HOSSAIN, M., FAISAL, N., PRATHURU, A., KURUSHINA, V., RAJENDRAN, V., CAI, Q., HORRI, B. and KUMAR, A. 2024. Introduction to hydrogen and hydrogen economy: opportunities and challenges. Keynote presented at the 4th International conference on sustainable energy, environment and green technologies 2024 (ICSEEGT 2024), 9-10 August 2024, Jaipur, India: [virtual event].

Introduction to hydrogen and hydrogen economy: opportunities and challenges.

HOSSAIN, M., FAISAL, N., PRATHURU, A., KURUSHINA, V., RAJENDRAN, V., CAI, Q., HORRI, B. and KUMAR, A.

2024

Introduction to Hydrogen & Hydrogen Economy: Opportunities and Challenges

Mamdud Hossain, Nadimul Faisal, Anil Prathuru, Victoria Kurushina, Vinooth Rajendran

School of Engineering, Robert Gordon University, Aberdeen, Scotland

Qiong Cai, Bahman Horri, Ajith Kumar

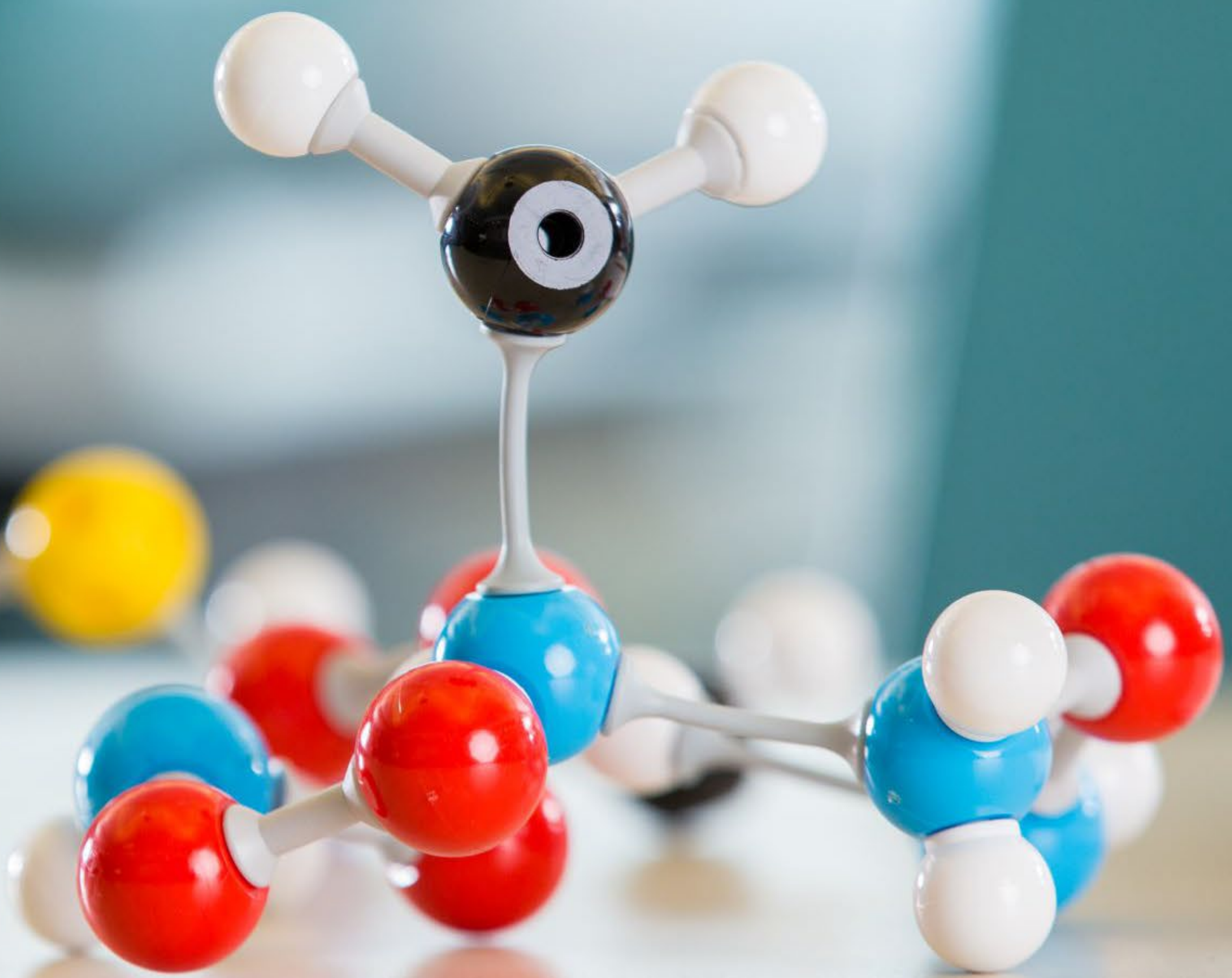
School of Chemical and Process Engineering, University of Surrey, UK

ROBERT GORDON UNIVERSITY ABERDEEN

Robert Gordon University provides industry led undergraduate and postgraduate courses leading to highly relevant awards and degrees

Student number: 16000 UG 10000, PG 6000
1st in Scotland and 2nd in the UK in the Graduate Employment Rate measure (QS Graduate Employability Rankings 2022)

Hydrogen is a versatile energy career and is key to decarbonize a number of difficult sectors



Hydrogen can used in a number of ways to achieve energy transition

- Electricity generation: distributed, remote, stand alone, backup (using fuel cell)
- Transports: car, bus, truck, forklift, train, ship (using fuel cell)
- Chargers: mobile, laptop (using fuel cell)
- Domestic heating and electricity (using fuel cell)
- Domestic heating and cooking (blended with methane, combustion)
- Truck / digger: (blended with diesel)
- Energy storage and load balance for intermittent renewable energy: (production, storage and use)

What is H_2?

- H_2 is a gas. It is colorless, odourless, tasteless, non-toxic and highly combustible
- Its density – 0.08375 kg/m^3 (comparison: air 1.18 kg/m^3)
- The most abundant chemical element – contribute 75% of the mass of the universe
- But here is the problem – it is very scare as a gas, vast numbers of hydrogen atoms are contained in water, natural gas, plants etc.

Hydrogen is not available as a gas in nature

- It has to be produced from different sources:
  - Natural gas
  - Water splitting
  - Biomass

ROBERT GORDON UNIVERSITY ABERDEEN

Hydrogen and colour coding

Grey H2	• Produced by fossil fuels (natural gas, coal) • Emits CO2 in the process
Blue H2	• Produced by fossil fuels in combination with CCS • Reduces CO2 emissions in the process
Turquoise H2	• Produced by pyrolysis of fossil fuels • Solid carbon as by-product
Green H2	• Produced from water splitting in an electrolyser using electricity generated from renewable sources
Purple H2	• Produced from water splitting in an electrolyser using electricity from nuclear power plants
Yellow H2	• Produced from water splitting in an electrolyser using grid electricity

