Green Hydrogen and Ammonia Production

Challenges and opportunities

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- Ammonia
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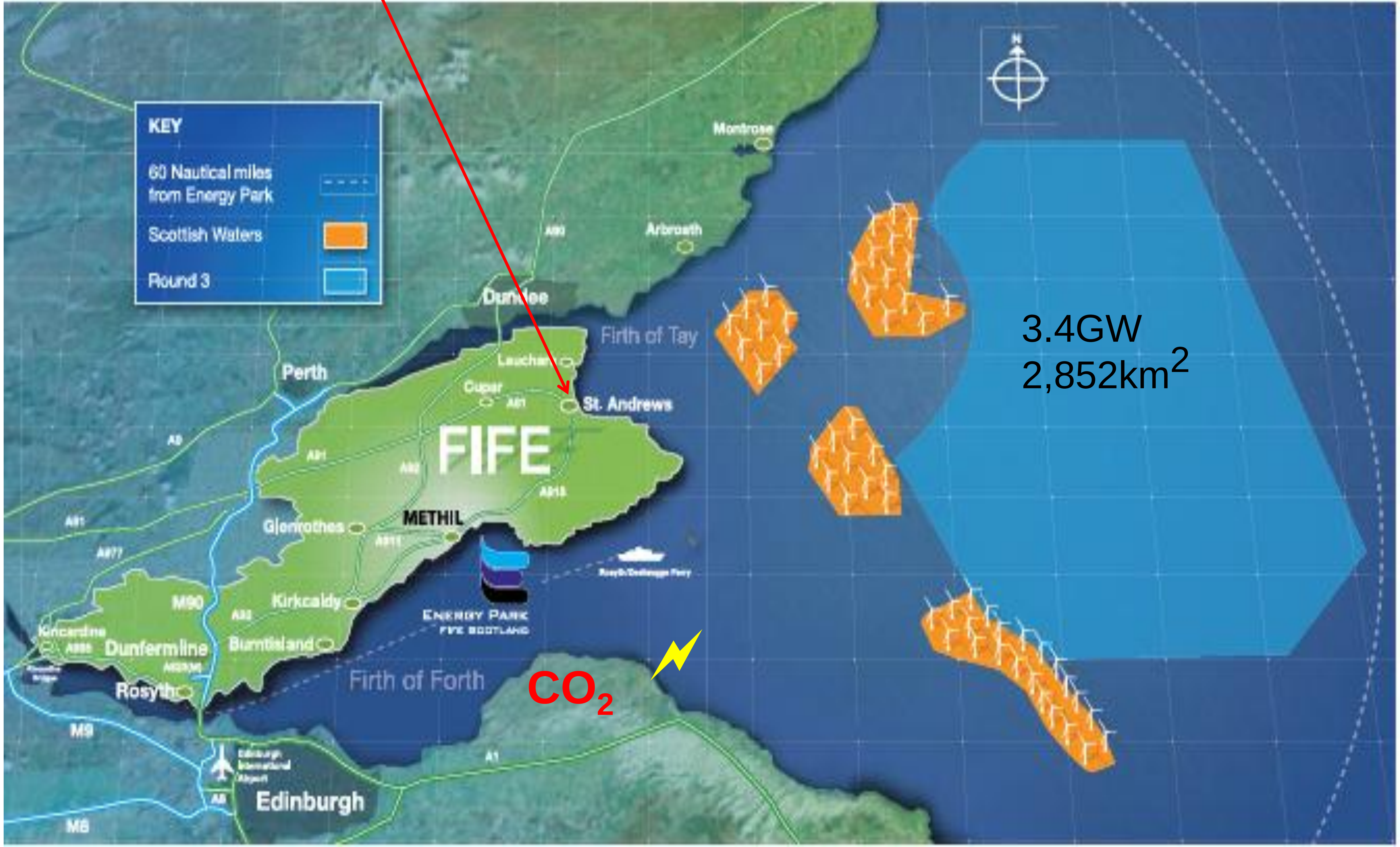
St Andrews


KEY
60 Nautical miles from Energy Park
Scottish Waters
Round 3
Montrose
Arbroath
Dundee
Firth of Tay
Perth
Leuchars
Cupar
St. Andrews
FIFE
METHIL
Glenrothes
Kirkcaldy
Burntisland
Dunfermline
Kincardine
Rosyth
Firth of Forth
ENERGY PARK FIFE SCOTLAND
Edinburgh
M90
M9
M8
A1
3.4GW
2,852km^2
CO_2

Saipem 7000 marks the start of offshore work on the Neart na Gaoithe (NnG) wind farm, August 2020

- Owned by EDF Renewables and ESB
- 15 km off the Fife coast
- 54 turbines

2023

- Power 375,000 homes
- 450 megawatts

https://ocean-energyresources.com/

Zero Emission Train Project

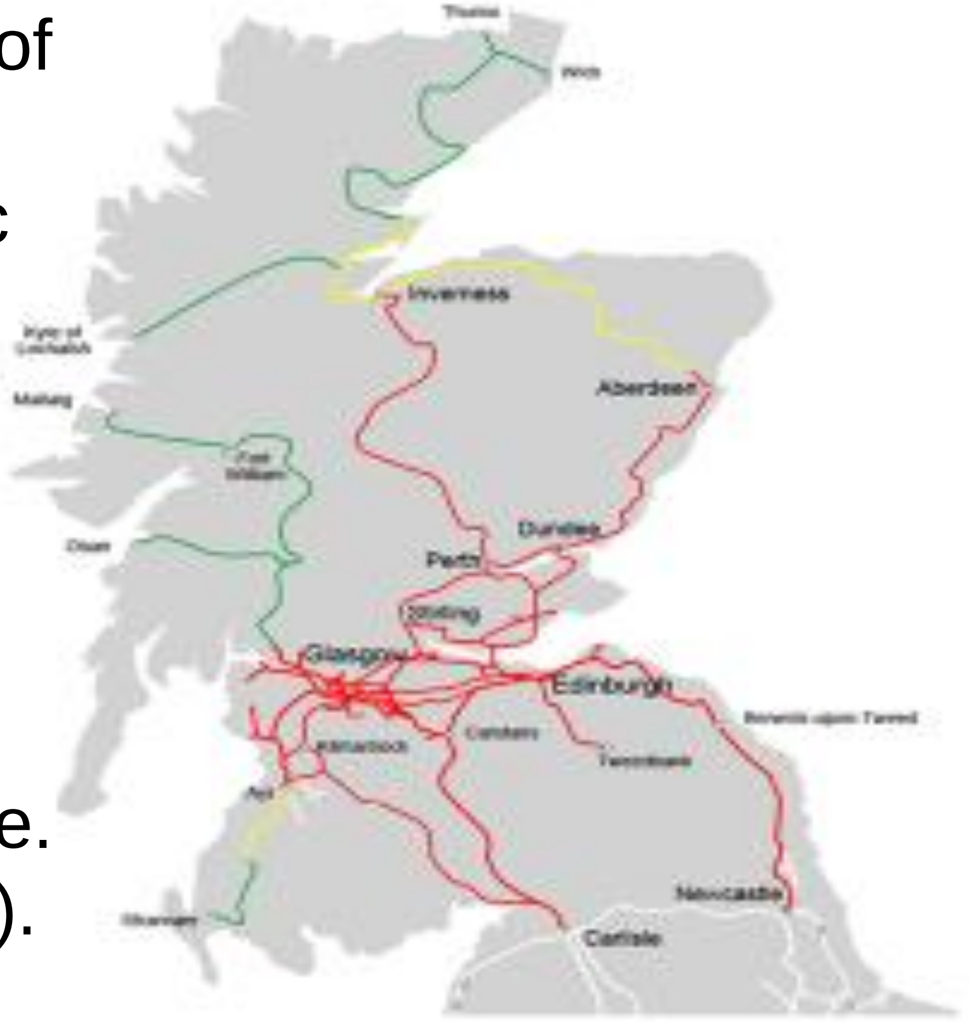
https://www.scottish-enterprise-mediacentre.com/news/hydrogen-train-project-looks-back-to-the-future

Hydrogen Fuel Cell Electric Trains
Our decarbonised rail network in Scotland, 2035

- Electrified network; some 1,622 of single track kilometres to be electrified. Sections of route may include discontinuous electrification and the use of battery/electric bi mode trains, e.g the Fife Circle.

- Alternative traction – transition solution(i.e. the use of alternative technology prior to electrification).

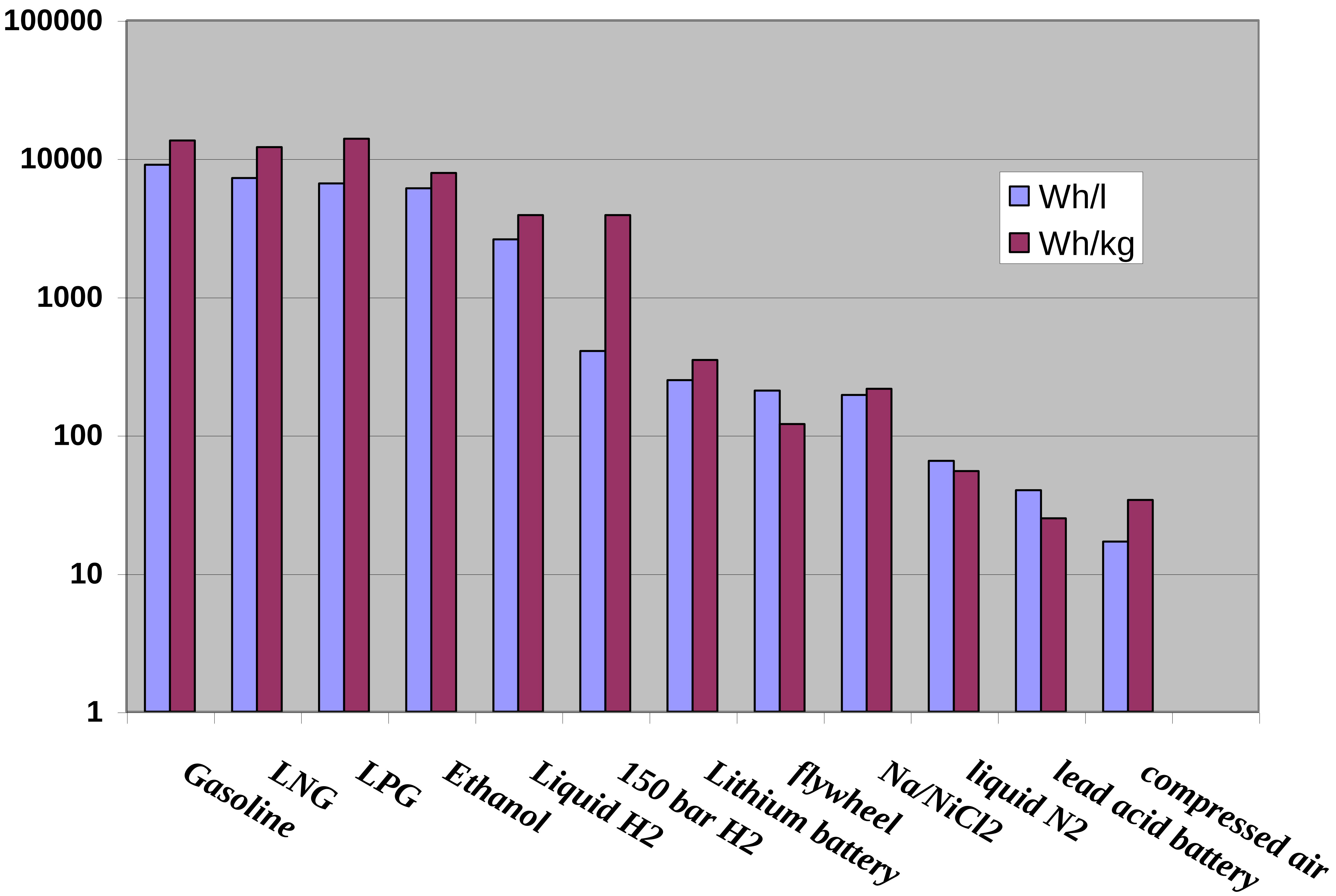
- Alternative traction – permanent solution (i.e. the use of battery and/or Hydrogen traction).



