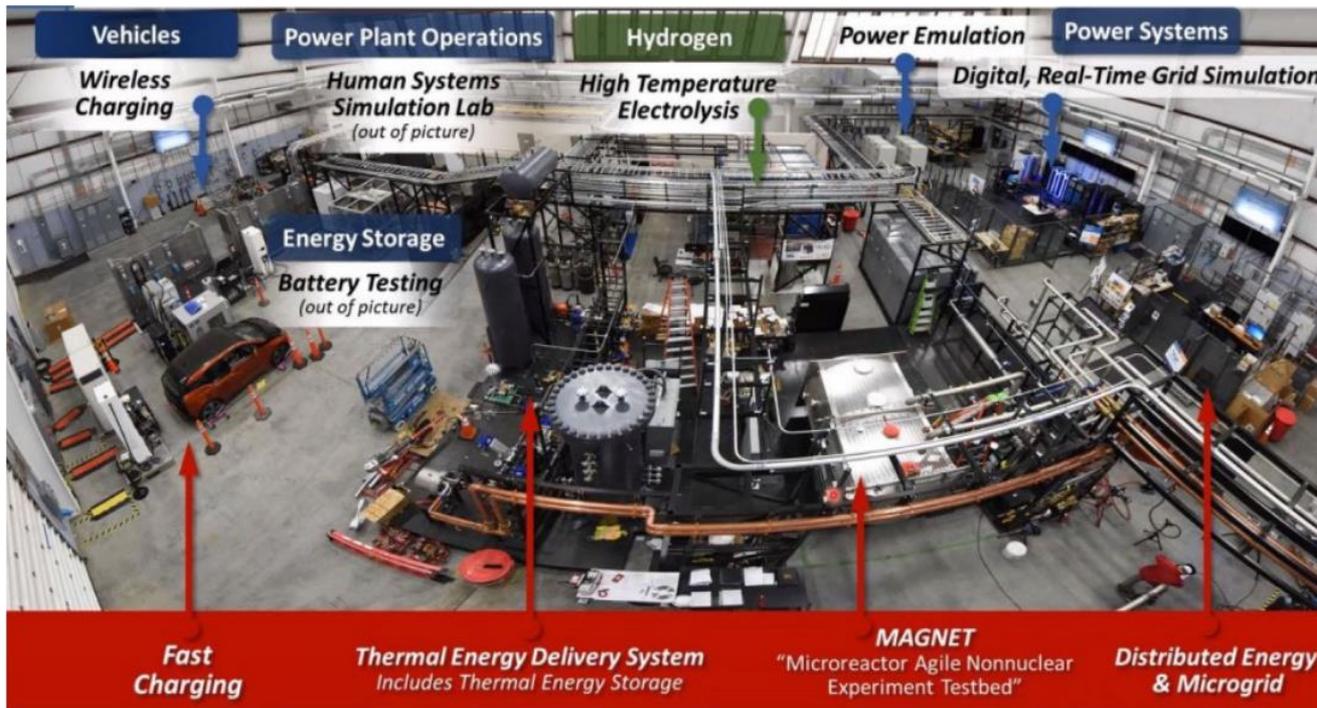
Researchers at Idaho National Lab (INL) in the United States have been conducting a variety of tests on Bloom Energy's solid oxide electrolyzer at the Dynamic Energy Testing and Integration Laboratory. These tests include physical steam and load simulations that replicate nuclear power station conditions, an important step in validating full compatibility with a nuclear facility. Early tests at high temperatures and high nuclear plant availability revealed that Bloom Energy's electrolyzer could produce hydrogen at 37.7 kWh per kilogram of hydrogen and with 88.5% electrical efficiency (with respect to LHV of hydrogen and conversion to direct current (DC)).<sup>56</sup> FuelCell Energy has also deployed a 250- kW electrolysis module at INL (Figure 27).

Actually harnessing nuclear process heat from an existing reactor for electrolysis is a lot more complicated than conducting a simulation. For instance, tapping into a boiling water reactor's steam system would require adding a radiation-shielded heat exchanger loop. This could quickly turn into a permitting nightmare, given the regulatory and safety requirements placed on nuclear plants, particularly in the United States. However in other regions like the UK regulators are willing to allow small modifications to plants without re-licensing. For pressurised water or gas cooled reactors which have a shielded loop, coupling with SOEC becomes a little easier, and indeed EDF has embarked on such a project. However, EDF has described three big limitations facing similar retrofits:

1. Steam harnessing potential is limited to low-pressure tap-off, significantly limiting the size of the electrolyser to double digit MWs
2. This site had an onsite alkaline electrolyser as part of the original design and license
3. The electrolyser had to be sited at least several hundred meters from the reactor for safety reasons, limiting the quality of heat that can be transferred to the SOEC to about 200C.

