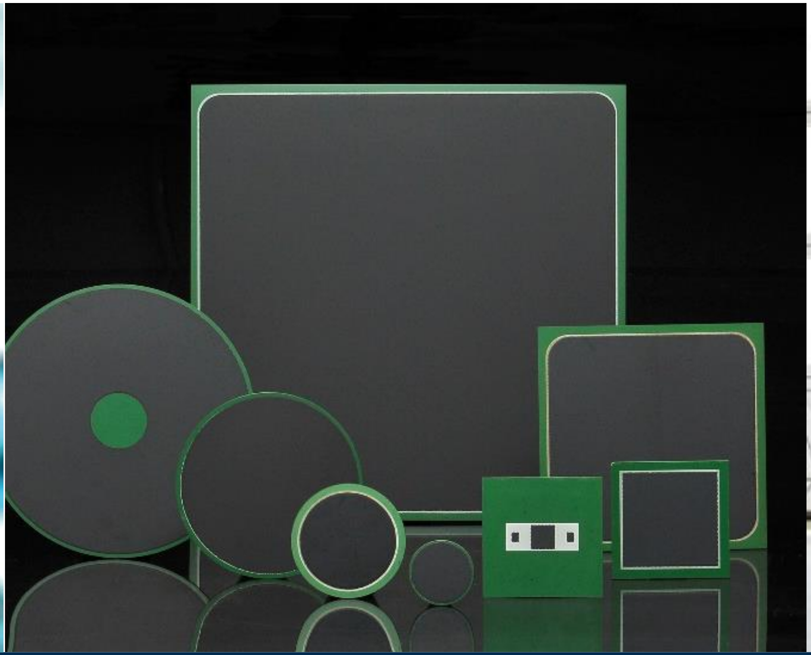




# The Need for Standardized Benchmarking of SOCs

10.10.2023 | CHRISTIAN LENSER AND NORBERT H. MENZLER

INSTITUTE OF ENERGY AND CLIMATE RESEARCH – MATERIALS SYNTHESIS AND PROCESSING (IEK-1)

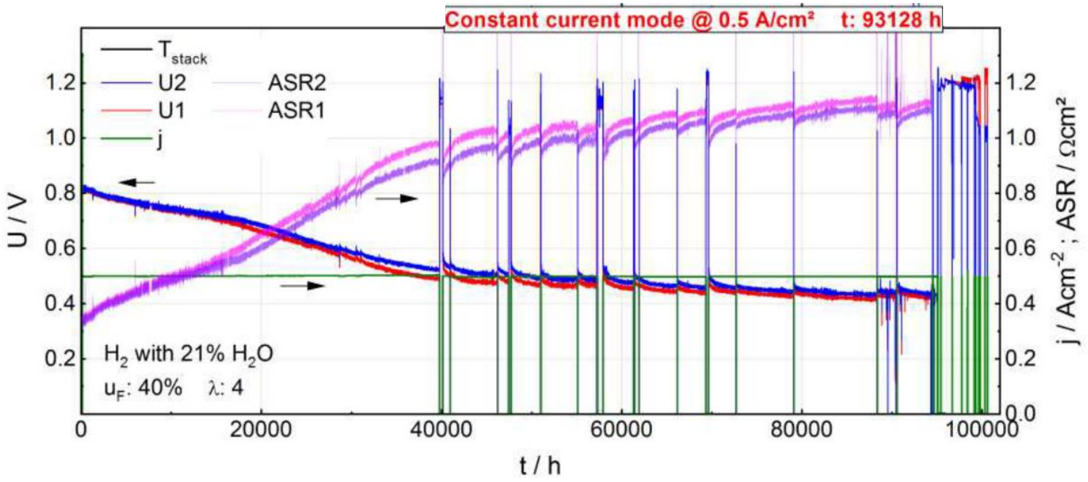
FORSCHUNGSZENTRUM JÜLICH, GERMANY

# Overview

- Benchmarking Solid Oxide Cells (SOCs) – status quo in literature
- Problems with the status quo
- Can we have better metrics?

# SOC research at Forschungszentrum Jülich

- SOC research for > 25 years
- From raw materials to stacks and systems
- Cell, interconnect, sealing, BoP, design & engineering




Q. Fang, L. Blum, D. Stolten, ECS Transactions, 91 (2019) 687-696.

10/40 kW rSOC system

- Highlights include degradation testing of SOFC / SOEC, rSOC system design and testing, and much more…

# SOC – R&D status and industrialization

- SOC technology is on the cusp of large-scale commercialization (MW to GW)
  - Fuel cell: Bosch (DE), Weichai (CN), Bloom Energy (USA), Elcogen (ES), SolydEra (IT), Convion (FI)…
  - Electrolysers: Bloom Energy (USA), Haldor Topsoe (DN), Sunfire (DE),…

- As the SOCs move toward a focus on production, there is a need for industry and key players to identify promising new technology and materials

- Cell testing is the gold standard to assess materials and cell design, but there some problems with how cell testing is reported

# Motivation

**Performance Benchmark of Planar Solid Oxide Cells Based on Material Development and Designs**

*David Udomsilp,* Christian Lenser, Olivier Guillon,* and Norbert H. Menzler**

- Review article about the state-of-the-art in SOC
- Searched for current density (A cm$^{-2}$) at 0.7 V
- Quick reference for cell / materials performance
- Major obstacle: the way that cell performance is reported

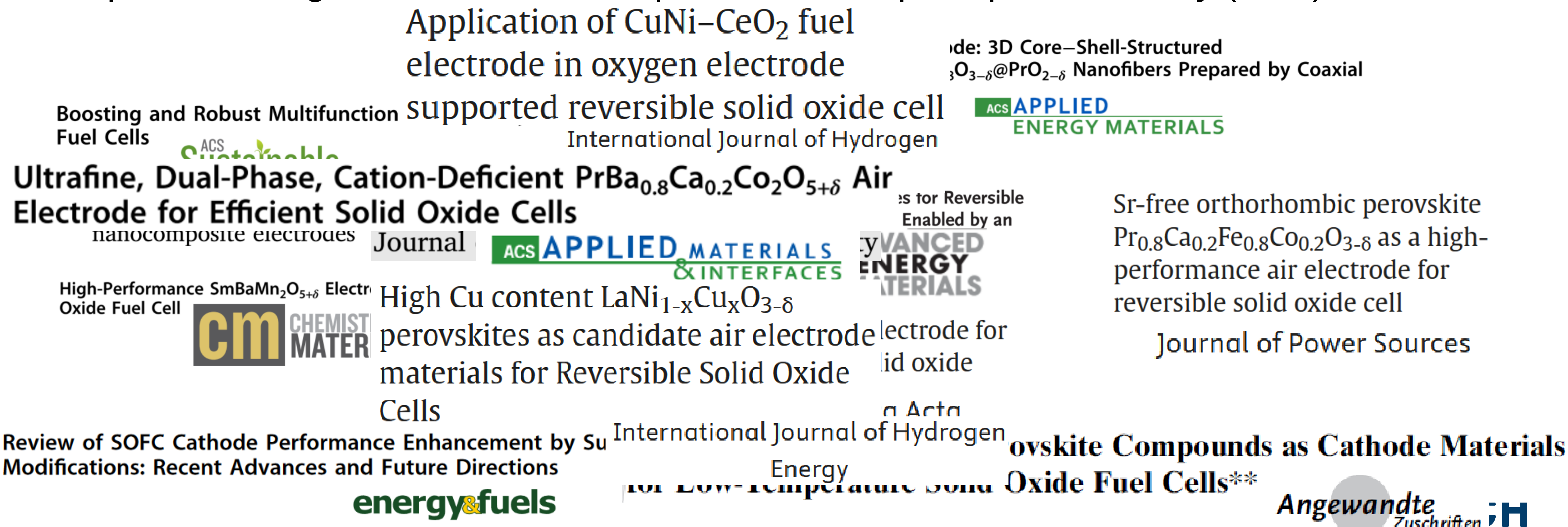
| 600 °C | | 700 °C | |
|---|---|---|---|
| $j_{0.7\,V}$ [A cm$^{-2}$] | $R_p$ [Ω cm$^2$] | $j_{0.7\,V}$ [A cm$^{-2}$] | $R_p$ [Ω cm$^2$] |

