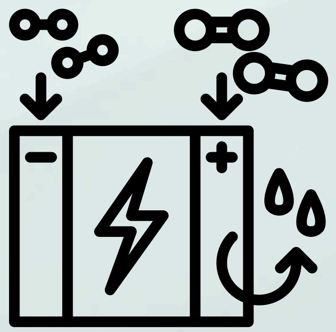


SOLID OXIDE FUEL CELLS

(SOFCS)

Theory of Operation, Materials, Comparison with PEM Fuel Cells, and Promising Applications in Aviation

PRESENTED BY: DAVID THOMPSON-AJAYI

Agenda

Presentation Date
10-June-2025

Time Slot
2pm-2:20pm

Duration
20 Minutes

1. Motivation
2. Theory of Operation
   - Cathodic Reactions (ORR)
   - Anodic Reactions (HOR)
   - Overall Reaction
   - Triple Phase Boundary
   - Cell Stack
3. Material of SOFC
   - Electrolytes in HT SOFCs
   - Anionic Conductivity of YSZ
   - Anode & Cathode in HT SOFC
4. Material of LT SOFC
5. Comparison
6. Applications of SOFCs in Aviation
7. Conclusion
8. References

Presentation Outline

1. Motivation

Why Solid Oxide Fuel Cells?

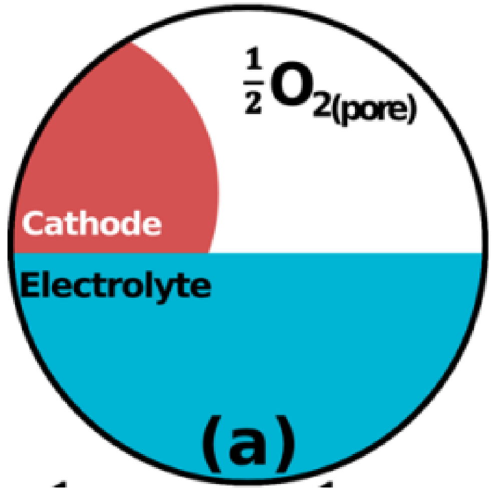
1. **High efficiency 50~60%, and up to 85~90% combined heat and power (CHP) systems.**

2. No precious metals needed, i.e. (Platinum (Pt), reaction kinetics are fast due to high temperature

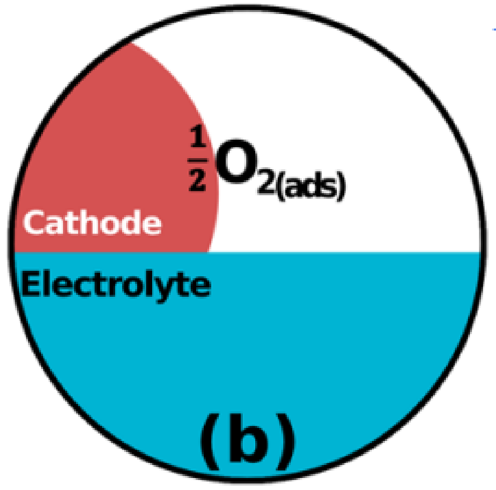
3. Fuel Flexibility
- **Can run on hydrogen, natural gas, ammonia, or even biogas.**
- **Capable of internal reforming of hydrocarbons. (methane steam reforming)**

2. Theory Of Operation

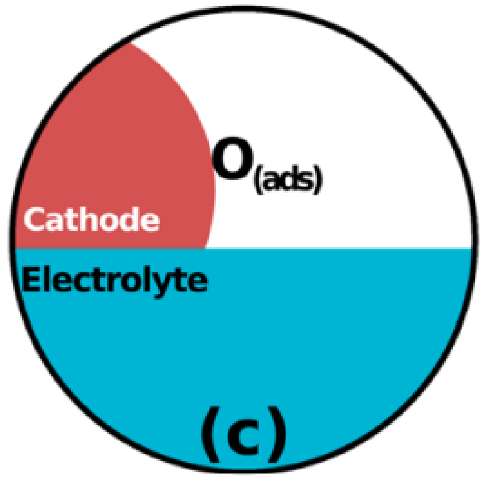
2.1. Cathodic reactions (Oxygen Reduction Reaction ORR)



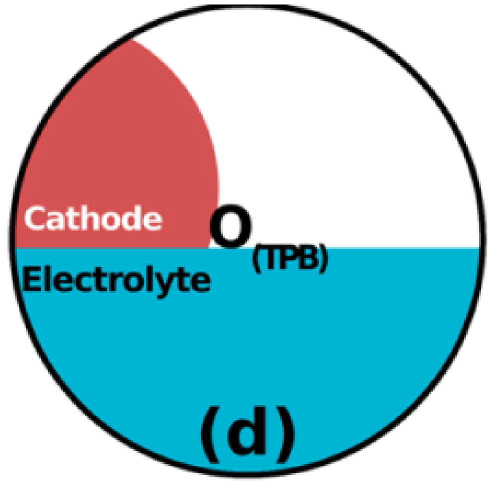
$$\frac{1}{2}O_{2(g)} \rightarrow \frac{1}{2}O_{2,\text{pore}}$$



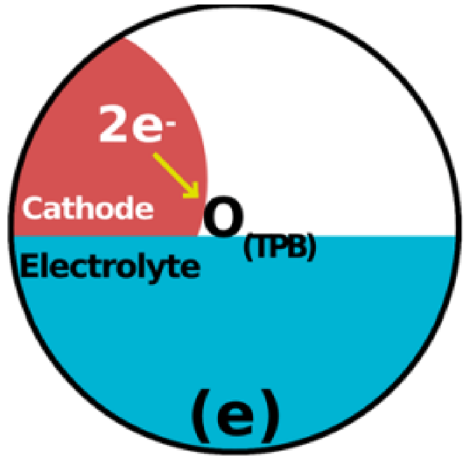
$$\frac{1}{2}O_{2,\text{pore}} \rightarrow \frac{1}{2}O_{2,\text{ads}}$$



$$\frac{1}{2}O_{2,\text{ads}} \rightarrow O_{\text{ads}}$$

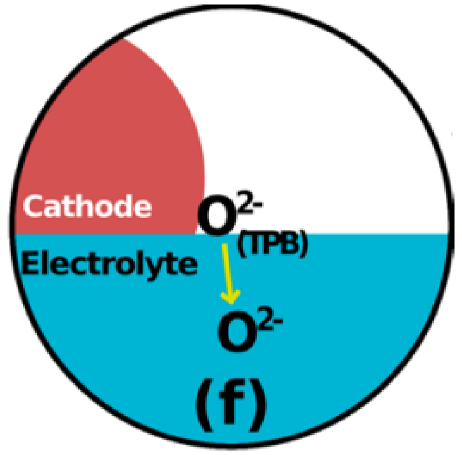


$$O_{\text{ads}} \rightarrow O_{\text{TPB}}$$



$$O_{\text{TPB}} + e^{-} \rightarrow O^{-}_{\text{TPB}}$$

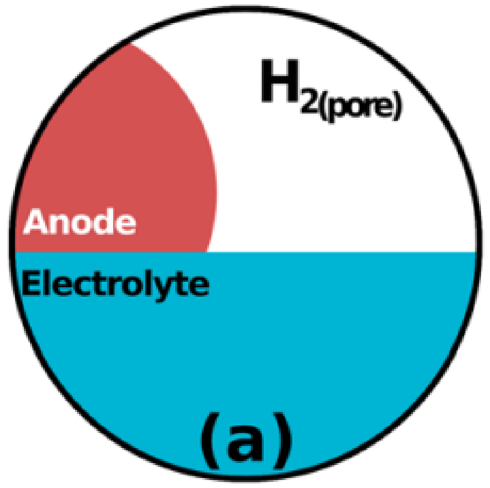
$$O^{-}_{\text{TPB}} + e^{-} \rightarrow O^{2-}_{\text{TPB}}$$



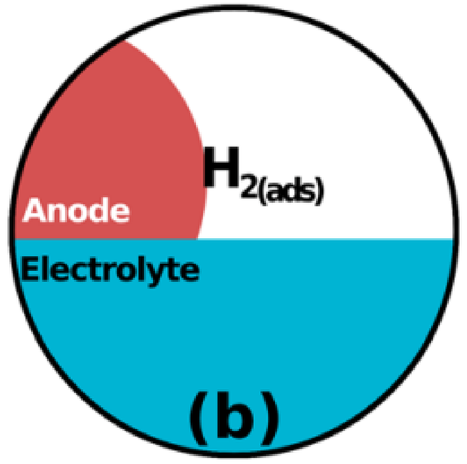
$$O^{2-}_{\text{TPB}} + V_{\ddot{O}} \rightarrow O^{\times}_{O}$$

2. Theory Of Operation

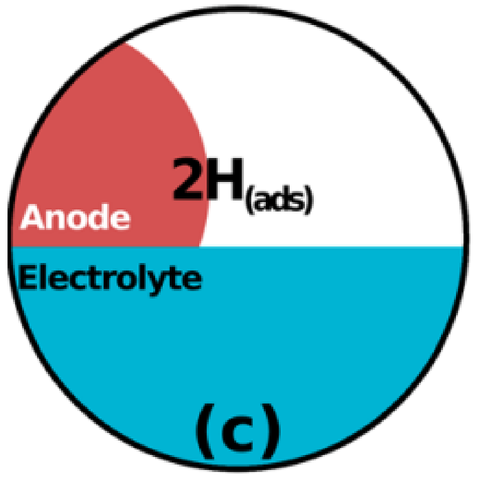
2.2. Anodic reactions (Hydrogen Oxidation Reaction HOR)



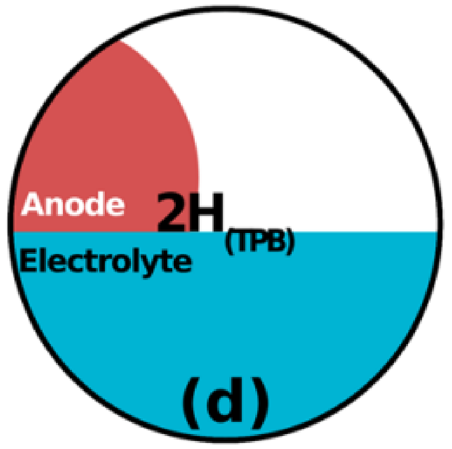
$$H_2 \rightarrow H_{2,\mathrm{pore}}$$



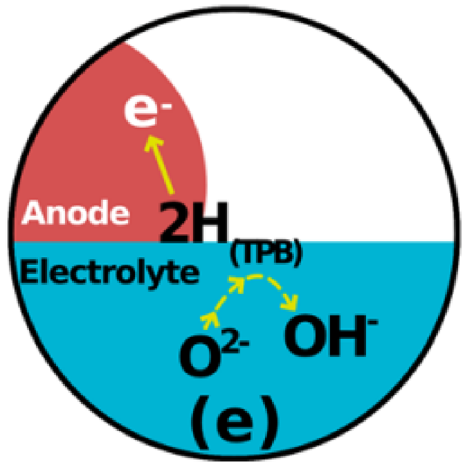
$$H_{2,\mathrm{pore}} \rightarrow H_{2,\mathrm{ads}}$$