Green Hydrogen Production : water + renewable electricity and electrolyser

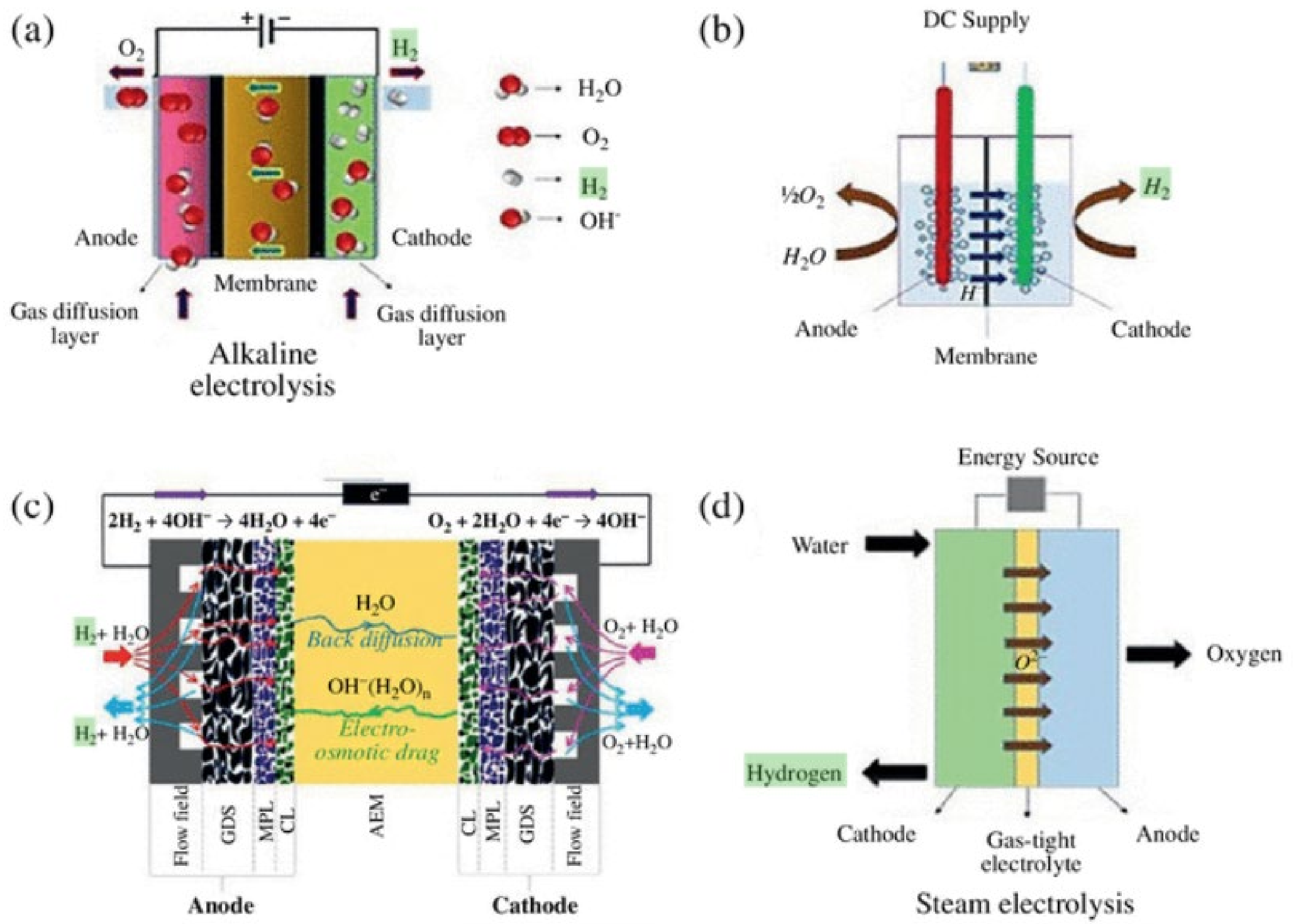
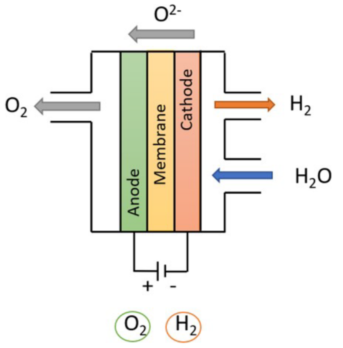
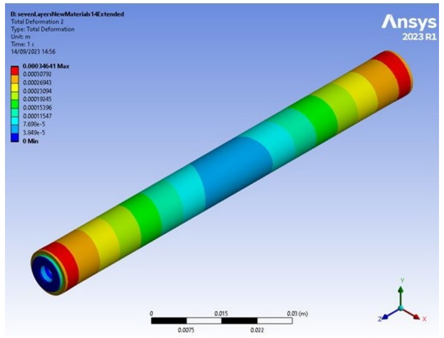
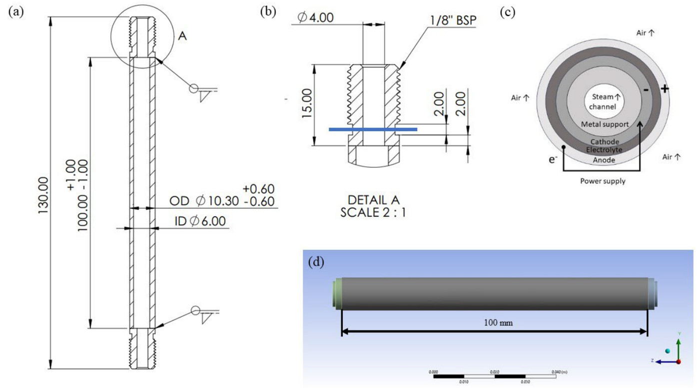


Fig. 1 Schematic of different electrolyzer systems (A) Alkaline electrolyzer, (B) PEM electrolyzer, (C) AEM electrolyzer [6], (D) Steam electrolyzer or high-temperature electrolyzer.

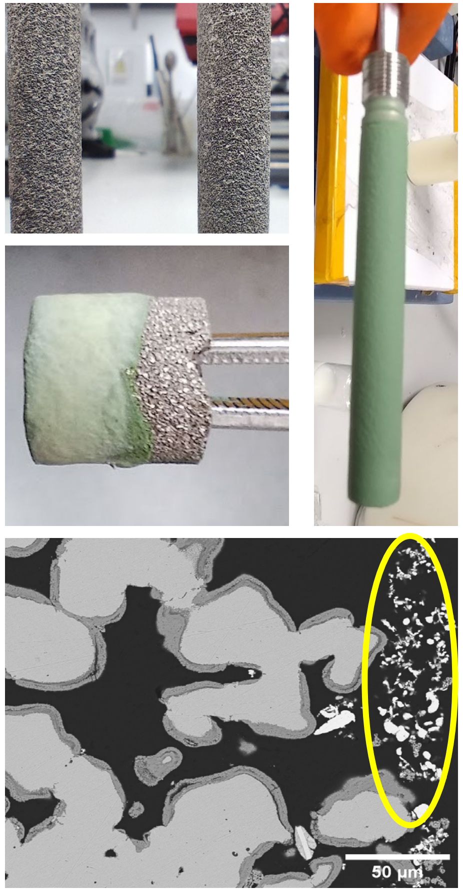
WP1: Design & Optimisation



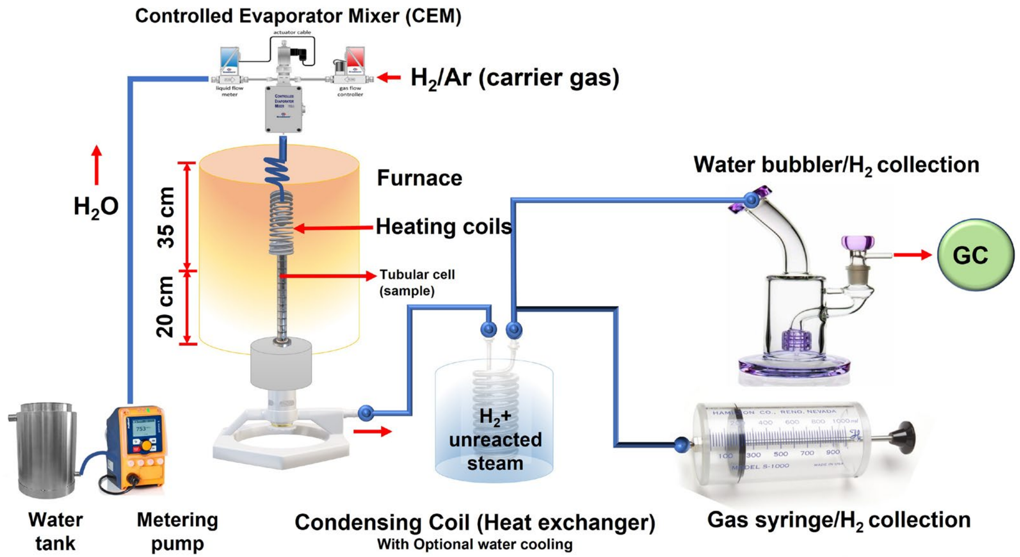




WP2: Materials & Manufacturing



WP3: Electrolyser Cell & Module



EP/W033178/1

Scalable metamaterial thermally sprayed catalyst coatings for nuclear reactor high temperature solid oxide steam electrolysis (METASIS)

Robert Gordon University Researchers

- Dr Victoria Kurushina, PDRF
- Vinooth Rajendran, RA

Investigators

- Prof Nadimul Faisal
- Prof Mamdud Hossain
- Dr Anil Prathuru

University of Surrey Researcher

- Dr Ajith Soman, PDRF

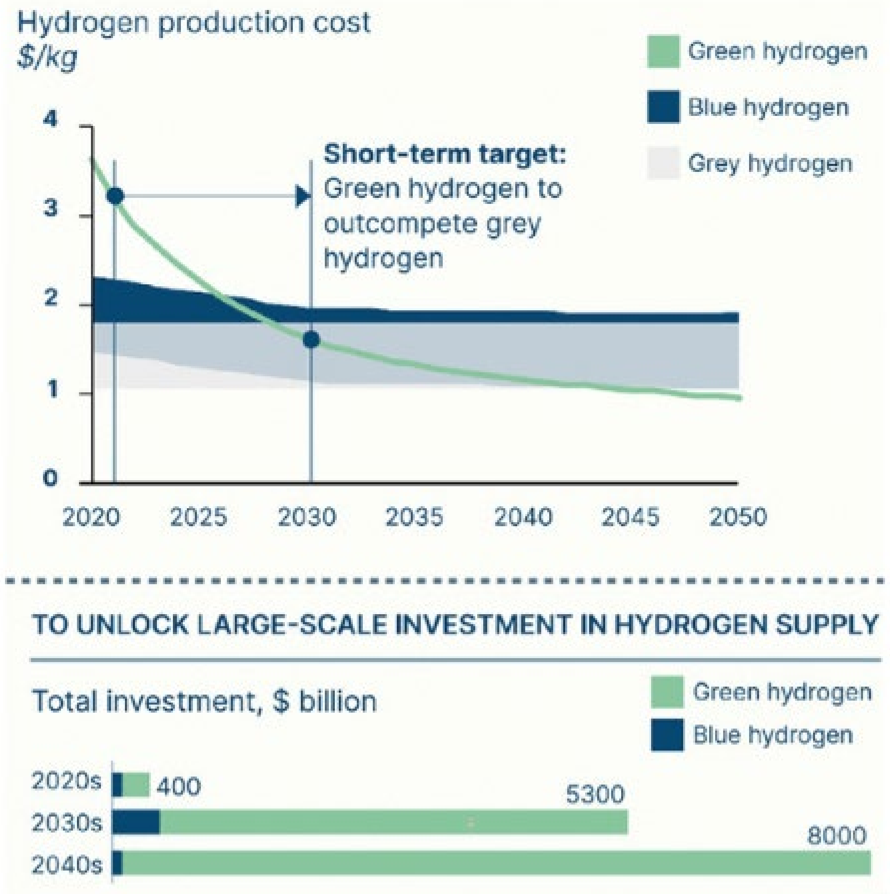
Investigators

- Dr Bahman Horri
- Dr Qiong Cai

ROBERT GORDON UNIVERSITY ABERDEEN
UKRI Engineering and Physical Sciences Research Council
UNIVERSITY OF SURREY
UKRI Science and Technology Facilities Council
NATIONAL NUCLEAR LABORATORY