[1] D. Udomsilp, C. Lenser, O. Guillon, N.H. Menzler, Energy Technology, 9 (2021) 2001062.

# Benchmarking SOFC – the status quo

- Searching Web of Science (results in last 5 years, „solid oxide fuel cell“, „electrode“)

➢ Papers focusing on materials development use the peak power density (PPD) as metric



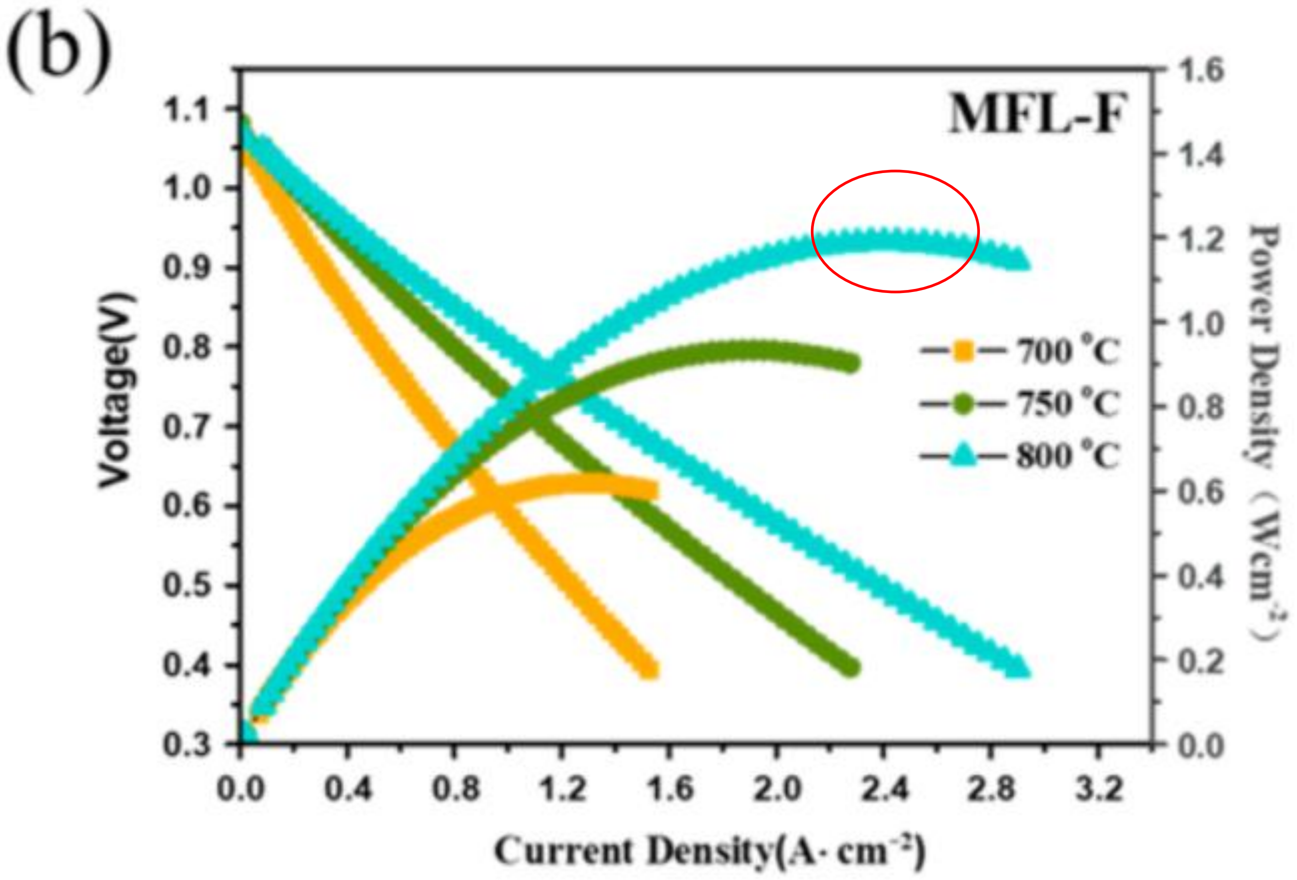
# Availability of data

## Information supplied in main paper

| Reference | Area | Gas composition/ flow rates | Contacting materials | Current sweep rate |
|---|---|---|---|---|
| A | | | | |
| B | | | | |
| C | | | | |
| D | | | | |
| E | | | | |
| F | | | | |

[A] Z. Yue, L. Jiang, Z. Chen, N. Ai, Y. Zou, S.P. Jiang, C. Guan, X. Wang, Y. Shao, H. Fang, Y. Luo, K. Chen, ACS Applied Materials & Interfaces, 15 (2023) 8138-8148.
[B] J. Bai, D. Zhou, X. Zhu, N. Wang, R. Chen, B. Wang, ACS Applied Energy Materials, 5 (2022) 11178-11190.
[C] Z. Zheng, J. Jing, H. Yu, Z. Yang, C. Jin, F. Chen, S. Peng, ACS Sustainable Chemistry & Engineering, 10 (2022) 6817-6825.
[D] S. Yoo, A. Jun, Y.-W. Ju, D. Odkhuu, J. Hyodo, Y. Jeong Hu, N. Park, J. Shin, T. Ishihara, G. Kim, Angewandte Chemie International Edition, 53 (2014) 13064-13067.
[E] J. Zamudio-García, L. dos Santos-Gómez, J.M. Porras-Vázquez, E.R. Losilla, D. Marrero-López, Journal of the European Ceramic Society, 43 (2023) 1548-1558.
[F] Y. Niu, Y. Zhou, W. Zhang, Y. Zhang, C. Evans, Z. Luo, N. Kane, Y. Ding, Y. Chen, X. Guo, W. Lv, M. Liu, Adv. Energy Mater., 12 (2022) 2103783.