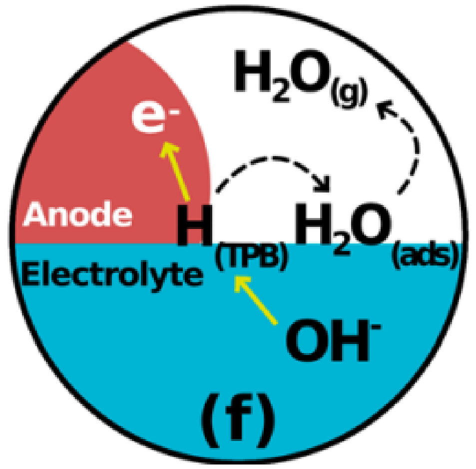
$$H_{2,\mathrm{ads}} \rightarrow 2H_{\mathrm{ads}}$$



$$2H_{\mathrm{ads}} \rightarrow 2H_{\mathrm{TPB}}$$



$$2H_{\mathrm{TPB}} + O_O^{\times} \rightarrow H_{\mathrm{TPB}} + OH_O^{\bullet} + e^-$$



$$OH_O^{\bullet} \rightarrow OH^-_{\mathrm{ads}} + V_O^{\bullet\bullet}$$

$$H_{\mathrm{TPB}} + OH^-_{\mathrm{ads}} \rightarrow H_2O_{\mathrm{ads}} + e^-$$

$$H_2O_{\mathrm{ads}} \rightarrow H_2O_{(g)}$$

Presentation Outline

2. Theory Of Operation

2.3. Overall reaction

- Oxygen ions diffuse through the solid electrolyte via a vacancy hopping mechanism.

$$[V_O^{\bullet\bullet}] \uparrow\uparrow \longrightarrow \sigma_{\text{ion}} \uparrow\uparrow$$

- the requirement that the electrolyte has a high ionic conductivity offers opportunities for optimization through combinations of various materials. (as we will see)

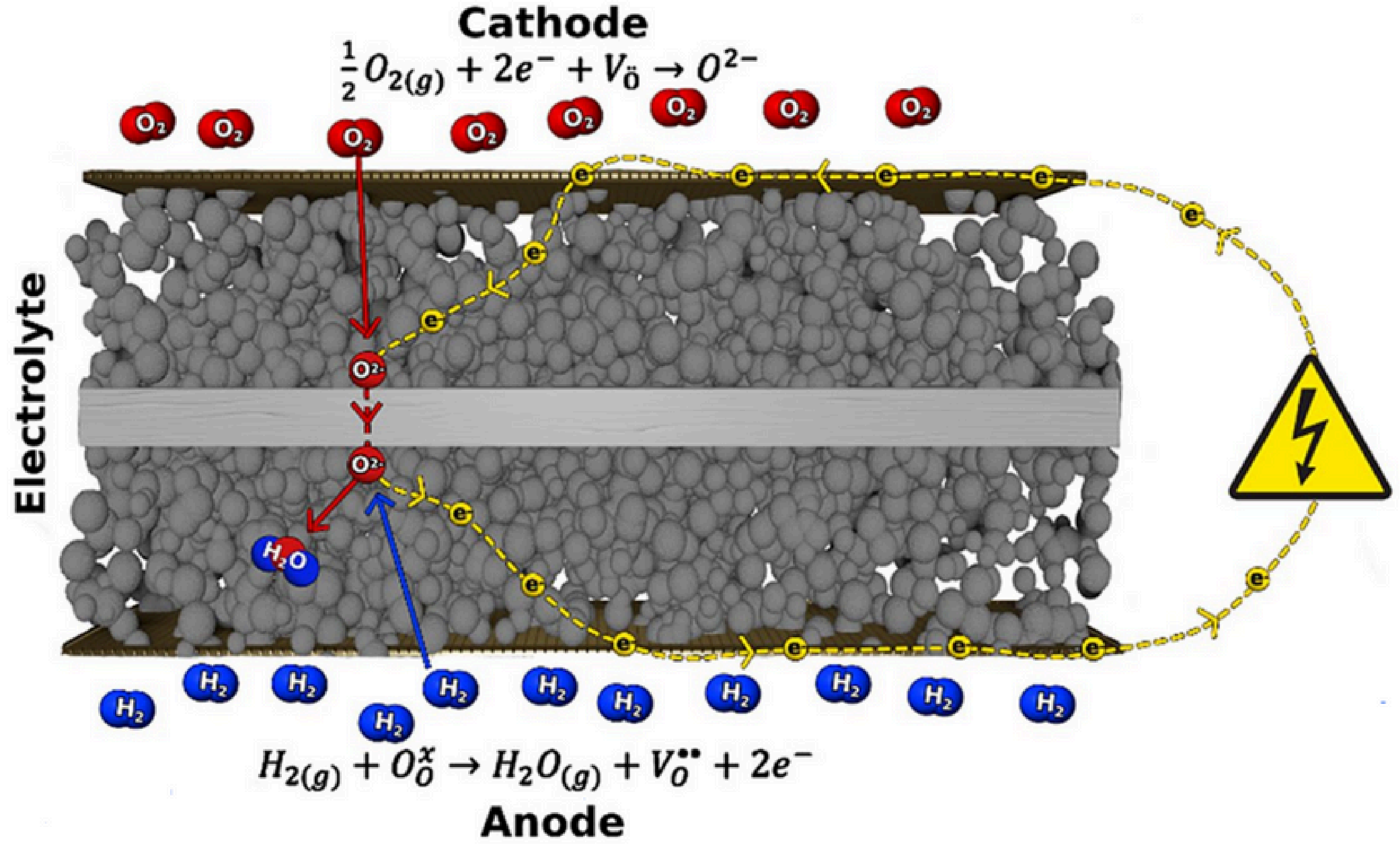
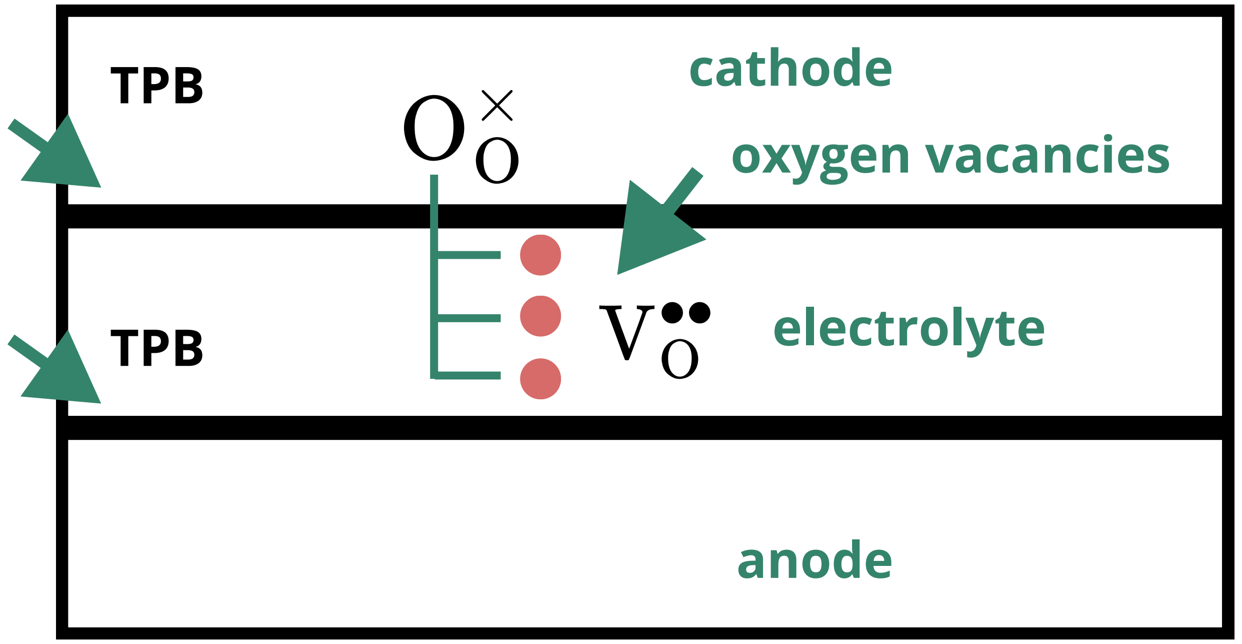


Fig 2.1: Overall reaction in Solid Oxide Fuel Cell

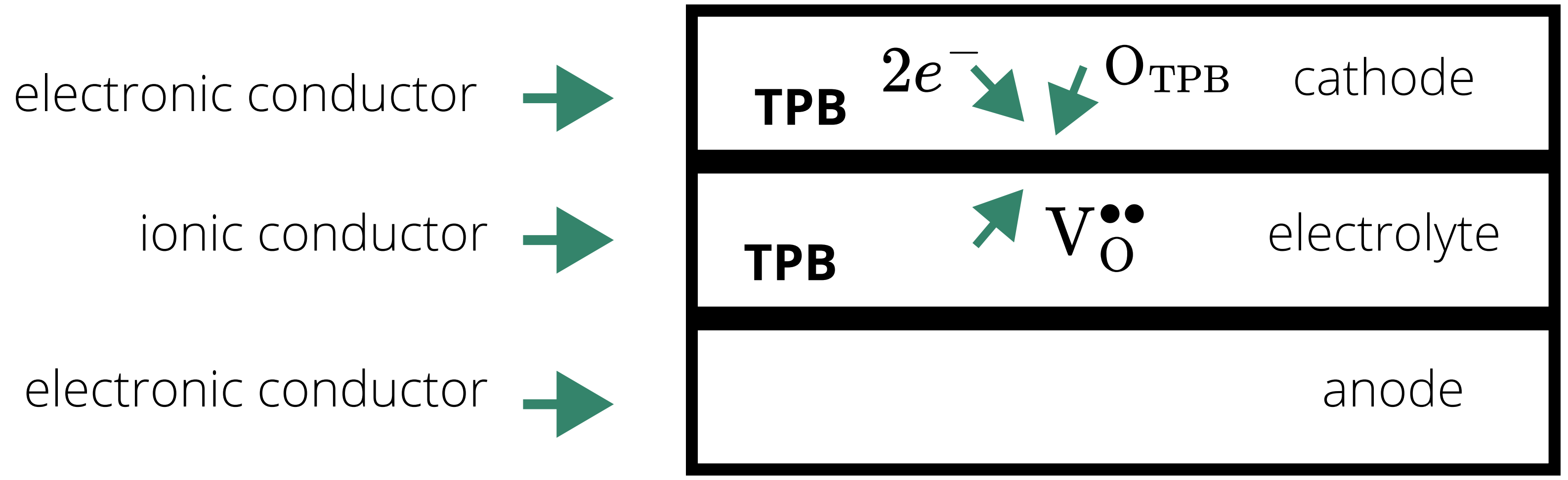
Source: Zuo, C., Liu, M., Yang, L., Liu, M., & Wang, W. (2021). A tutorial review on solid oxide fuel cells: Fundamentals, materials, design, and applications.



2. Theory Of Operation

2.4. Triple phase boundary TPB (cathodic and anodic TPB)

The line or region within the porous electrode where three distinct phases meet:
1. Electron-conducting phase (e.g., Ni in the anode, LSM in the cathode)
2. Ion-conducting phase (electrolyte like YSZ – Yttria-Stabilized Zirconia)
3. Gas phase (the fuel, e.g., H_2 or O_2)



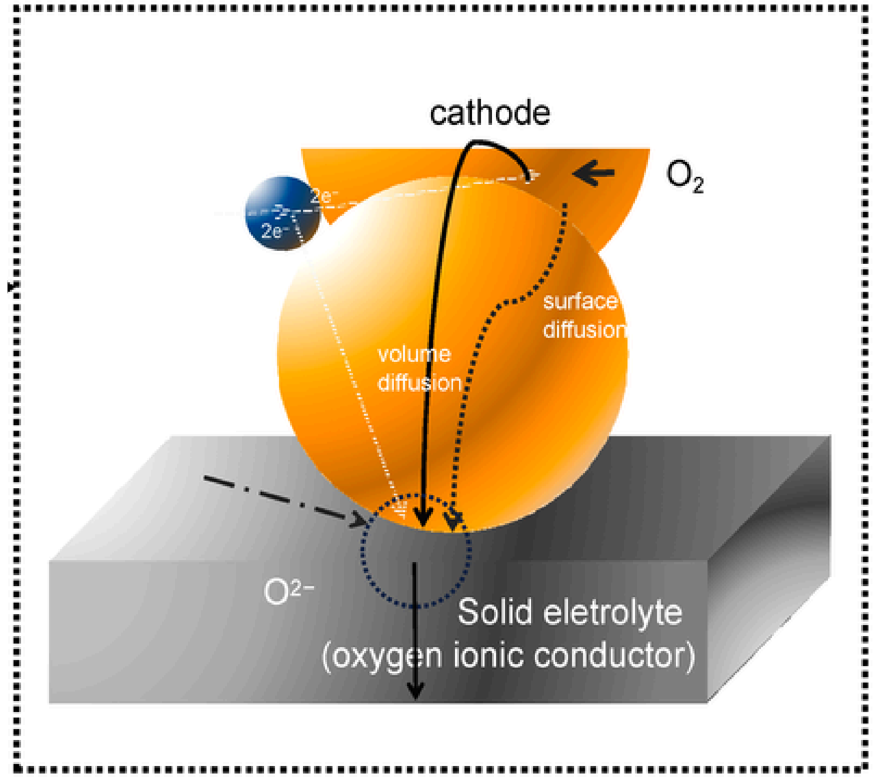


Fig. 2.2: Triple Phase Boundary in SOFC.
Source: Xie, Y., Chen, X., Li, Y., Liu, T., Wang, H., Zhu, W., ... & Liu, M. (2019). Recent progress in semiconductor–ionic conductor composites for low-temperature solid oxide fuel cells.