Green H2 cost is high across the whole value chain

Green H2 prices needed to be reduced to 1 $/kg from 4 $ /kg (below the production cost of grey H2)



Several challenges hampering green hydrogen taking bigger role

- Technical challenges
  - Green hydrogen production from water electrolysis: 60-70% (1/3rd of electricity wasted in heat)
  - Hydrogen compression and storage: 10% loss
  - Electricity production in fuel cell: 40-55%
  - Electricity to Hydrogen to Electricity: 38%
  - Work with excess Renewable Energy to improve efficiency.

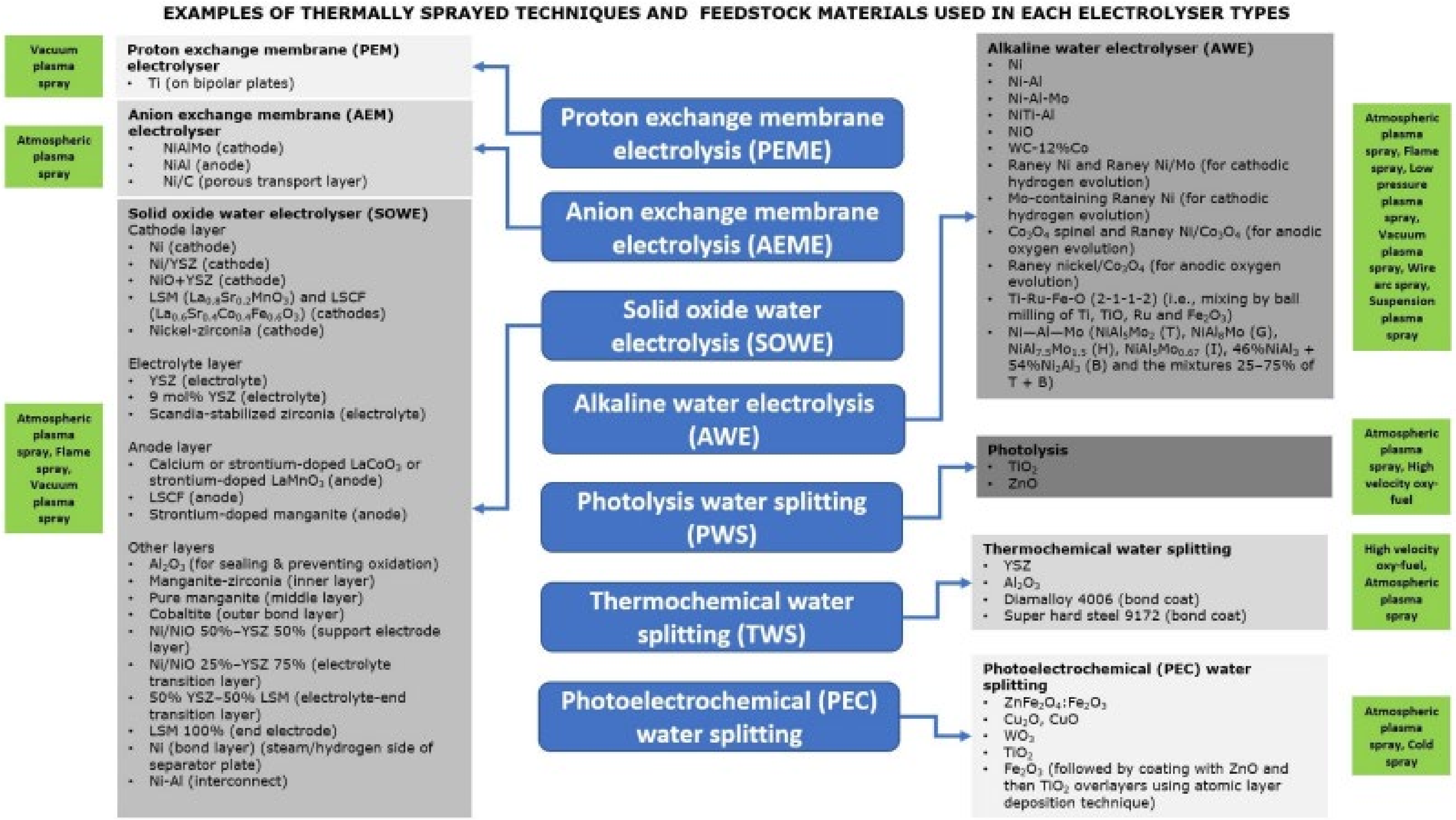
Only 1% of world water is fresh water

- 1 kg H2 production needs more than 20 kg of water (stochiometric, 1 kg H2 uses 9 kg water)
- Seawater desalination using reverse osmosis is expensive: (50% efficient and 1 m^3 water costs 0.7-2.5 $).

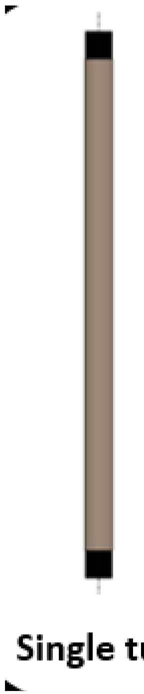
Electricity accounts for 50-70% of the production cost of Hydrogen

- Renewables are intermittent and thus it is difficult to optimise green hydrogen production systems
- The price of fuel cells and electrolysers depends on the use of Nobel materials such as platinum.
- Platinum is scare material, considerably high cost and resource is concentrated and short supply.
- Geopolitical problem due to the location of mines in social or politically unstable locations.

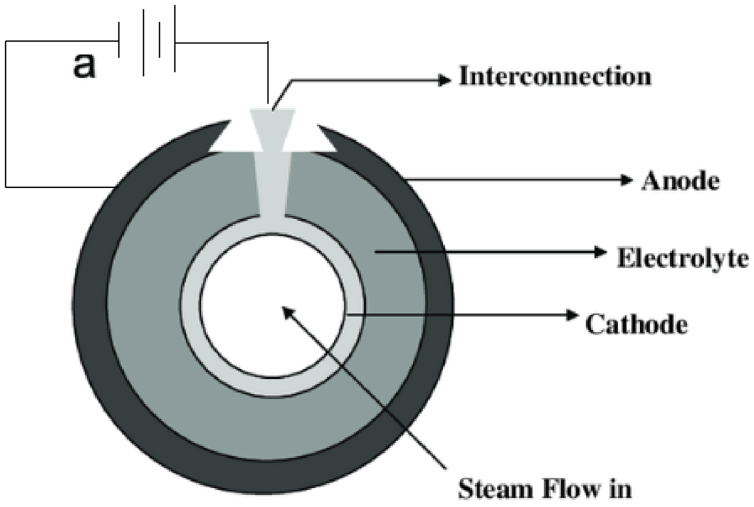
Electrolyser materials are expensive rare and degrades quickly

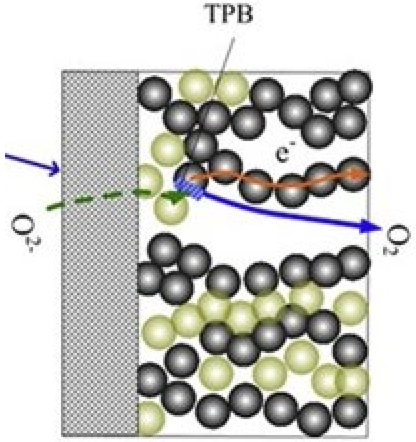


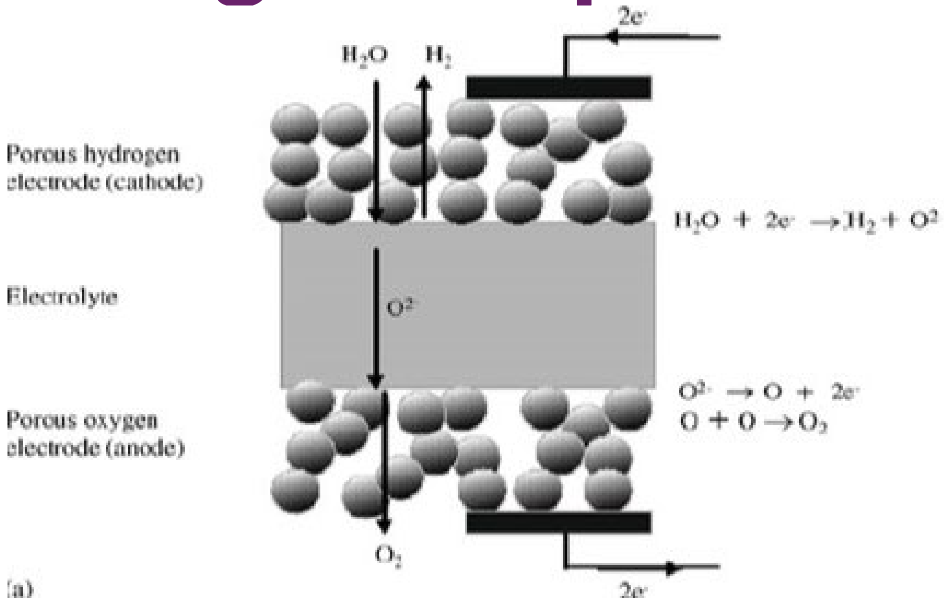
Solid Oxide Electrolyser Working Principle



