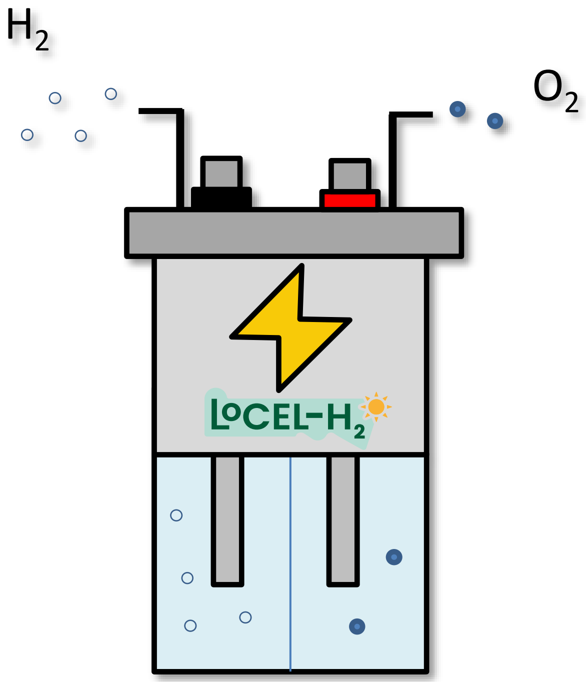
Hydrogen Winter School – Loughborough University

Elizabeth Ashton

Elizabeth Ashton

Research Associate at Loughborough University

Combined battery and electrolyser



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Contents

LoCEL-H_2

HyDEX

- Introduction – current green hydrogen production
- Combined battery and electrolyser
- Application
- LoCEL-H_2 project
- Technology development
- Conclusion – future plans

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Colours of Hydrogen

GREY HYDROGEN

Generated through SMR* using natural gas or fossil fuels

BLUE HYDROGEN

Generated through SMR with carbon capture using natural gas or fossil fuels

GREEN HYDROGEN

Generated through electrolysis using renewable electricity

YELLOW HYDROGEN

Generated through electrolysis using solar power, specifically

PINK HYDROGEN

Generated through electrolysis using nuclear energy

**SMR = steam methane reformation*

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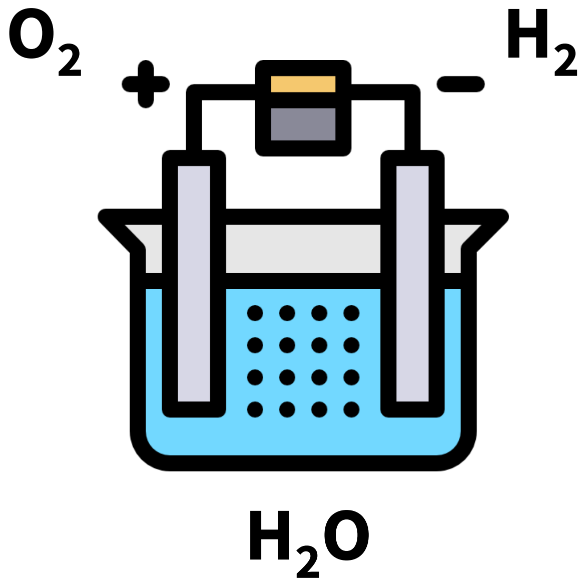
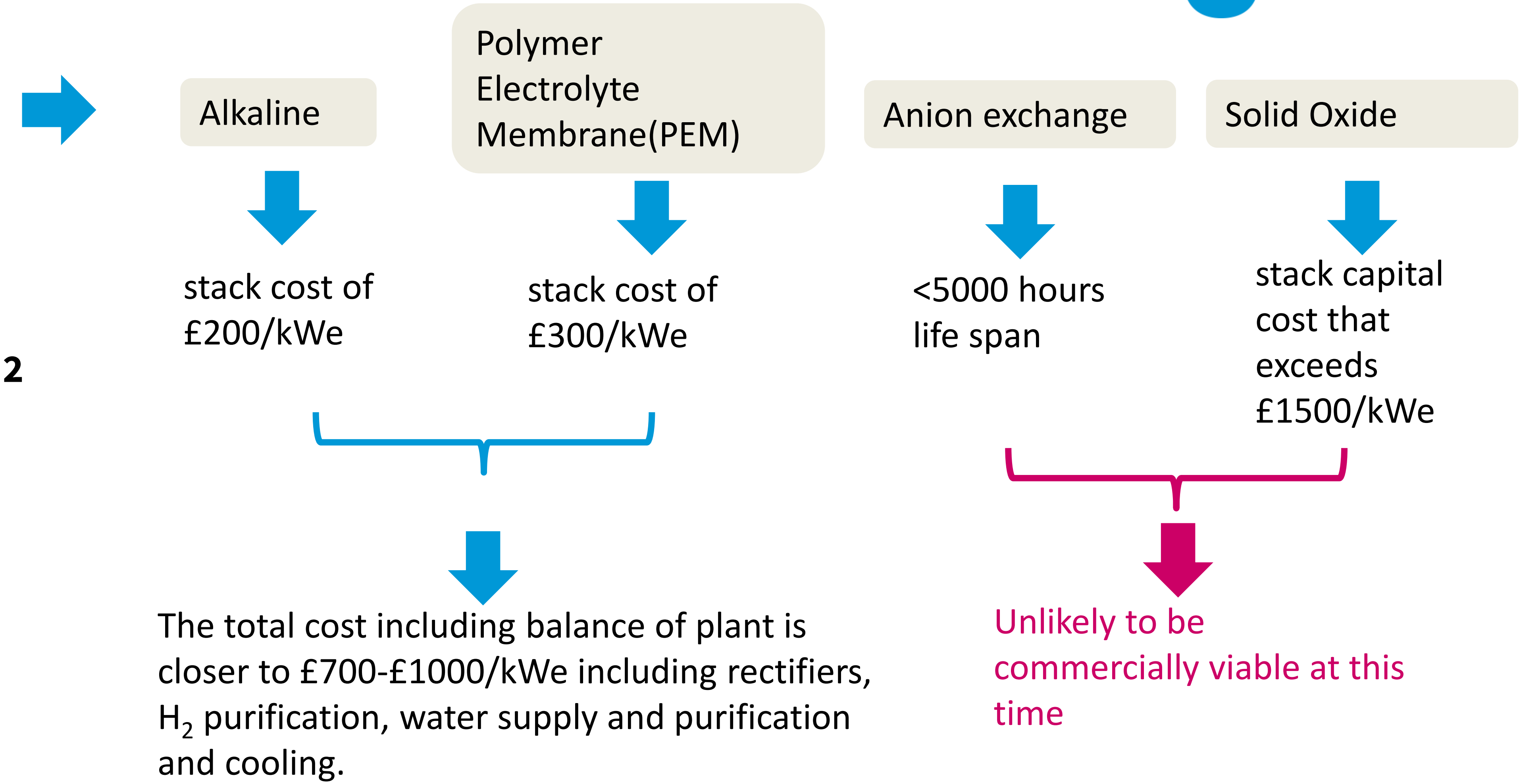
Green Hydrogen

1. Electrolysis of Water
2. Thermochemical
3. Photochemical
4. Biochemical
5. Photosynthesis





Alkaline

stack cost of £200/kWe

Polymer Electrolyte Membrane(PEM)

stack cost of £300/kWe

Anion exchange

<5000 hours life span

Solid Oxide

stack capital cost that exceeds £1500/kWe

The total cost including balance of plant is closer to £700-£1000/kWe including rectifiers, H_2 purification, water supply and purification and cooling.

Unlikely to be commercially viable at this time

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Electrolyser – economics

Element	Approx. Global abundance mg/L [1]	Cost $/g [2]	CO_2 used in extraction [3]
Platinum	0.005	$27	12,500kg CO_{2e}/kg
Iridium	0.001	$196	8,860kg CO_{2e}/kg
Lead	14	$0.002	1.3kg CO_{2e}/kg

- Annual production of Iridium & Platinum only able to support 3-7.5GW of electrolyser production annually [4].
- Using significant amounts of these materials to scale up production goes against the government mandate to reduce scarce material utilisation.
- Most electrolysis units are manufactured at around 1MW, however, there are plans for a 20MW trial unit.
- Other methods are at trial stage and not close to commercialisation

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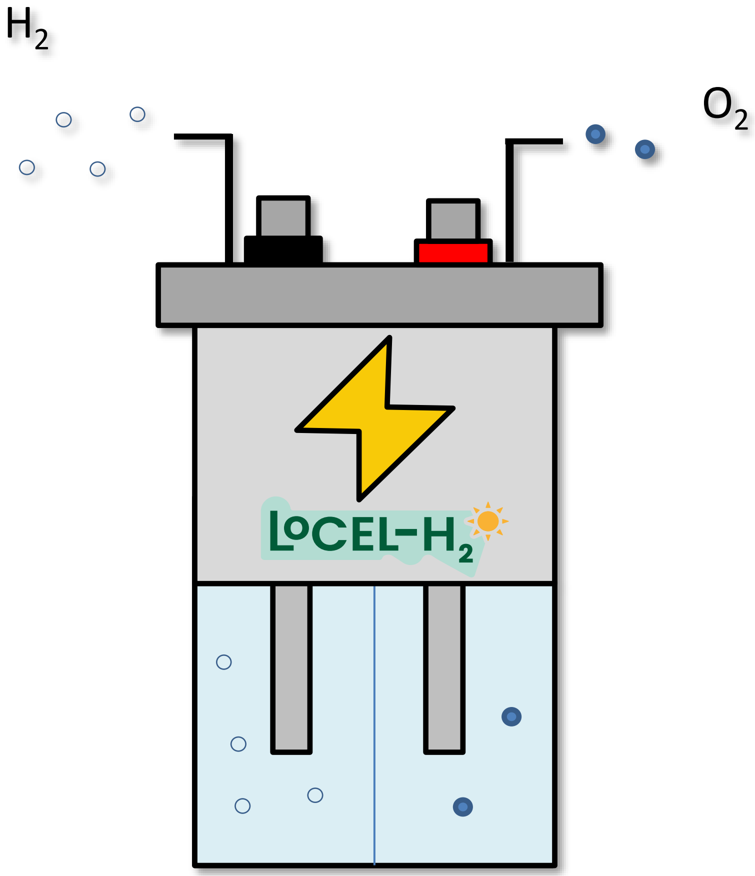
COMBINED BATTERY AND ELECTROLYSER



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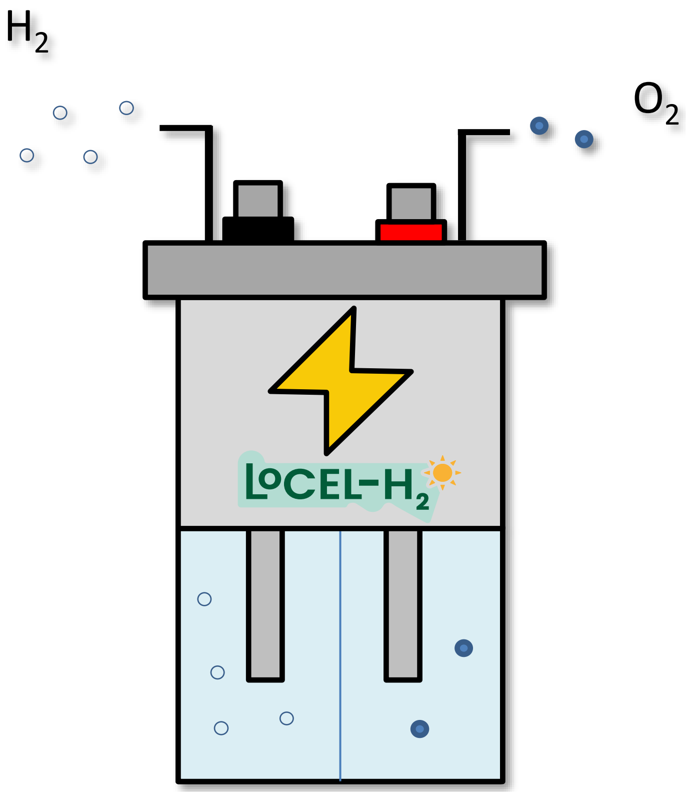
Combined battery and electrolyser

Lead acid battery technology allows the cell to charge and discharge as a battery

Electrolysis occurs when the cell is over charged – splitting water from the electrolyte into H_2 and O_2 gas.