# What is the peak power density (PPD)?




Z. Zheng, J. Jing, H. Yu, Z. Yang, C. Jin, F. Chen, S. Peng, ACS Sustainable Chemistry & Engineering, 10 (2022) 6817-6825.

- PPD is the maximum of the power density vs current density curve
- PPD provides one value that describes cell performance at a given temperature
- ….or does it?

# PPD – the problems

| Reference | Temperature (°C) | Voltage (V) | Current density (A $cm^{-2}$) | Power density (W $cm^{-2}$) |
|---|---|---|---|---|
| A | 700 | 0.47 | 1.3 | 0.61 |
| B | 700 | 0.5 | 2.3 | 1.15 |
| C | 700 | 0.55 | 0.4 | 0.22 |

- PPD is never at the same working point for different cells

- PPD is always at rather low voltages
    - Consequences for efficiency
    - Unstable operation

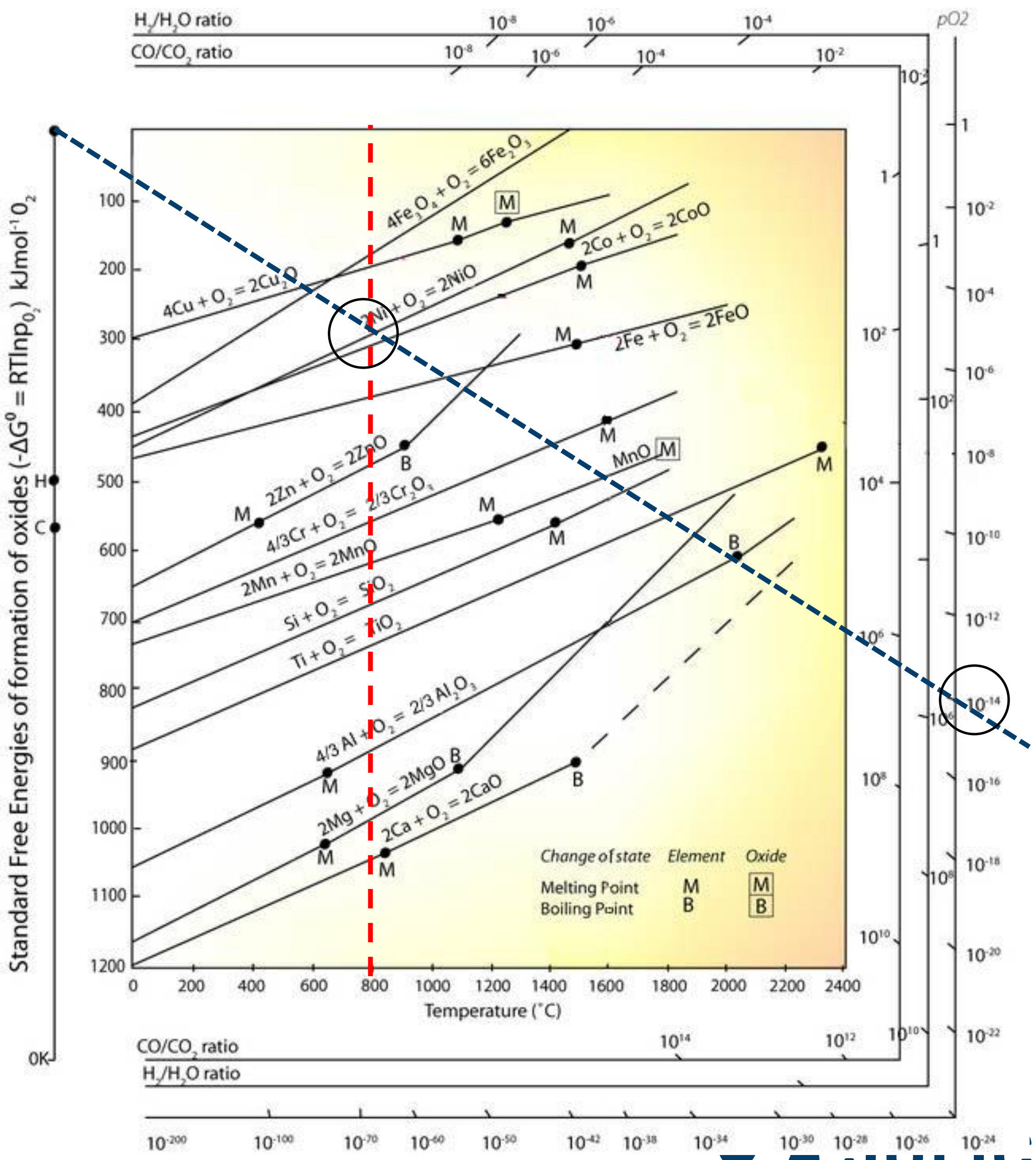
# PPD – voltage efficiency

- Fuel cells operating below the thermoneutral voltage $V_{TN} = \frac{-\Delta H}{nF}$ generate heat
- As $V_{TN}$ ~ 1.3 V at 800 °C, SOFCs always produce heat
- The further $V_{cell}$ is below $V_{TN}$, the more heat (and less electricity) is produced
- Definition:

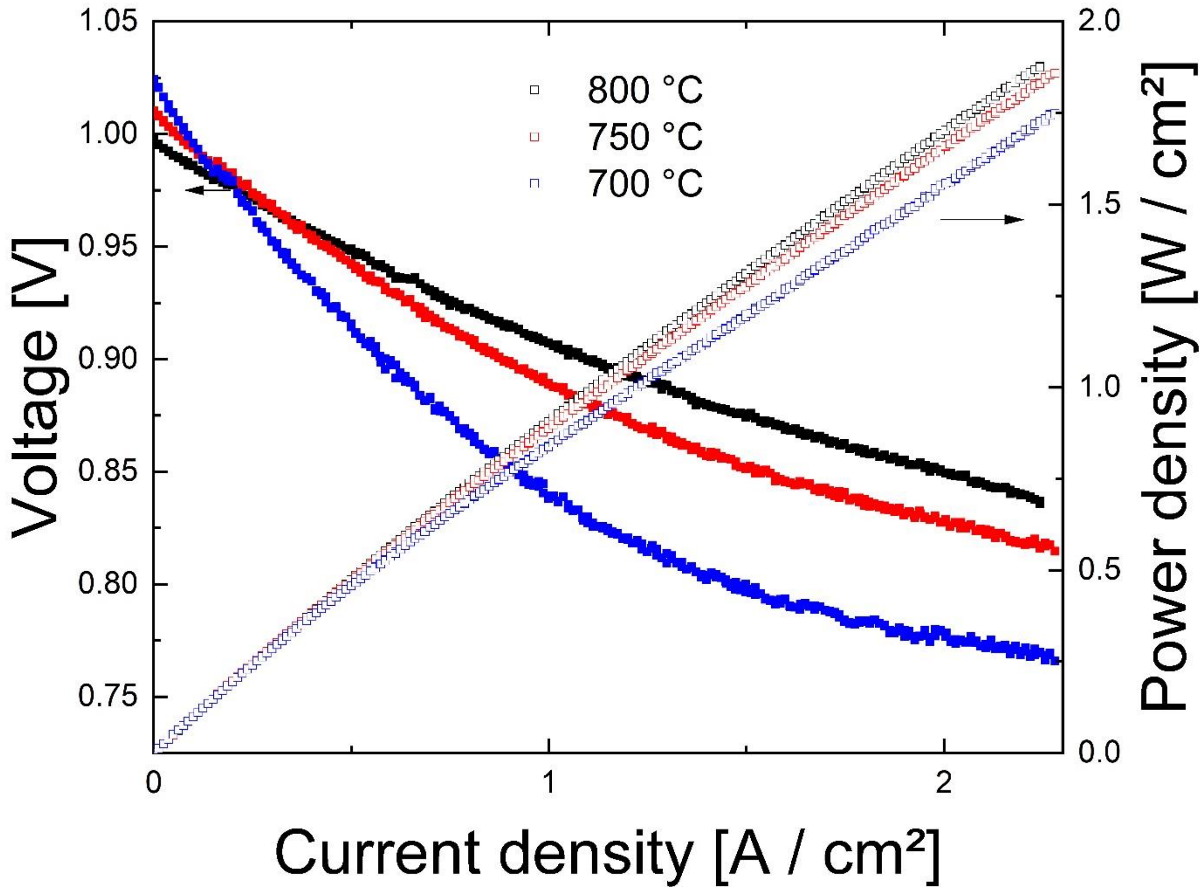
$$Voltage\ efficiency = \frac{Operating\ voltage\ (V)}{Thermodynamic\ voltage\ (E)}$$

# PPD – low voltage

- Ellingham diagram: equilibrium $pO_2$ for Ni oxidation is ~ $10^{-14}$ atm at 800°C
- With $E = -\frac{RT}{4F}\ln\left(\frac{pO_2}{0.21}\right)$; this $pO_2$ corresponds to a cell voltage of 700 mV at 800 °C
- From this simple analysis, it should be clear the PPD at ~ 500 mV does **not** reflect a **stable** operation point of the SOFC



# PPD – find the maximum?




Cell: LSC | 0.5 µm GDC | 2 µm YSZ | Ni-YSZ
A = 16 cm²; 20% $H_2O$ / $H_{2;}$ air

- Measuring single cells with 16 cm² electrode area results in currents of 32 A @ 2 A/cm²
- No maximum in power density
- The maximum current depends on the experimental setup, not the cell!
- What if you reduce the active area?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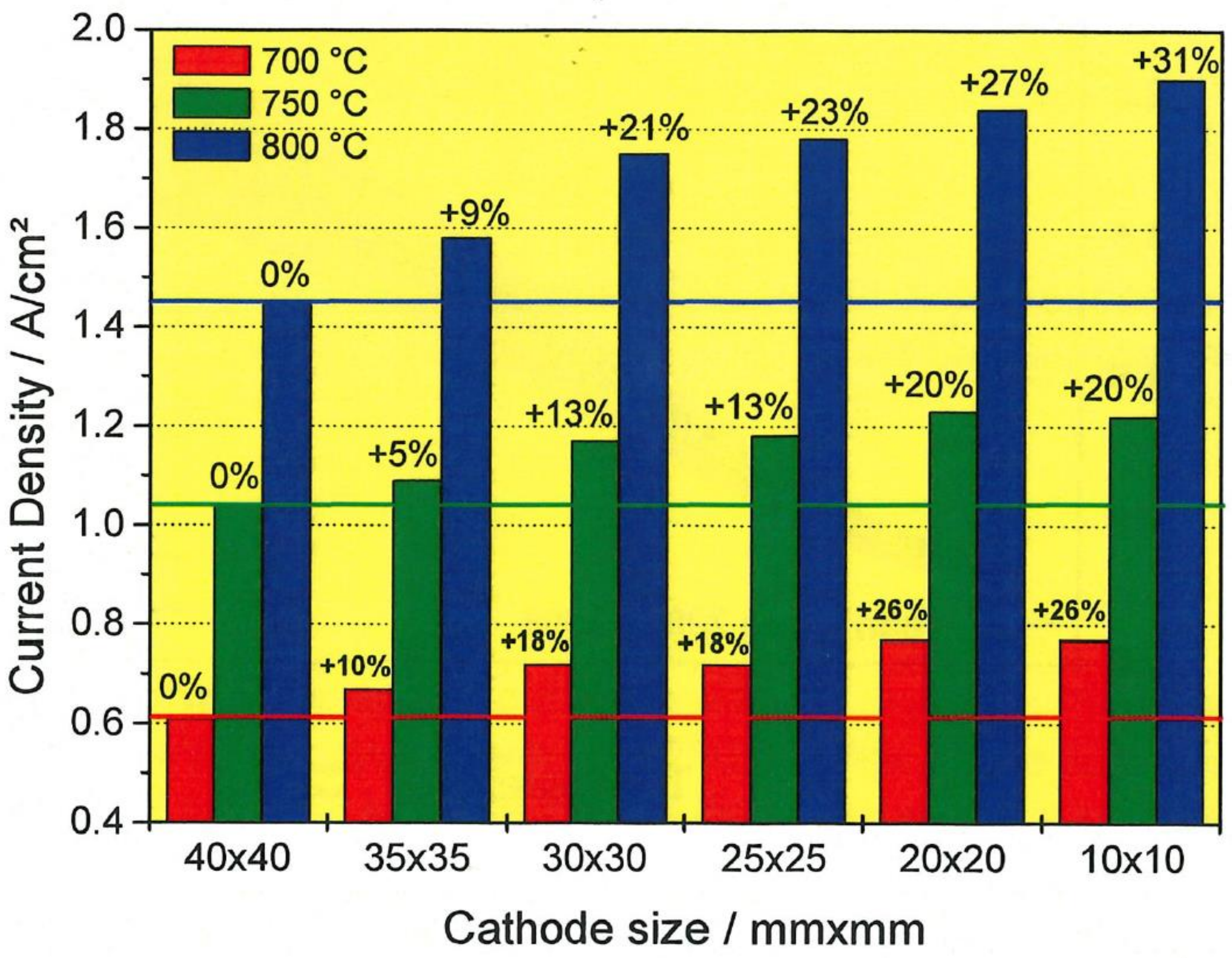
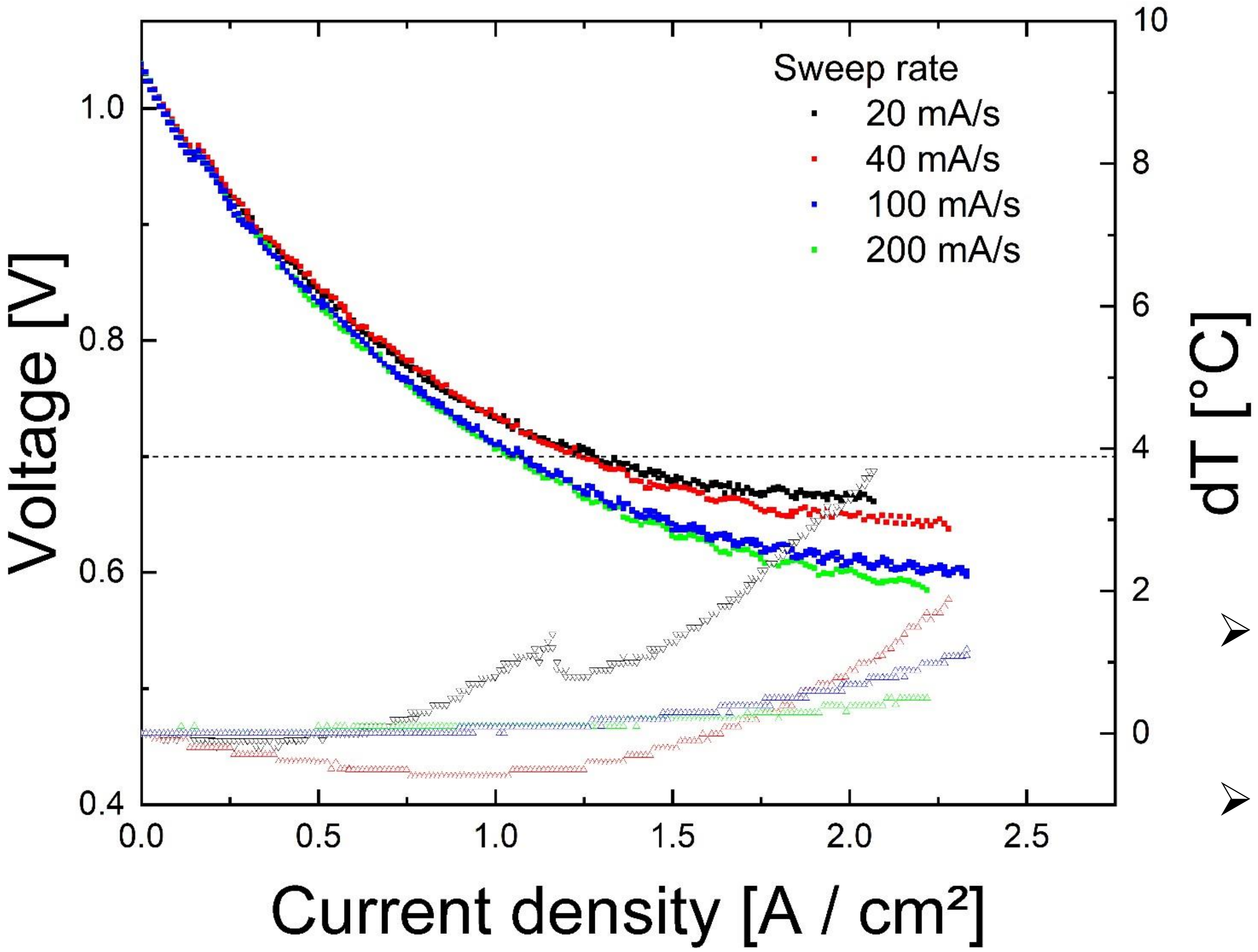
# Effect of electrode area