Single tube







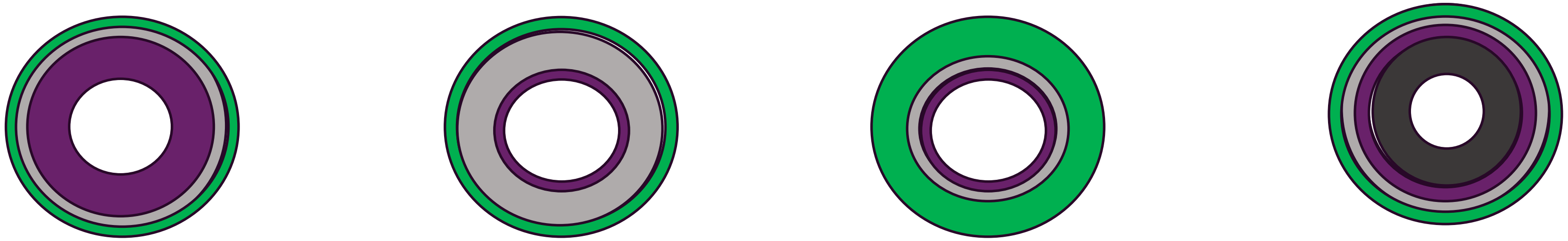
Cathode: $H_2O + 2e^- = H_2 + O^{2-}$
Anode: $O^{2-} = ½\ O_2 + 2e^-$
Overall: $H_2O = H_2 + ½\ O_2$

Cathode: Ni-YSZ porous, 500 µm
Electrolyte: YSZ dense, ion conductor, 20 µm
Anode: LSM-YSZ, 50 µm
Length: 0.4m

SOEL Cell designs

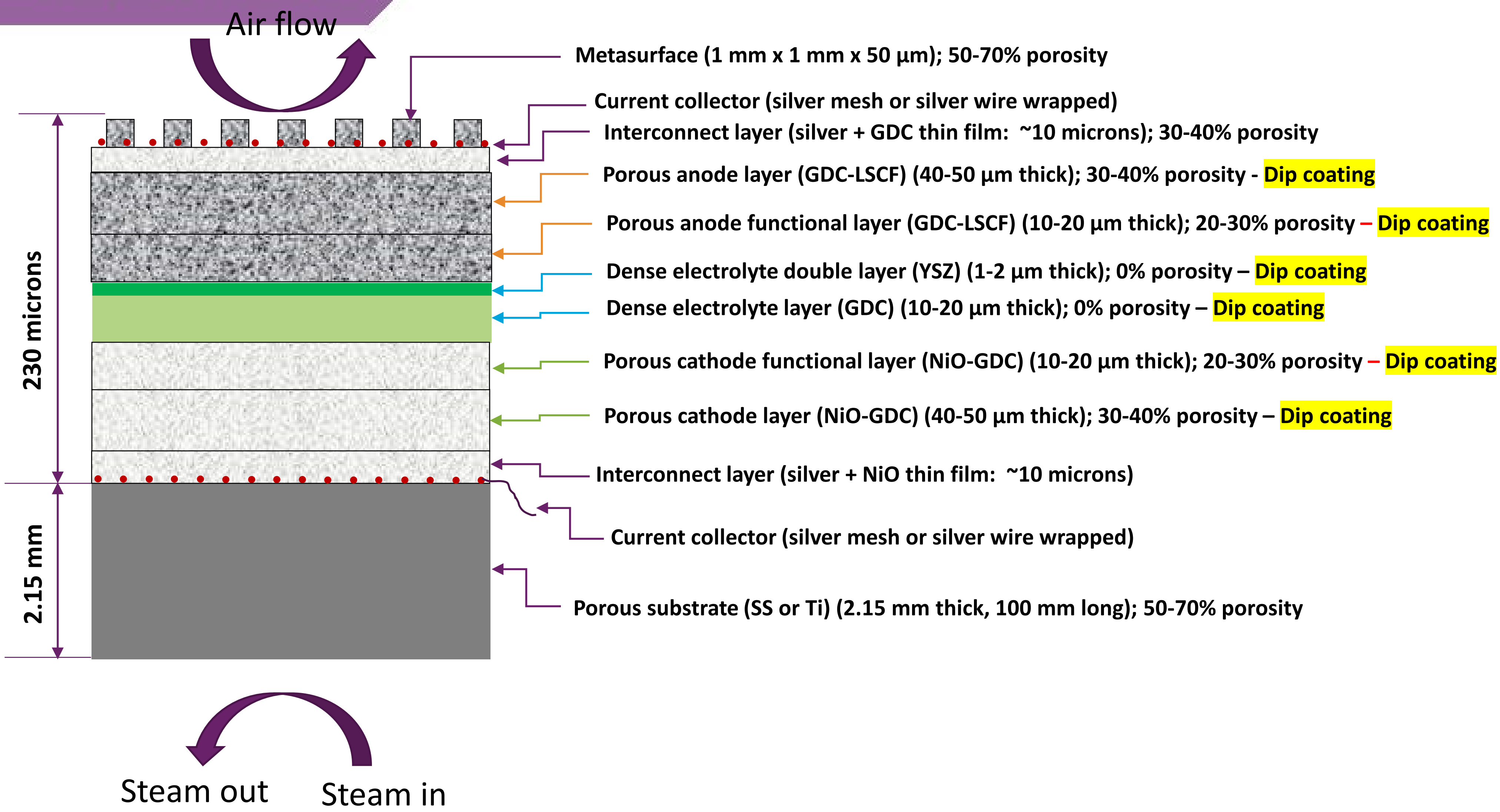
Support type

Cathode-supported cell	Electrolyte-supported cell	Anode-supported cell	Metal-supported cell