Rail Decarbonisation Plan launched at the end of ***July 2020***. Decarbonisation of the rail network by 2035. First market engagement by ***September 2020***

…

Energy Storage Technologies



Alternative hydrogen carriers

- Ammonia
- Methanol
- Methane
- Hydrocarbons
- Diesel

Ammonia

- Ammonia is one of the most important industrial chemicals
- Widely used in agriculture as a fertiliser for food production.
- Conventionally ammonia is produced at very large scale utilising fossil energy sources
- Cost via H_2 SMR is very low, even lower than bulk hydrogen
- Historically produced utilising hydrogen produced from Hydro power.

HISTORICAL LARGE SCALE PLANTS

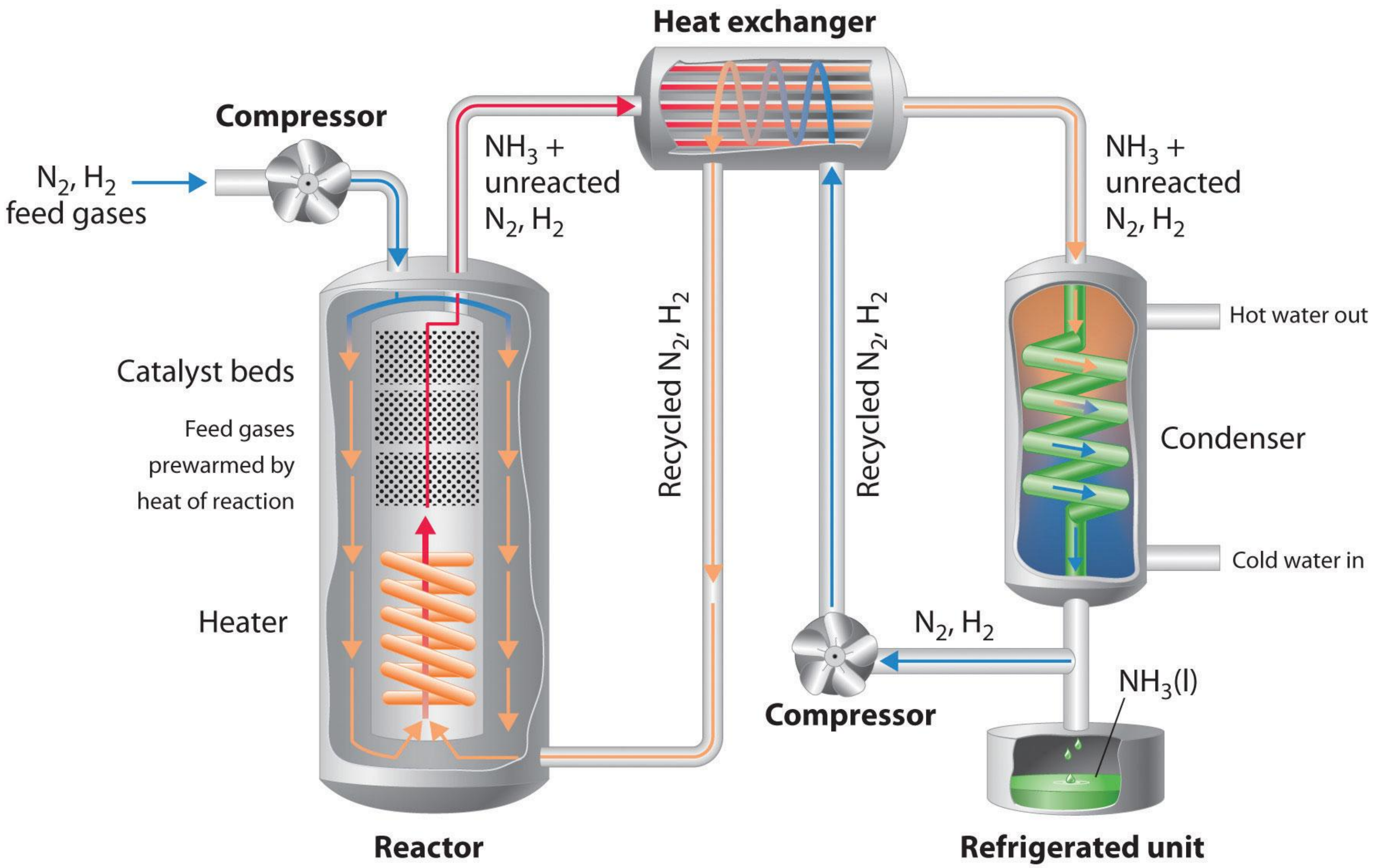
Rjukan, Norway; 1927 – 1970's

Glomfjord, Norway; 1953 – 1991

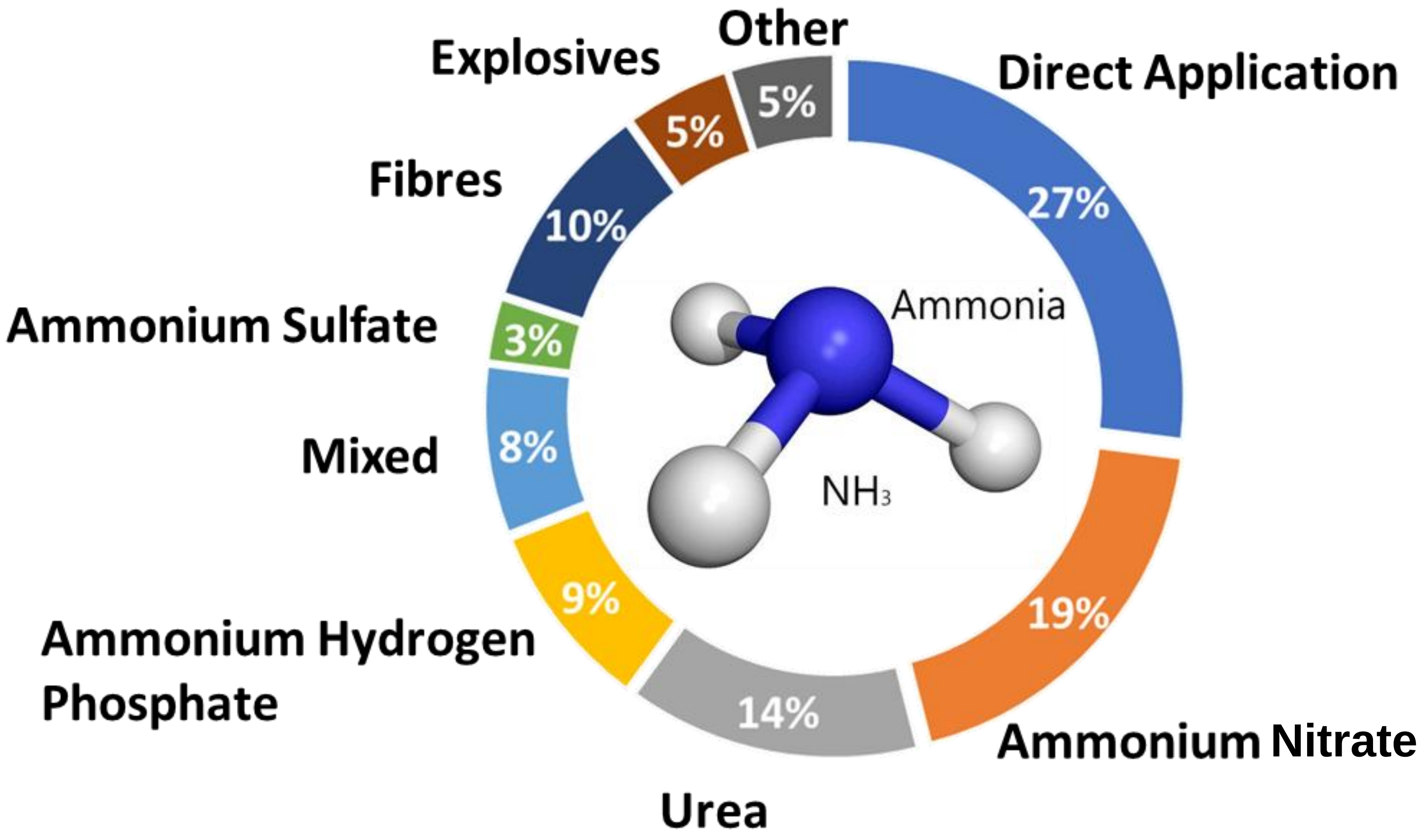
- Two largest electrolyser plants worldwide
- Capacity: 30 000 Nm^3/h each
- Energy consumption: approximately 135 MW each
- Supplied by renewable hydro power

NEL HYDROGEN

Haber-Bosh Process



Main applications



High temperatures (400–500 ° C)
High pressures (150–200 atm)

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3\,(g)\quad \Delta H = -92\ \text{kJ mol}^{-1}$$

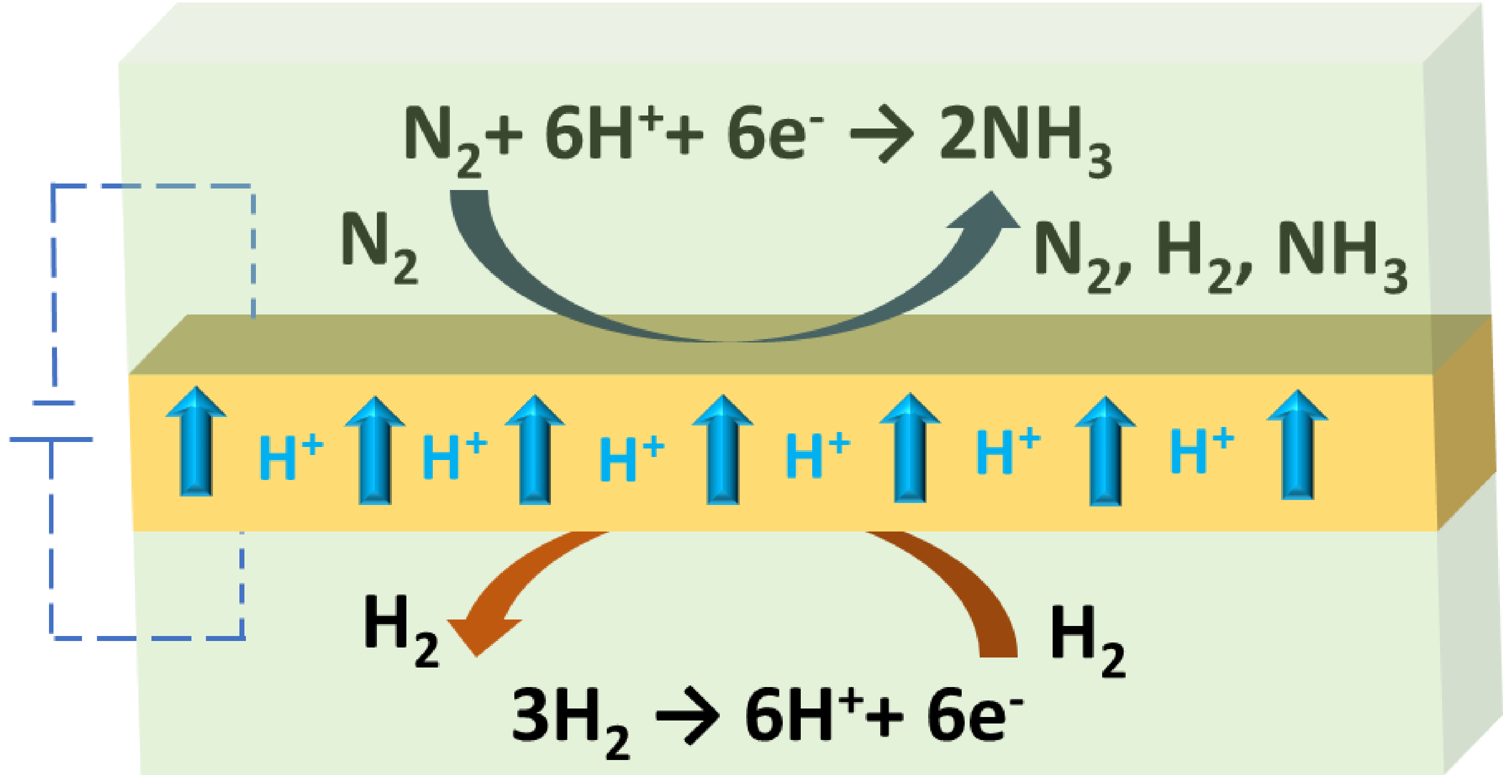
Alternative energy-saving pathway?