Hydrogen gas is collected at the negative electrode as a method of chemical energy storage during excess renewable energy production

Renewable energy is stored either as electrical energy in the battery or chemical energy as hydrogen gas

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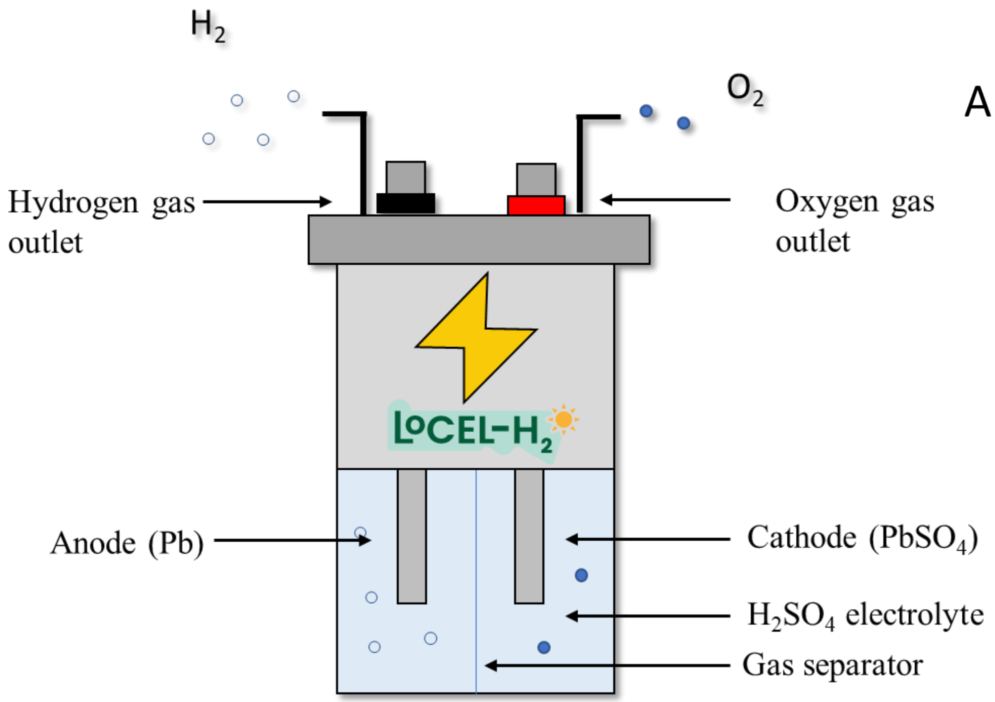
Combined battery and electrolyser



Battery

Cathode: $Pb + {SO_4}^{2-} \leftrightarrow PbSO_4 + 2H^+ + 2e^-$ $(E^0 = 0.36\ V)$

Anode: $PbO_2 + {SO_4}^{2-} + 4H^+ + 2e^- \leftrightarrow PbSO_4 + 2H_2O$ $(E^0 = 1.69\ V)$

Overall: $PbO_2 + Pb + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O$ $(E^0 = 2.05\ V)$

Electrolyser

Cathode: $2H^+ + 2e^- \rightarrow H_2$

Anode: $H_2O \rightarrow {}^1/_2\, O_2 + 2H^+ + 2e^-$

Overall: $H_2O \rightarrow 2H_2 + {}^1/_2\, O_2$

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Comparison of :

- Battery
- Electrolyser
- Battolyser

Using published data on a curtailed 1GW wind farm

Energy Storage device	Battery Round Trip Efficiency	Hydrogen production efficiency
Battery	80%	-
Electrolyser	-	80%
Battery electrolyser	80%	62%

Cost range: 100-700K

Battery	Min-Max cost range (£k/MW for 1hr storage)
Capex cost Lithium Ion (encompassing NMC, LFP and LTO)	£147k - £697k
Lead Acid	£98.4k - £238k
Opex cost (pa)	£8k-£10.3k

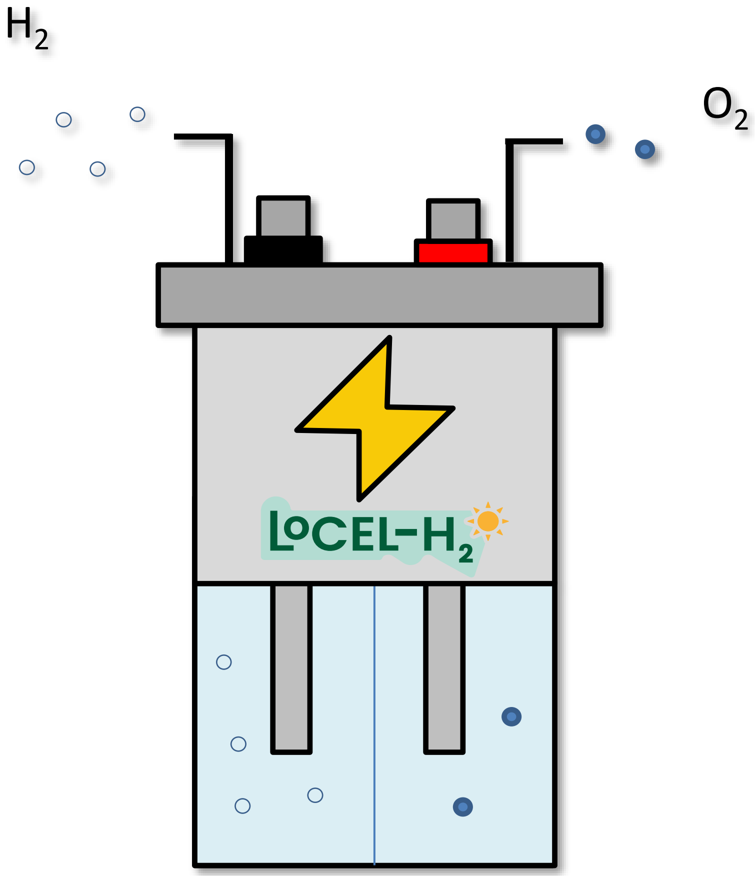
Cost range: 500-1800K

Electrolyser	Min-Max cost range (£k/MW for 1hr storage)
Capex cost Electrolyser (encompassing Alkaline and PEM)	£410k - £1476k
BOP	£80k - £362k
Opex cost (pa including stack replacement x2)	£93k-£104k

Cost range: 180-550K

Battery electrolyser	Min-Max cost range (£k/MW for 1hr storage)
Capex cost Lead acid battolyser (battery part)	£98.4k - £238k
Capex cost Lead acid battolyser (hydrogen part)	£80k - £362k
Opex cost (pa)	£8.4k-£18k

APPLICATIONS



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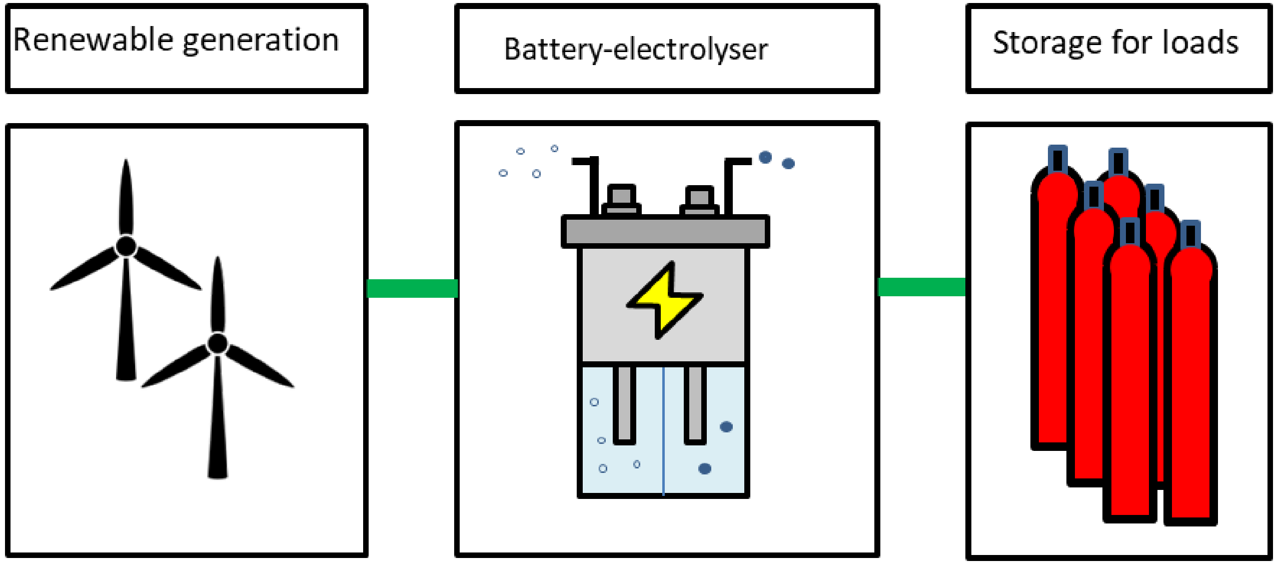
Applications – wind

There is currently no low-cost electrolyser on the market that works with poor load factor such as renewable generation