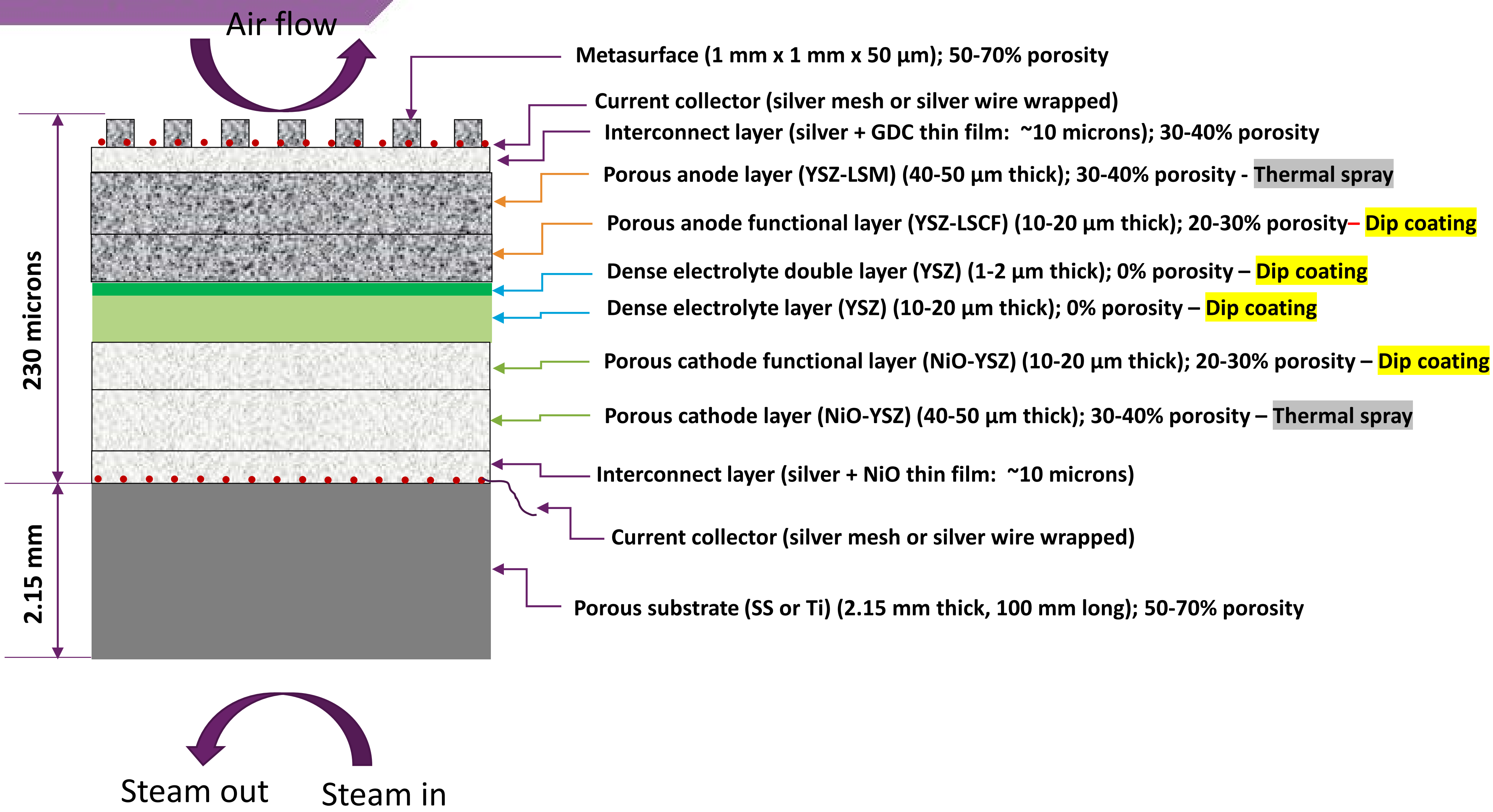


Thick cathode	Thick electrolyte	Thick anode	Thick metal
+ Good cell stability during electrochemical process - High resistance for polarization	+ High mechanical robustness + Good gas diffusion properties - High ohmic losses in the thickened electrolyte layer	+ Lower operating temperature + Low ohmic resistance + Lower costs of material + Considered to be easier for fabrication - Lower mechanical reliability	+ High mechanical stability - Energy losses in the supporting porous metal layer

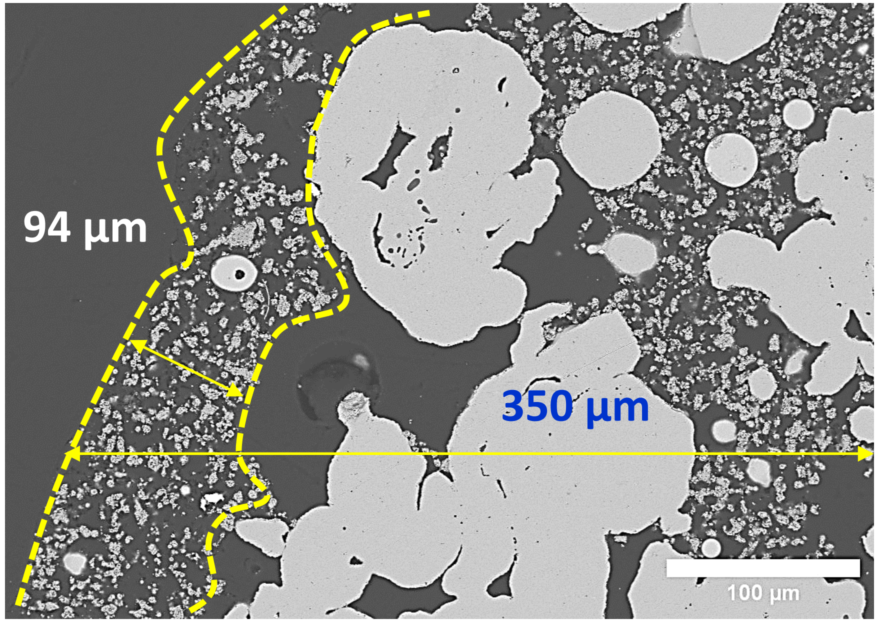
Plan A – Dip coating



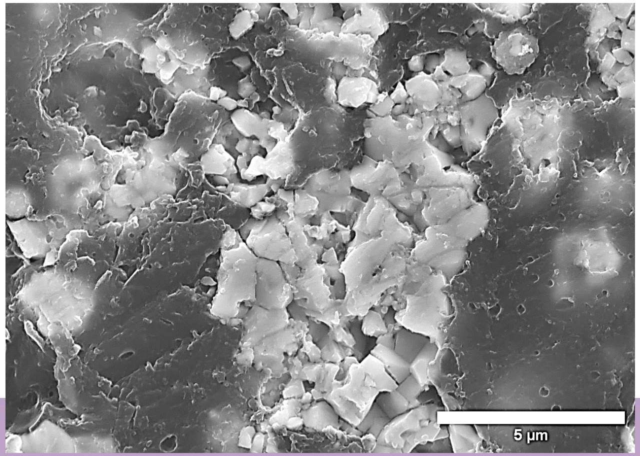
Plan B - Dip coating and thermal spray



Cross sectional morphology of tubular SS supported NiO-YSZ (60:40 wt%) cathode layer



Back Scattered Electron image & Elemental mapping of SS/Ag/NiO-YSZ coating



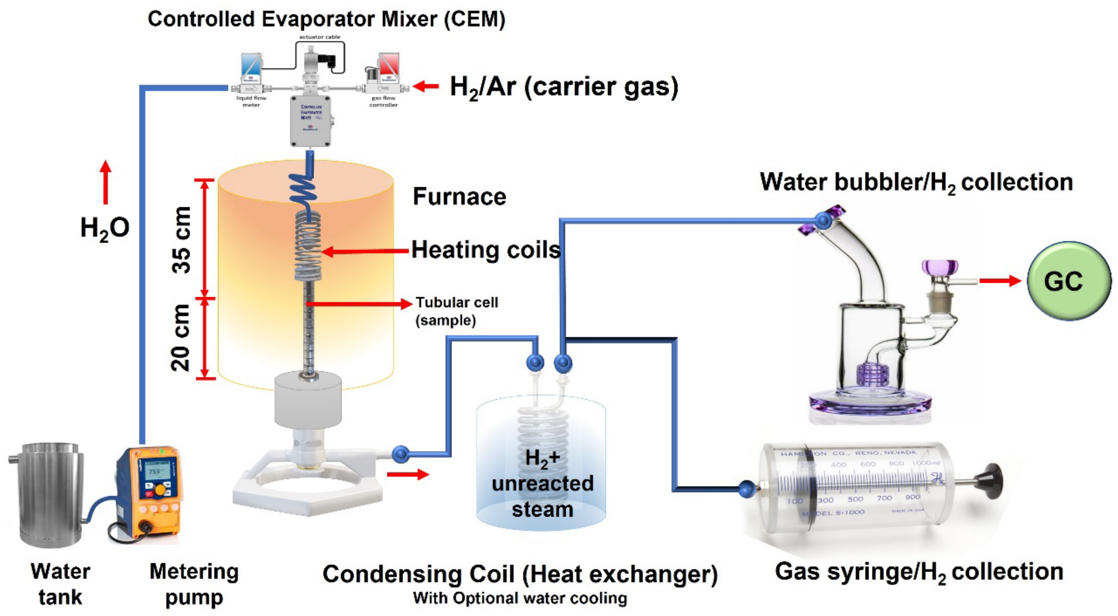
Combinations	Area %
Steel	36.48
Mounting Resin	43.08
ZrO2	1.53
2NiO	11.42
Ag	0.60
Ni rich	6.89

Experimental Tests

Our targets

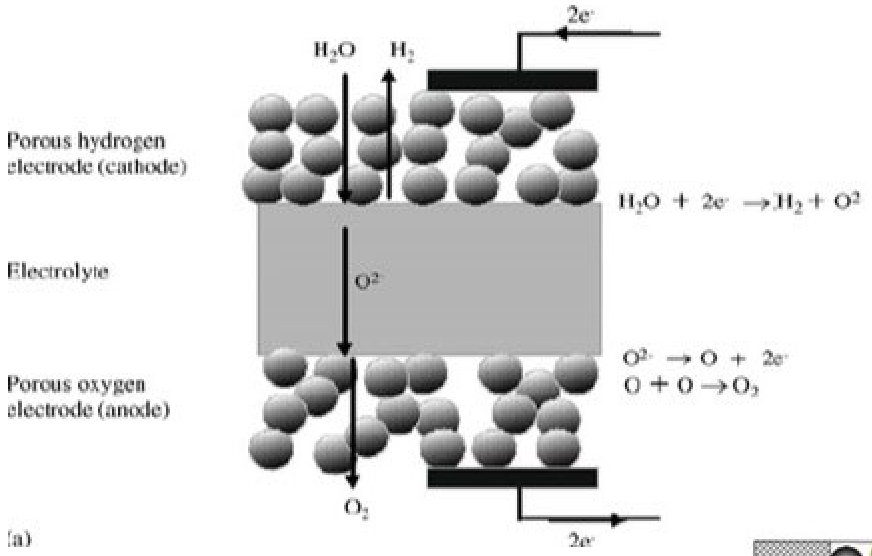
- Improving efficiency
- Lower cost
- Durability
- Scalability & system integration