Wind and ammonia

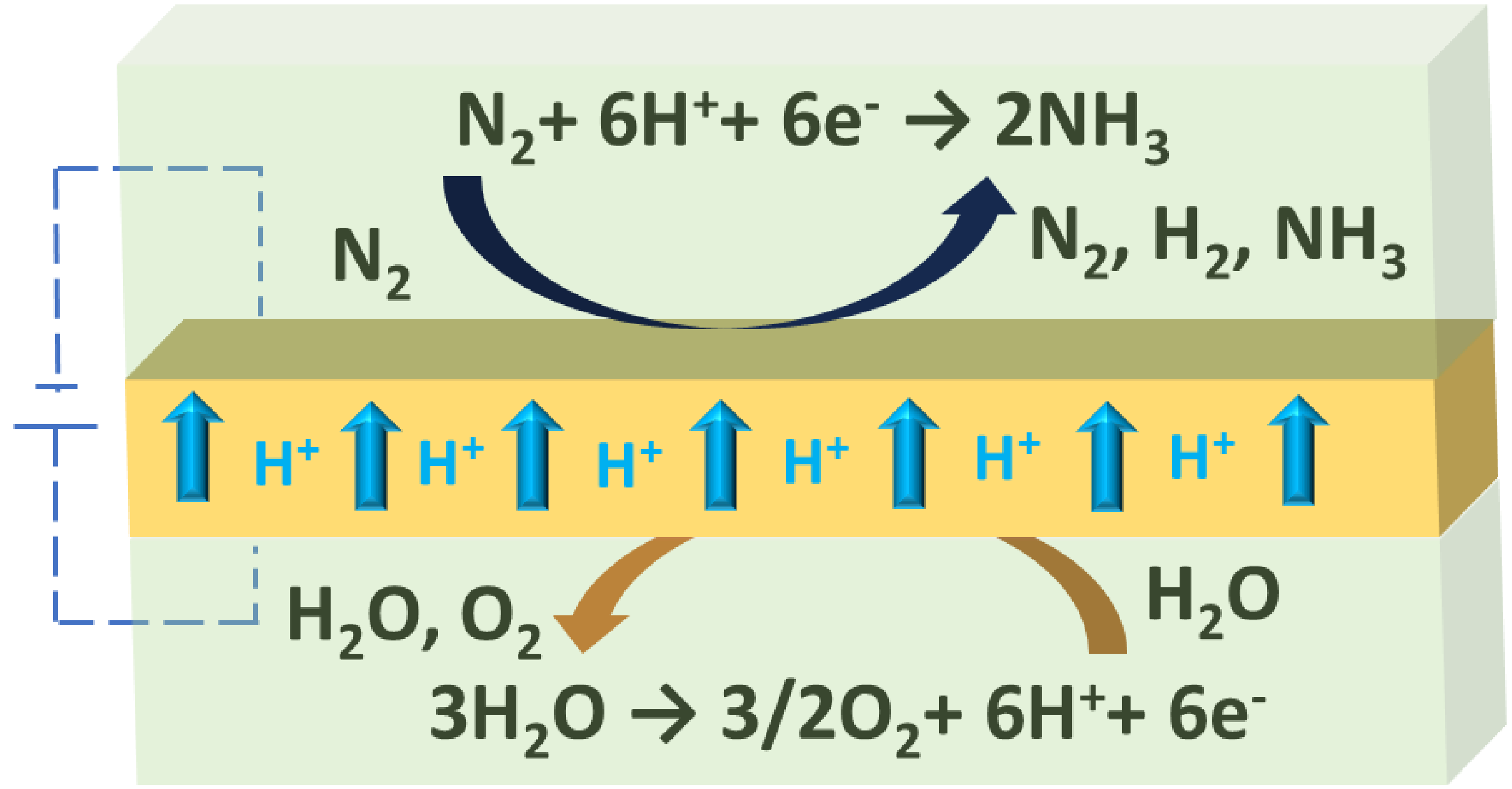
http://freedomfertilizer.com/

Protonic ceramic conductors

With H_2 proton source



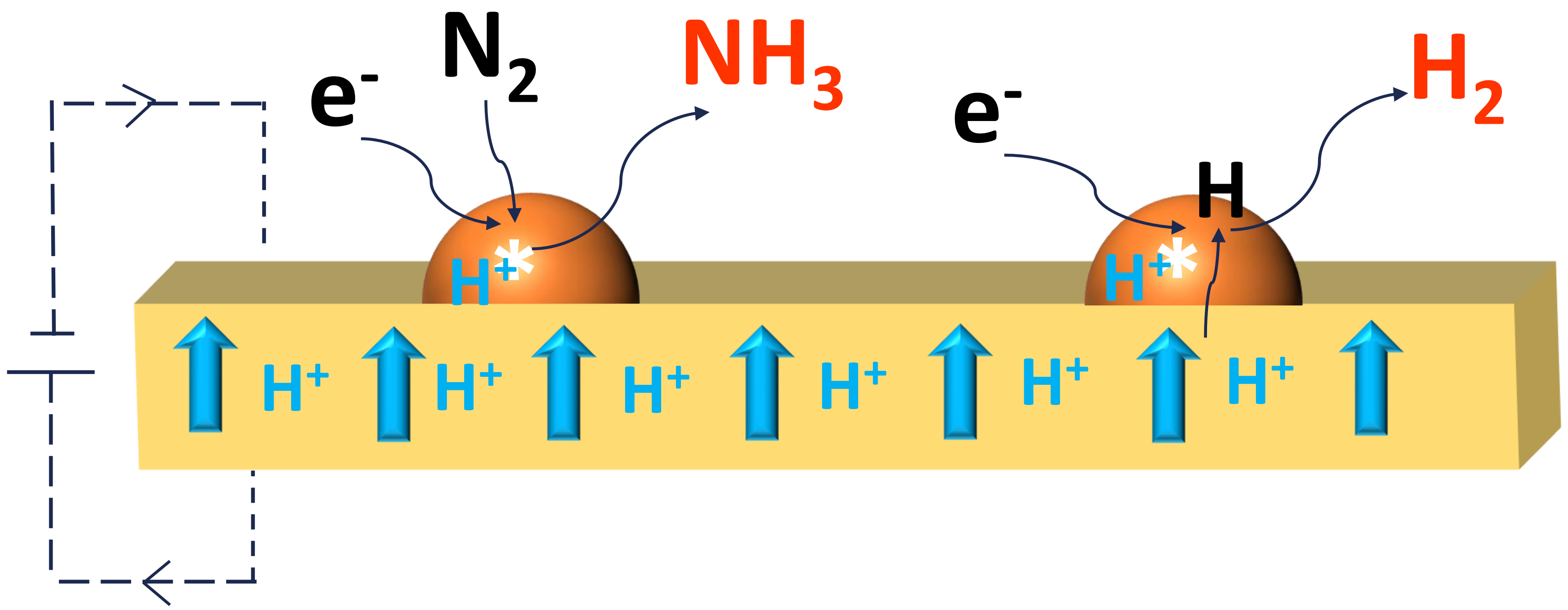
With H_2O proton source



Competing mechanisms

$$H^+ + e^- + * \rightleftharpoons *H \qquad (1)$$

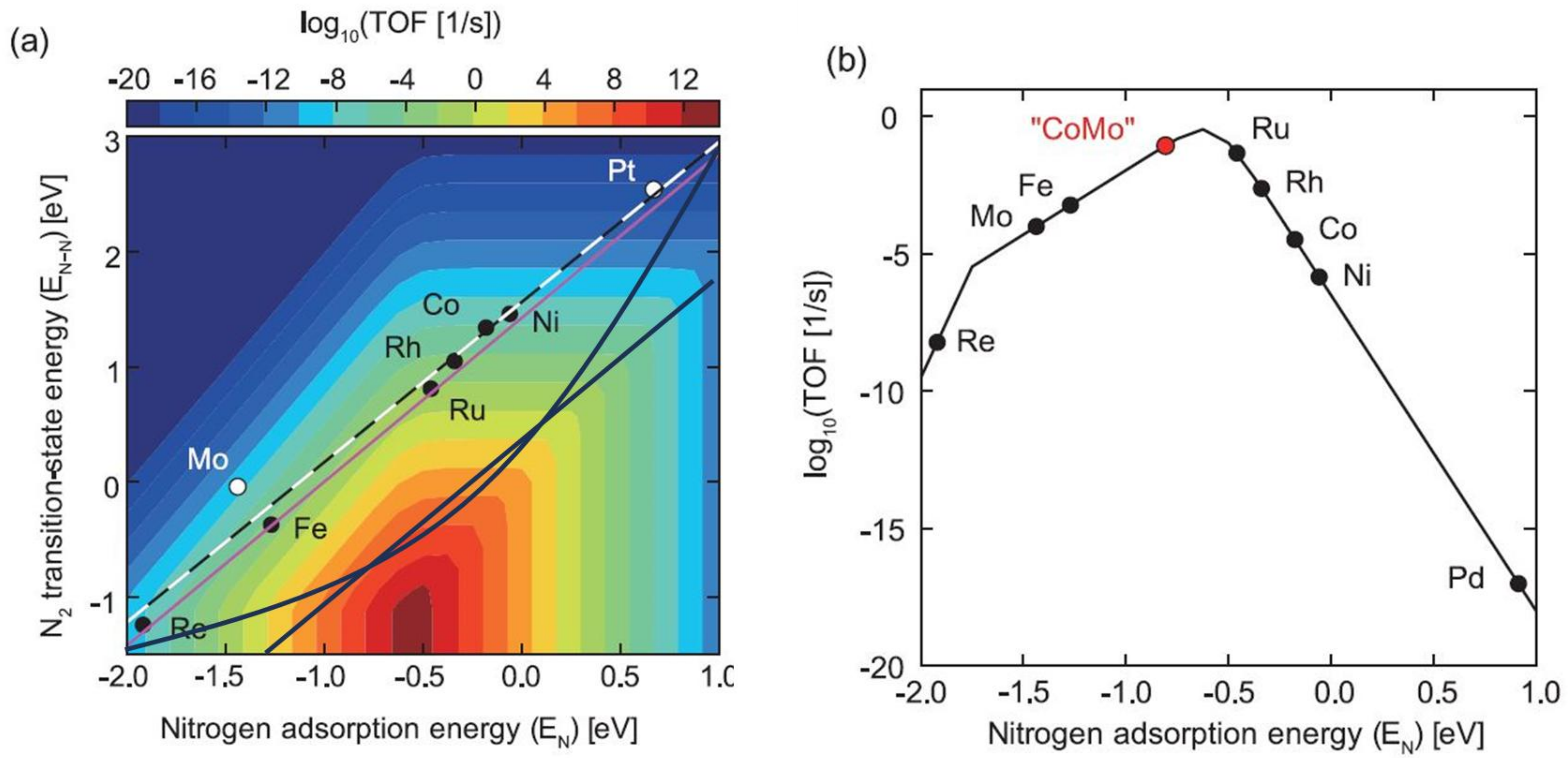
$$N_2 + * \rightleftharpoons *N_2 \qquad (2)$$



$$H^+ + e^- + *N_2 \rightleftharpoons * N_2H \qquad (3)$$

$$H^+ + e^- + *H \rightleftharpoons H_2 + * \qquad (4)$$

Electrocatalysis



Vojvodic, A.; Nørskov, J. K. Natl. Sci. Rev. 2015, 2, 140−143.