Thus, it is unlikely that SOEC will be deployed in 100s of MW scale at existing nuclear plants. If we are to see any big rollout of SOEC at greenfield nuclear plants, it's imperative that these plants are designed, engineered, and licensed with solid oxide electrolyser optionality from the get-go.

# Dynamic Energy Testing and Integration Laboratory - Idaho National Lab (INL) USA. tests de sistemas Bloom Energy's y FuelCell Energy



# TOPSOE

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
<p>Topsoe is a Danish company founded in 1940 which specialises in catalysis and process technology in chemical and hydro processing.</p> <p>Topsoe has been active in solid oxide development since 2004. From 2014 the company has focussed on developing electrolysis systems for the production of hydrogen, synthesis gas, and pure carbon monoxide. Topsoe has 80+ years of experience in catalysis utilized in SOEC development.</p>	<p>500 MW by 2025 with optionality to expand to 5 GW</p>	<ul style="list-style-type: none"> <li>■ Anode supported manufacturing.</li> <li>■ Operates at 750°C.</li> <li>■ Current 2nd Generation lifetime of 4 years.</li> <li>■ 3rd Generation coming in second half of this decade will feature improvements to lifetime, cost, and a new geometry.</li> <li>■ Focused on coupling their electrolyzer product to ammonia and methanol production, where they have complementary expertise through their catalyst business.</li> </ul>	<ul style="list-style-type: none"> <li>■ First Ammonia signed a capacity reservation agreement with Topsoe for 500MW with the option to increase to 5GW to produce green ammonia as fuel for transportation, power storage &amp; generation, and fertilizer.<sup>53</sup></li> </ul>



Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
<p>Sunfire was founded in Germany in 2010 and originally focussed exclusively on solid oxide technologies. As of 2021, Sunfire had also expanded into the alkaline electrolysis market by acquiring Industrie Haute Technologie.</p>	<p>Today: 1 – 10 MW</p>	<ul style="list-style-type: none"> <li>■ Electrolyte supported manufacturing.</li> <li>■ Operational temperature of 850°C.</li> <li>■ Co-electrolysis capability is a unique selling point, positioning the company well for the emerging PtL market.</li> <li>■ The company is planning for a pre-commercial 10 MW pilot to reach TRL level 8 in the next five years, focussing on proving longevity of over 10 years.</li> </ul>	<ul style="list-style-type: none"> <li>■ Norsk e-fuels plans to commission a PtL (power to liquids) plant running on a mixture of alkaline and SOEC electrolyzers from Sunfire in 2024.<sup>62</sup></li> </ul>



RENEWABLES  
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RENEWABLE HYDROGEN FOR INDUSTRIAL APPLICATIONS

## SUNFIRE-HYLINK SOEC



### PRODUCT

Sunfire-HyLink SOEC is the world-leading high-temperature electrolysis solution based on solid oxide cells. The electrolyzer uses steam as feed instead of liquid water to produce hydrogen. Smart integration of waste heat from industrial processes lowers renewable electricity demand, thus substantially cutting operational costs compared to alternative low-temperature electrolysis technology.

### APPLICATIONS

The electrolyzer provides renewable hydrogen as an essential feedstock for decarbonizing industries.

- + Steel: Direct reduction of iron, blast furnace injection, protective atmosphere, etc.
- + Refineries: Desulphurization, hydrocracking, hydrogenation, etc.
- + Chemicals: Ammonia production, hydrogenation, isotope separation, etc.