Material characterization tests to be performed in the Robert Gordon University



High temperature tests to be performed in the University of Surrey

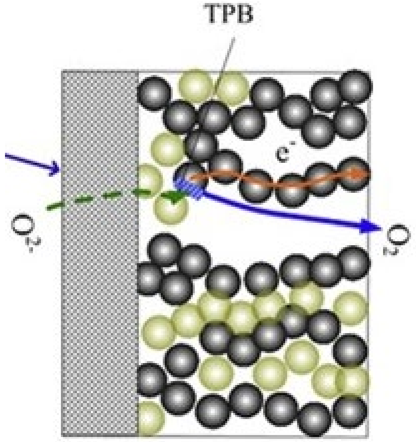
Electrochemistry



$$V = V^{rev} + \eta_{ohm} + \eta_{conc,cath} + \eta_{conc,an} + \eta_{act,cath} + \eta_{act,an}$$

$$\eta_{conc,an} = \frac{RT}{4F}\ln[\frac{C_{O_2}^{TPB}T}{C_{O_2,ref}T_{ref}}]$$

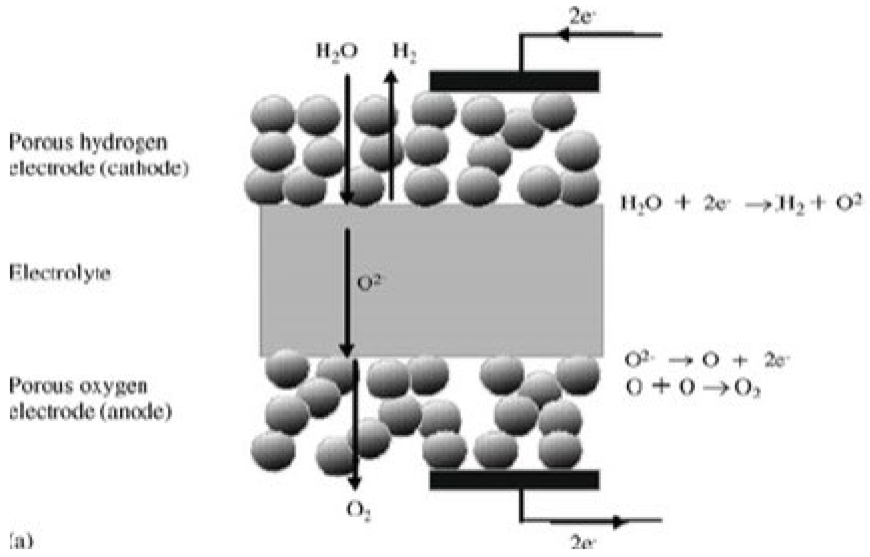
$$i = i_{o,an}\left(\frac{C_{O_2}^{TPB}}{C_{O_2,ref}}\right)^{\gamma_{O_2}} \left\{\exp\left(\frac{2\alpha F\eta_{act,an}}{RT}\right) - \exp\left(-\frac{2(1-\alpha)F\eta}{RT}\right.\right.$$



CFD modelling

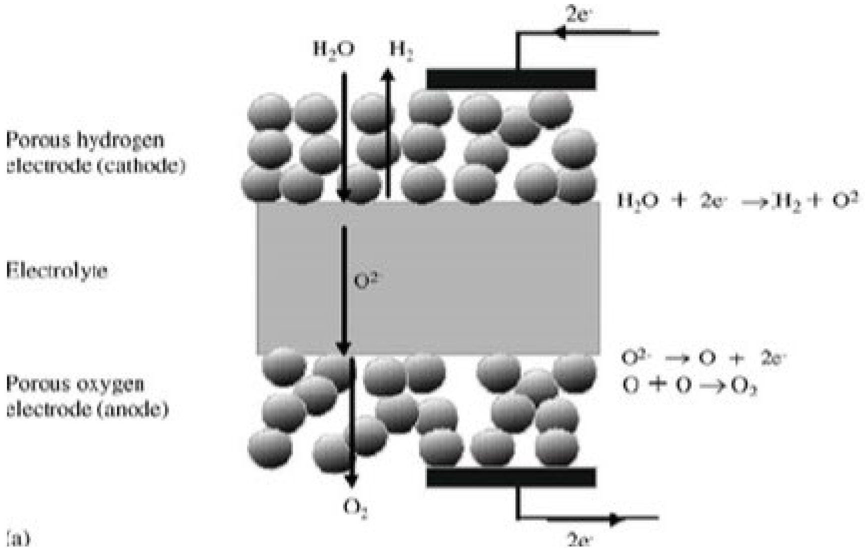
- Continuity and momentum
- Heat transfer
- Species concertation (i.e. H_2O, H_2, O_2)
- Species source term:

$$S_{H_2} = i/2F$$



CFD modelling

- **Electron and ionic transport:**

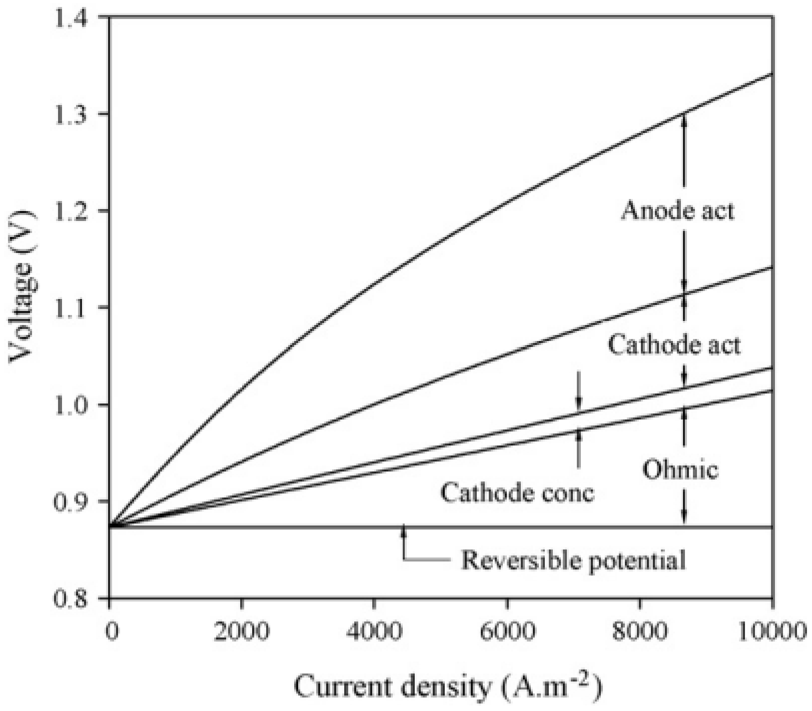


$$\Delta.(\sigma\Delta\phi) = 0$$

$$\sigma_{ion} = \frac{100}{0.3685 + 0.002838e^{\frac{10300}{T}}}$$

- **Gas phase diffusivity through porous electrodes – multicomponent diffusivity, or dilute gas and Knudsen diffusivity**

An I-V curve is an effective way to explain SOEL performance



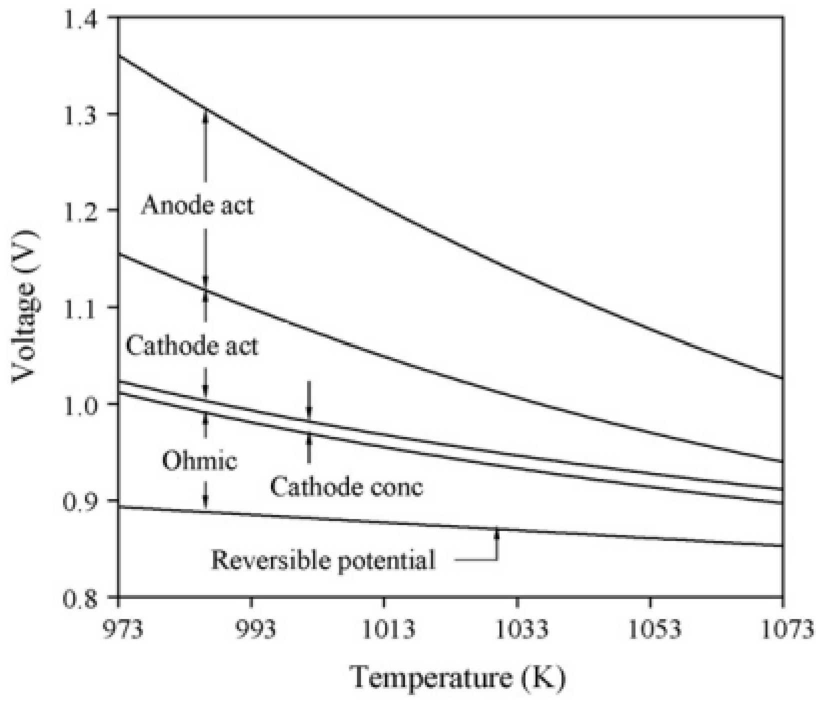
J. Udagawa et al. (2007) - doi:10.1016/j.jpowsour.2008.01.069

Higher current density, higher production rate of H_2, but higher voltage i.e. higher power required