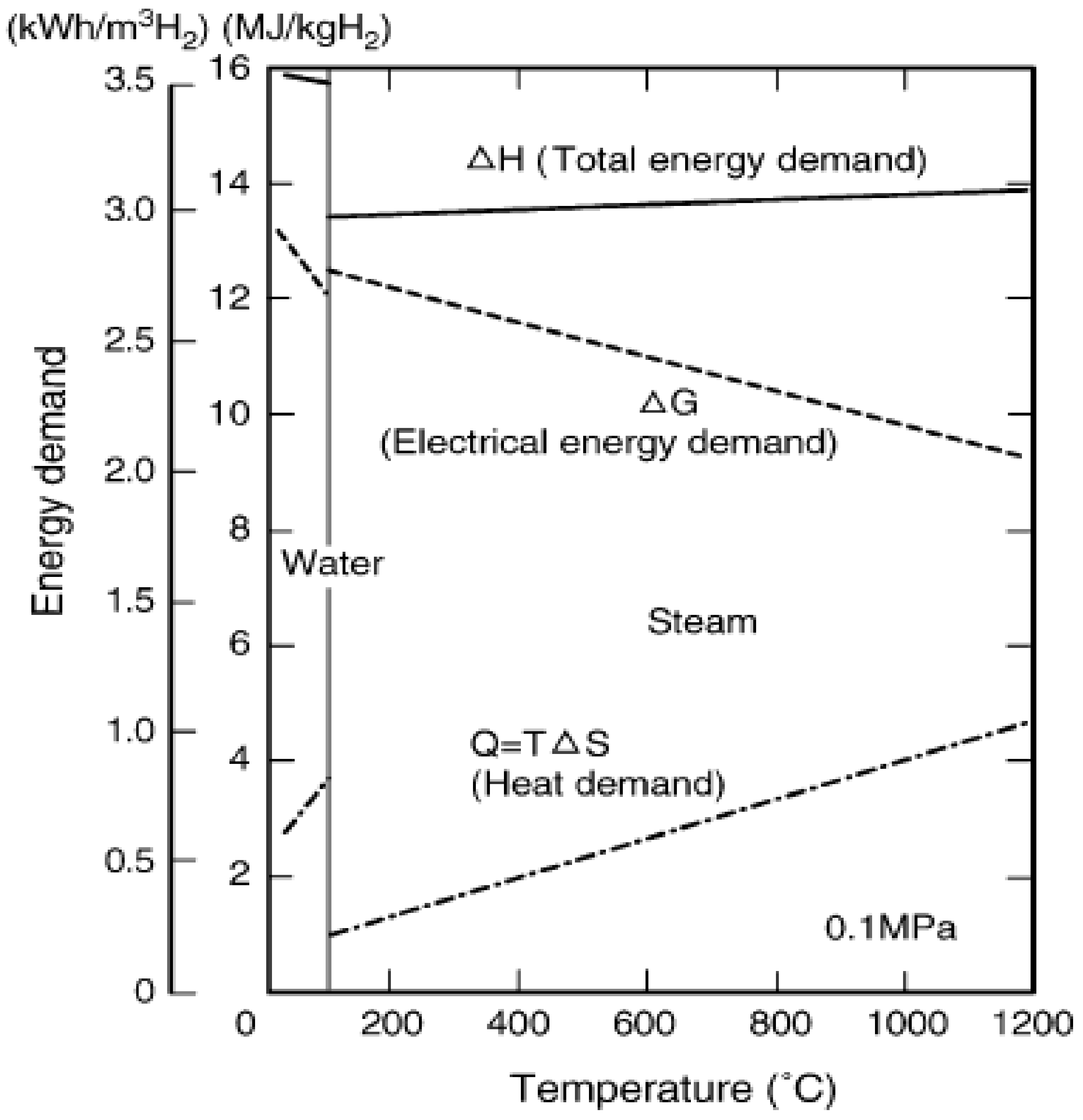
Solid Oxide Electrolysis

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

$H_2O \rightarrow H_2 + 1/2 O_2$

$\Delta H = 285.8$ kJ/mol at 25^{o}C

$\Delta G = -zEF = -2EF.$



The 3 modes of HTSE

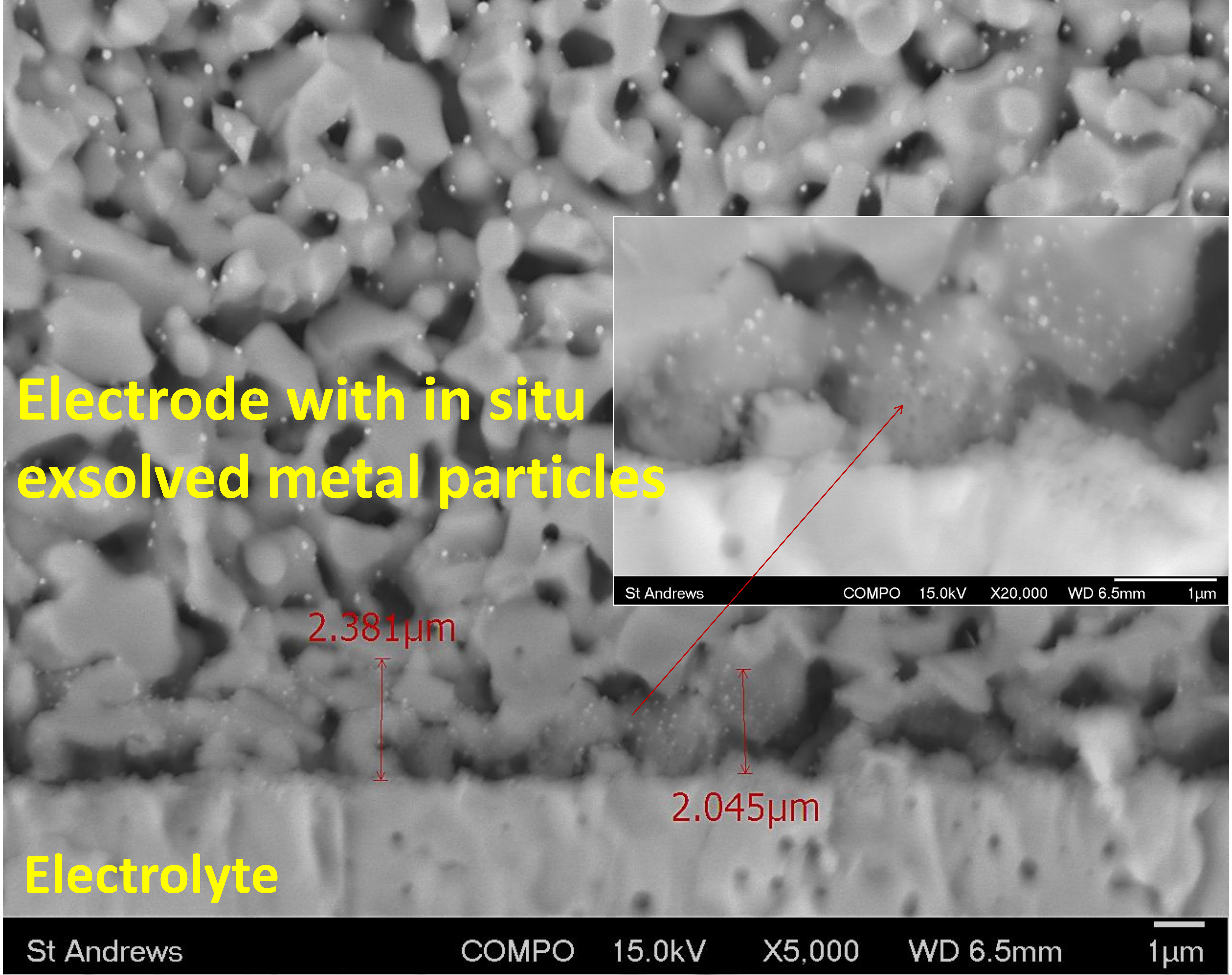
- Thermoneutral:
  - Joule heating = heat consumed by the endothermic reaction
  - Electrical-to-chemical efficiency = 100 %
- Exothermic:
  - Joule heating > heat consumed by the endothermic reaction
  - Electrical-to-chemical efficiency < 100 %
- Endothermic:
  - Joule heating < heat consumed by the endothermic reaction
  - External heat source required
  - Electrical-to-chemical efficiency > 100 %

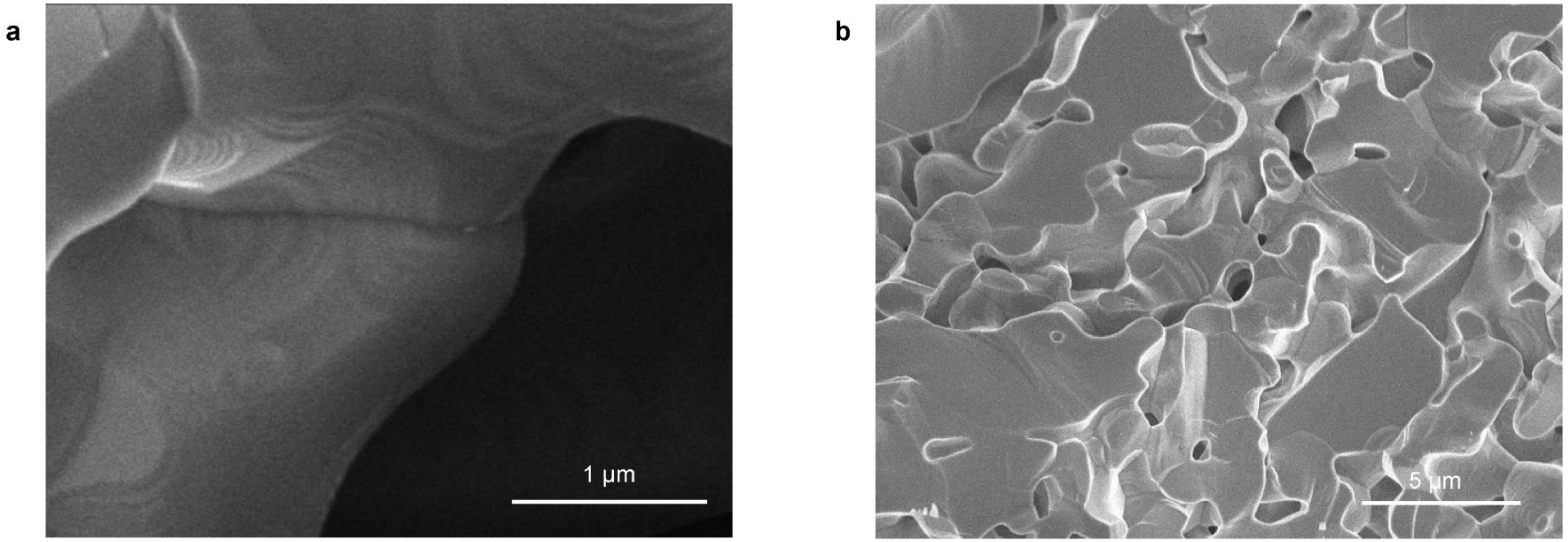
Switching on electrocatalytic activity in solid oxide cells

Electrochemical vs Chemical Reduction

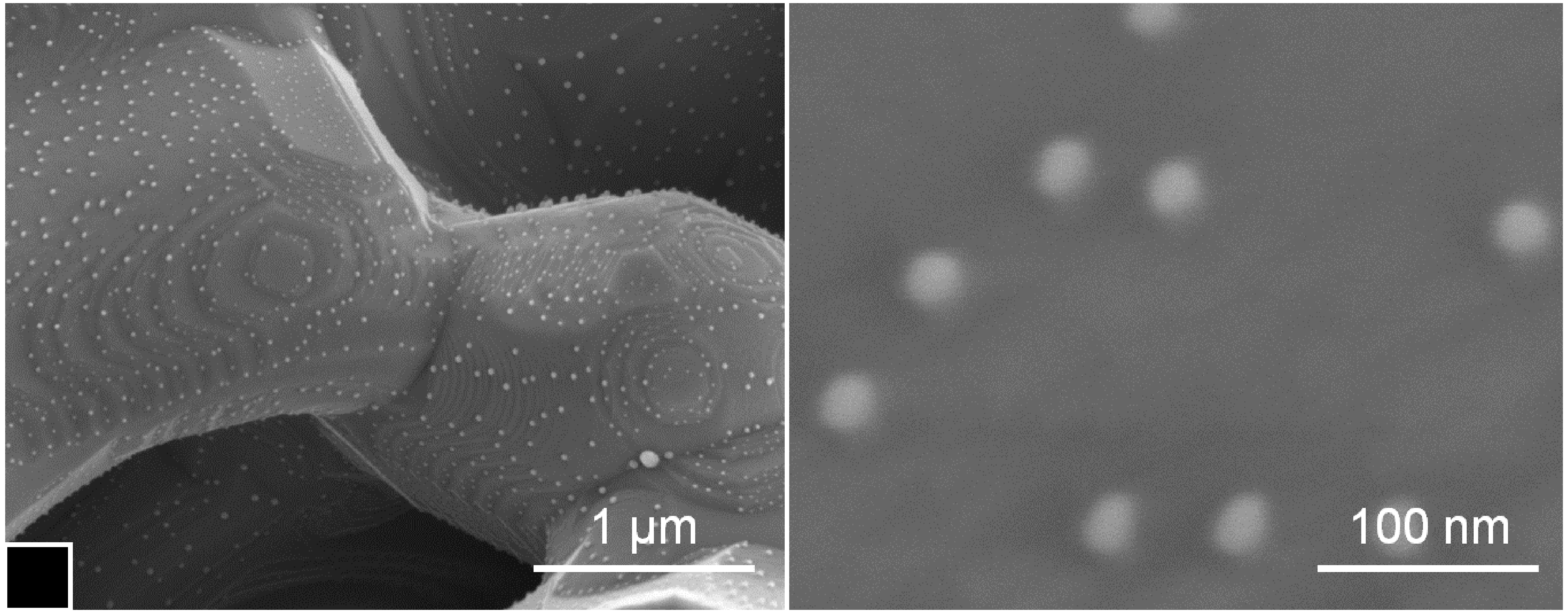
$La_{0.43}Ca_{0.37}Ni_{0.06}Ti_{0.94}O_{3-\gamma}$