Confidential data from Forschungszentrum Jülich, V. Haanappel

- Electrode-supported cells (Ni-YSZ|YSZ|LSM) contacted with Ni and Pt meshes
- Electrode area varied between 1 cm² and 16 cm²
- Substantial increase in current density (@ 700 mV) with decreasing electrode size
- Difference in power density is likely due to differences in fuel utilization (gas flow rate was constant for all cells)

# Effect of current sweep rate

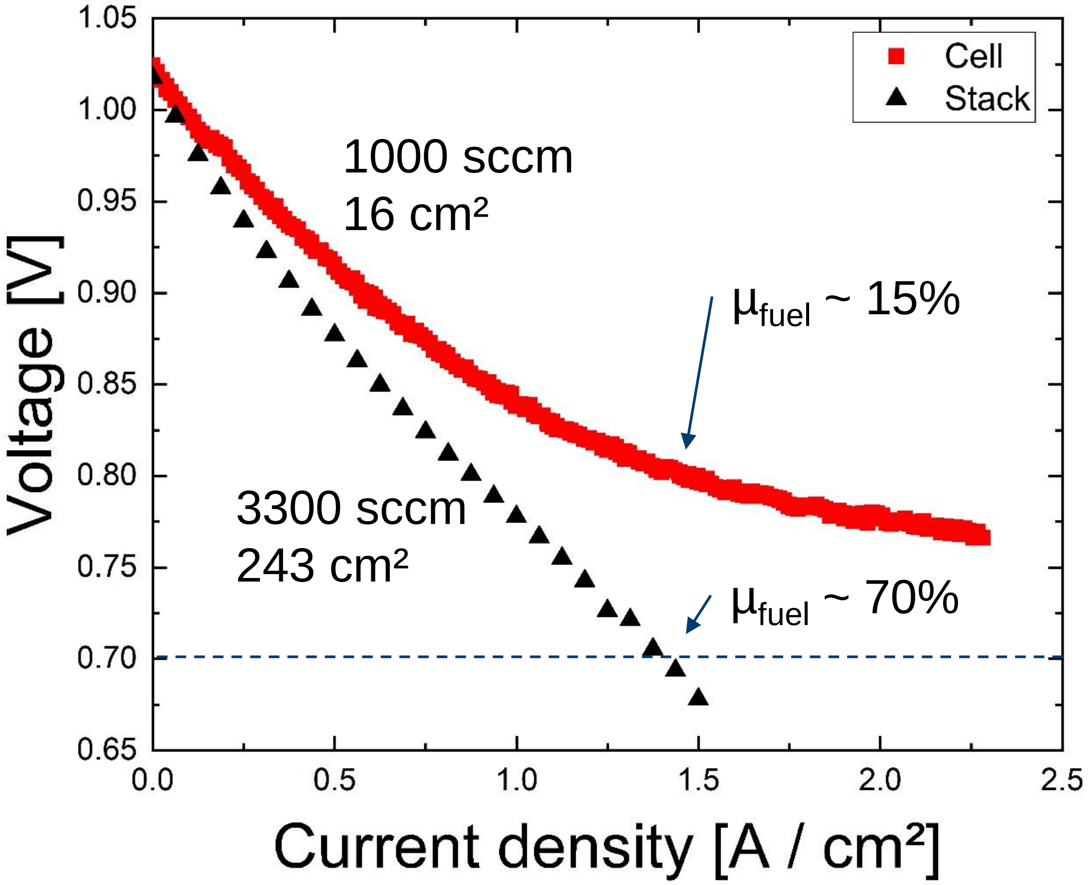



Cell: LSC | 0.5 µm GDC | 2 µm YSZ | Ni-YSZ
A = 16 cm²; 20% $H_2O$ / $H_2$; air; 650 °C

| Sweep rate (mA/s) | Current density at 0.7 V (A/cm²) |
|---|---|
| 20 | 1.27 |
| 40 | 1.23 |
| 100 | 1.07 |
| 200 | 1.06 |