2.5. Cell stack

- As the irreversible standard voltage of the cell is only **1.23 V**, usually cells are connected in "***Stack***" in practical applications.
- interconnect materials are used to connect the cathode of a cell to the anode of the corresponding other cell.
- these interconnect materials must be highly ***electronic conductive***

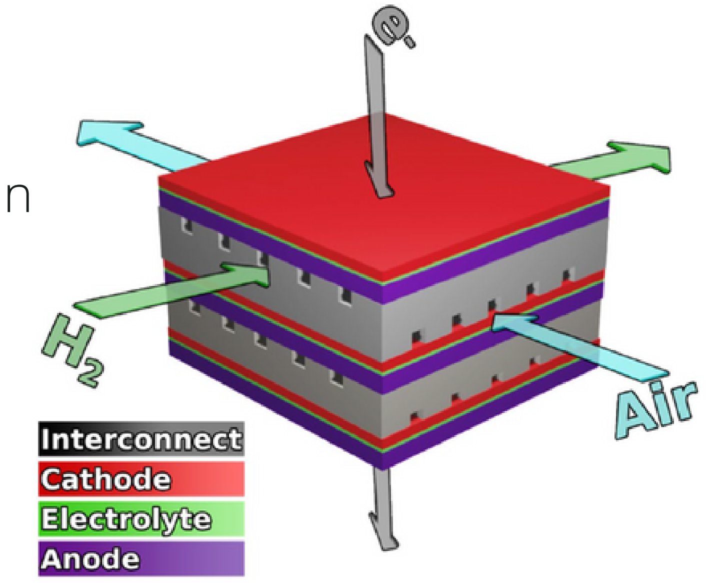
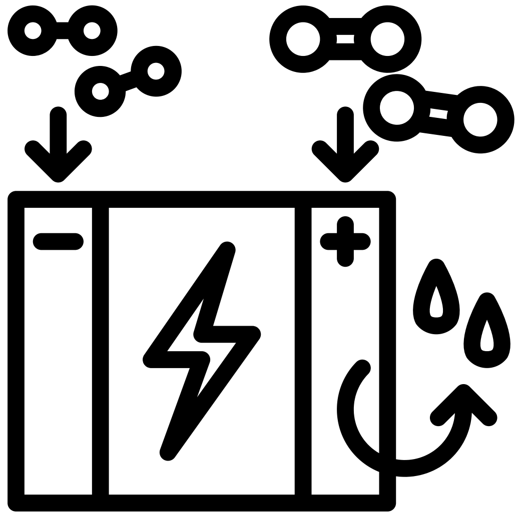


Fig 2.3: Interconnect between two cells

Presentation Outline

Materials of SOFCs

Electrolyte, Anode & Cathode



3.1 Electrolyte in HT SOFCs

Required Properties of Electrolyte Material

- High ionic conductivity and negligible electronic conductivity to minimize ohmic loss.
- Dense, gas-tight structure to prevent cross-leakage of anode and cathode gases.
- Chemically stable under both oxidizing and reducing conditions at high temperatures.
- Compatible thermal expansion with electrodes to avoid mechanical stress and failure.

YSZ (Yttria-Stabilized Zirconia)

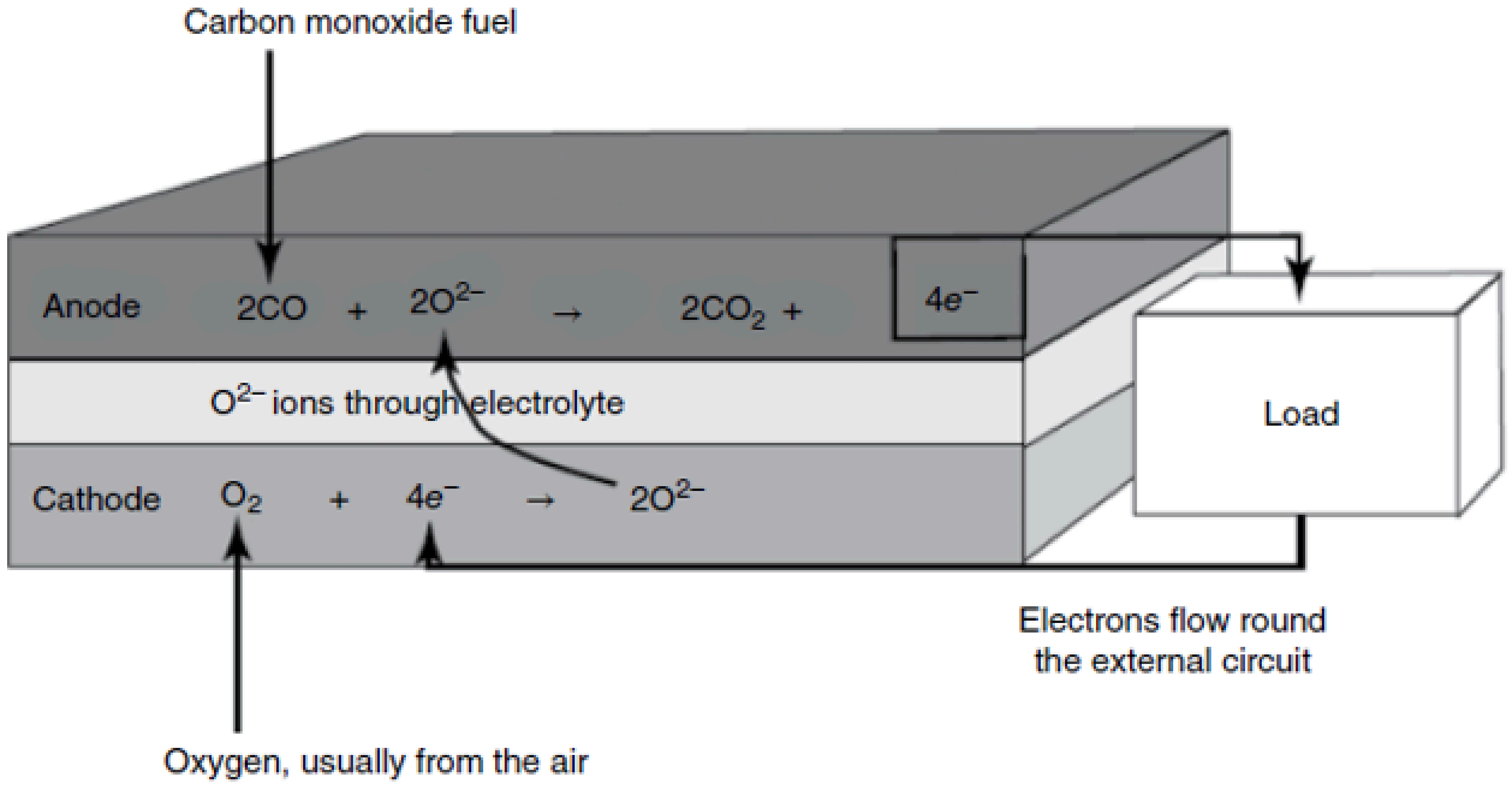


Fig 3.1: Anode and cathode reactions for the SOFC, when using hydrogen and carbon monoxide fuel

Source: Reproduced from Dicks, A. L., & Rand, D. A. J. Fuel Cell Systems Explained, 3rd ed., Wiley, Chichester, UK, 2018. © John Wiley & Sons Ltd.

3.2. Anionic Conductivity of YSZ

Electrolyte in HT SOFCs

$$Y_2O_3 \rightarrow 2Y'_{Zr} + V_O^{\bullet\bullet} + 3O_O^{\times}$$

- Zirconia (ZrO_2) is a poor ionic conductor at low temperatures.
- At high temperatures, zirconia undergoes phase changes: monoclinic → tetragonal → cubic fluorite.
- The cubic fluorite structure greatly enhances ionic conductivity.
- Doping zirconia with Y^{3+} replaces some Zr^{4+} ions, creating oxygen vacancies in the lattice.
- These oxygen vacancies enable oxide ions (O^{2-}) to move via vacancy hopping.
- Oxide ions travel from cathode to anode through these vacancies in the electrolyte.
- YSZ ionic conductivity increases with temperature, reaching ~0.1 S/cm at 1000°C, comparable to liquid electrolytes.

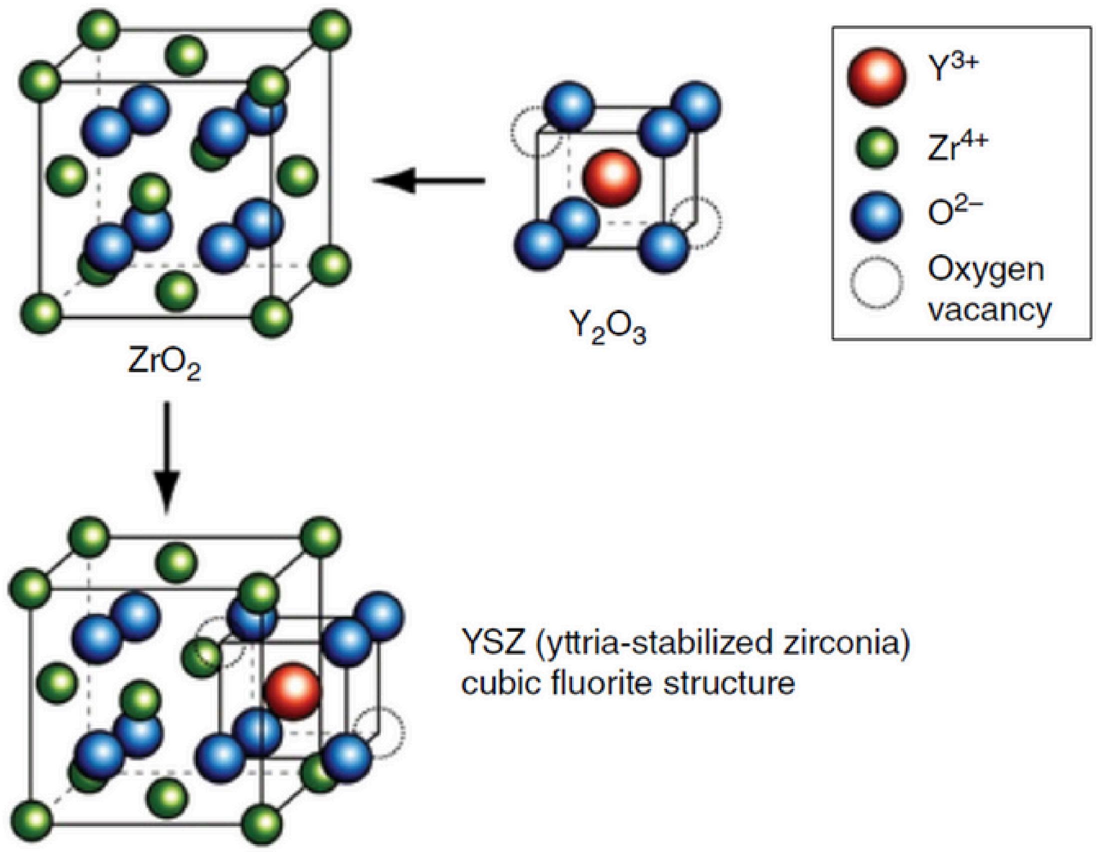


Fig 3.2: Anode and cathode reactions for the SOFC, when using carbon monoxide fuel

Source: Reproduced from Dicks, A. L., & Rand, D. A. J. Fuel Cell Systems Explained, 3rd ed., Wiley, Chichester, UK, 2018. © John Wiley & Sons Ltd.