J-H. Myung, D. Neagu, DN. Miller & JTS. Irvine,
Nature, 2016. 537, 528-531


Electrode with in situ exsolved metal particles
Electrolyte
2.381μm
2.045μm
St Andrews COMPO 15.0kV X20,000 WD 6.5mm 1μm
St Andrews COMPO 15.0kV X5,000 WD 6.5mm 1μm



Microstructures of as-prepared electrode, before any reduction



After reduction in 5%H_2

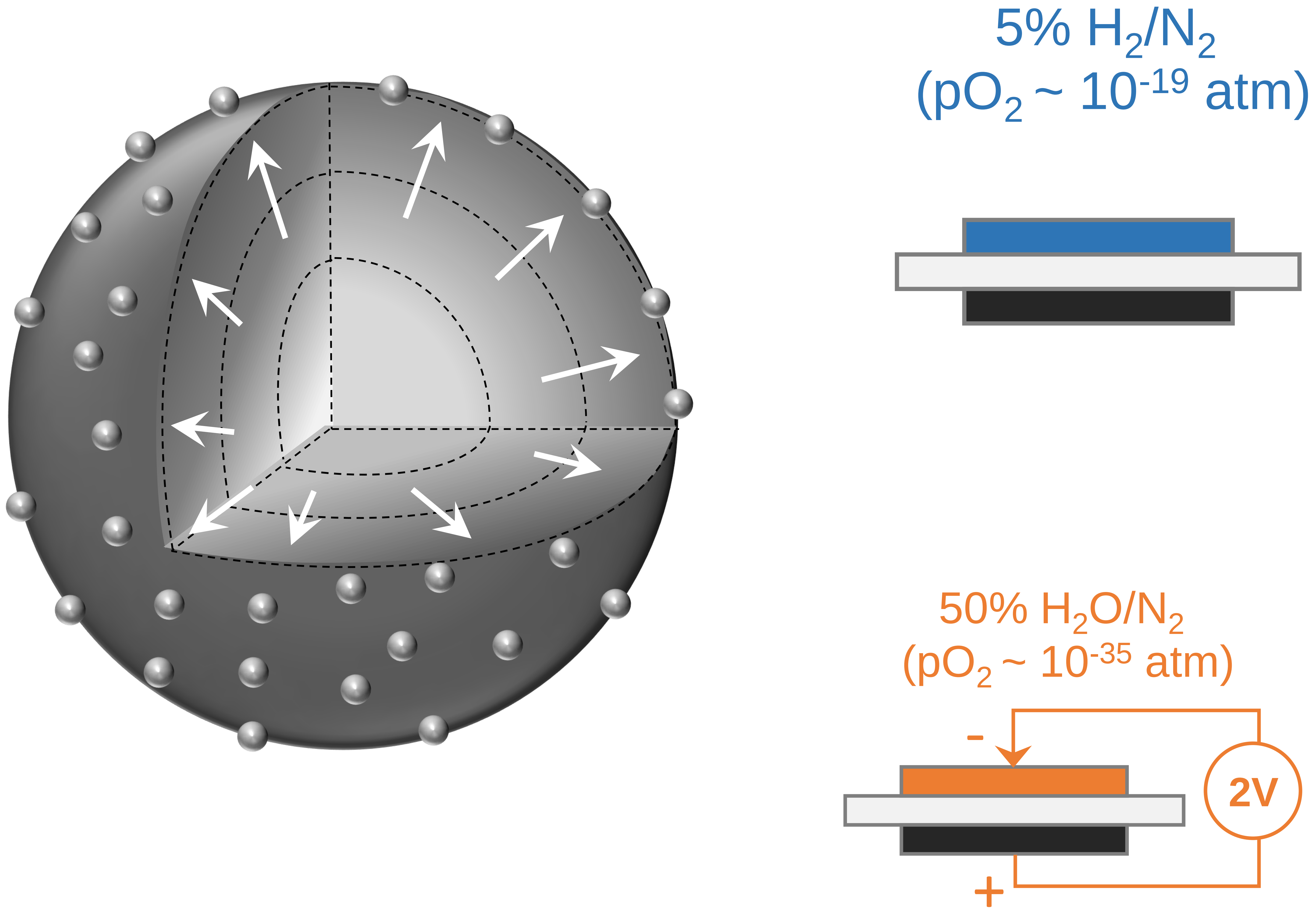
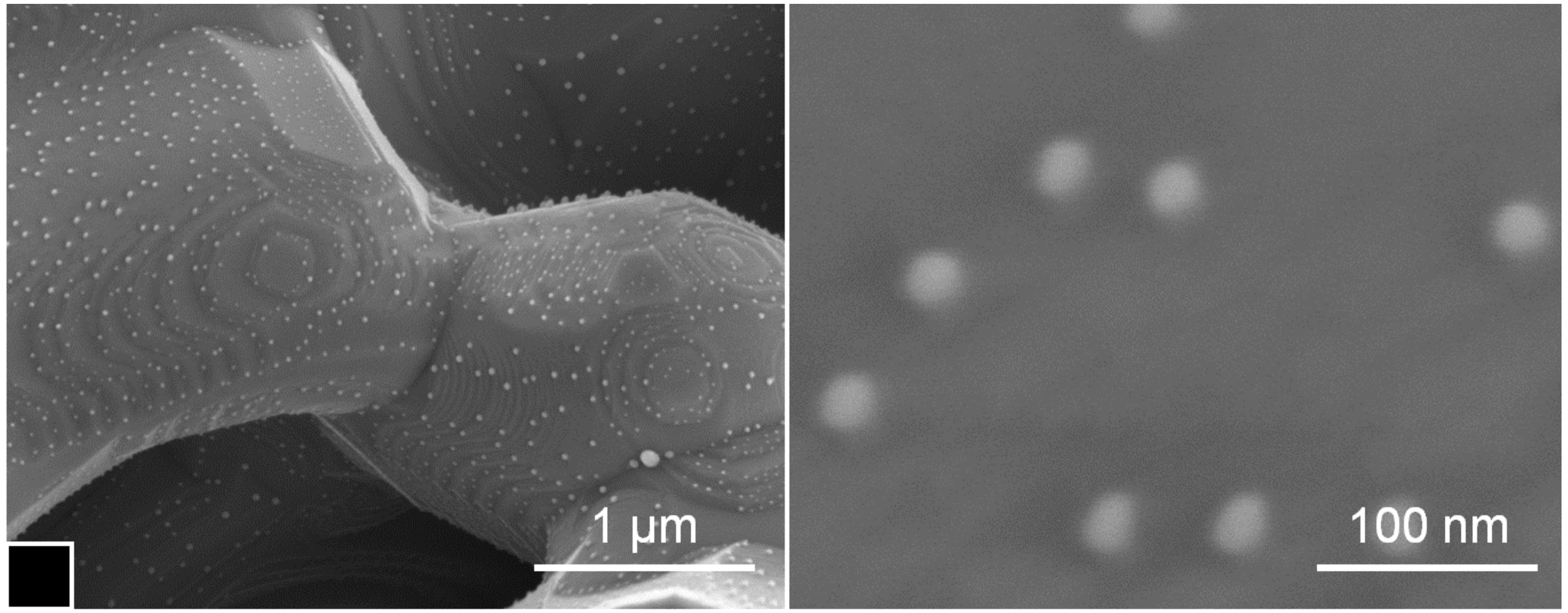

5% H_2/N_2
($pO_2 \sim 10^{-19}$ atm)
50% H_2O/N_2
($pO_2 \sim 10^{-35}$ atm)
-
+
2V

Figure 1(e)