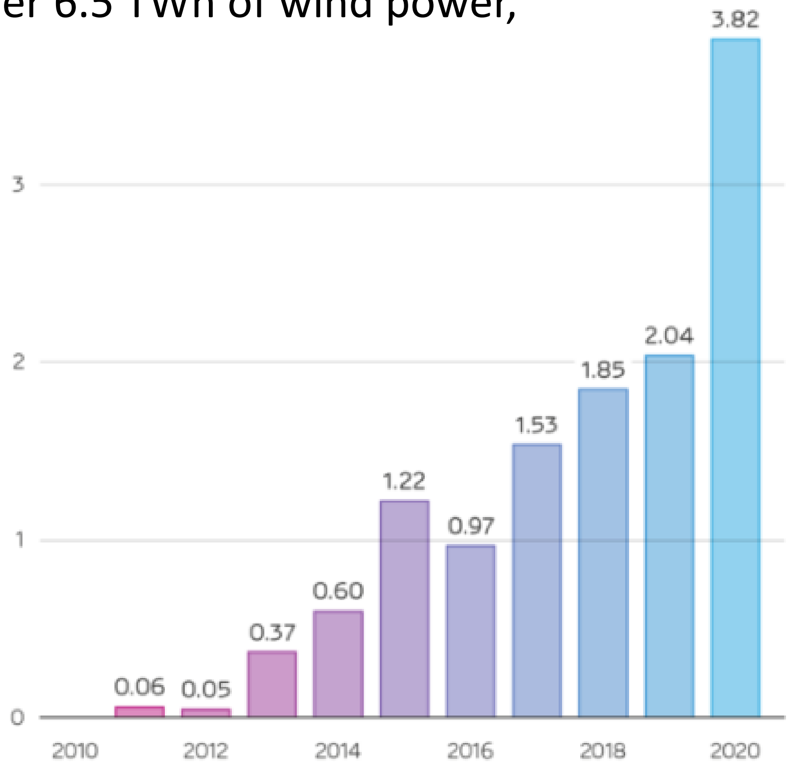
In the UK, from January 2021 to April 2023, £1.5 billion was invested to curtail over 6.5 TWh of wind power, resulting in 2.5 million tonnes of CO_2 emissions[1]



Renewable generation

Battery-electrolyser

Storage for loads



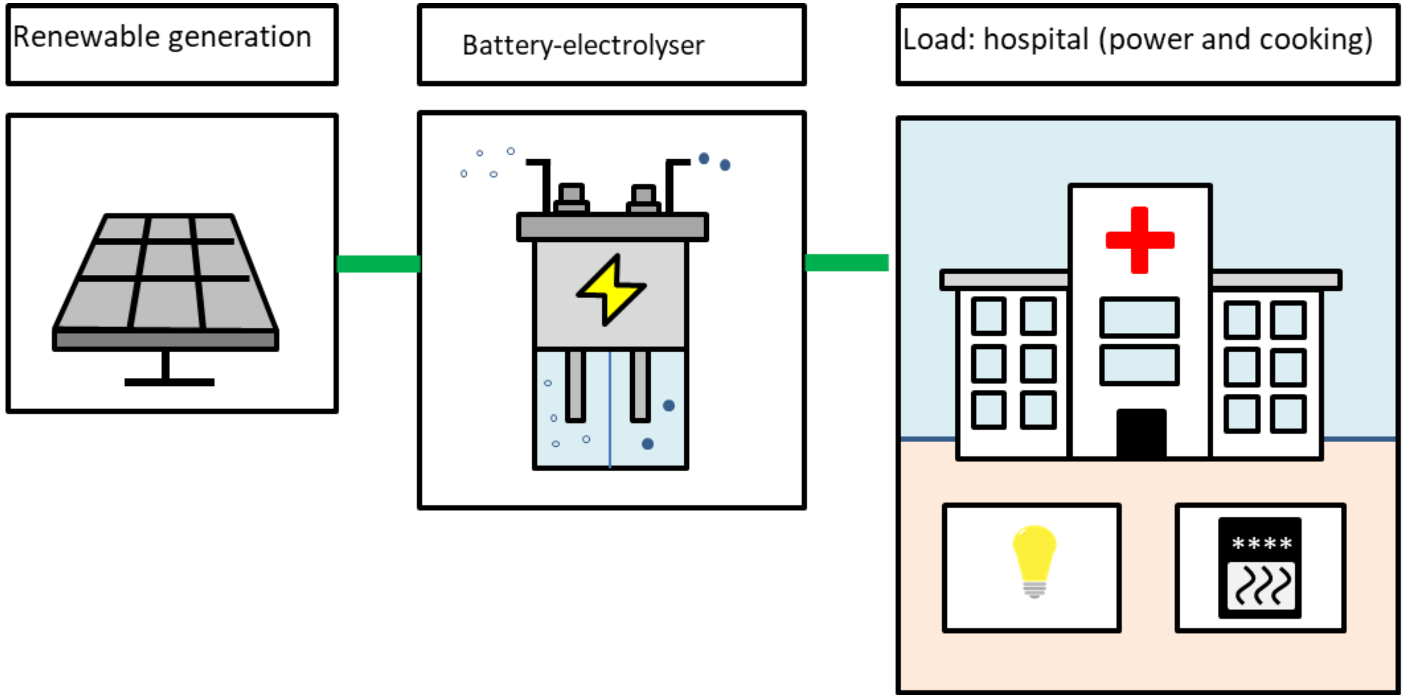
https://reports.electricinsights.co.uk/q4-2020/record-wind-output-and-curtailment/

Applications – solar

There is currently no low-cost electrolyser on the market that works with poor load factor such as renewable generation

In Africa, about 1 billion people rely on polluting fuels, like wood, charcoal and kerosene for cooking, lighting and heating.

This causes around 700,000 premature deaths yearly—10% of total mortality in the region.


Renewable generation

Battery-electrolyser

Load: hospital (power and cooking)

https://www.nihr.ac.uk/case-studies/clean-air-africa (accessed 30 December 2023)

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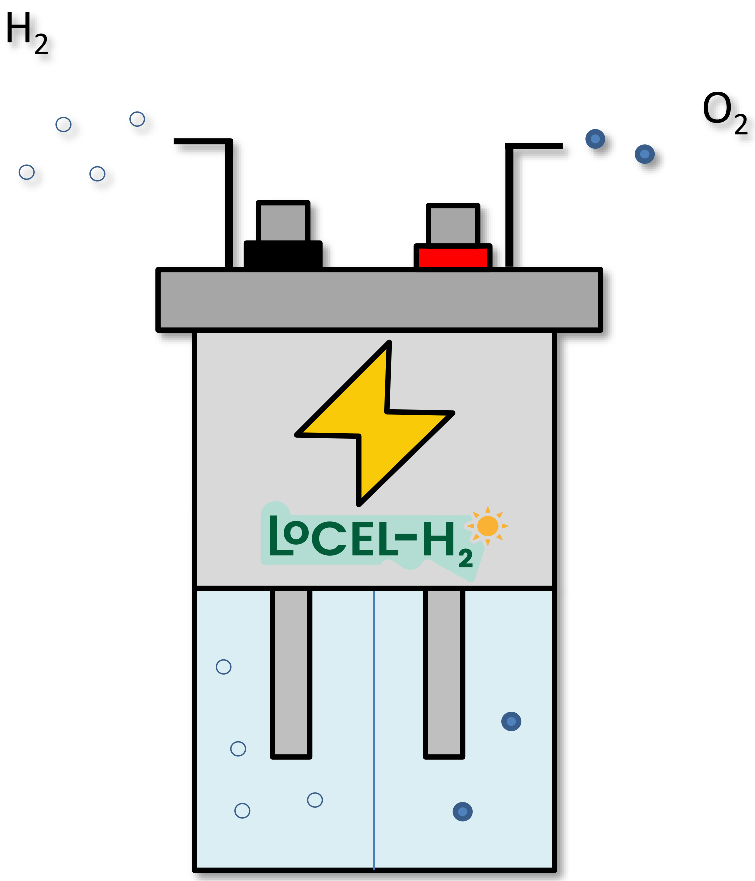
LOCEL-H2 PROJECT



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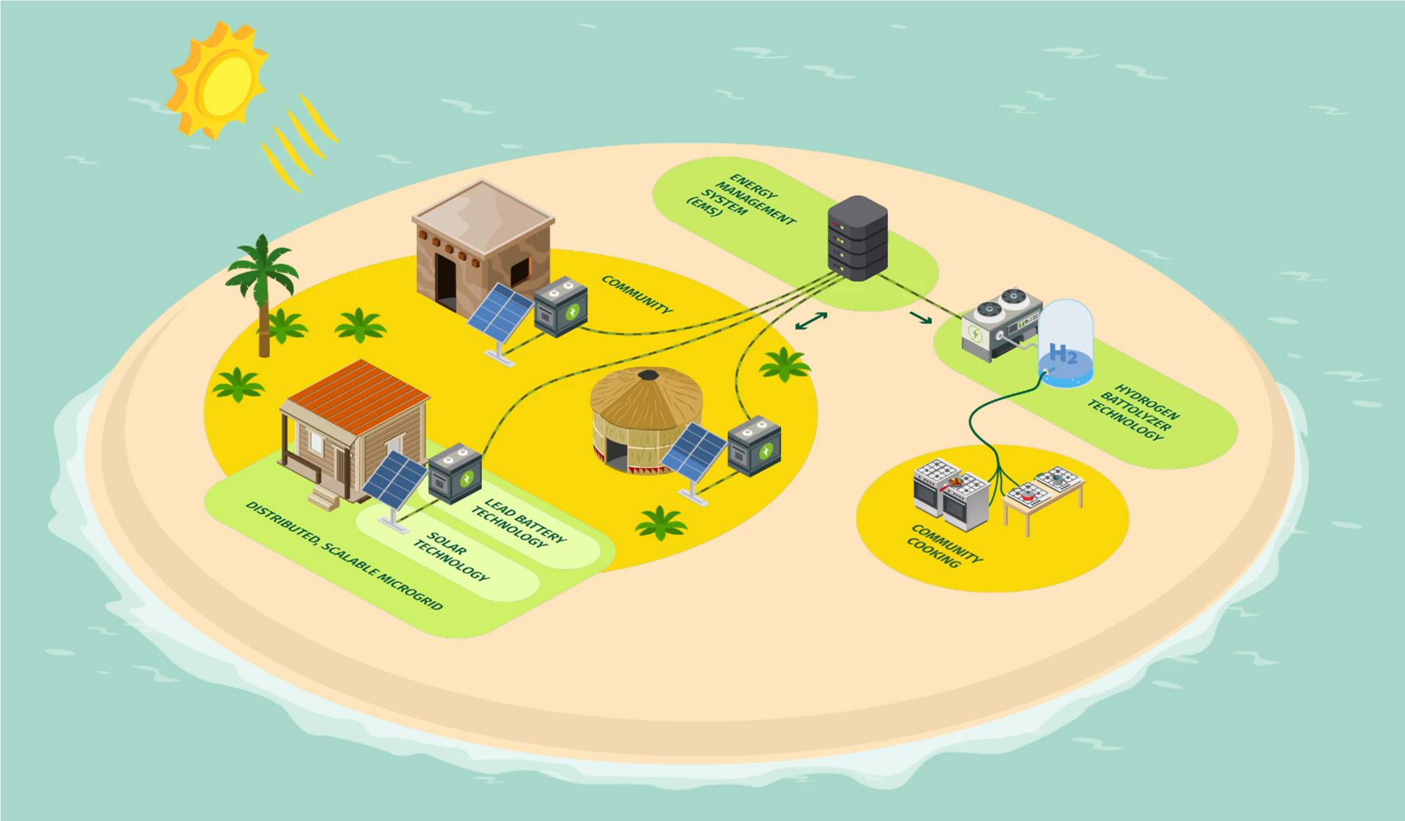
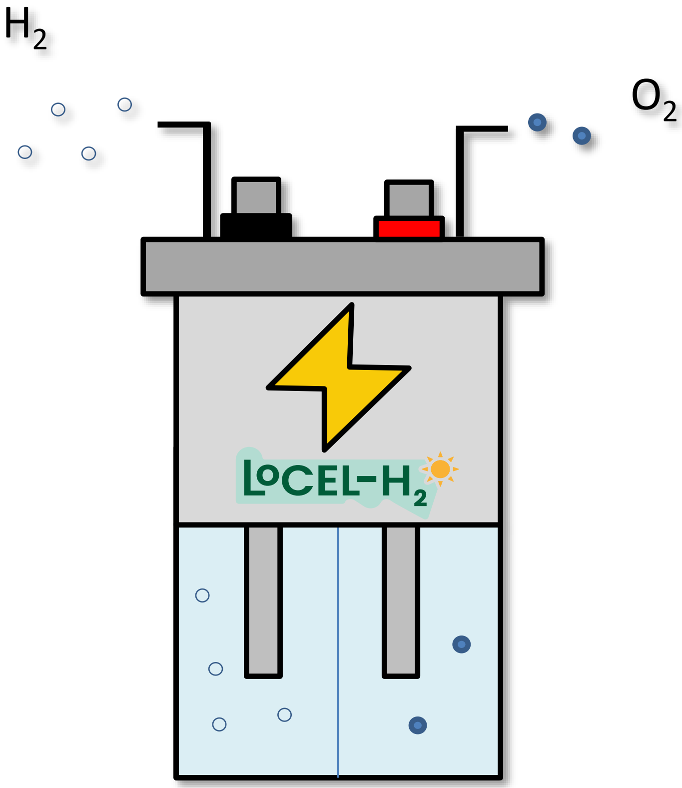
LoCEL –H_2 Project

Two pilot programs, one located in Zambia and the other in the Ivory Coast.