### CORE ADVANTAGES

- + **Steam electrolysis**  
Utilization of industrial off-heat as steam reduces electricity demand
- + **Efficiency**  
Market-leading efficiency (84%<sub>HHV,DCAC</sub>) yields lowest hydrogen costs
- + **Reliability**  
Certified electrolyzers with proven long-term operation
- + **Flexibility**  
Modular design simplifies scaling to any desired electrolysis capacity
- + **Sustainability**  
No use of PGM-based materials in electrolyzer production

## SUNFIRE-HYLINK SOEC – TECHNICAL DATA



### HYLINK SOEC

Hydrogen production	
Net production rate	750 Nm <sup>3</sup> /h
Production capacity dynamic range	5 % ... 100 %
Hot idle ramp time	< 10 min
Delivery pressure	0 bar (g)
Hydrogen purity	max. 99,99 %
Power input and electrical efficiency	
System power rating (AC)	2,680 kW
Specific power consumption at stack level (DC)*	3.3 kWh/Nm <sup>3</sup>
Specific power consumption at system level (AC)*	3.6 kWh/Nm <sup>3</sup>
System electrical efficiency**	84 %
Steam input	
Consumption	860 kg/h
Temperature	150 °C ... 200 °C
Pressure	3.5 bar (g) ... 5.5 bar (g)
Other specs	
Footprint***	~ 300 m <sup>2</sup>
Ambient temperature	-20 °C ... 40 °C

\* Power consumption at ambient pressure

\*\* Lower heating value of hydrogen referred to AC power input

\*\*\* Average space requirement for a 2.68 MW system comprising all auxiliary systems

# Bloomenergy®

Brief description	Electrolyzer mfg capacity per year <sup>69</sup>	Technology	Upcoming electrolyzer projects
<p>US based manufacturer of solid oxide systems. Spun-out in 2001 from NASA tech to create fuel and oxygen using Martian water.</p> <p>Bloom has deployed over 1 GW of solid oxide fuel cells worldwide and has recently returned to providing an electrolyzer product. They had recently built, installed, and operationalised the largest solid oxide electrolyzer in the world – 4 MW – all in a span of two months</p>	<p>Today: 2GW</p>	<ul style="list-style-type: none"> <li>■ Electrode-supported manufacturing.</li> <li>■ Built a 2 GW electrolyser/1 GW fuel cell factory in less than two years.</li> <li>■ Operational temperature above 800°C.</li> <li>■ Current modules of 120 kW can be combined to form 2 MW blocks.</li> <li>■ Above-industry average stack lifetimes exceeding 5 years and even reaching 8 years.</li> <li>■ R&amp;D focussed on increasing power density and further automating manufacturing</li> </ul>	<ul style="list-style-type: none"> <li>■ 10 MW electrolyzer with LSB Industries.</li> <li>■ Westinghouse and Bloom Energy signed a letter of intent to accelerate large-scale hydrogen production in the nuclear industry.</li> <li>■ Bloom announced plans to install a 240 kW electrolyzer at Xcel Energy's Prairie Island nuclear plant in Minnesota. Power-on expected in early 2024.<sup>60</sup></li> <li>■ Bloom is also expected to provide stacks for a nuclear-powered hydrogen micro hub in South Korea.<sup>61</sup></li> </ul>

# ceres

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
<p>Ceres is a UK based solid oxide technology developer. The company traces its roots to research at Imperial College London and has been spun out in 2001.</p>	<p>Ceres is a technology developer and licenses out its tech for other companies to manufacture.</p>	<ul style="list-style-type: none"> <li>■ Gadolinium-doped ceria (GDC) electrolyte allows lower temperature operation (500°C– 600°C) which improves durability and allows the use of standard automotive gaskets and stainless steel, as the temperature is below the evaporation point of chromium, a strong poison to SOEC.</li> <li>■ The trade-off with using GDC is lower current density at a given temperature.</li> <li>■ Metal supported manufacturing.</li> </ul>	<ul style="list-style-type: none"> <li>■ Ceres had signed an agreement with Shell to deliver a 1 MW solid oxide electrolyzer demonstrator in 2023 in Bangalore, India.</li> <li>■ Another 1 MW demonstrator is scheduled for deployment and testing by 2024 with Bosch and Linde Engineering.</li> </ul>

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
<p>Elcogen is an Estonia based solid-oxide technology developer and manufacturer. The company has been operating since 2001.</p>	<p>Today: 1 to 10 MW Soon: 100 to 200 MW</p>	<ul style="list-style-type: none"> <li>■ Anode supported manufacturing, enabling a thin electrolyte that operates at 650°C which improves conductivity.</li> <li>■ Current R&amp;D focussed on automating stack assembly process – cell printing already takes single digit seconds.</li> <li>■ Focussed on scaling manufacturing.</li> </ul>	<ul style="list-style-type: none"> <li>■ Elcogen's system integrator partner – Convion – is collaborating with Shell to deploy a 1 MW demonstrator system out of four 250kW stacks at Shell's Energy Transition campus in Amsterdam.</li> </ul>



Quote no. 759 / 1 Customer code 649 Page 1 / 1

Quote date 16.02.2022 Printout date 16.02.2022

Our reference SZ7 Your reference Lilliana Moggi

Your VAT no. Inquiry no.