Main losses: Anode activation loss, then cathode activation loss and ohmic loss

Operating at 1023 K

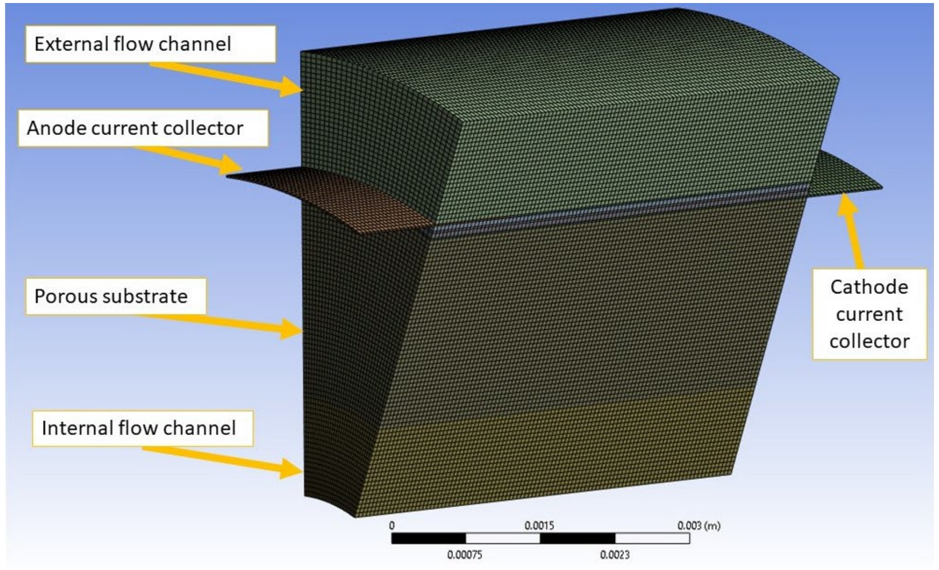
An I-V curve is an effective way to explain SOEL performance



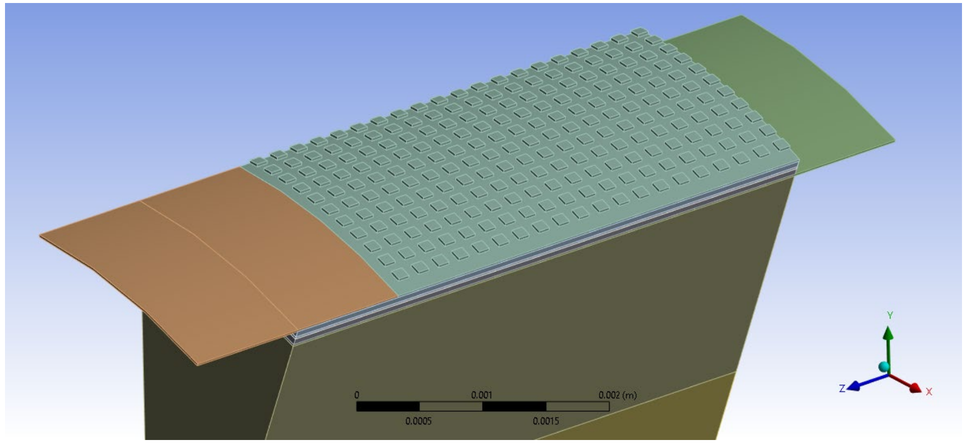
Higher temperature leads to better performance due to reduction in anode and cathode activation overpotential. However, it creates thermal stress and less durable cells