Presentation Outline

3.3. Anode & Cathode in HT SOFCs

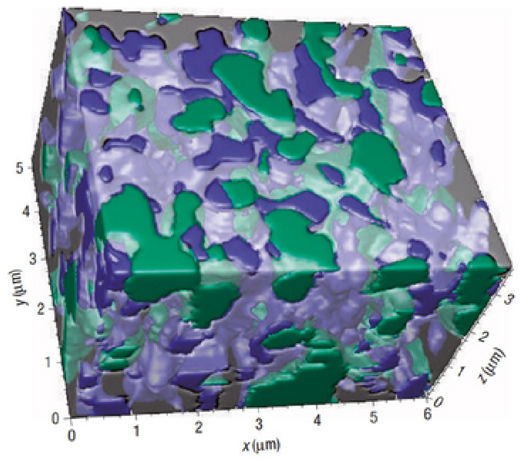


Fig 3.3: A view of the 3D reconstruction of a Ni-YSZ composite anode showing the Ni (green),YSZ (translucent/grey), and pore (blue) phases

Source:Reproduced from Sikstrom, D., & Thangadurai, V. A tutorial review on solid oxide fuel cells: fundamentals, materials, and applications.

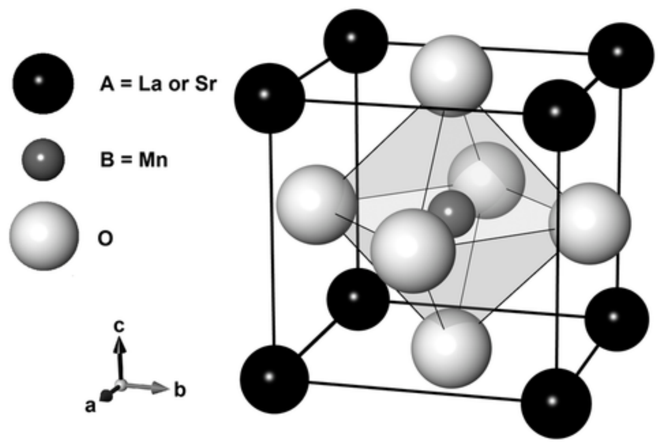


Fig 3.4: Perovskites LSM structure

Source: Reproduced from Yunphuttha, C., Saisa-ard, M., Rangkupan, R., & Chanlek, N. Phys. Chem. Chem. Phys., 2016, 18, 20784–20791. DOI: 10.1039/C6CP02338J,

Cermet (Ni+YSZ)

Strontium-Doped Lanthanum Manganite (LSM)

Perovskites?

The perovskite crystal structure (ABO_3) has a cubic form with a large A-site cation, smaller B-site cation, and oxygen at face centers.

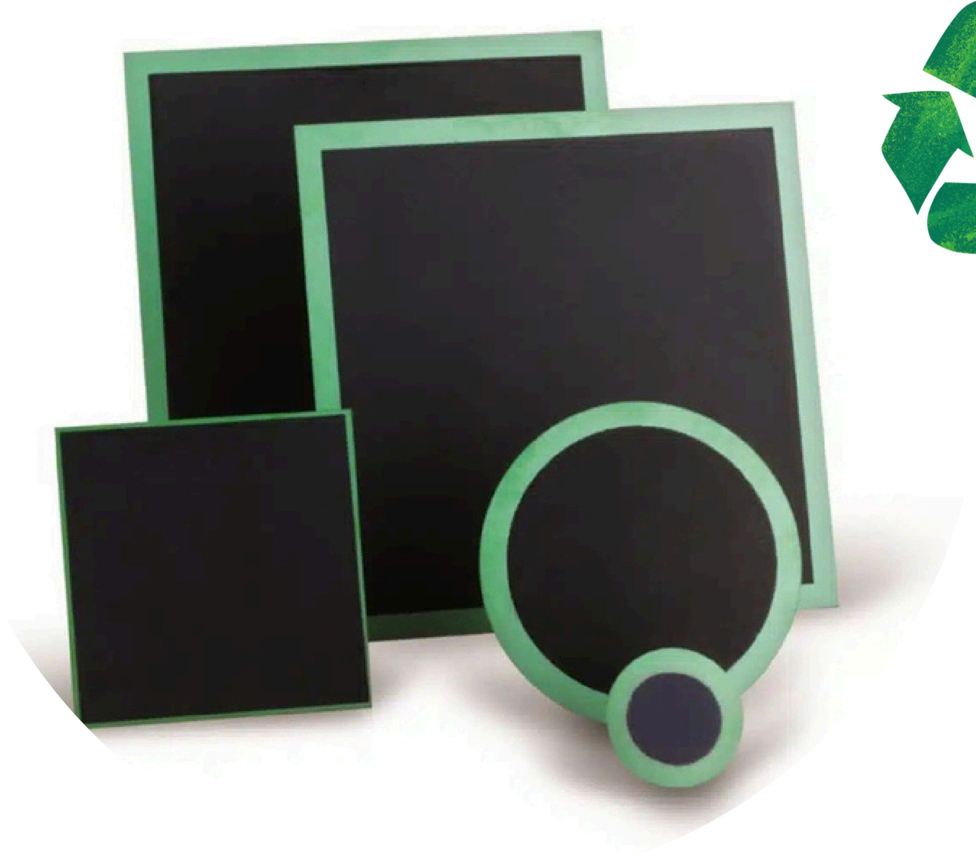
Required Properties of Anode & cathode Materials

Anode Material Properties:
- All key electrolyte properties (chemical & thermal compatibility, etc.)
- High electronic conductivity for electron transport
- Acts as an electrocatalyst for the fuel oxidation reaction

Cathode Material Properties:
- All key electrolyte properties (chemical & thermal compatibility, etc.)
- High electronic conductivity for electron transport
- Acts as an electrocatalyst for the oxygen reduction reaction

Presentation Outline

Materials of Low Temperature SOFCs



4. Materials of LT SOFCs

Why Shift Toward Low-Temperature SOFCs?

Problems associated with HT SOFCs

- Electrode delamination due to thermal expansion mismatch and high-temperature stresses.
- Sealing challenges between cells, bipolar plates, and support hardware.
- Temperatures >800 °C require expensive alloys (e.g., Inconel) for hardware components.

Problems with Low-Temperature SOFCs

Lower temperatures reduce oxide-ion conductivity, necessitating faster conductors or thin electrolyte films to maintain performance.

Presentation Outline

4. Materials of LT SOFCs

Component	Material Options Available
Electrolyte	• **Metal oxide Ceria**: Gadolinium-doped ceria (GDC) & samaria-doped ceria (SDC) • **Perovskites:** Strontium–magnesium-doped lanthanum gallate (LSGM) & bismuth metal vanadium oxide (BIMEVOX)
Cathode	Lanthanum strontium ferrite and lanthanum strontium cobaltite
Anode	• Ni-Ceria & Cu-Ceria • Mixed Ionic Electronic Conductor

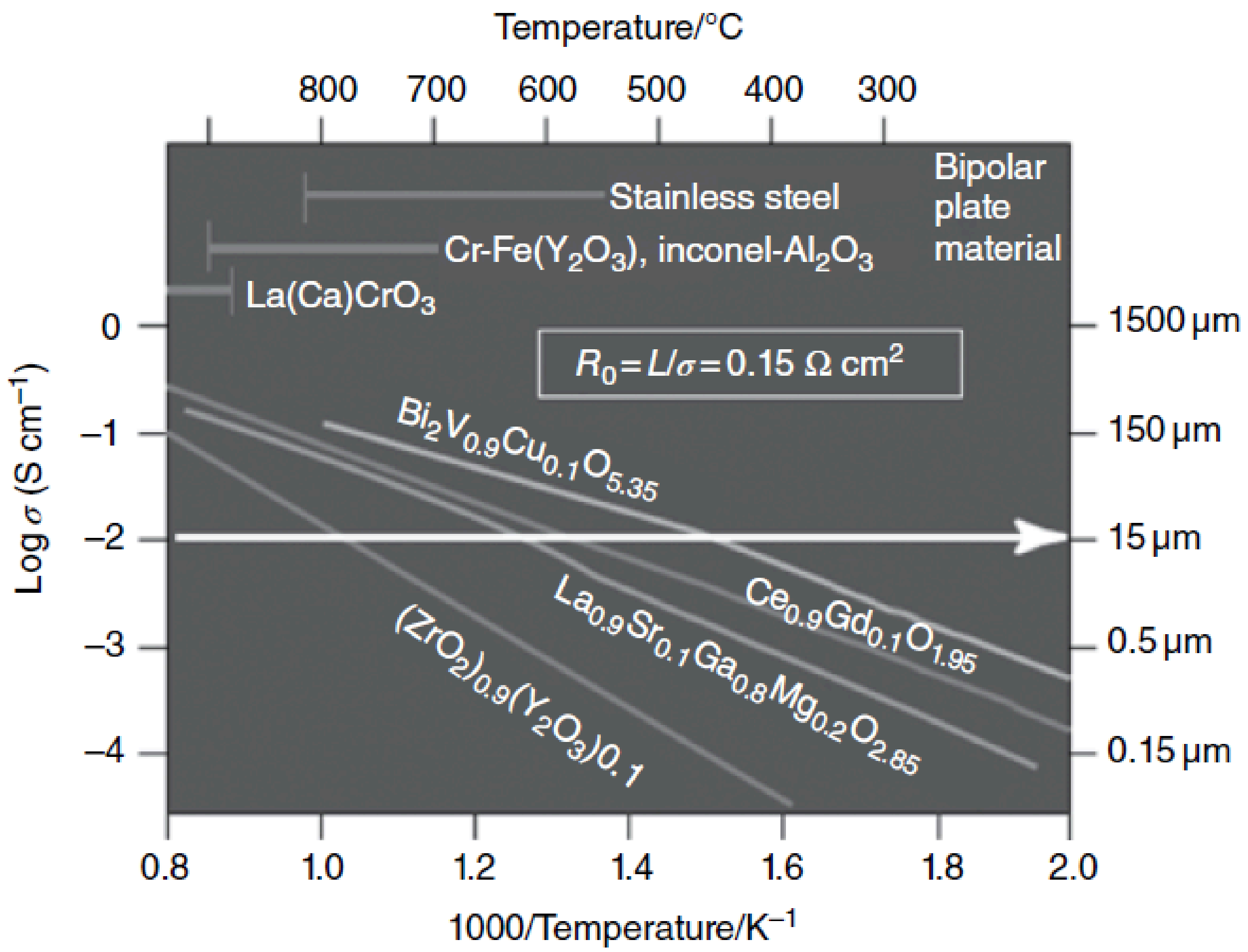


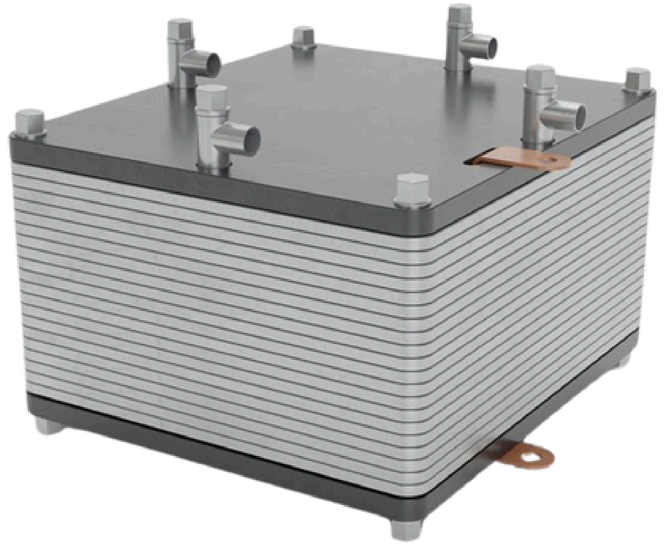
Fig 4.1: Specific conductivity versus reciprocal temperature for selected solid oxide electrolytes

Source: Reproduced from Dicks, A. L., & Rand, D. A. J. Fuel Cell Systems Explained, 3rd ed., Wiley, Chichester, UK, 2018. © John Wiley & Sons Ltd.