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LoCEL –H_2 Project

LoCEL-H_2

HyDEX

LoCEL-H2 Consortium

cea

Consortium for Battery Innovation

Hollingsworth & Vose Creating a Cleaner World

HOPPECKE POWER FROM INNOVATION

Loughborough University

LUMS A Not-for-Profit University

RHYDE Réseaux hydrogène décarboné

SUKKOFA ENERGY

Université de Gabès

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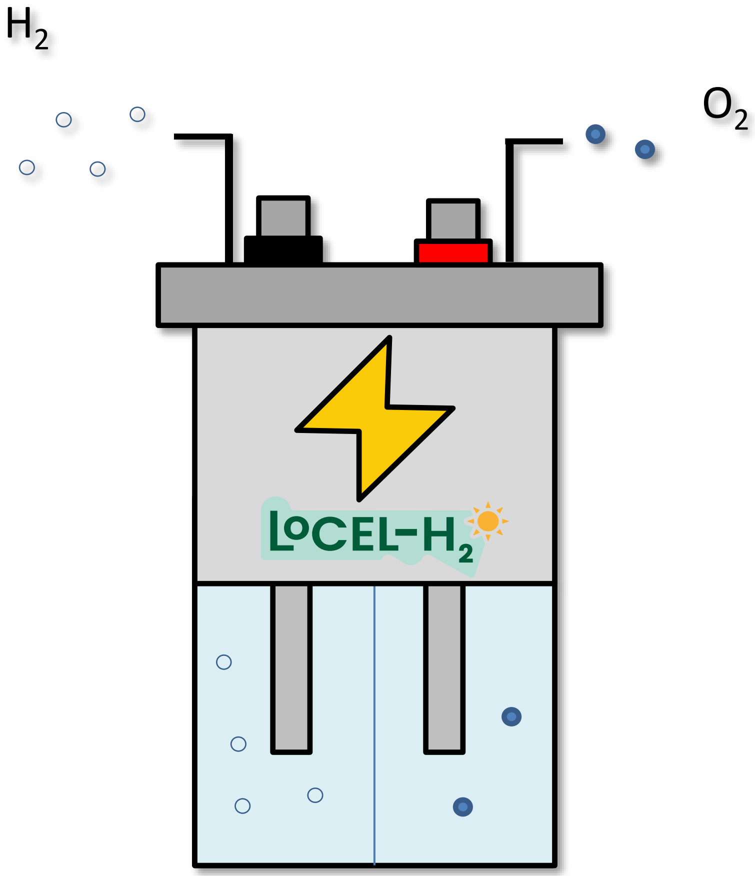
TECHNOLOGY DEVELOPMENT



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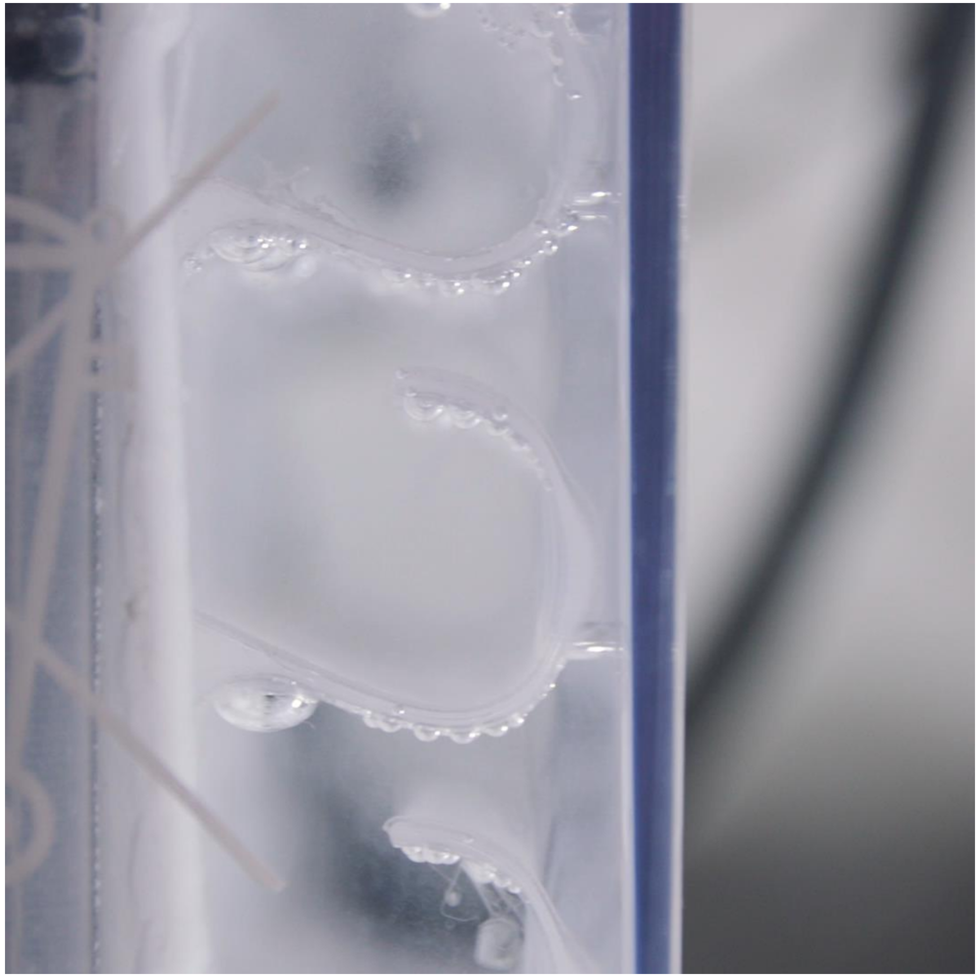
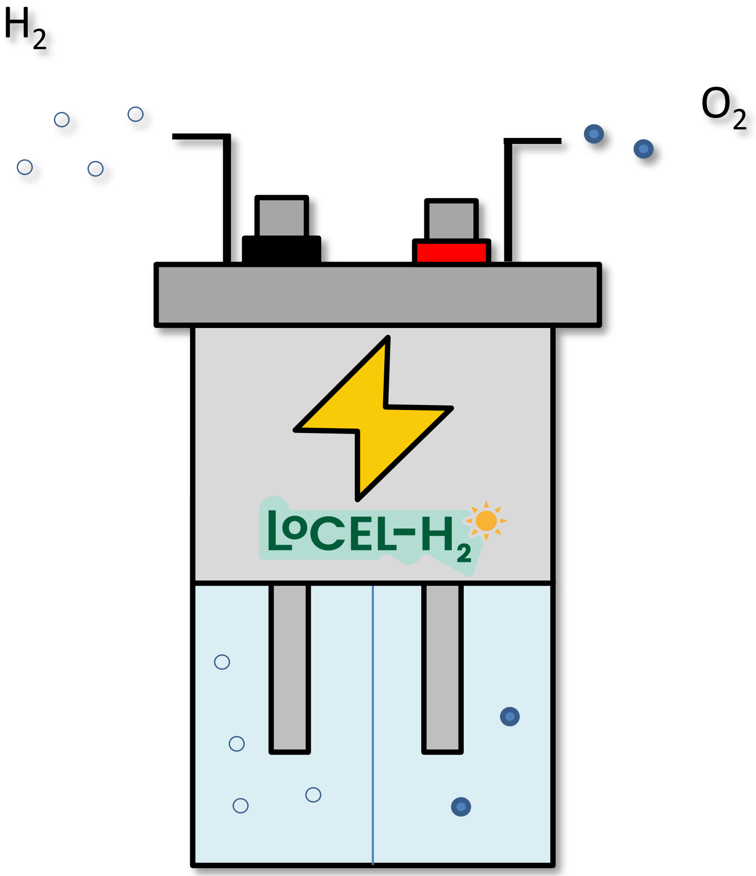
Combined battery electrolyser video





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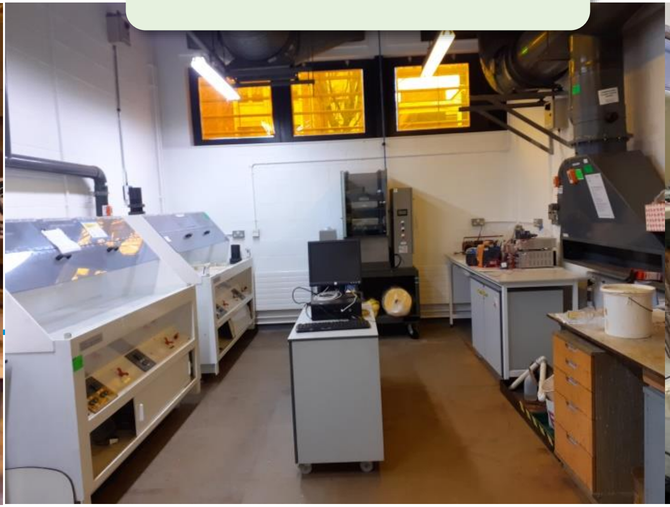
Laboratory set-up

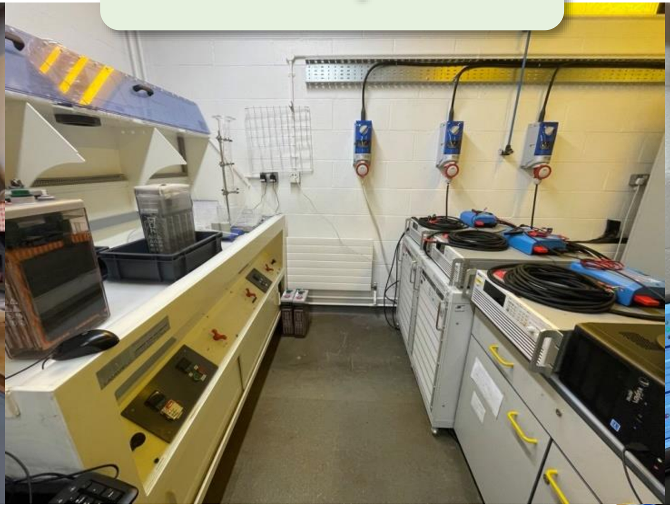
- New laboratory set up.
- Installation of fume hoods, sockets, power supply and load banks.
- Three full scale cells now in operation.
- Multiple cell testing with automated operation and gas measurement.