- Current sweep rate has a profound effect on measured performance (~ 20%)
- Probably related to local temperature increase (local temperature ≠ thermocouple temperature)

# Transfer of cell performance into stacks

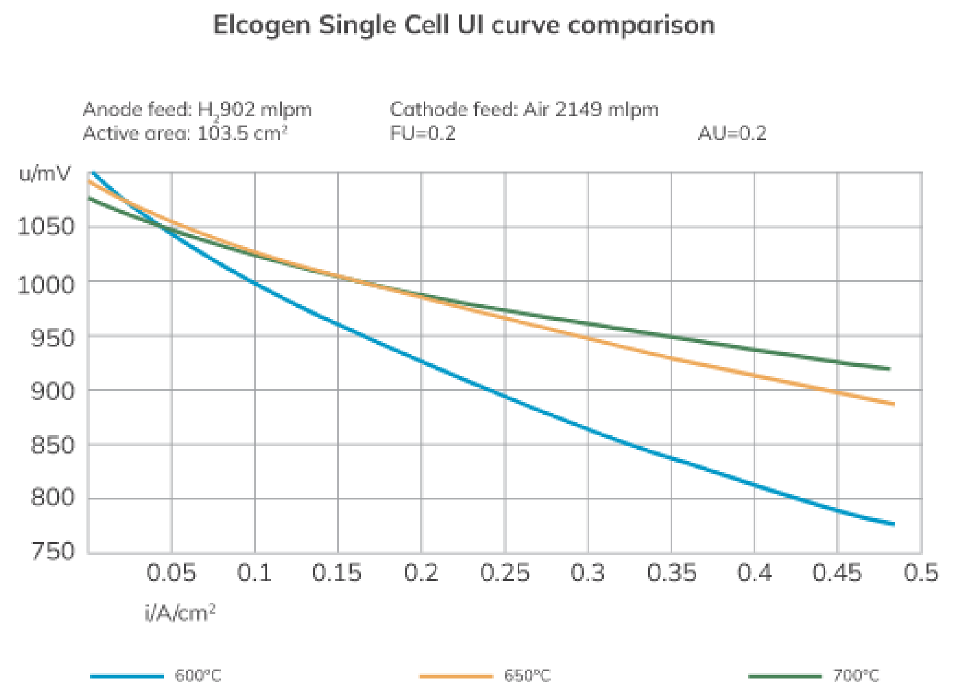



Cell: LSC | 0.5 µm GDC | 2 µm YSZ | Ni-YSZ

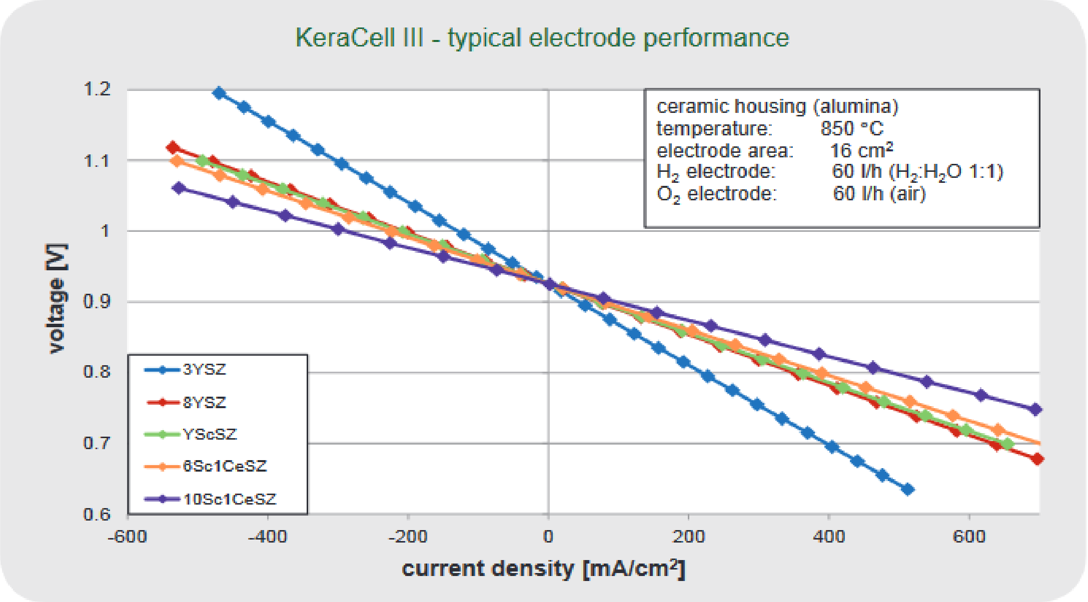
- Integrating cells into stack leads to lower power due to:
  - Contact resistances
  - High fuel utilization
- “Real” operation in a stack makes high current density very difficult to realize (high gas flow rates and pressure drops, large gradients across cell)
- High current density → low system efficiency
- Difference between cell and stack performance increases with higher current density

# Cell testing – how does industry do it?

Example: Elcogen (ES)
(https://elcogen.com/products/solid-oxide-fuel-cells/)




Example: Kerafol (DE)
(https://www.kerafol.com/_wpframe_custom/downloads/files/Kerafol_SOFC_Datenblaetter_KeraCell-III_EN_06-21___143516-14062021.pdf)




- ➢ The (few) published metrics from industry reflect the concerns about cell testing. Testing is kept to low current densities.