J. Udagawa et al. (2007) - doi:10.1016/j.jpowsour.2008.01.069

CFD Modelling

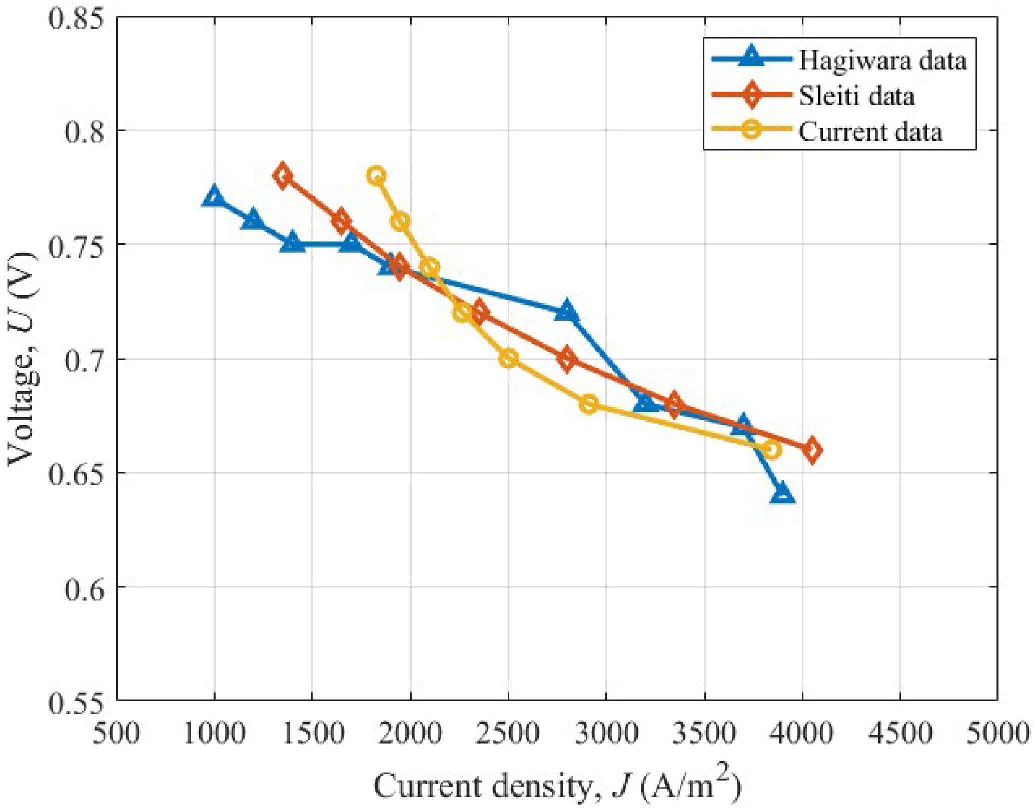


Plane Cell

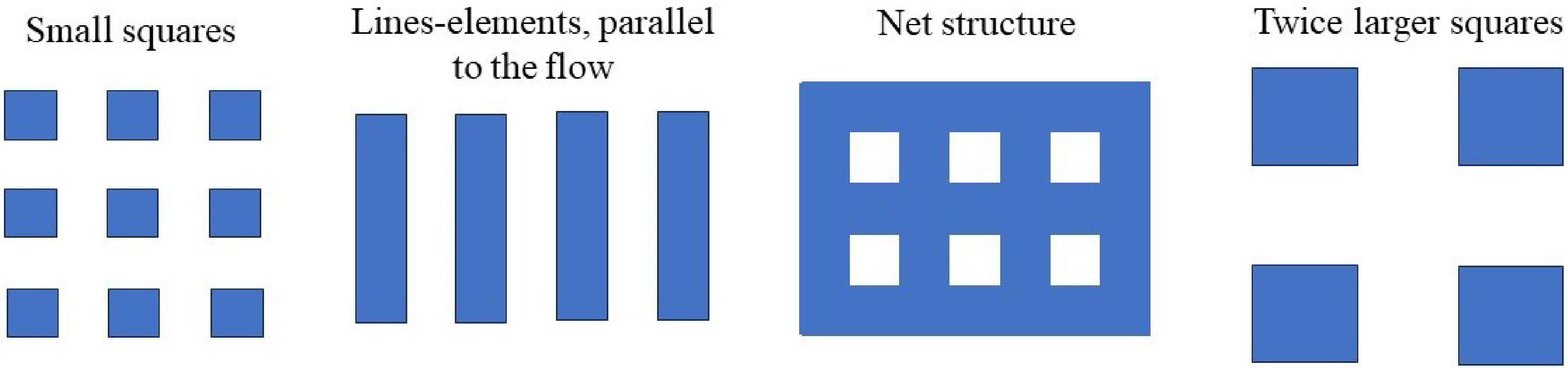


Metasurface cell

Comparison with previous studies

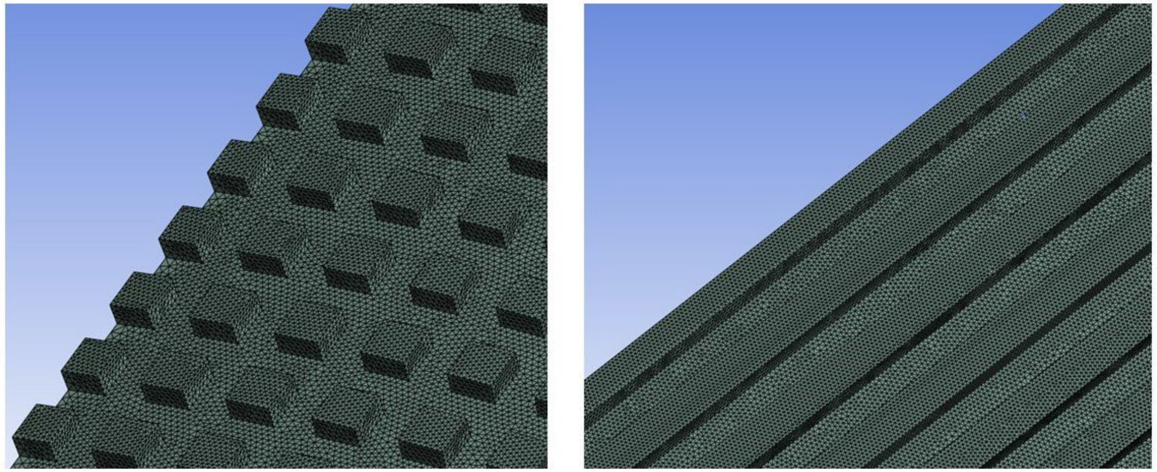


Different Meta Surfaces

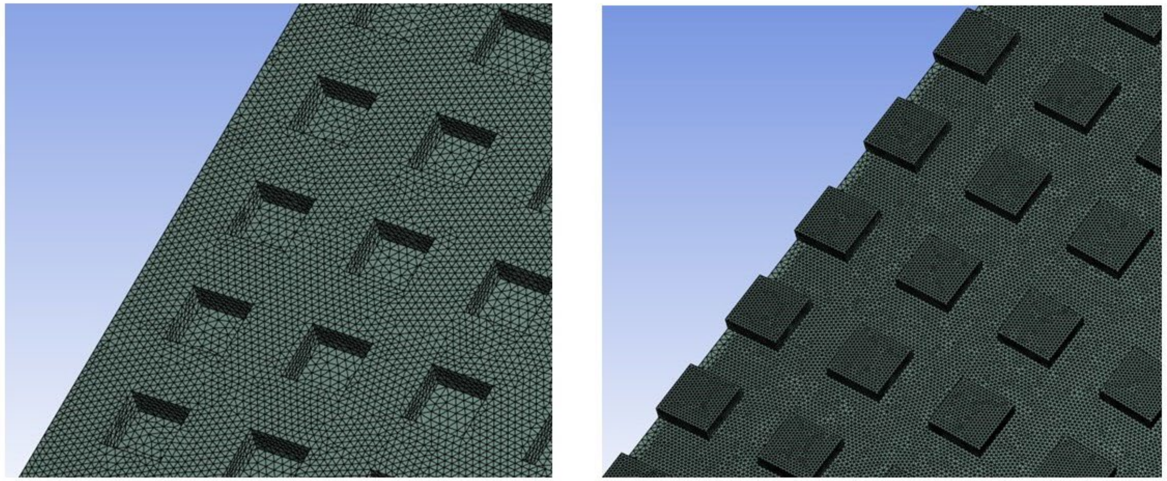


Mestasurface meshes

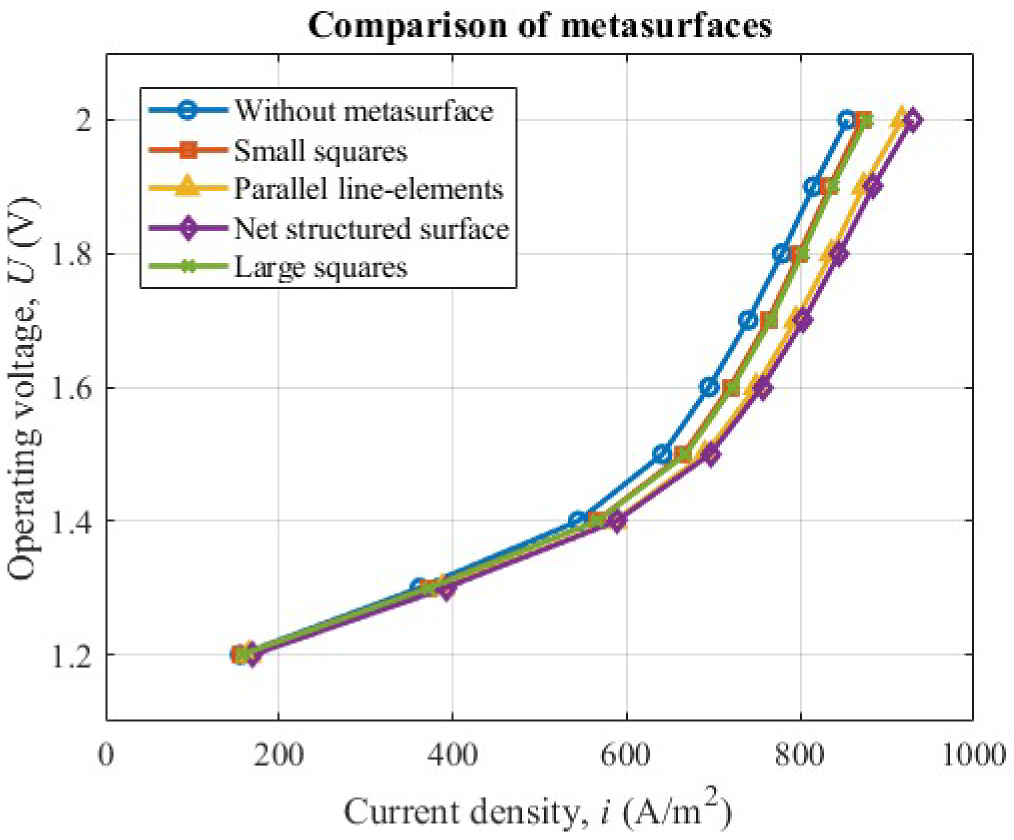
(a) (b)



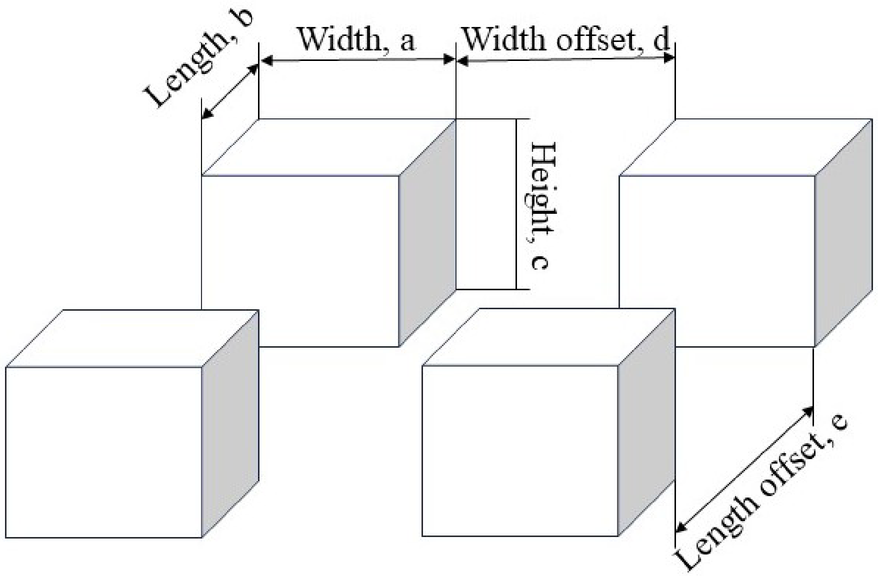
(c) (d)

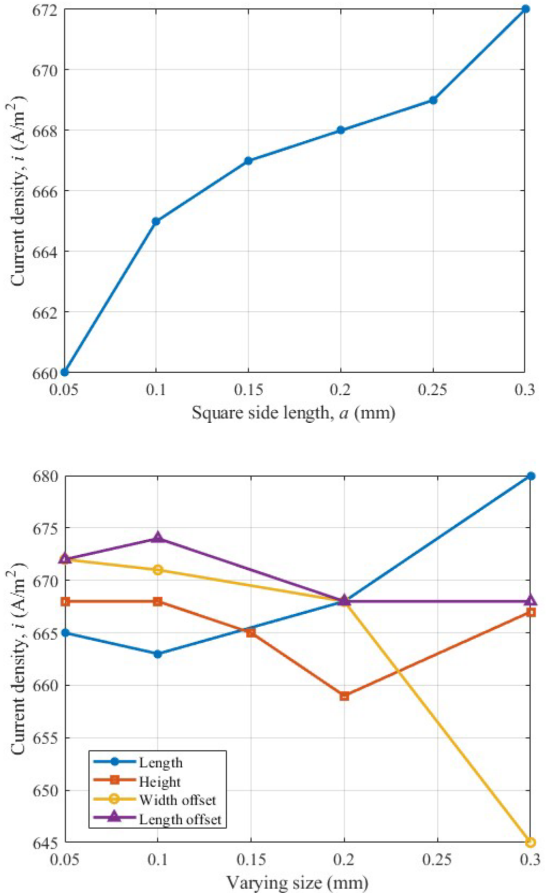


CFD Simulation – comparision of metasurfaces



Optimisation of met surface geometry





Summary

- Metasurface elements applied for solid oxide electrolysers open a new design space of potential cell improvements.
- the best performance curve belongs to the net structure, among the studied options, with up to 8.58% improvement compared to the case without the metasurface

Acknowledgements

The authors acknowledge high temperature steam electrolysis related funding by the UKRI EPSRC via Grant No. EP/W033178/1 (METASIS).


ROBERT GORDON
UNIVERSITY ABERDEEN
RGU
Any Question?