January

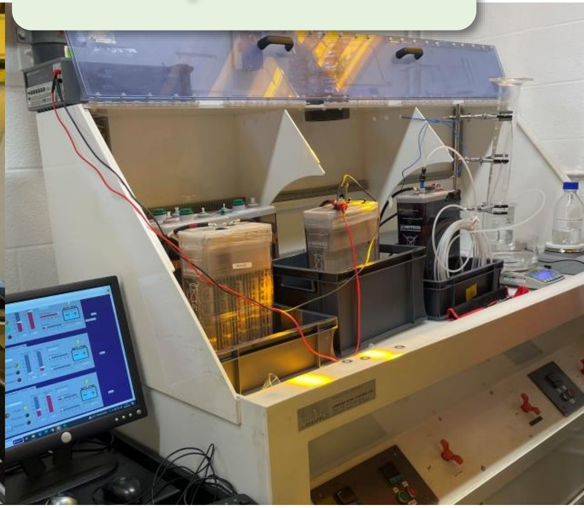
March



July



September

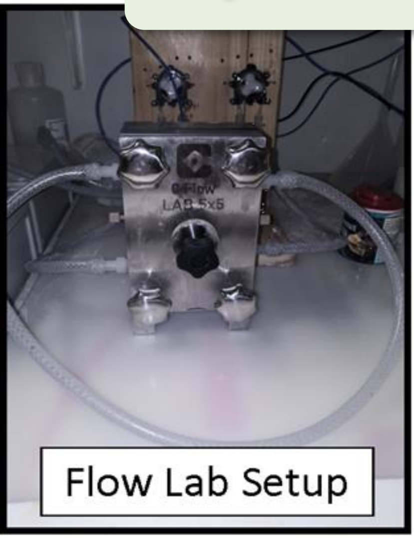


Cell design and manufacture

- Scaled up small pre-Locel-H2 test cells.
- Three full scale cells now in operation.

- Electrolyte composition including additive composition determined.
- Manufacturing process optimised.

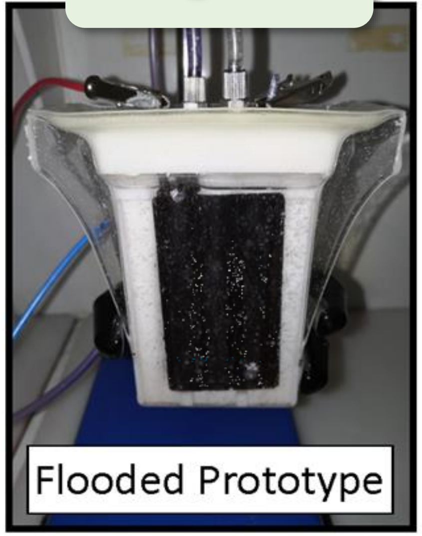
Apr 2022


Flow Lab Setup

Aug 2022

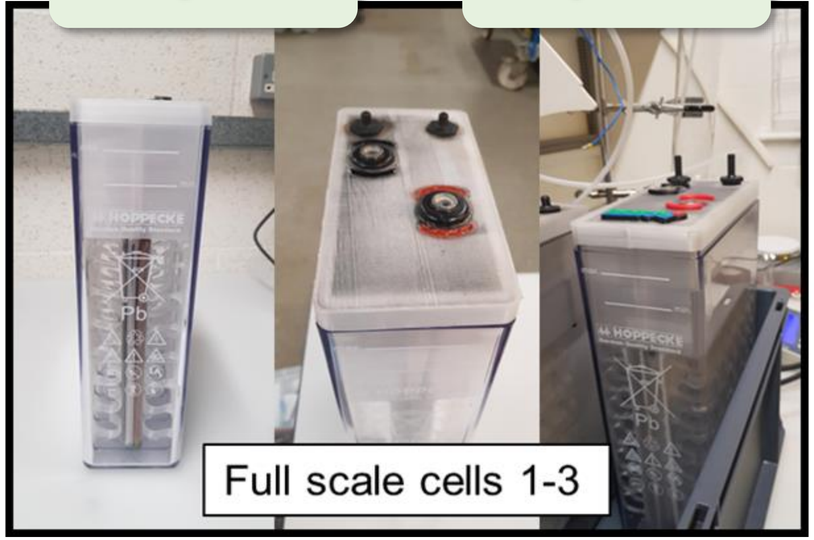

Flooded Prototype

Aug 2022

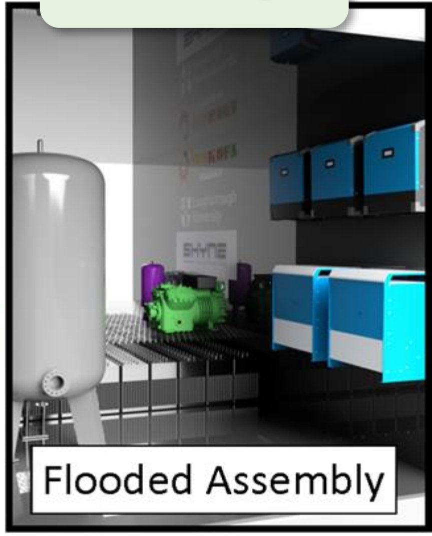

Flooded Prototype

May 2023

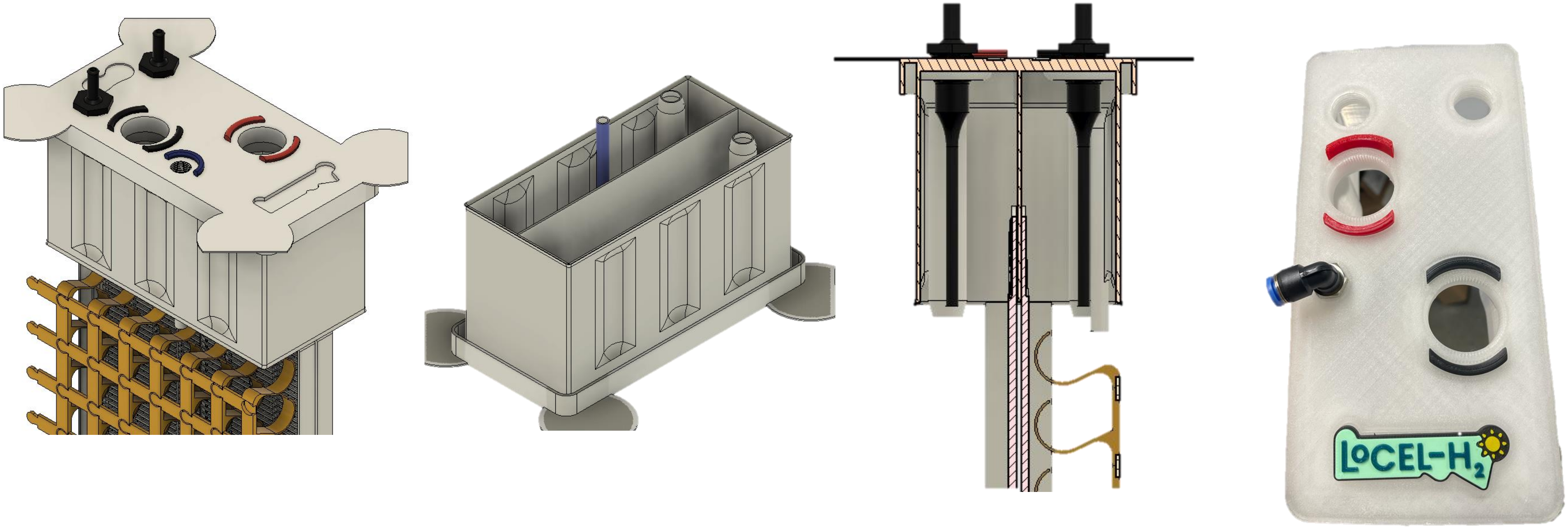
Sept 2023


Full scale cells 1-3

Next steps


Flooded Assembly

Improvements to lid design



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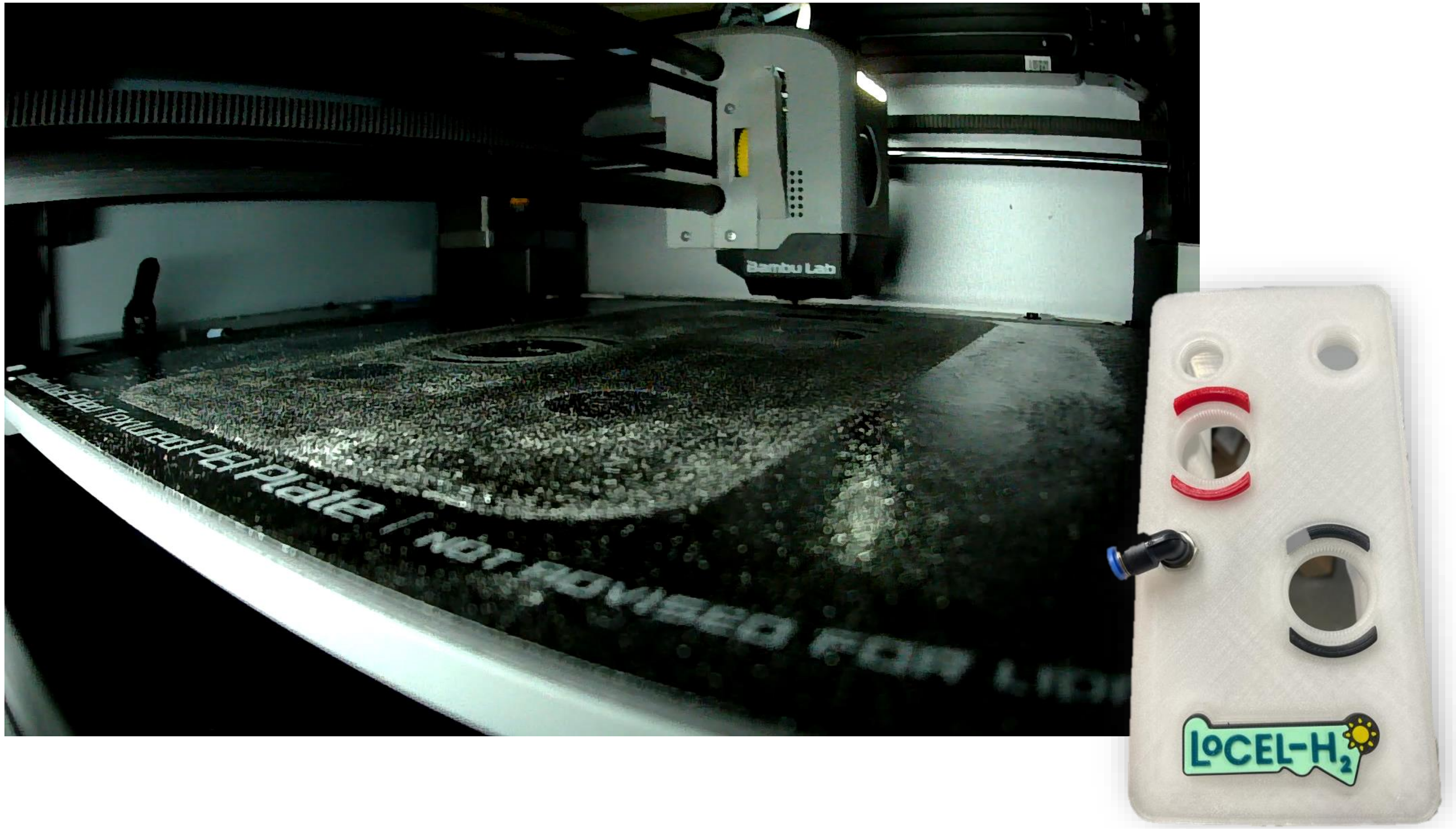
HyDEX