# Problems with PPD - summary

- The PPD is typically found at a point that:
  - shows low cell efficiency
  - is unstable with regards to Ni oxidation
  - is not available for every experiments
  - depends on cell geometry / test bench characteristics
- Cell performance depends on
  - Gas composition & flow rate
  - Contacting materials
  - Temperature measurement & increase
  - Current sweep rate

Recommended reading:

A. Weber, tm - Technisches Messen, 89 (2022) 97-106.

V.A.C. Haanappel, M.J. Smith, A review of standardising SOFC measurement and quality assurance at FZJ, Journal of Power Sources 171 (2007) 169–178

# A better metric

- Variables to define
  - Temperature
  - Current density / voltage
  - Electrode size
  - Gas flow rates or gas utilization
  - Gas composition
- Variables to eliminate
  - Sweep rate -> constant operation
  - Open circuit voltage (leakage in test setup) -> use increased humidity

# Performance metrics for SOEC

- The situation is better for electrolysis
- The thermoneutral voltage $V_{TN} = \frac{-\Delta H(T)}{nF}$ is the voltage at which the cell neither produces nor consumes heat (under isothermal conditions!)
- Since $Voltage\ efficiency = \frac{V_{TN}}{V_{cell}}$, voltage efficiency is 100% at $V_{cell} = V_{TN}$

- The current density at $V_{TN}$ is therefore a good metric for SOECs
- Other parameters (especially gas composition, also flow rates etc) must be controlled

# Summary

- Peak power density (PPD) is extensively used to report cell performance
- However, there are a number of problems with PPD
- Ultimately, it is important to report all significant parameters to enable an interpretation of cell performance
- Implementing better metrics may improve reliability of literature data

# THANK YOU FOR YOUR ATTENTION

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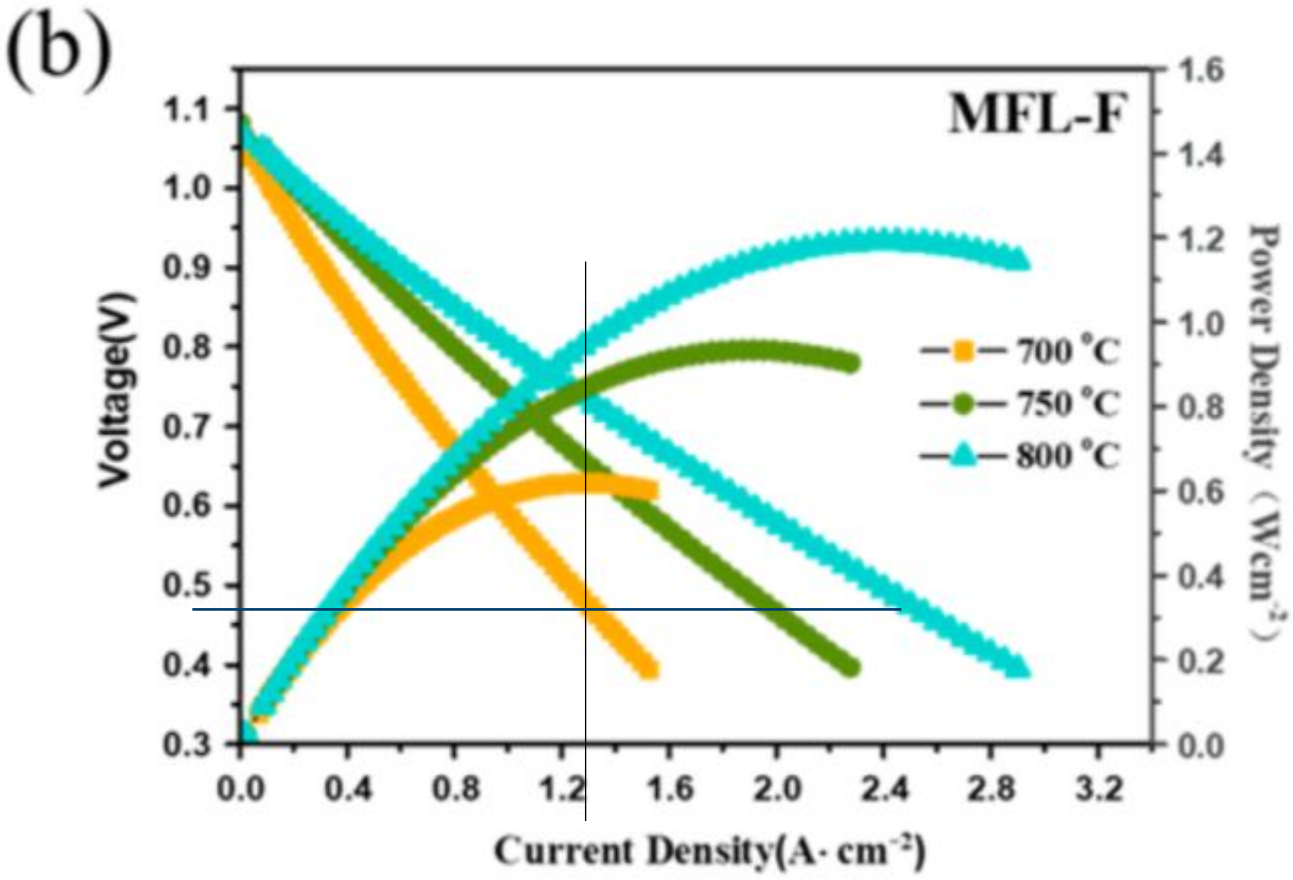
# Ref A


(b)
MFL-F
Voltage(V)
Power Density（Wcm⁻²）
Current Density(A· cm⁻²)
700 °C
750 °C
800 °C
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