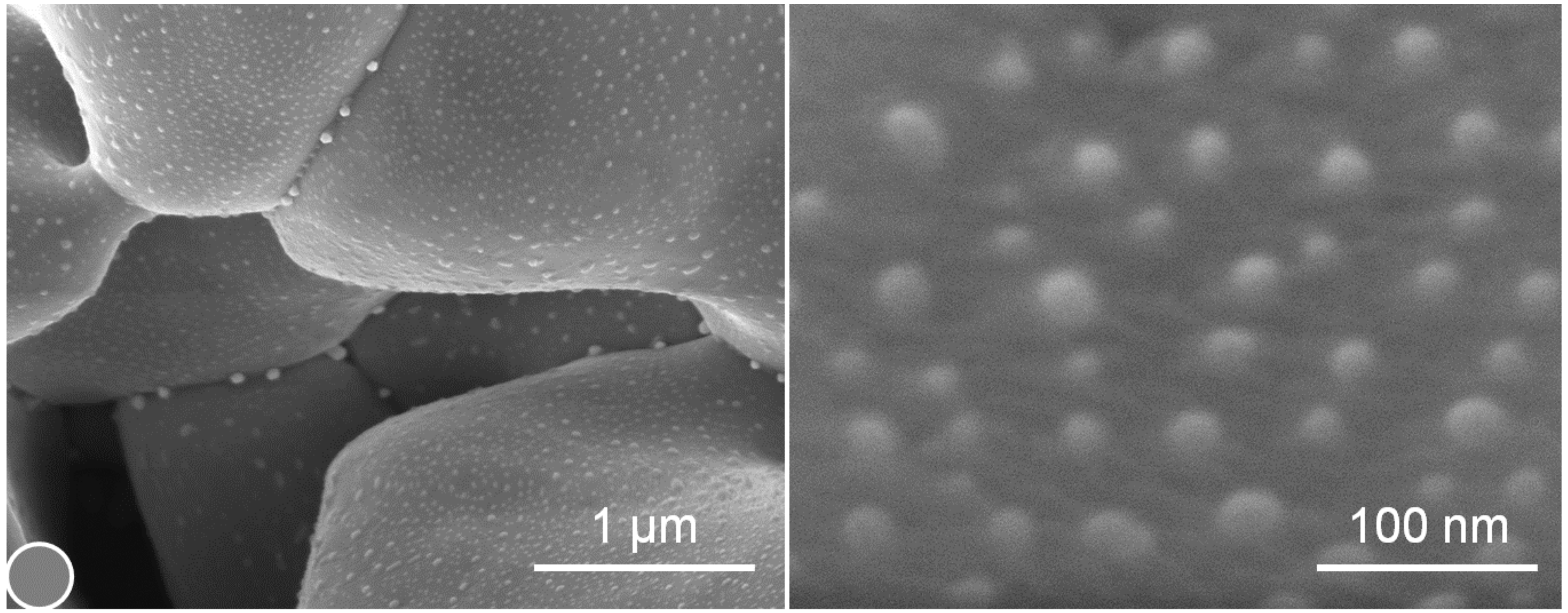


Reduction by H_2 at 900 ℃ for 20 h

Chemical reduction

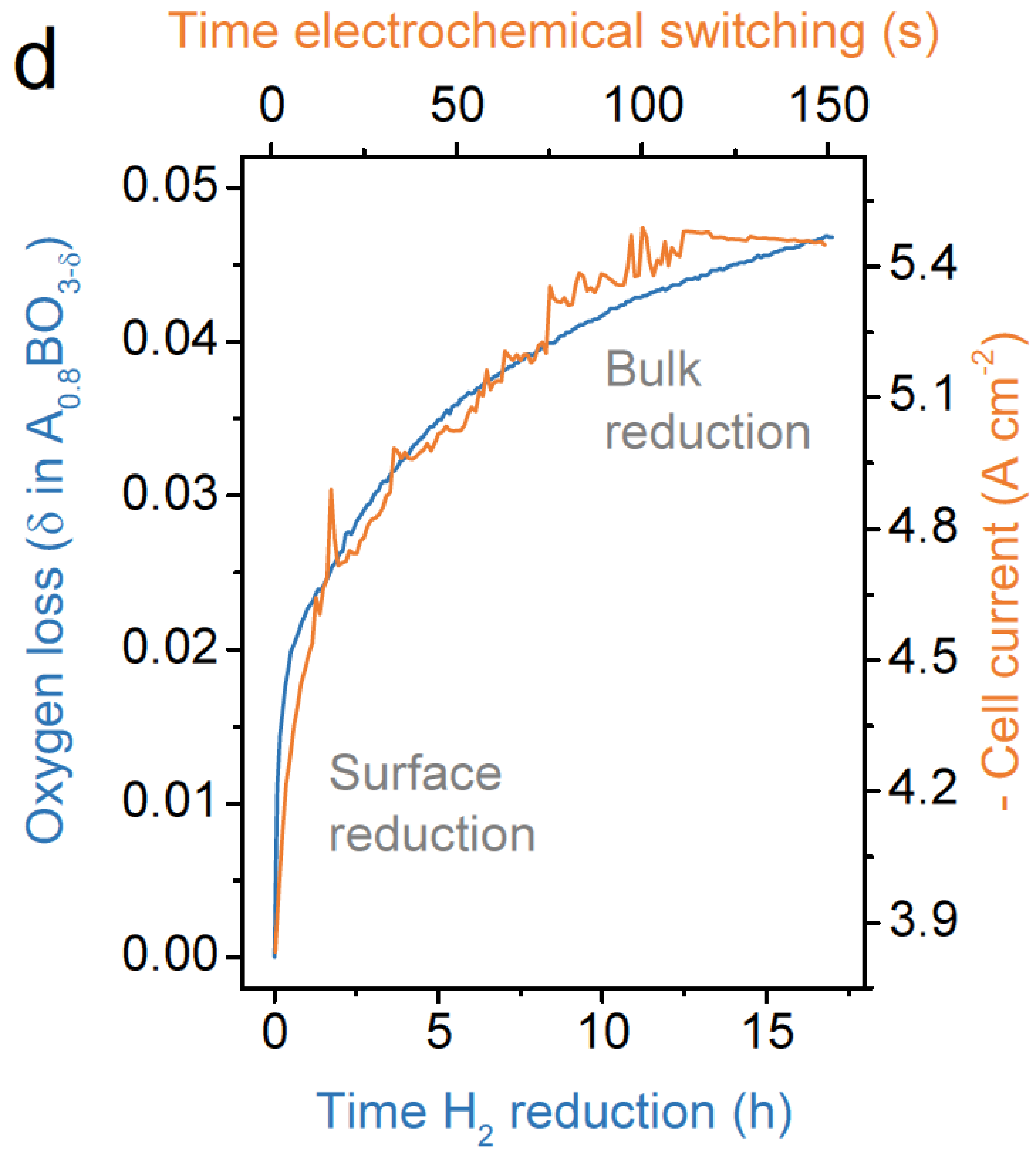
Compared to

Figure 1(f)