3D PRINTED LID DESIGN



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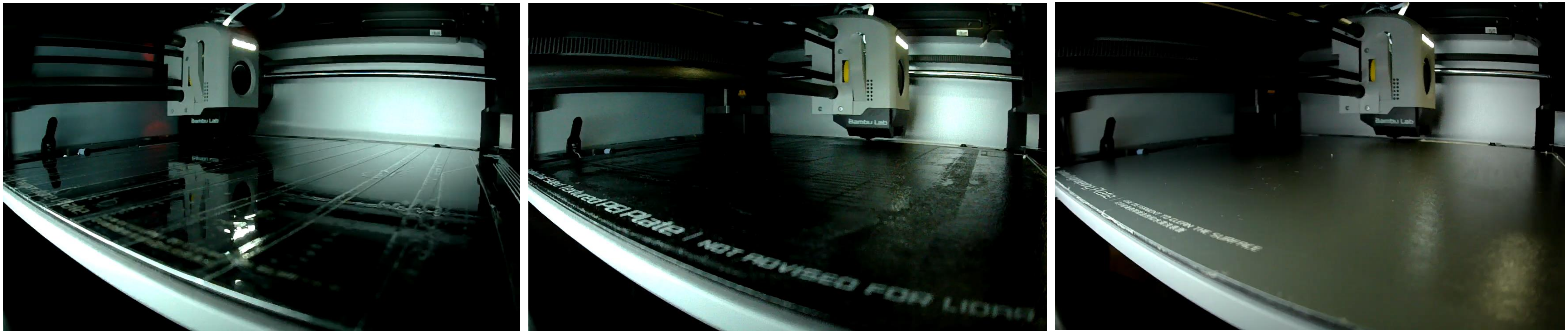
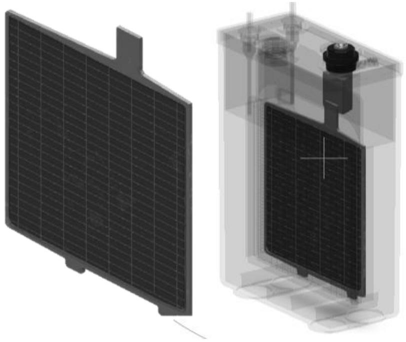
Warping issues using PP



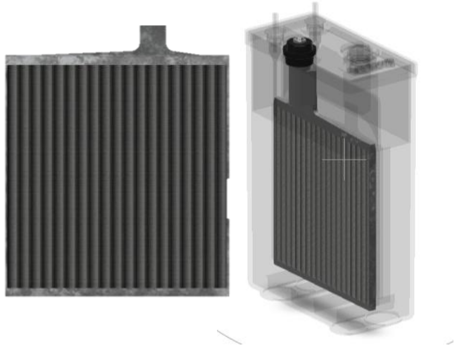
Electrode optimisation

Terminal

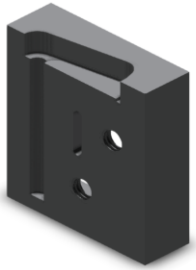
Negative electrode



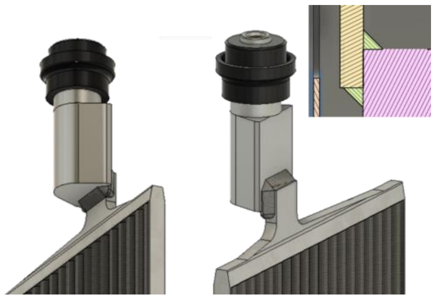
Positive electrode



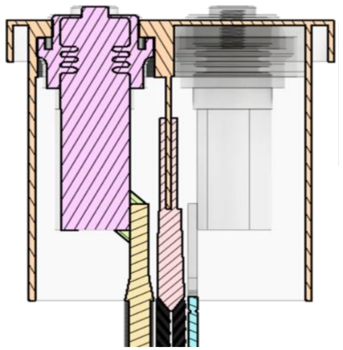
Welding rig



Idealised weld



labyrinth and weld



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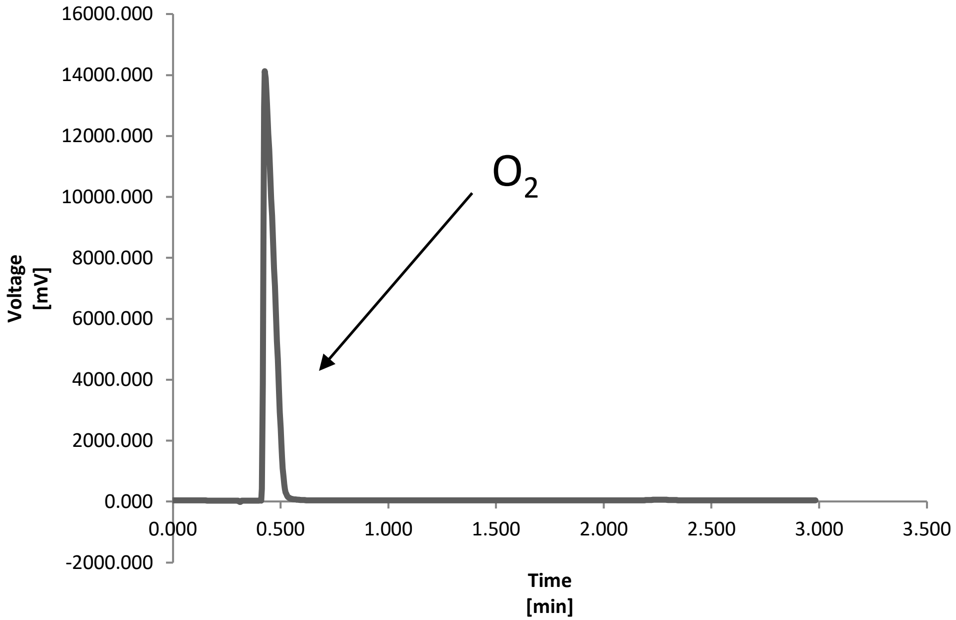
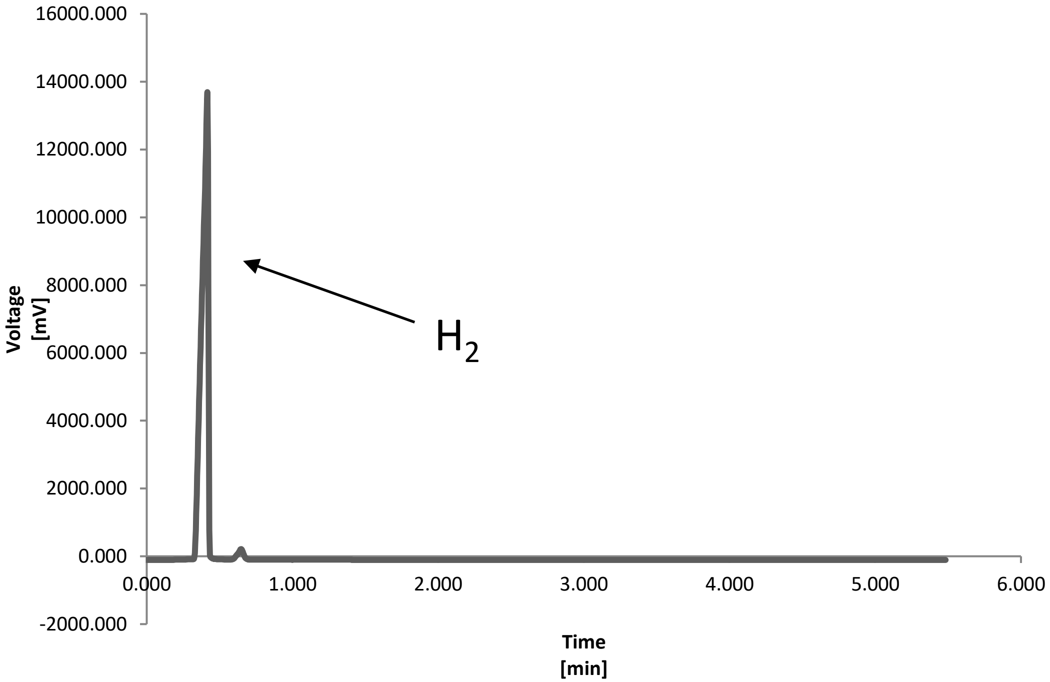
GC analysis– with gas separation

GC analysis of oxygen



GC analysis of hydrogen



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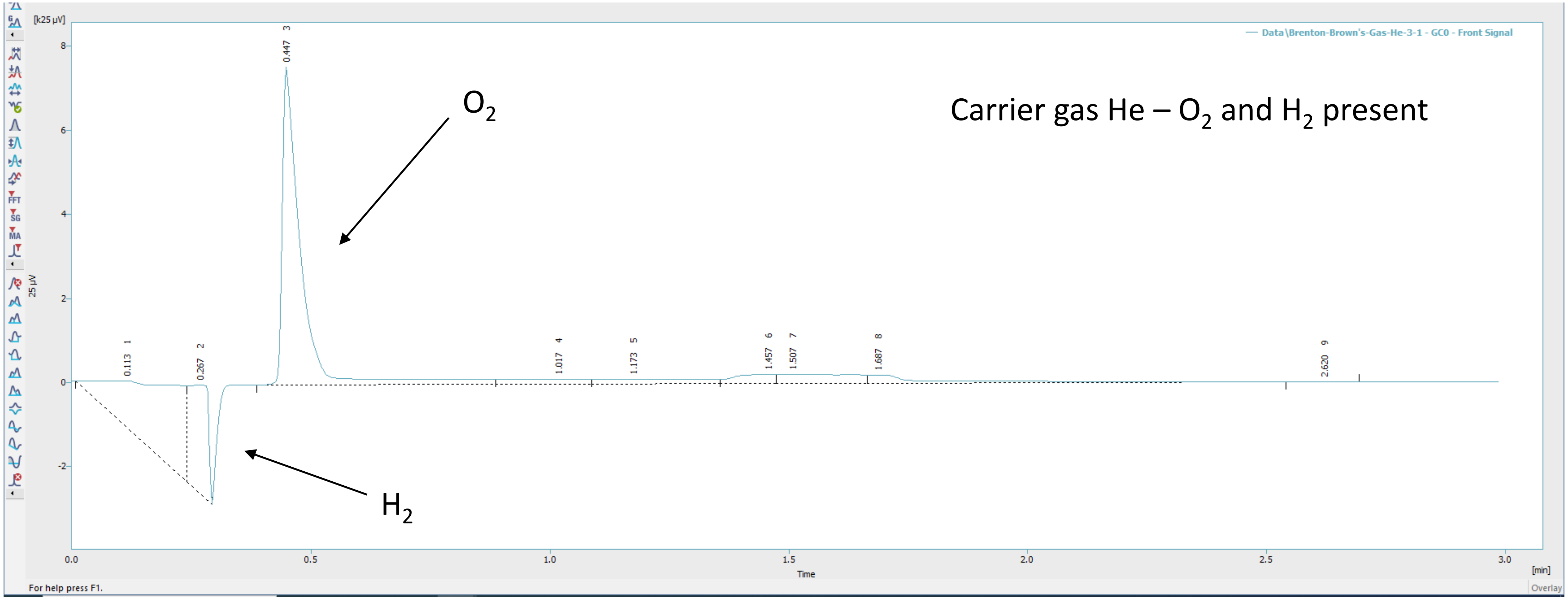
GC analysis of Hoppecke battery – without gas separation