Presentation Outline

SOFC vs PEMFC: Comparative Analysis

Performance, Efficiency, and Application Differences



Presentation Outline

Schematic Comparison

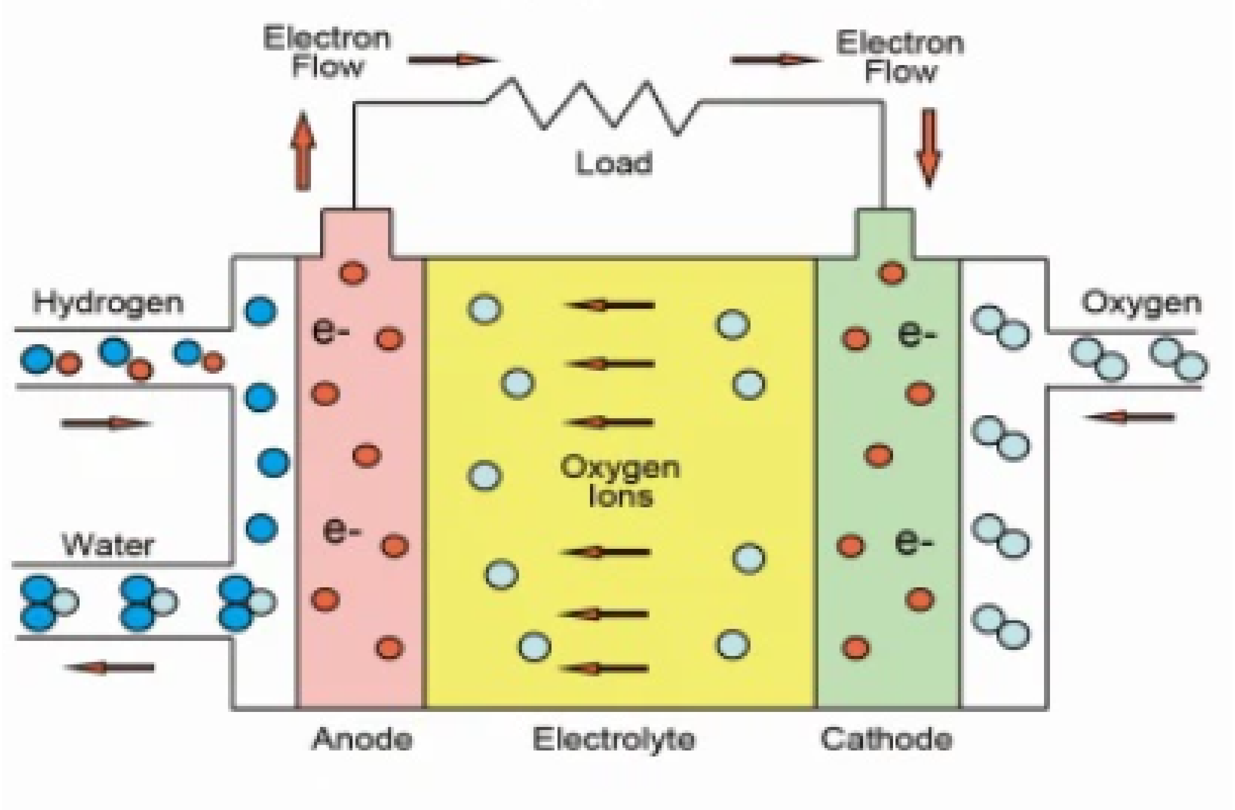


Fig 5.1 : Solid Oxide Fuel Cell (SOFC)

Source: TopTiTech. (n.d.). What is the Solid Oxide Fuel Cell (SOFC)?. Retrieved June 8, 2025, from TopTiTech website: knowledge.electrochem.org/info/what-is-the-solid-oxide-fuel-cell-sofc-91419340.html

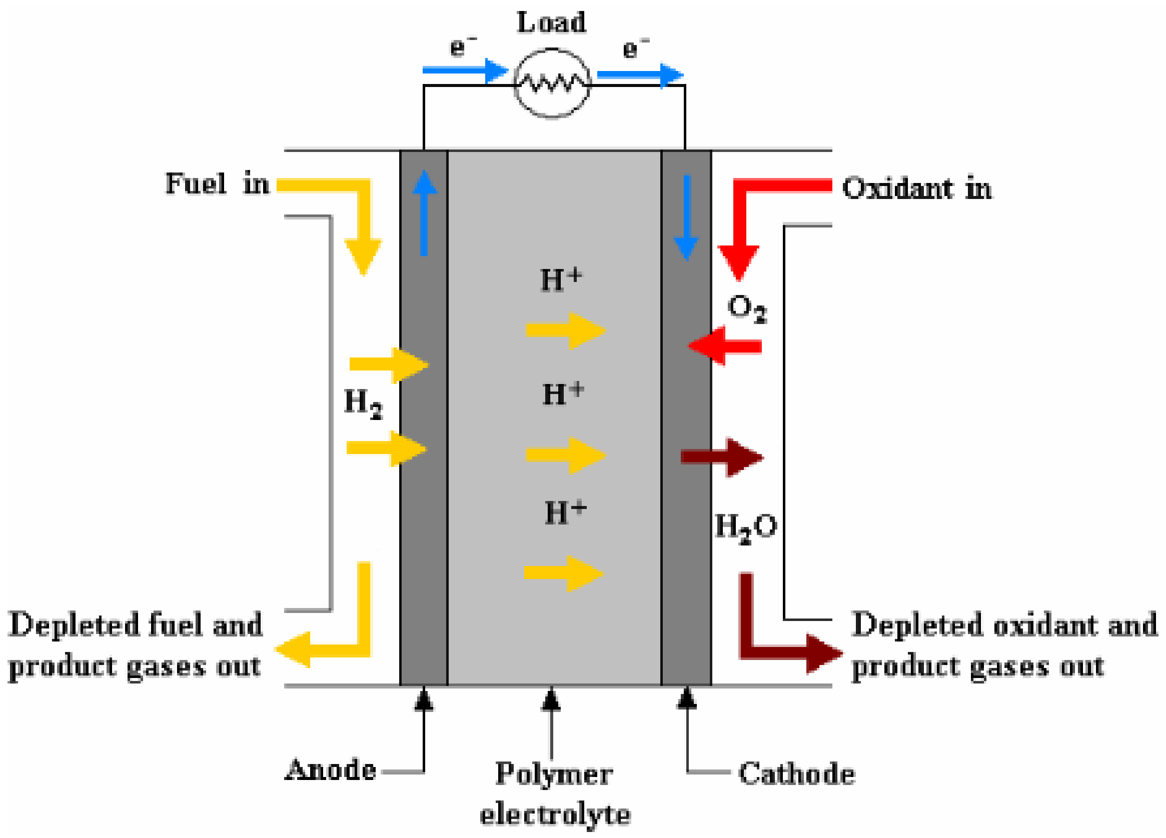


Fig 5.2: Proton Exchange Membrane Fuel cell (PEMFC)

Source: Baker, R., & Zhang, J. (2011, April). Proton Exchange Membrane (PEM) fuel cells. In Electrochemistry Encyclopedia. Institute for Fuel Cell Innovation, National Research Council of Canada. Retrieved June 8, 2025, from Electrochemistry Encyclopedia website: knowledge.electrochem.org/encycl/art-f04-fuel-cells-pem.htm

SOFC

PEMFC

Presentation Outline

Table of Comparison

Parameter	SOFC	PEMFC
Operating Temp	500- 1000 C	80–100 C
Electrolyte	Ceramic (O^{2-})	Nafion (H^+)
Fuel Flexibility	H_2, CH_4, CO	Pure H_2 only
Catalyst	Ni (no Pt needed)	Platinum required
Electrcial Efficiency	40–60%	50–60%
CHP	80–90%	Low (~30%)

Source: Reproduced from Dicks, A. L., & Rand, D. A. J. Fuel Cell Systems Explained, 3rd ed., Wiley, Chichester, UK, 2018. © John Wiley & Sons Ltd.

Source: EG&G Technical Services, Inc. (2004). Fuel Cell Handbook (7th ed.). U.S. Department of Energy.

Presentation Outline

1. Motivation
2. Theory of Operation
   - Cathodic Reactions (ORR)
   - Anodic Reactions (HOR)
   - Overall Reaction
   - Triple Phase Boundary
   - Cell Stack
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   - Electrolytes in HT SOFCs
   - Anionic Conductivity of YSZ
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Effect of Temperature on Power Output

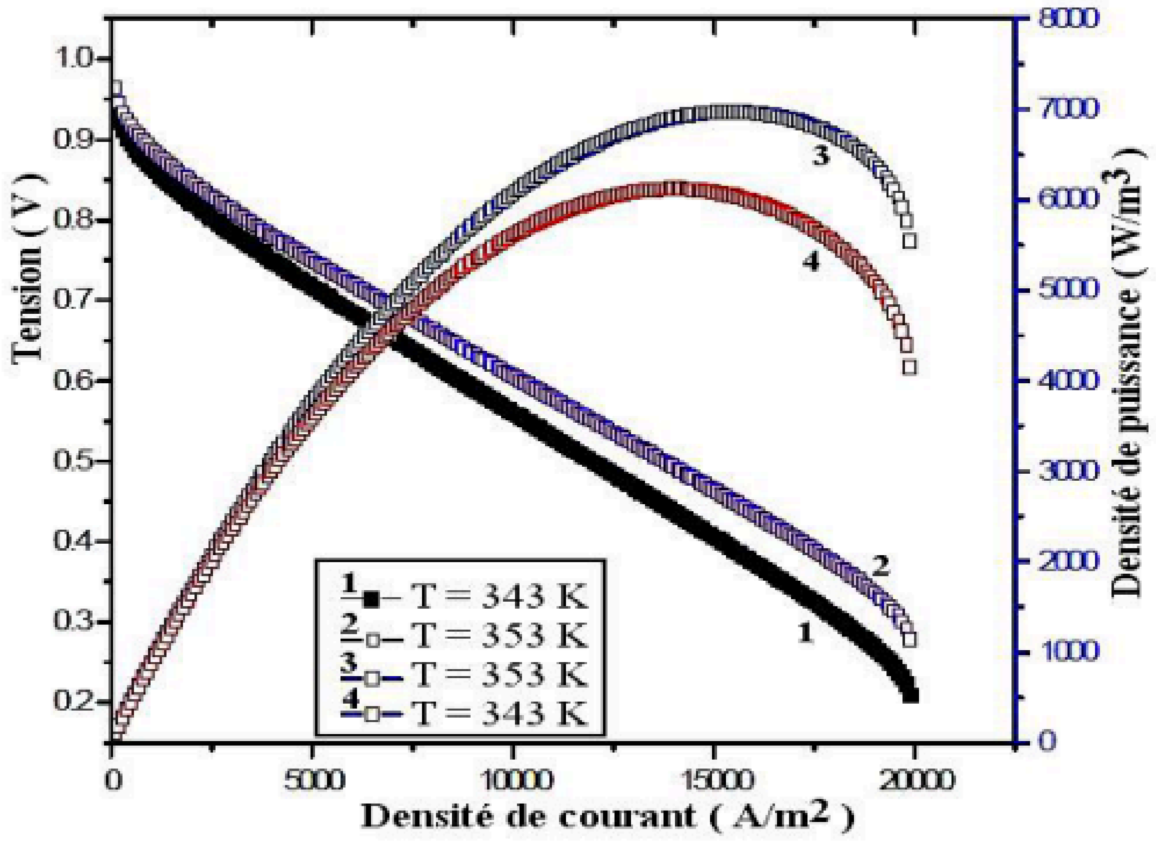

Fig 5.3: Effect of Temperature on PEMFC perofrmance

Source: Reproduced from Belkhiri, Z., Zeroual, M., Ben Moussa, H., & Zitouni, B. (2011). Effect of temperature and water content on the performance of PEM fuel cell. Journal of Renewable Energies, *122–129