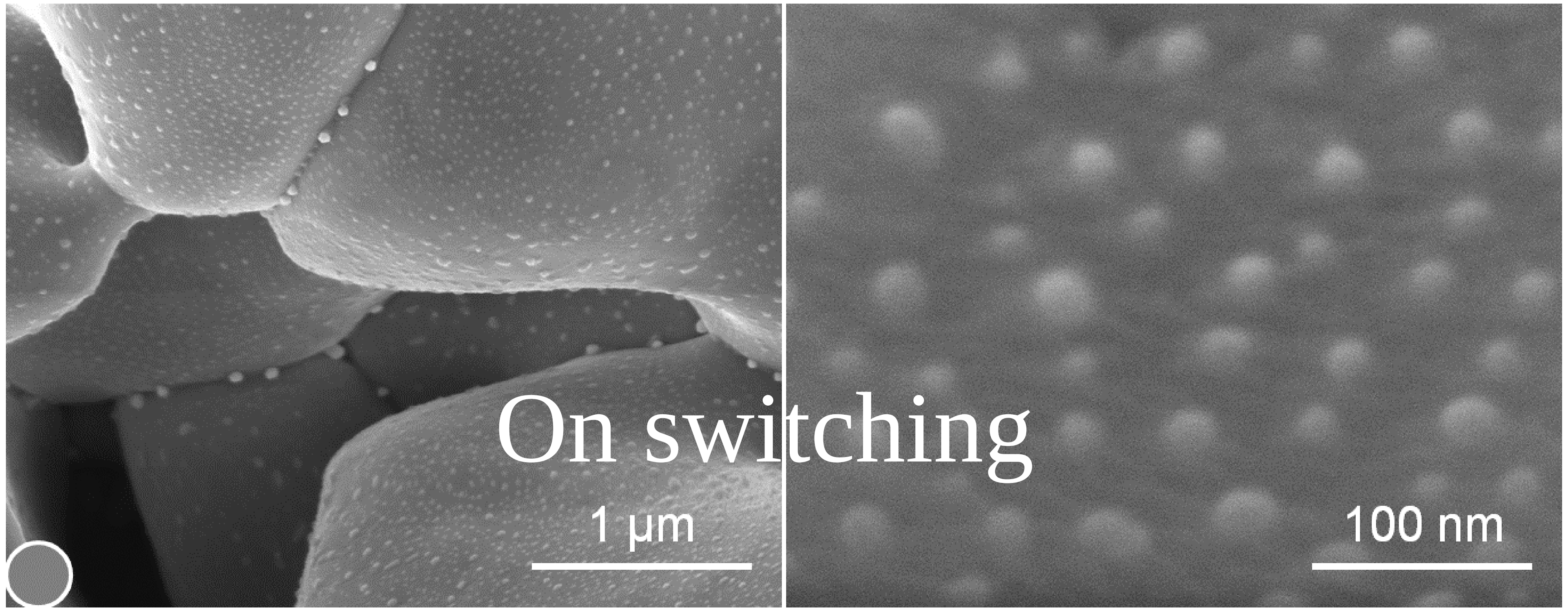


Electrochemical Switching

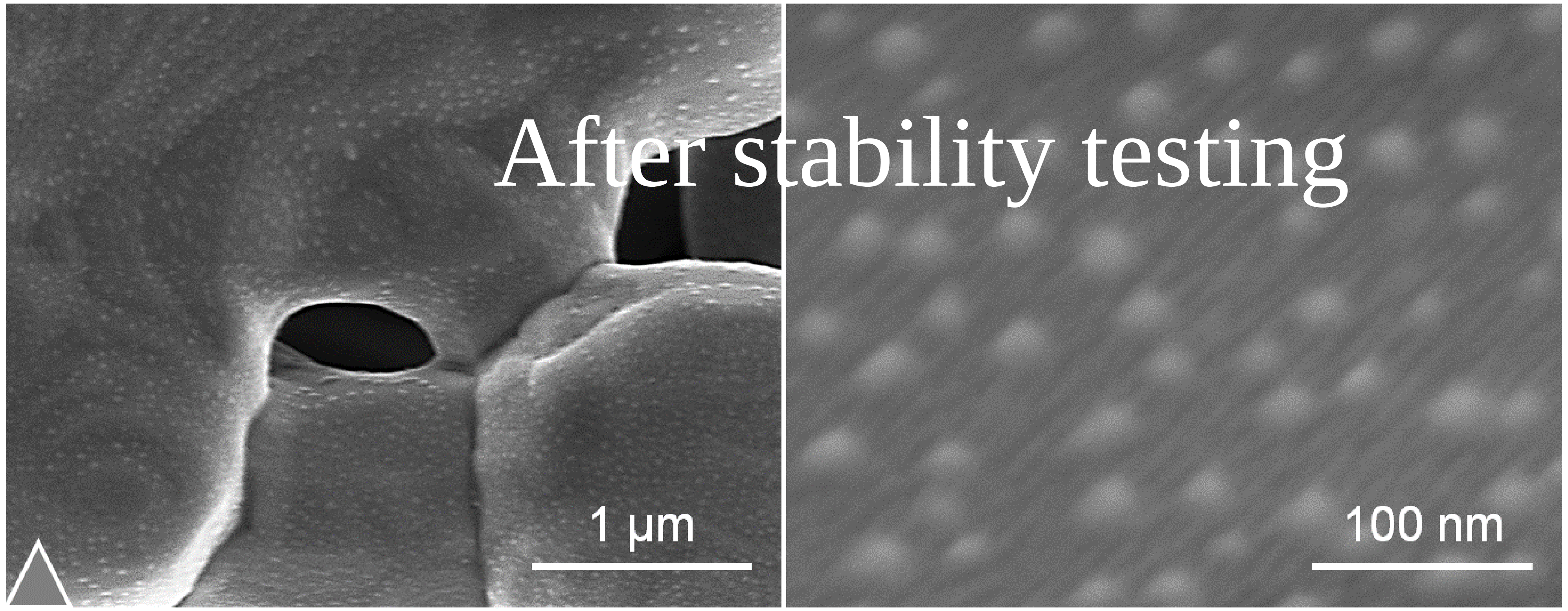
Under 50% H_2O/N_2, 900 ℃, 150 s

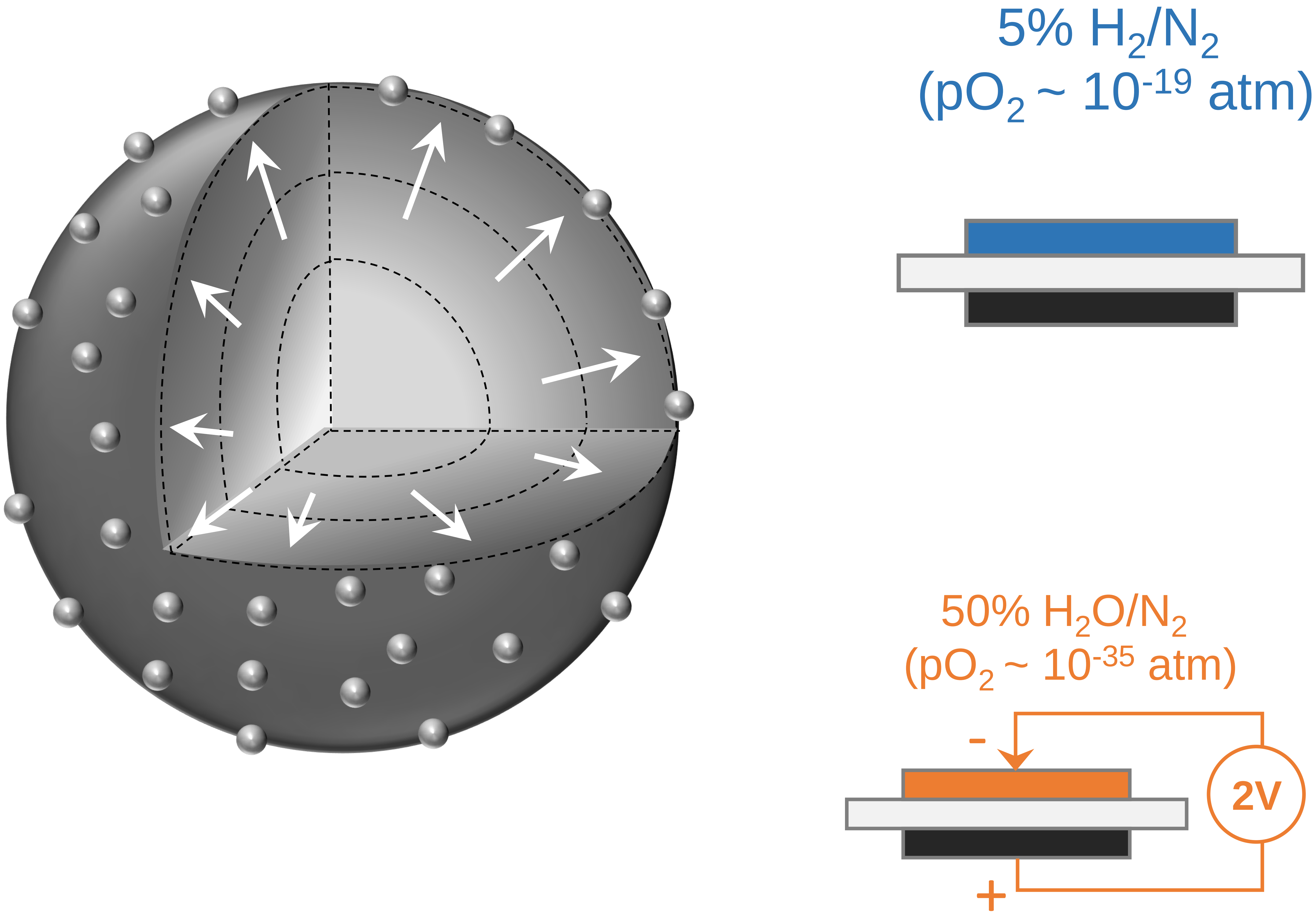


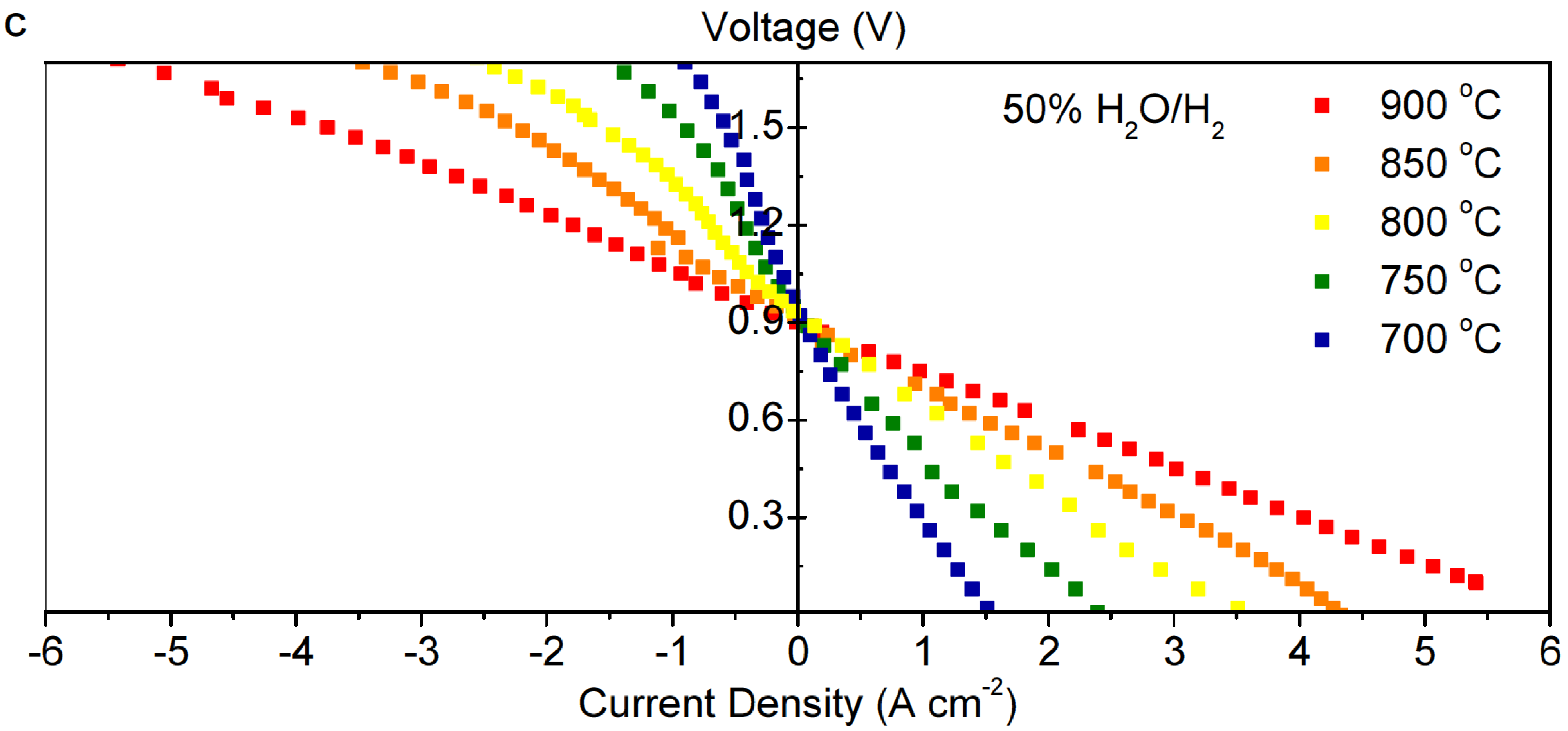
$La_{0.43}Ca_{0.37}Ni_{0.06}Ti_{0.94}O_{3-γ}$



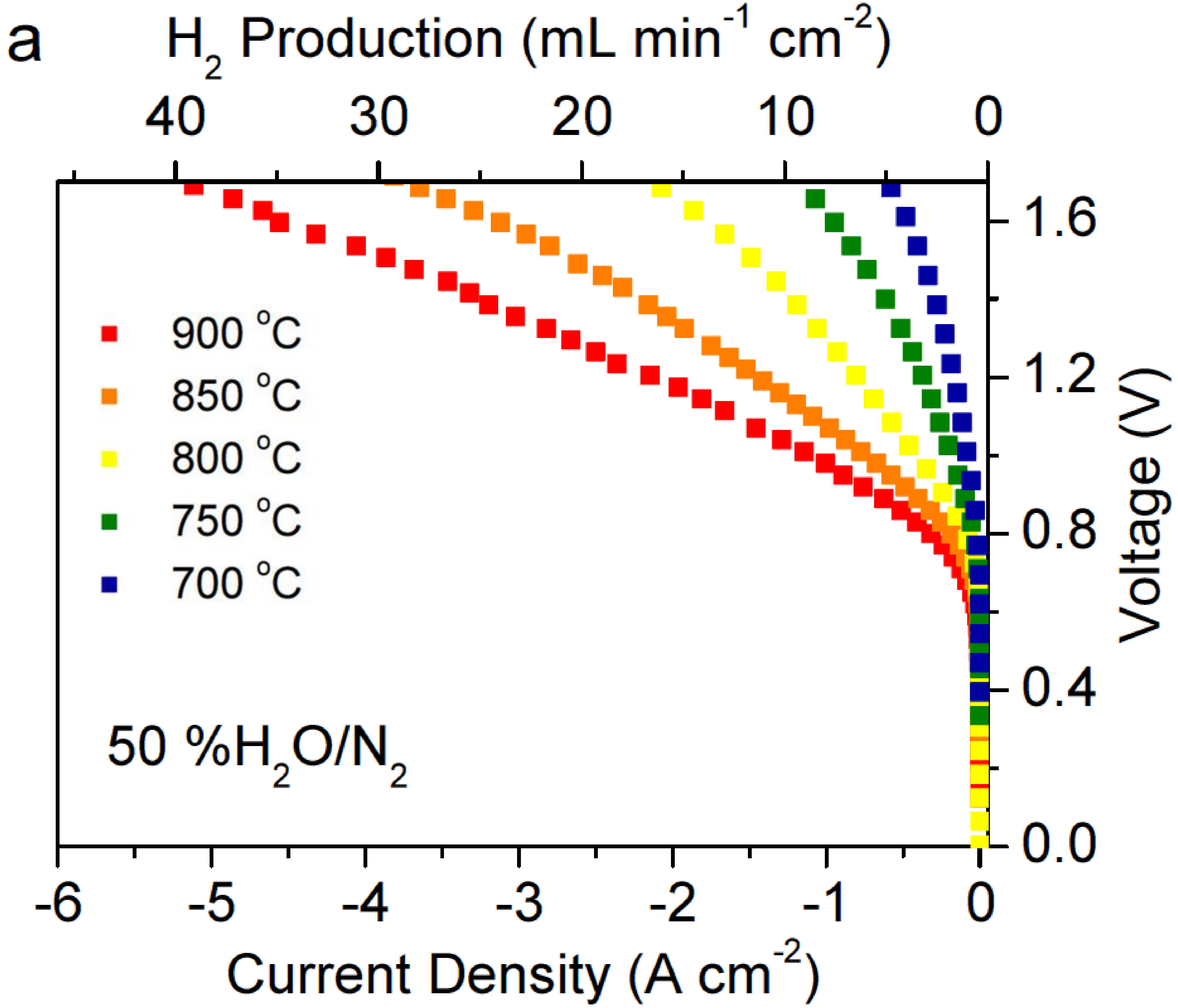
after 100 h of fuel cell testing at 750 ℃ in 3% H_2O/H_2 at 0.7 V




5% H_2/N_2
($pO_2 \sim 10^{-19}$ atm)
50% H_2O/N_2
($pO_2 \sim 10^{-35}$ atm)
-
+
2V

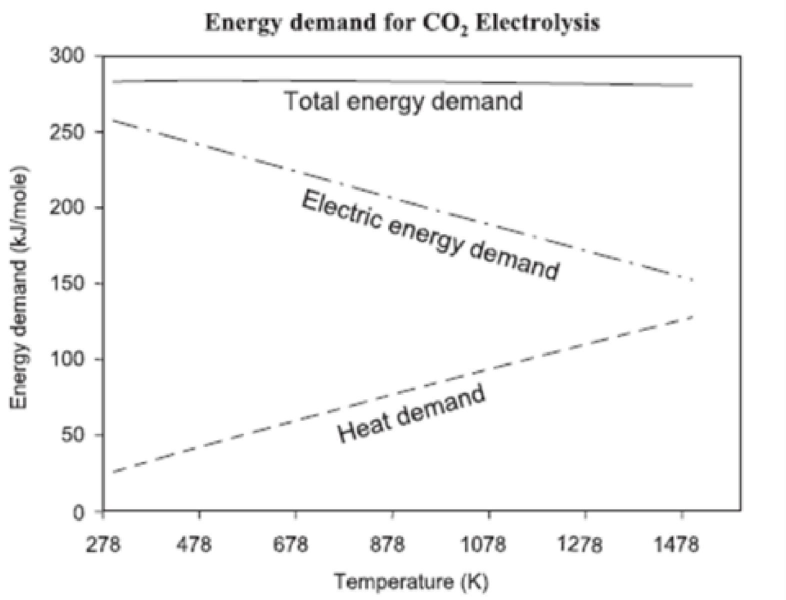


Solid oxide cell based on electrochemical switching.
reversible cell mode in 50% H_2O/H_2. 80 μm thick electrolyte