<p><b>Delivery address</b> Comisión Nacional de Energía Atómica Centro Atómico Bariloche Av Bustillo 9500, S.C. Bariloche Zip Code 8400</p> <p>Argentina</p> <p><b>Terms of delivery</b> EX works Delivery method Air Valid through 30 days from quote date</p>	<p><b>Mailing address</b> Comisión Nacional de Energía Atómica Centro Atómico Bariloche Av Bustillo 9500, S.C. Bariloche Zip Code 8400</p> <p>Argentina</p> <p><b>Terms of payment</b> 100% prepayment Delivery time 120 days from order date Goods label</p>
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Pos	Part no.	Name	Qty	Price each	%	Price with %	Ami
1	900003/001	FC400B/12x12/11.2x11.2/11x11/R Nio-YSZ: 120x120mm R5 GDC: 112x112mm LSC: 110x110mm Round corner	50,00 pcs	230,00		230,00	11 50
2	900003/001	FC400B/12x12/11.2x11.2/11x11/R Nio-YSZ: 120x120mm R5 GDC: 112x112mm LSC: 110x110mm Round corner	100,00 pcs	205,00		205,00	20 50
3	900003/001	FC400B/12x12/11.2x11.2/11x11/R Nio-YSZ: 120x120mm R5 GDC: 112x112mm LSC: 110x110mm Round corner	250,00 pcs	185,00		185,00	46 25
4	900003/001	FC400B/12x12/11.2x11.2/11x11/R Nio-YSZ: 120x120mm R5 GDC: 112x112mm LSC: 110x110mm Round corner	500,00 pcs	165,00		165,00	82 50,...
5	02	EX Packing & Handling (per shpm)	1,00	45,00		45,00	45,00
6	05	EX Transportation (optional)	1,00	400,00		400,00	400,00
<b>Total excl. VAT ( EUR )</b>							161 195,00



425mW/cm2 @700°C (100 cm2, corriente de 45 A, 0.95 V → potencia de cada celda sería 40 W. → 10 kW 250 celdas 46.000 EUR

<b>Model</b>	E3000 (fuel cell)	
Power output	3000 W	SOFC
Voltage	81 + 143 V DC	
Current	0.. 30 A	
Operating Temp	580 – 720 °C	
Size	190(W) x 230(L) x 280 (H)	
Weight	33 kg	
<b>Model</b>	E3000	SOEC
Power required	3.2 kWh/m <sup>3</sup>	
Hydrogen production rate	3 Nm <sup>3</sup> /h	
Specific Energy Consumption	33 kWh/kg	
Voltage	143 – 214 V	
Current	61.5 A	
Operating Temp	650 – 700 °C	
Size	190(W) x 230(L) x 280 (H)	
Weight	33 kg	



Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
<p>Originally founded in 1969 Connecticut and called Energy Research Corporation. In 1992 renamed to FuelCell Energy and demonstrated first product – the molten carbonate fuel cell. As of 2011, FuelCell Energy is also in the business of developing solid oxide technology.</p>	<p>Today: 10 to 100 MW GW scale by 2030</p>	<ul style="list-style-type: none"> <li>■ Stacks are 95% recyclable.</li> <li>■ Current R&amp;D efforts to increase stack lifetime to five years, and beyond.</li> <li>■ Opted for disc shape to reduce manufacturing costs by repurposing DVD production machinery.</li> <li>■ Have recently announced they are taking commercial orders for electrolyzers.</li> <li>■ Also working on a reversible solid oxide stack product.</li> </ul>	<ul style="list-style-type: none"> <li>■ FuelCell Energy has an agreement with Malaysia and Marine Heavy Engineering Holdings (MHB) to collaborate on development of large-scale electrolyzers in Asia, Australia, and New Zealand.</li> <li>■ FCE is also partnering with Idaho National Lab to explore coupling of SOEC with nuclear energy to leverage process heat for steam imports, and to extend the life of nuclear plants. The 250-kW module is meant to enter operation in 2023.</li> </ul>

MUCHAS GRACIAS POR SU ATENCIÓN!!!