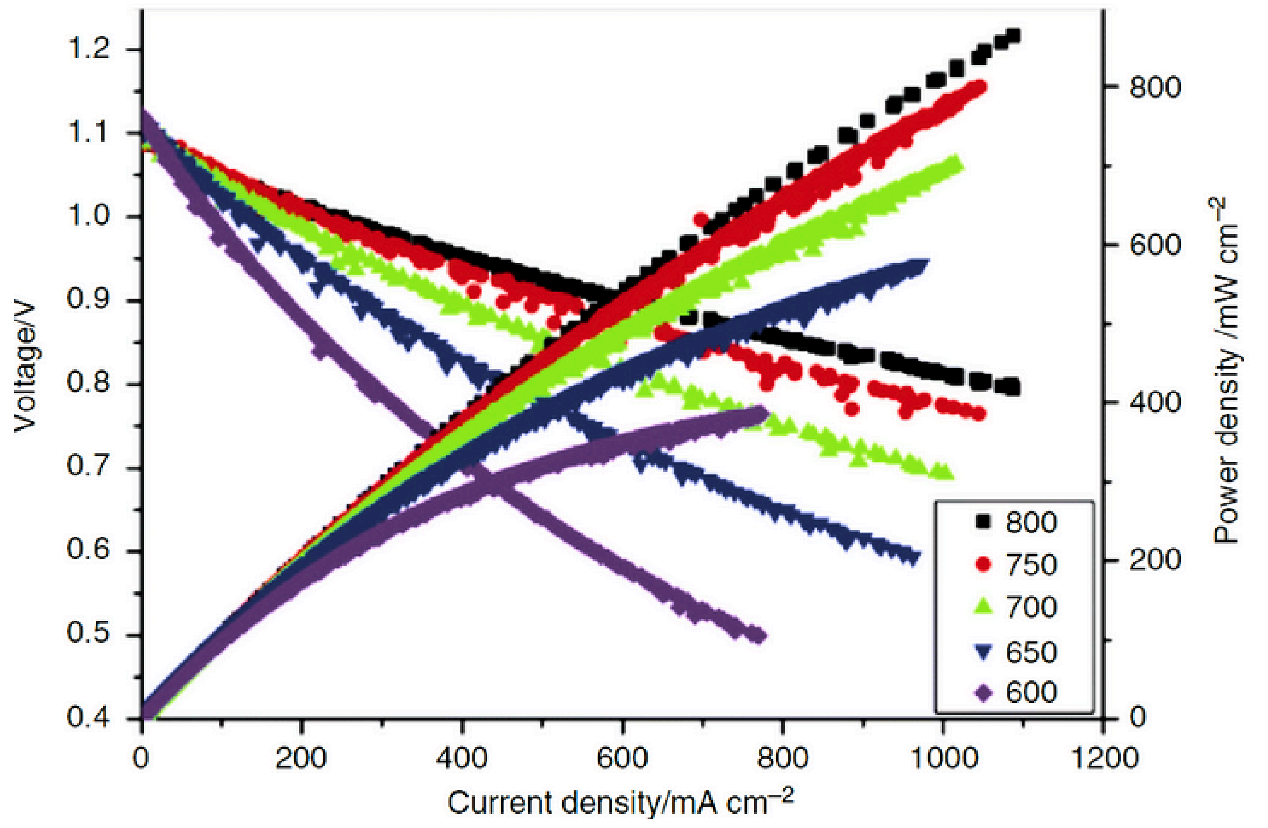

Fig 5.4: Effect of Temperature on SOFC performance

Source: Reproduced from Dicks, A. L., & Rand, D. A. J. Fuel Cell Systems Explained, 3rd ed., Wiley, Chichester, UK, 2018. © John Wiley & Sons Ltd. Used with permission.

- Power increases ~30% from 343K to 353K
- Improved proton conductivity and lower activation loss
- Power density = 650 mW/cm2 @ 353K

- Power density increases >50% from 973K to 1073K
- High temp improves ionic conductivity & kinetics
- Power density = 880 mW/cm2 @ 1073K

Type of Losses

Loss Type	SOFC	PEMFC
Activation Losses	🔽 Low (T↑ kinetics)	🔼 High (slow ORR at low T)
Ohmic Losses	🔽Low at high T	⚠️ Moderate, water-sensitive
Concentration Losses	⚠️ Moderate	⚠️ Moderate (depends on membrane hydration)

Source: EG&G Technical Services, Inc. (2004). Fuel Cell Handbook (7th ed.).
Source: Barbir, F. (2013). PEM Fuel Cells: Theory and Practice.

Polarization Curve: SOFC vs PEMFC

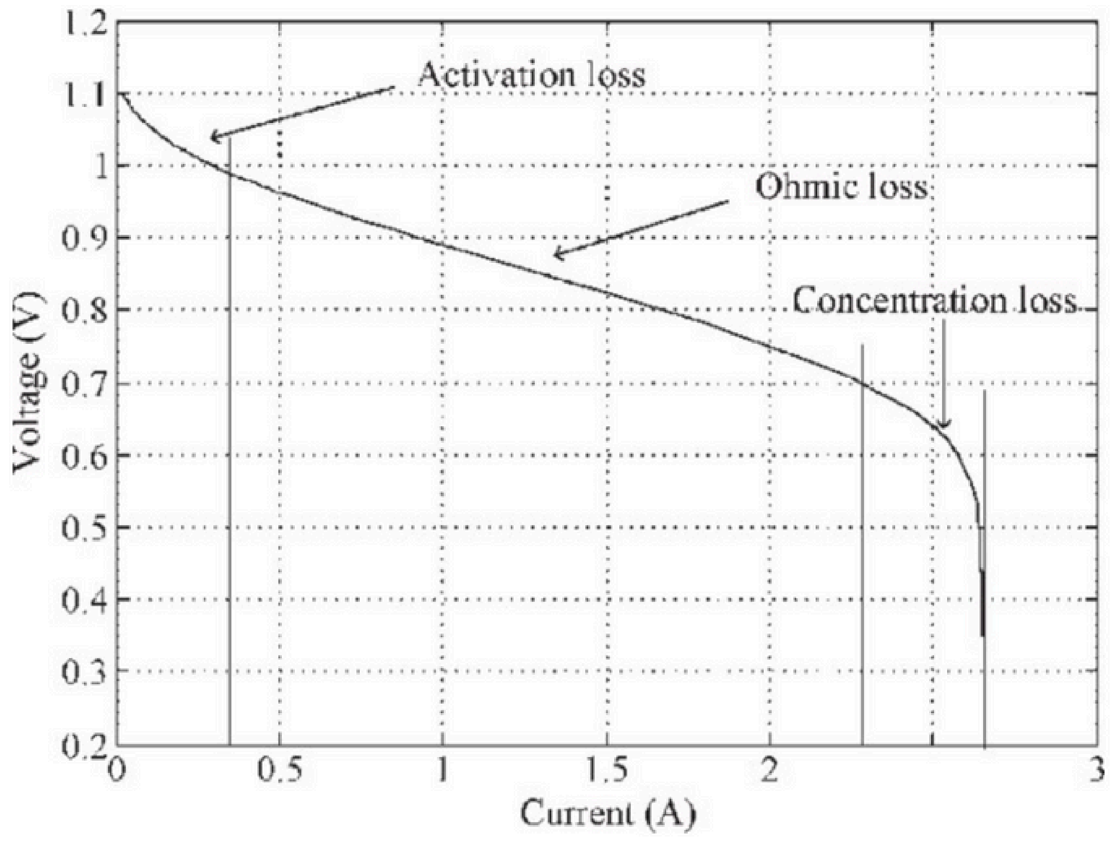

Fig 5.5: V-I polarization curve for SOFC

Source: Reproduced from Belkhiri, Z., Zeroual, M., Ben Moussa, H., & Zitouni, B. (2011). Effect of temperature and water content on the performance of PEM fuel cell. Journal of Renewable Energies, *122–129

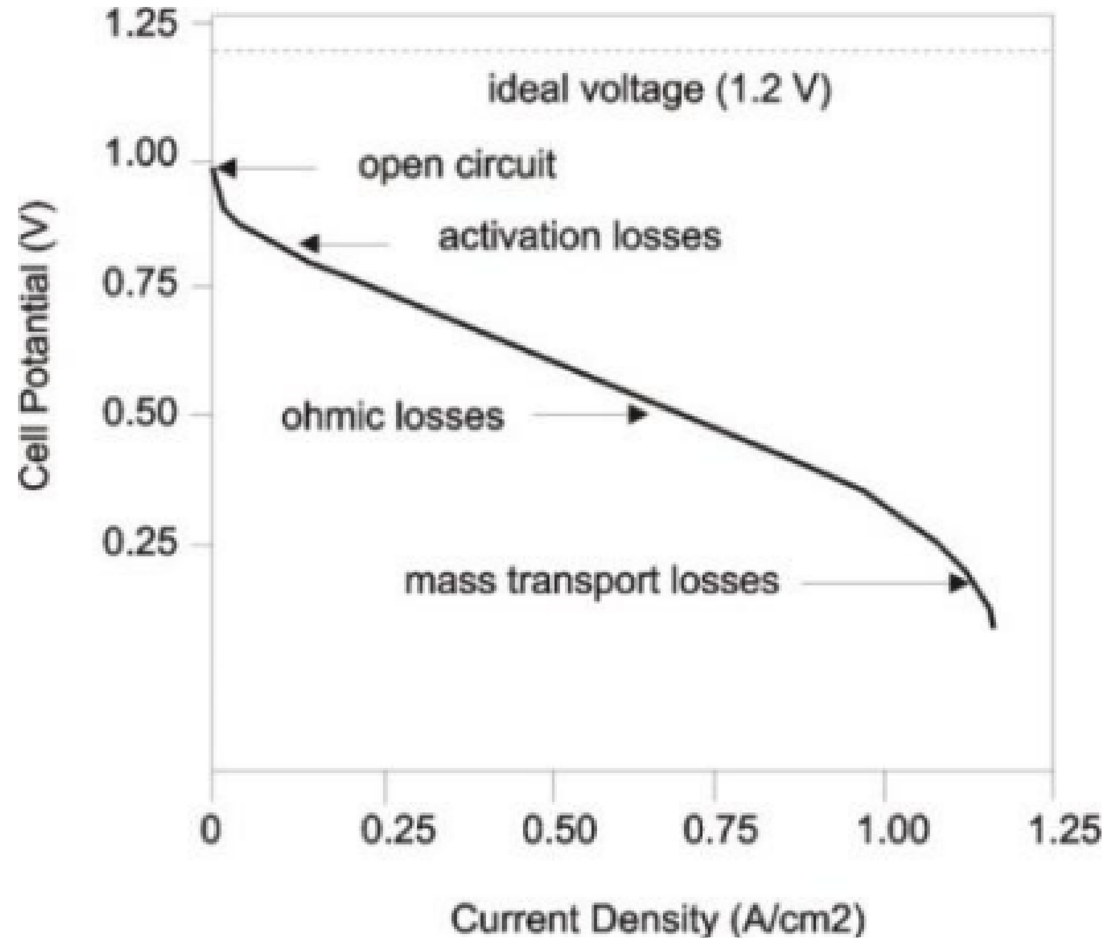

Fig 5.6: V-I polarization curve for PEMFC

Source: Reproduced from Belkhiri, Z., Zeroual, M., Ben Moussa, H., & Zitouni, B. (2011). Effect of temperature and water content on the performance of PEM fuel cell. Journal of Renewable Energies, *122–129

Application Scenarios

Sector	SOFC	PEMFC
Stationary Power	✅ Ideal for CHP	❌ Less efficient for heat
Transportation	❌ Slow start	✅ Quick startup
Remote/off-grid power	✅ Operates on biogas, CH_4	❌ Needs Pure H_2 only

Source: Reproduced from Adler, G., Strohmayer, A., & Hornung, M. (2023). Hydrogen-powered aircraft: Fundamental concepts, key technologies and environmental impact. eTransportation, 17, 100197.