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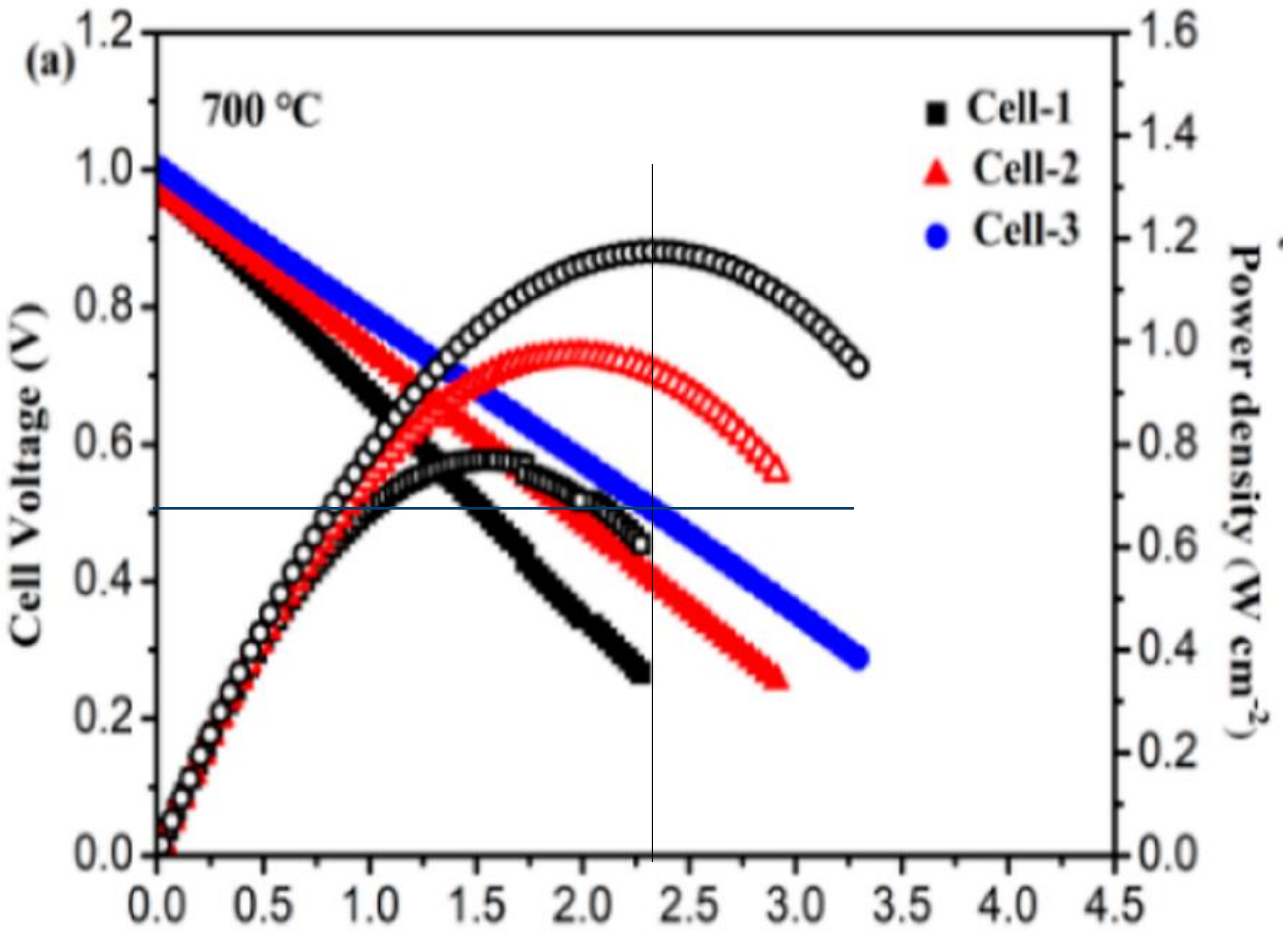



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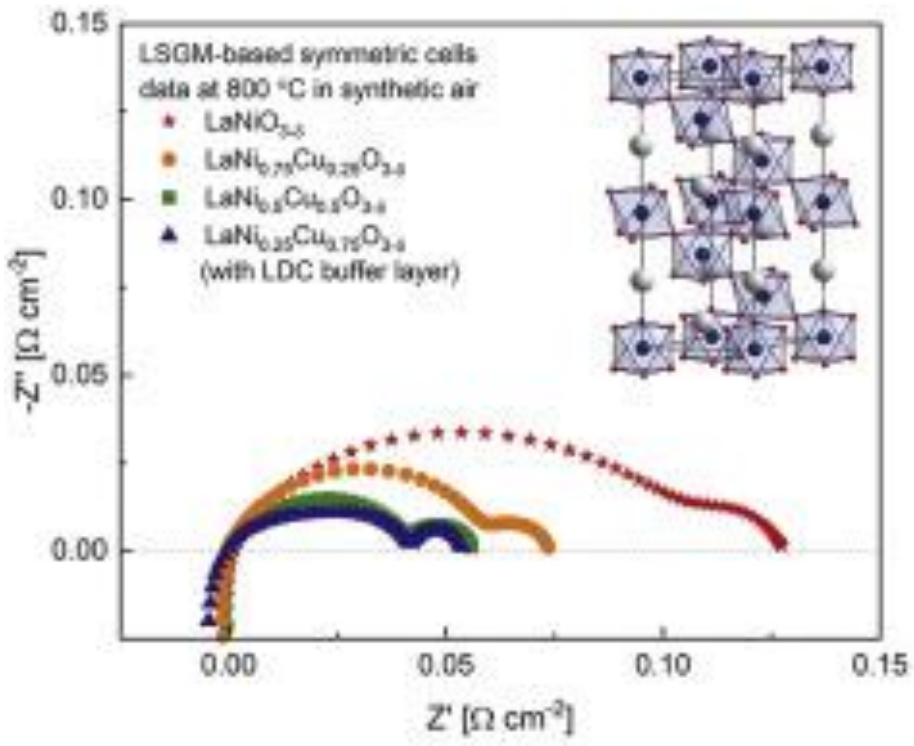


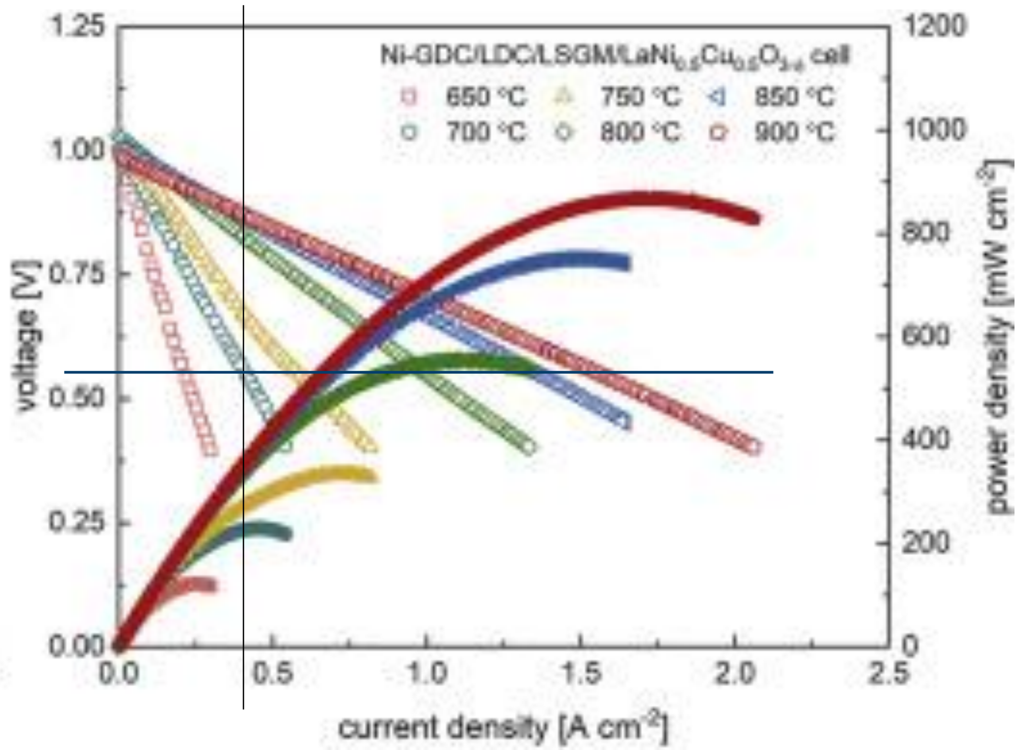




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