O_2

H_2

Carrier gas He – O_2 and H_2 present

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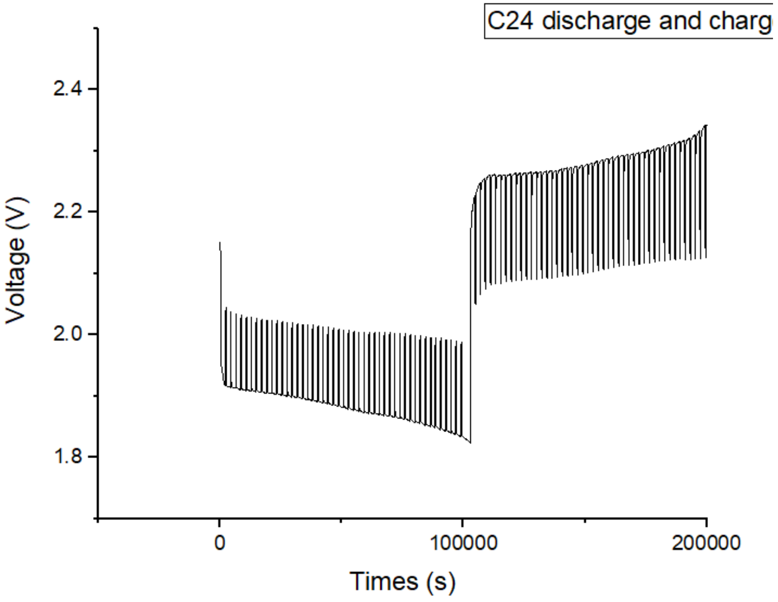
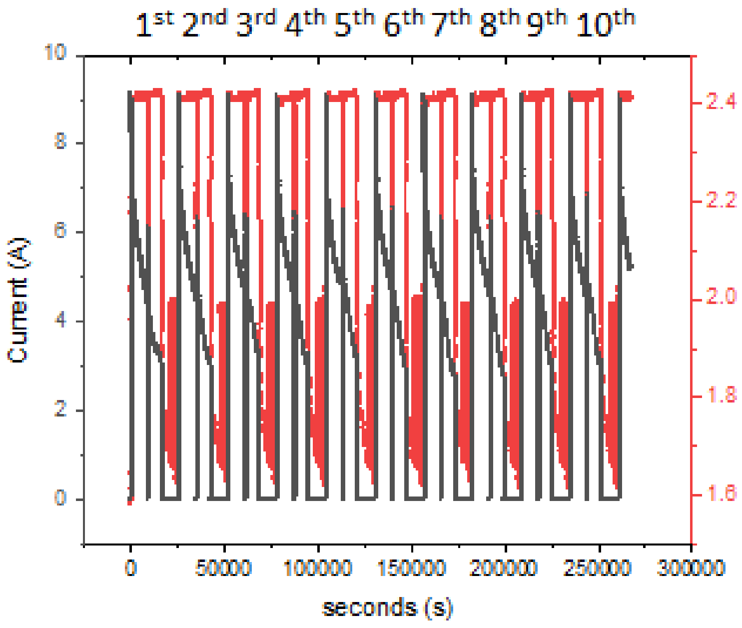
Durability and performance testing

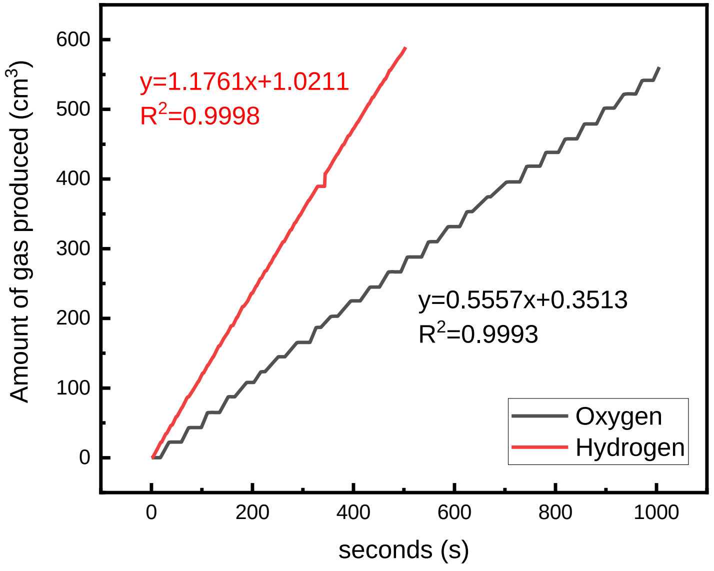
- Three full scale cells now in operation under different operating regimes.
- Automated cell cycling and data collection.
- No degradation yet recorded.



Cell 3 capacity discharge test



Cell 1 cycling



Cell 3 electrolysis test

Cell 001 – Operated as a battery

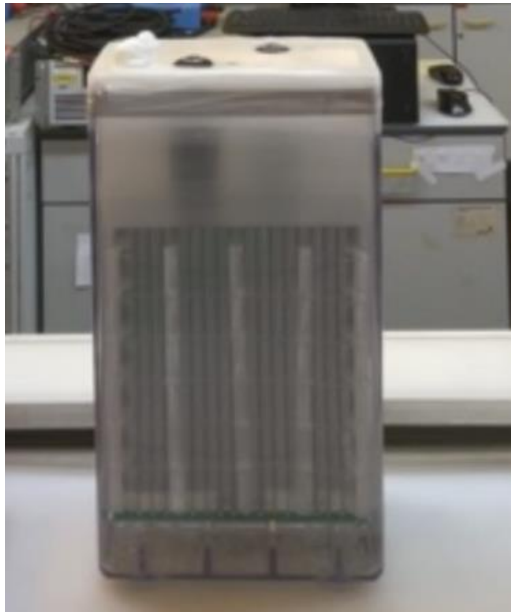
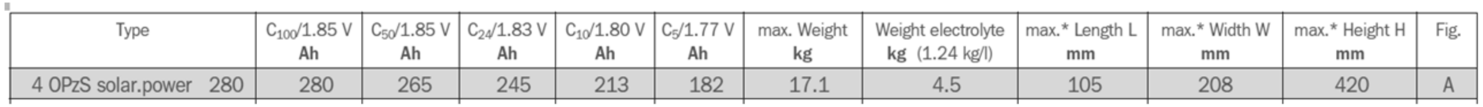


Table 1- Capacity as a function of discharge rate



Type	C_{100}/1.85 V Ah	C_{50}/1.85 V Ah	C_{24}/1.83 V Ah	C_{10}/1.80 V Ah	C_{5}/1.77 V Ah	max. Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
4 OPzS solar.power 280	280	265	245	213	182	17.1	4.5	105	208	420	A

	Capacity				
	C100 / 1.85 V (Ah)	C50 / 1.85 V (Ah)	C24 / 1.83 V (Ah)	C10 / 1.8 V (Ah)	C5 / 1.7 V (Ah)
4 OPzS solar.power 280	280	265	245	213	182
Paula (1 plate pair)	70	66.25	61.25	53.25	45.5

- C/24 2.55 A slow charge and discharge - 136.10 Wh (61.41 Ah) OCV every 30 mins.