Source: Reproduced from Dicks, A. L., & Rand, D. A. J. Fuel Cell Systems Explained, 3rd ed., Wiley, Chichester, UK, 2018. © John Wiley & Sons Ltd.

Applications of SOFCs in Aviation

Solid Oxide Fuel Cells (SOFCs) are being explored for decarbonizing aviation through integration into propulsion systems and auxiliary power units (APUs). With their high efficiency and ability to reform hydrocarbon fuels onboard, SOFCs offer significant promise for hybrid-electric aircraft and high-endurance flight scenarios

Source: Reproduced from GreyB, Decarbonizing Aviation: Why Executives Must Bet on Power-to-Liquid Technology, 2025, https://www.greyb.com/blog/power-to-liquid-technology/

Applications of SOFCs in Aviation

SOFCs in Hybrid-Electric Propulsion

SOFCs can serve as the primary power source in fuel-cell based electric aircraft. In hybrid concepts, SOFCs provide cruise power while turbines or batteries support takeoff. For example, NASA and industry studies have considered a turboelectric hybrid setup: a gas turbine and an SOFC stack work together, or an SOFC provides cruise power while a battery or turbine provides extra power for takeoff and climb.

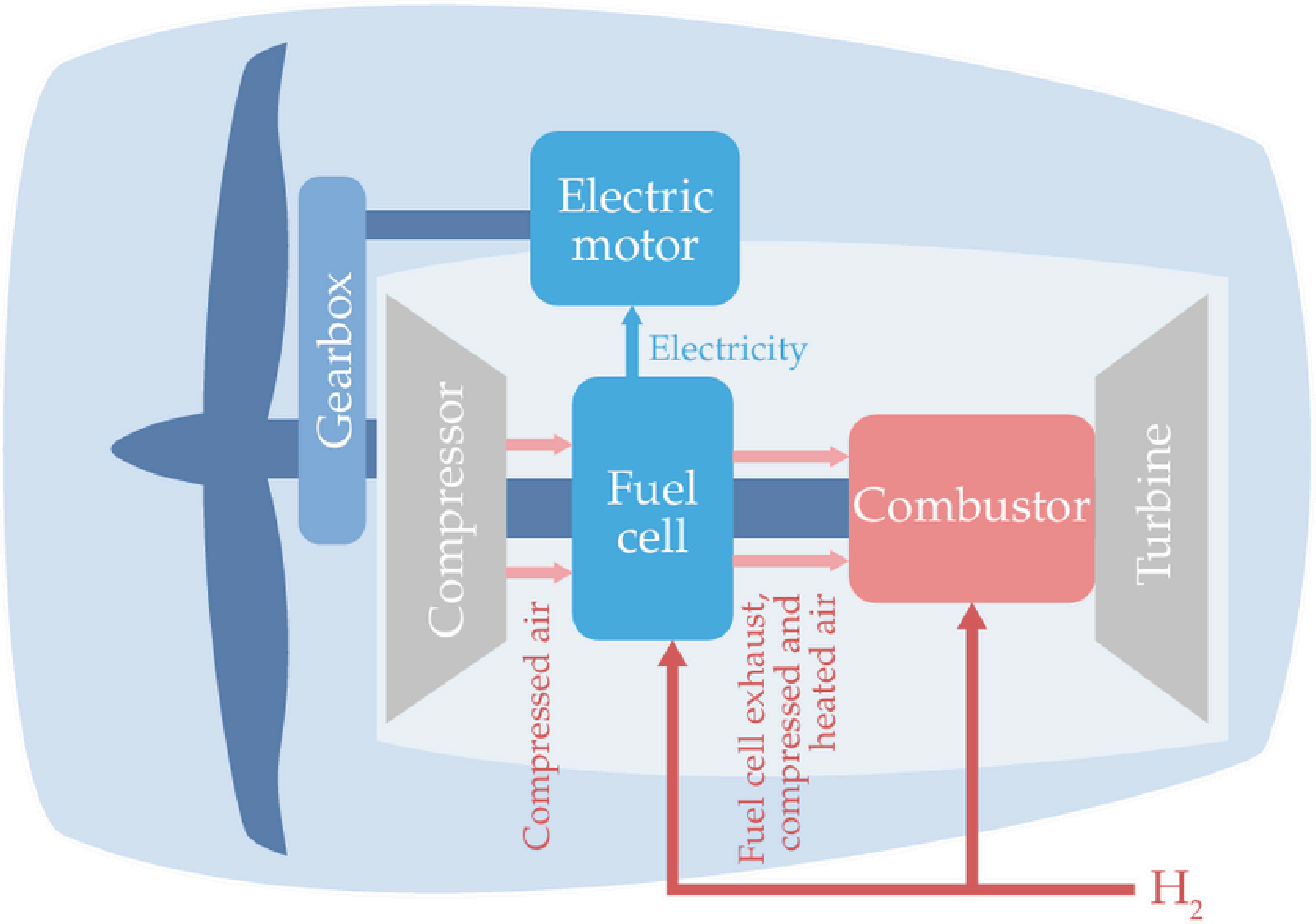

Fig. 6.1: A highly-integrated fuel cell and combustion hybrid propulsion architecture proposed by Bradley and Droney

Source: Reproduced from Adler, G., Strohmayer, A., & Hornung, M., Hydrogen-Powered Aircraft: Fundamental Concepts, Key Technologies and Environmental Impact, eTransportation, 2023, 17, 100197. DOI: 10.1016/j.etran.2023.100197

Applications of SOFCs in Aviation

SOFCs in Hybrid-Electric Propulsion

The high efficiency of SOFCs is especially attractive for cruise operation, where efficiency translates to less fuel burn and thus potentially reduced total weight.

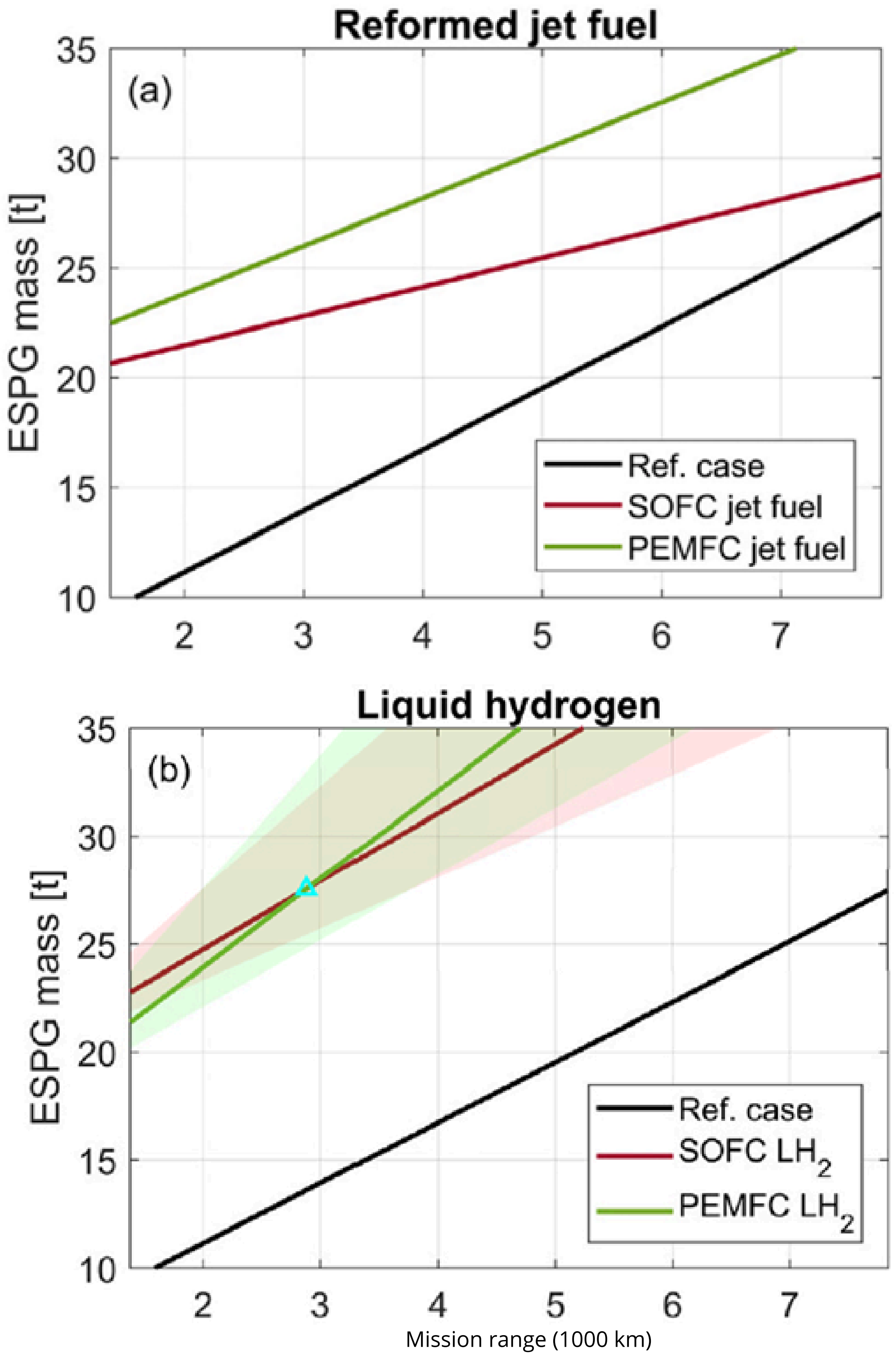

Fig. 6.2: ESPG mass comparison for different technologies and storage solutions in the future scenario. The black-coloured line refers to the Reference case (737 MAX fed by jet fuel). Coloured areas refer to different values of gravimetric energy density of the storage solutions, in particular η g =25–50%forLH 2 case.

Source: Reproduced from Peyrani, G., Marocco, P., Gandiglio, M., Biga, R., & Santarelli, M., Solid oxide fuel cells for aviation: A comparative evaluation against alternative propulsion technologies, eTransportation, 2025, 24, 100408. DOI: 10.1016/j.etran.2025.100408

Presentation Outline

Applications of SOFCs in Aviation

SOFCs as Auxiliary Power Units (APUs)

APUs on current aircraft are inefficient gas turbines. SOFC-based APUs can operate more efficiently at partial load, reduce fuel consumption, and generate less noise and pollution. Their ability to use hydrogen or jet fuel makes them flexible for various operational contexts (FCHEA.org; Himansu et al., 2006).