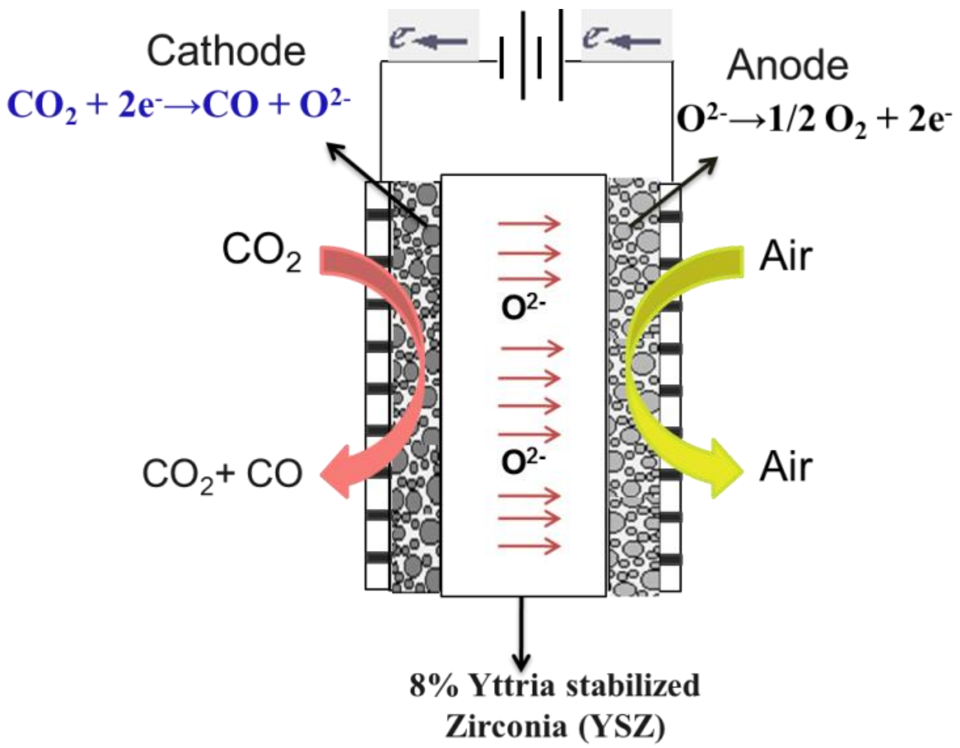


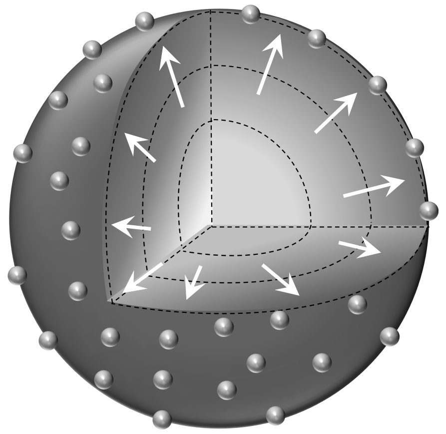
Solid oxide cell based on electrochemical switching. Current-voltage curves (square symbols) electrolysis mode under 50% H_2O/N_2, also showing equivalent H_2 production assuming 100% Faradaic efficiency

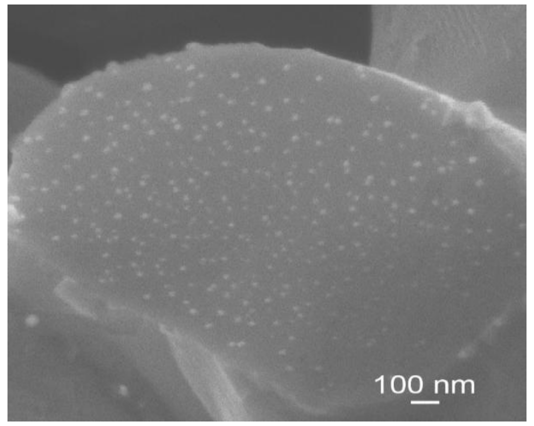
Carbon Dioxide electrolysis to syngas via oxide or protonic conduction



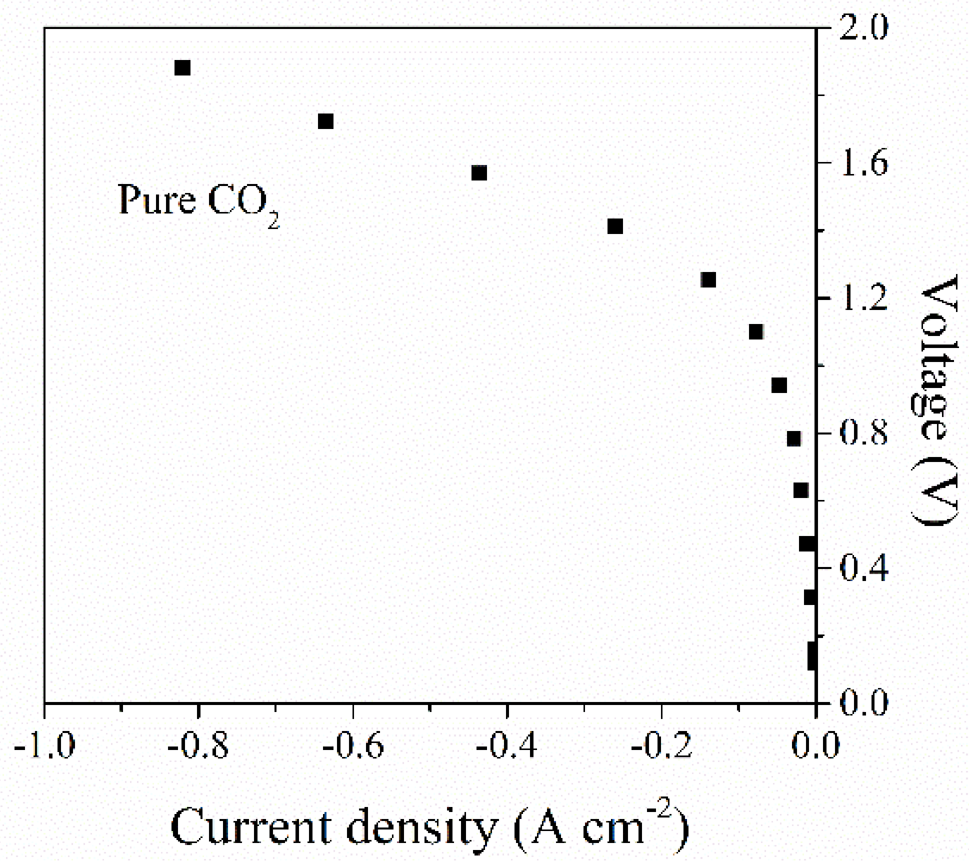
Advantage of high temperature CO_2 electrolysis



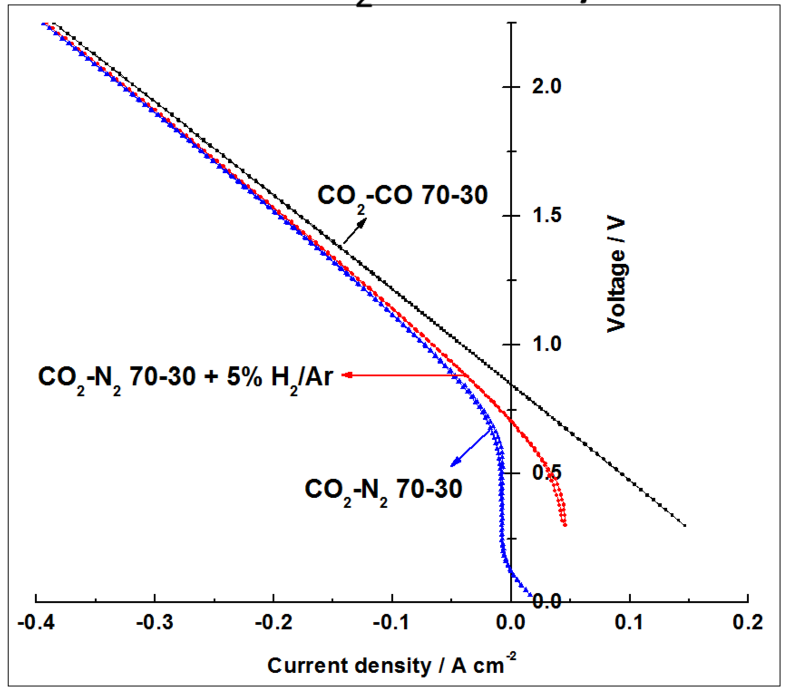




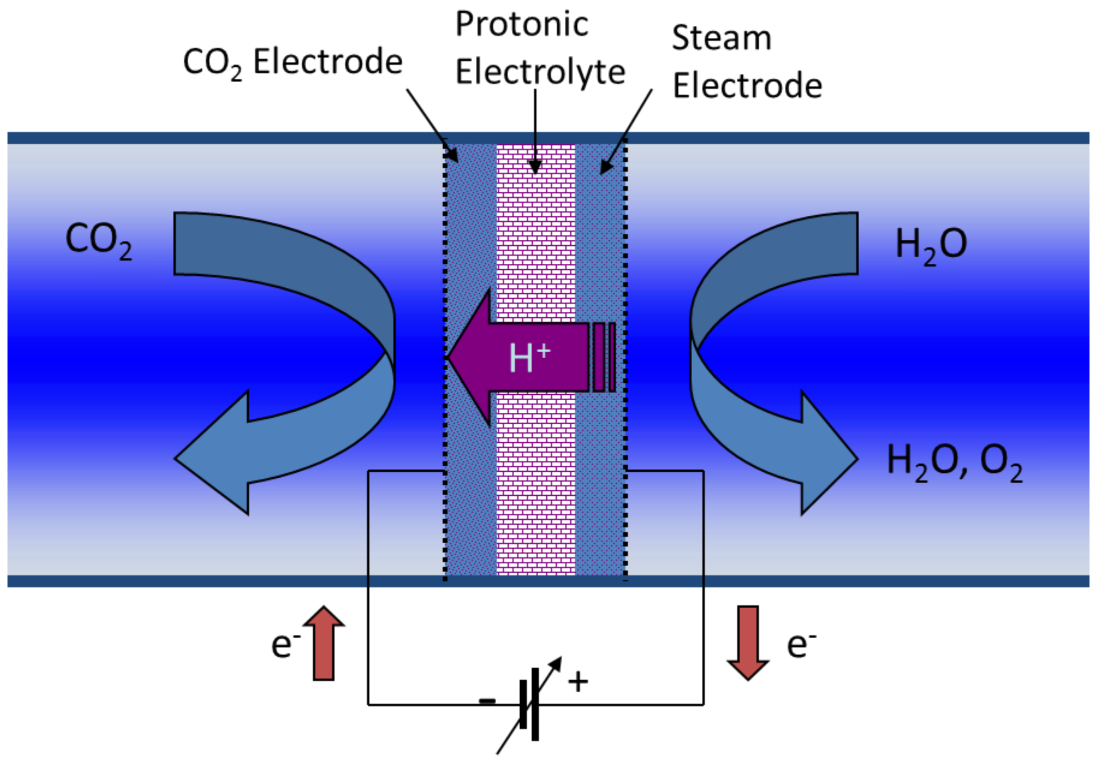
CO_2 Electrolysis at $La_{0.43}Ca_{0.37}Ni_{0.06}Ti_{0.94}O_3$
Electrochim. Acta. **306**, 159



Direct CO_2 Electrolysis

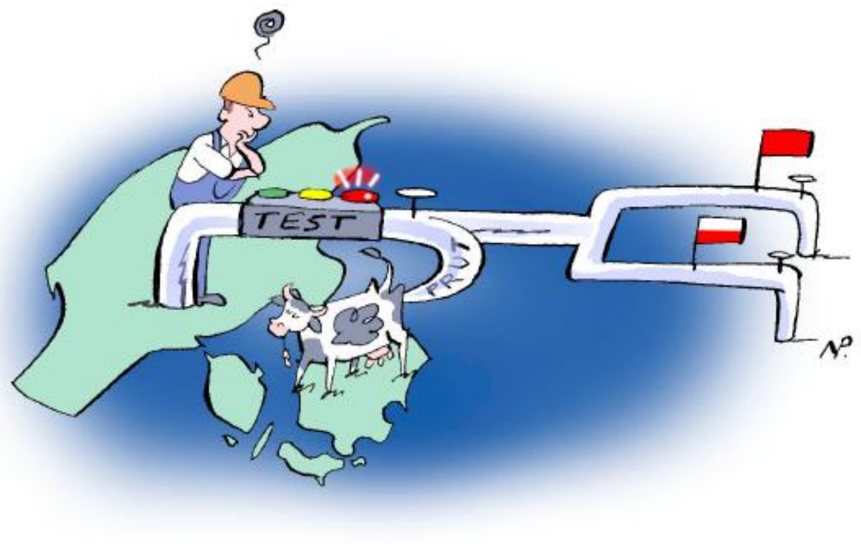


GDC impregnated LSCM cell



Danish 2050 model
Green gas system linked to SOFCs and SOECs

- Increased use of methane and “green” gases
- SOEC can produce methane to the gas system when electricity prices are low
- Possibilities for storage of heat and gas help prevent overflow and deficiency in the electricity system
- High prices: SOFC production of electricity and heat
- Low prices: SOEC production of methane



Acknowledgements

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