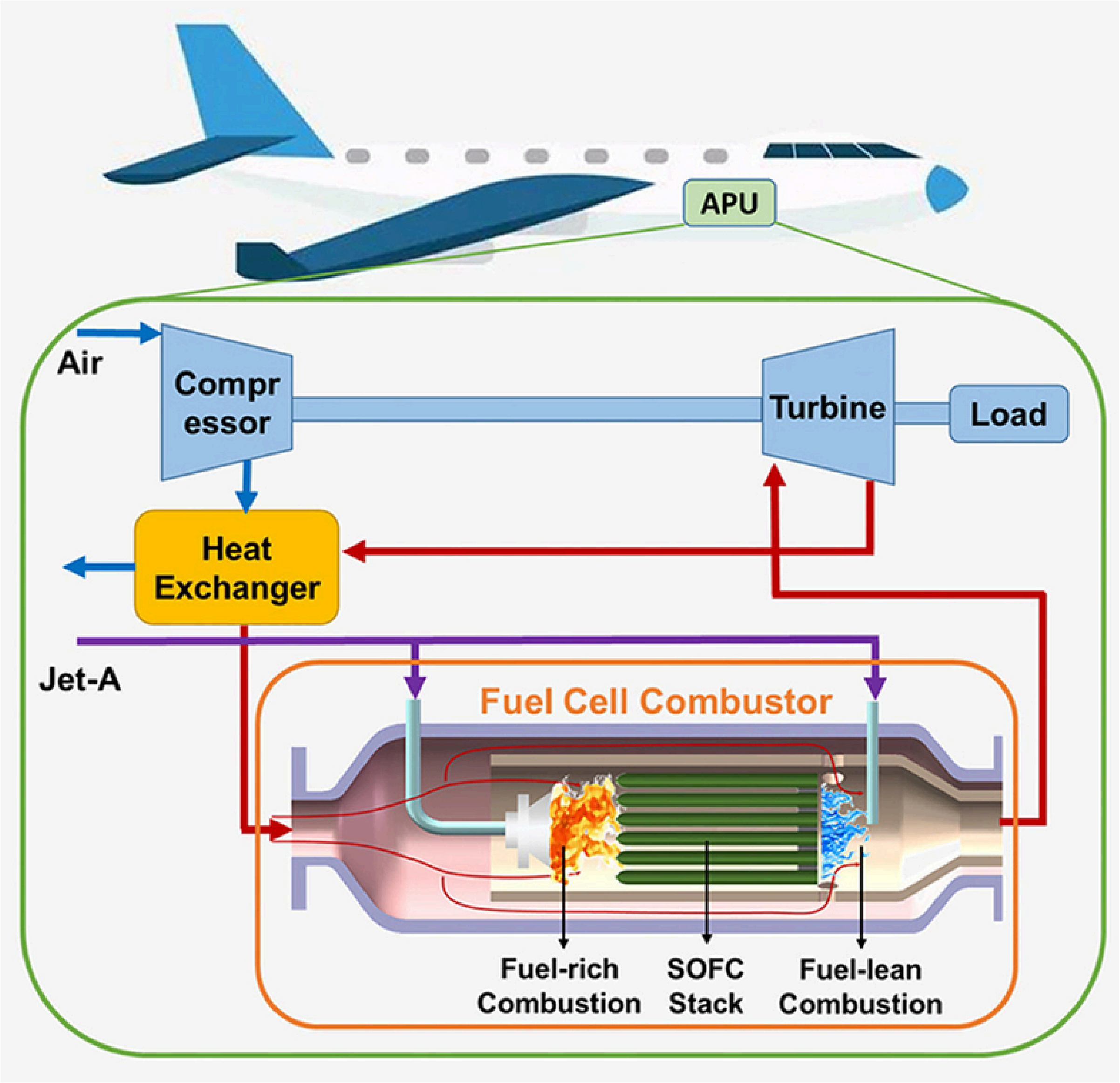

Fig. 6.3: SOFC-Gas Turbine Hybrid Architecture for Aircraft Auxiliary Power Unit"

Source: Reproduced from Yu, J., Gong, X., Zhang, Z., & Zhang, C., A hybrid solid oxide fuel cell and gas turbine system using jet fuel for aircraft auxiliary power unit application, International Journal of Hydrogen Energy, 2023, 48, 7134–7148. DOI: 10.1016/j.ijhydene.2022.10.276

Presentation Outline

Applications of SOFCs in Aviation

FlyECO FUTURE ENABLING TECHNOLOGIES FOR HYDROGEN-POWERED ELECTRIFIED AERO ENGINE FOR CLEAN AVIATION

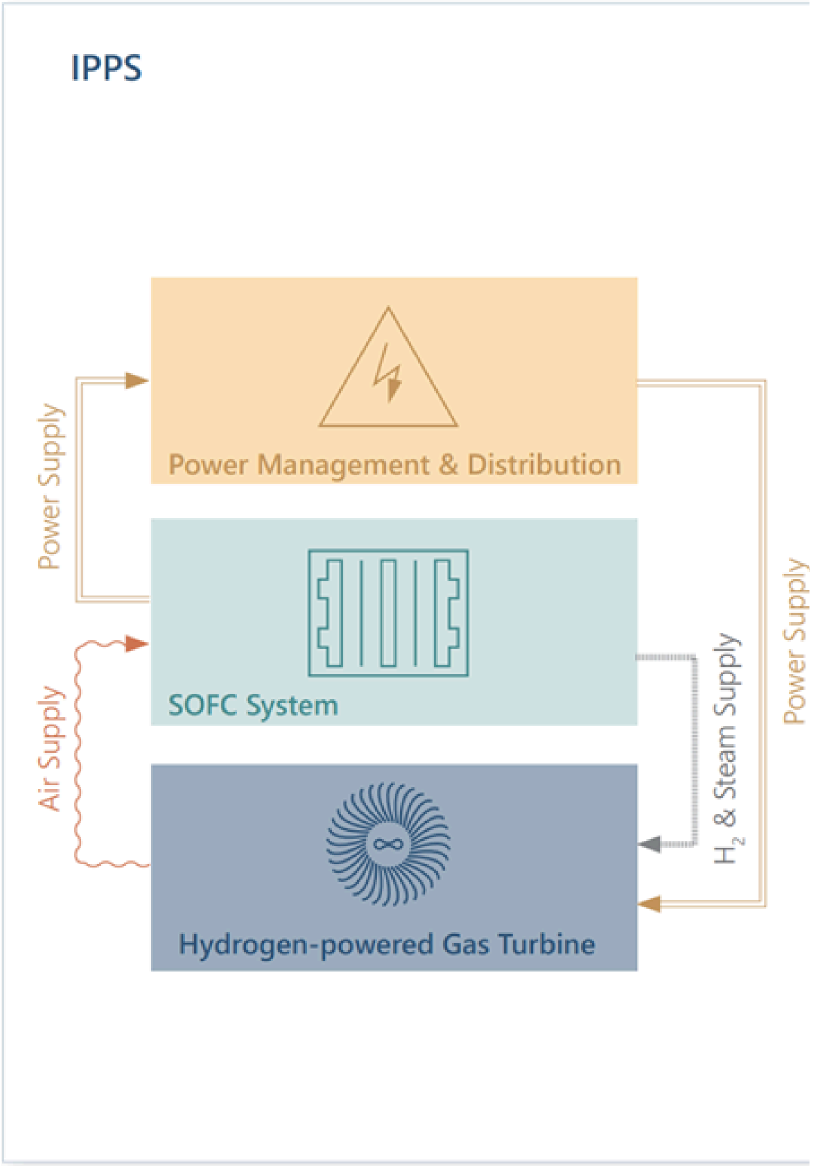

Fig. 6.4: Integrated Power and Propulsion System (IPPS) Concept Architecture

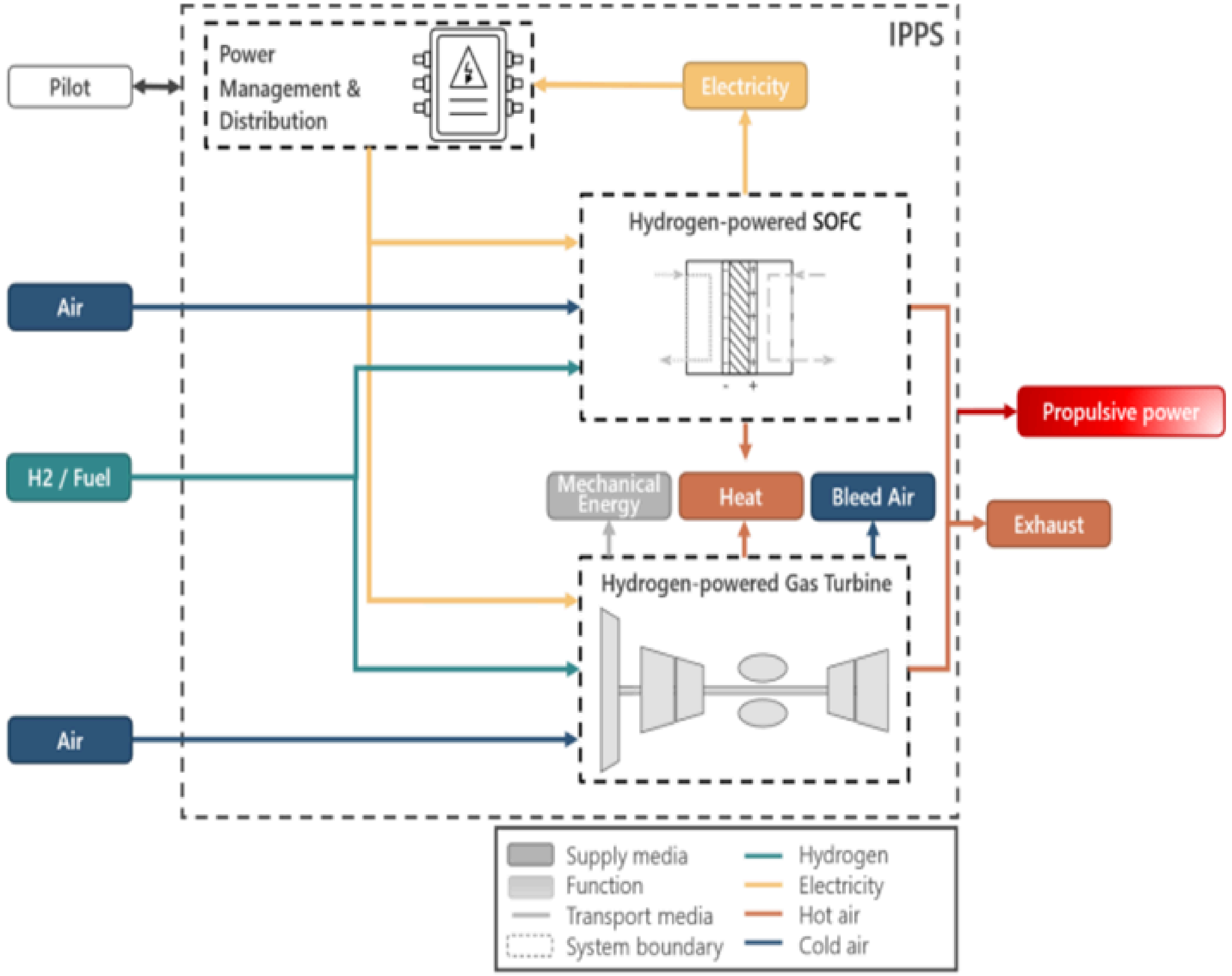

Fig. 6.5: Hydrogen-Based IPPS Functional Flow Diagram

FlyECO Project. (2024). Future enabling technologies for hydrogen-powered electrified aero engine for clean aviation [Project Poster]. European Union Horizon Europe Programme, Grant No. 101138488. Retrieved from https://www.flyeco-european-project.eu

7. Conclusion

SOFCs enable efficient, high-temperature electrochemical energy conversion through oxygen ion transport across a solid electrolyte. The triple phase boundary—where gas, ion conductor, and electron conductor meet—is essential for sustaining this process. Compared to PEM fuel cells, SOFCs offer superior fuel flexibility and thermal efficiency, albeit with slower startup and higher material demands. With proven high-temperature materials like YSZ and LSM, and growing research on low-temperature alternatives, SOFCs are poised to complement PEMFCs. Especially in aviation, their potential shines in long-range and HALE applications, while auxiliary power units present a viable near-term opportunity. As material and system advances continue, SOFCs may become key enablers in a decarbonized future.

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Thank you !