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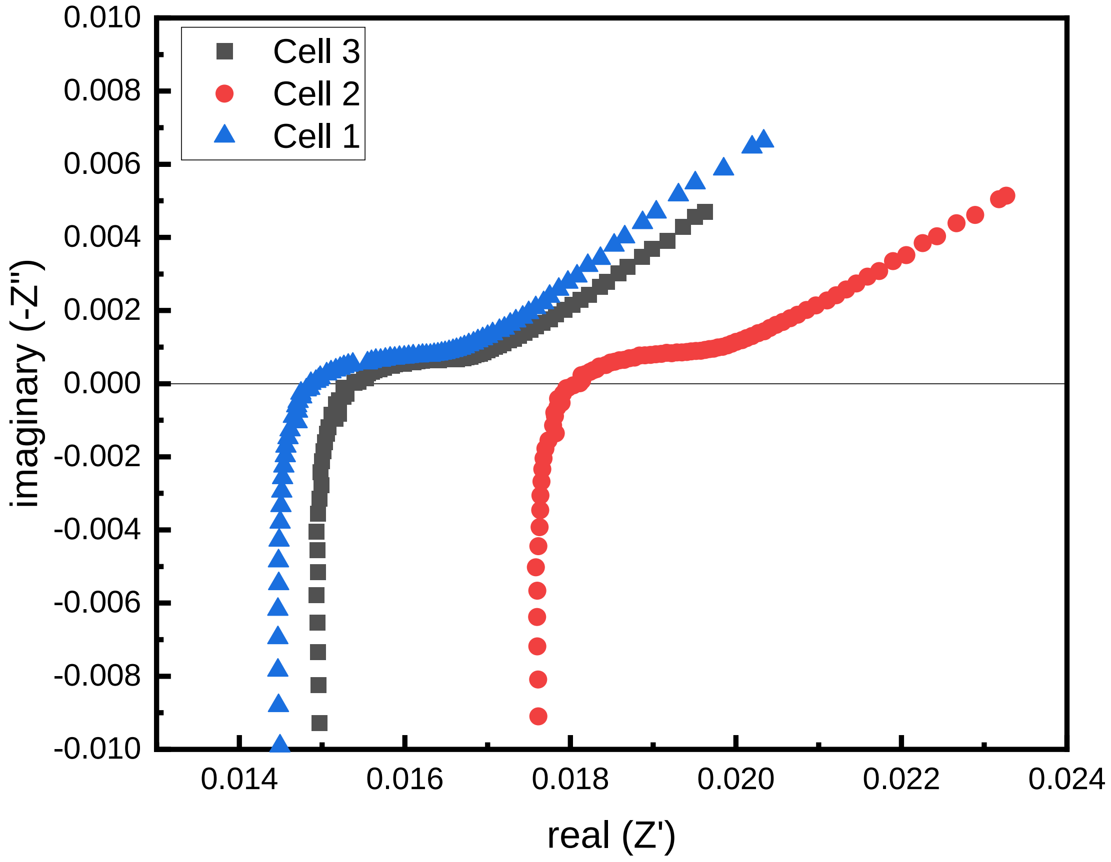
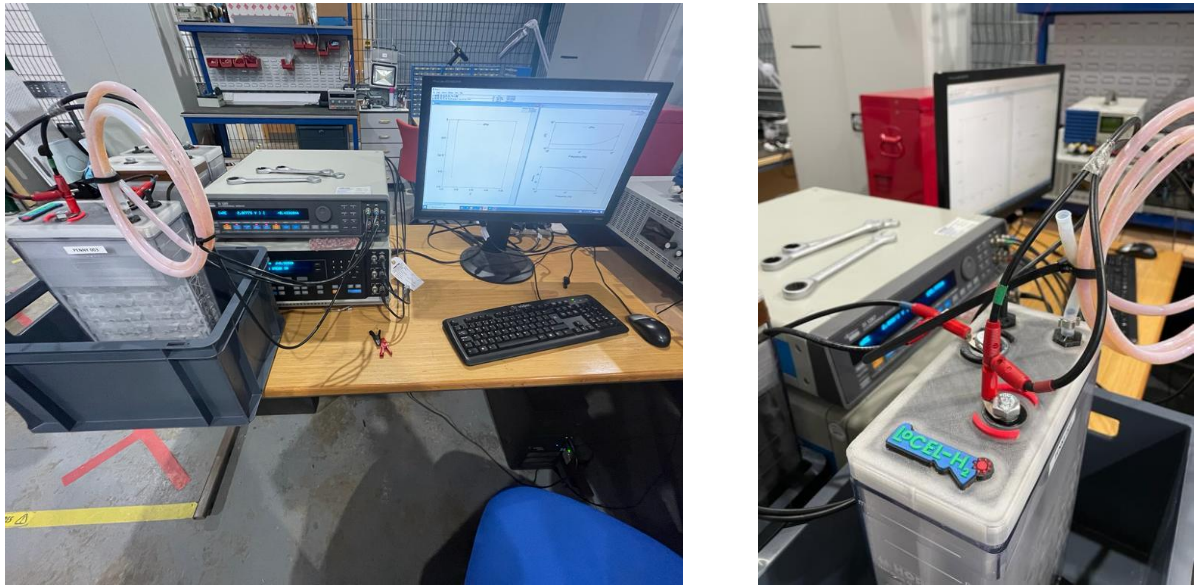
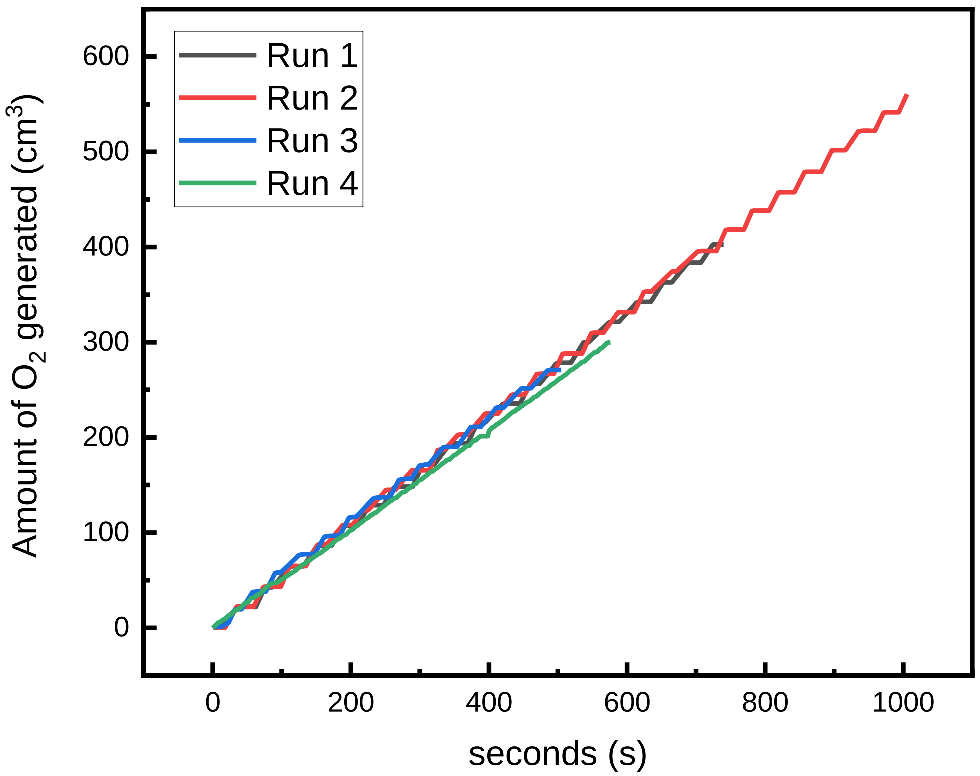
Electrochemical Impedance Spectroscopy (EIS)

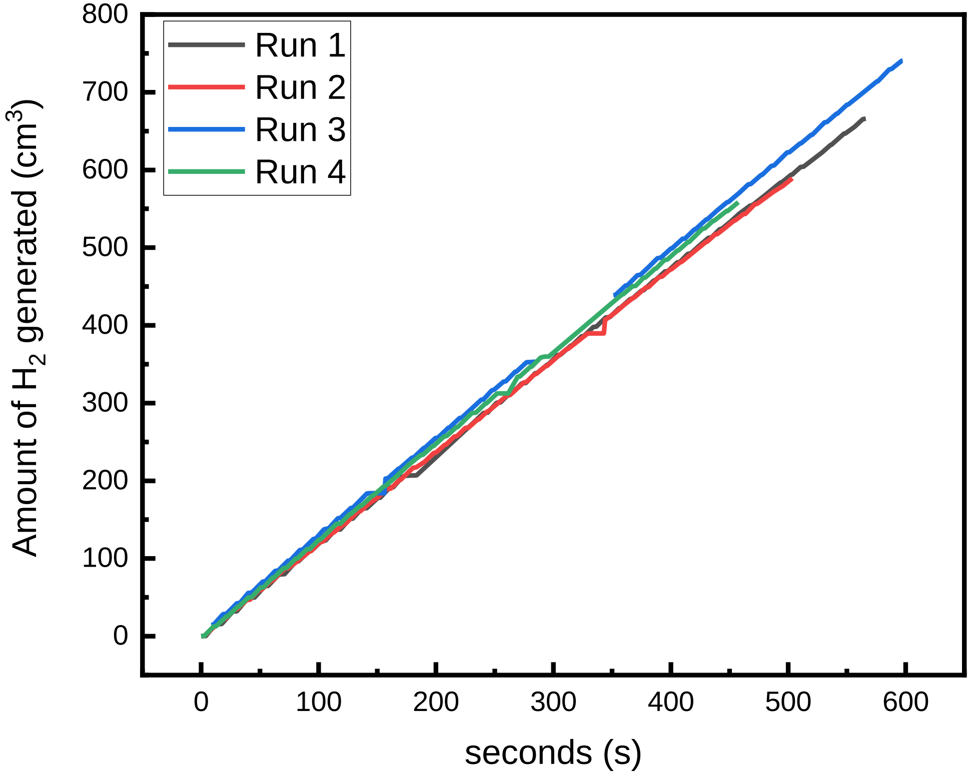




EIS initial frequency of 9400 Hz and final frequency of 0.1 Hz

Electrolysis of cell 003





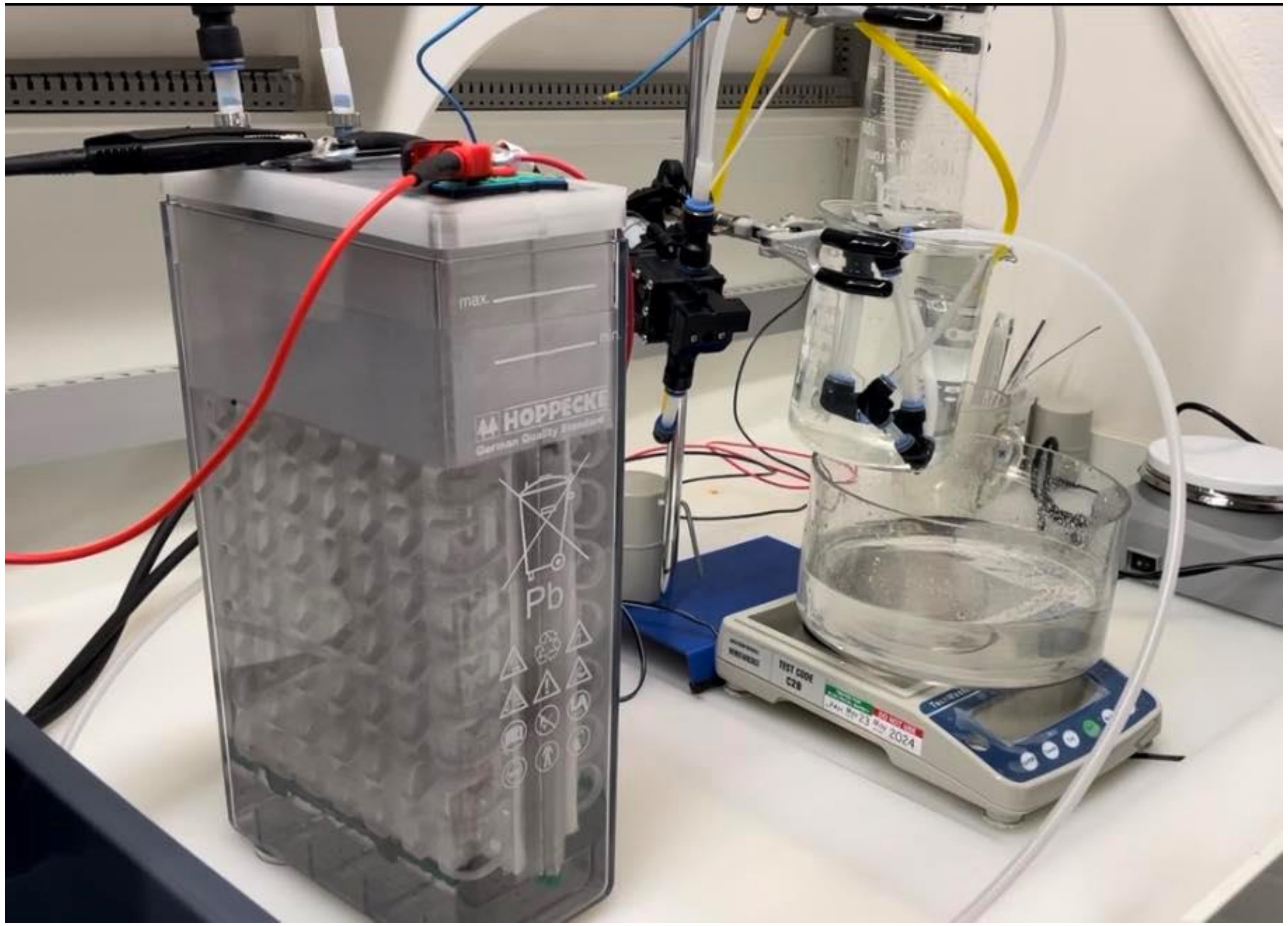
Average rate of O_2 production = 0.546 ± 0.017 $cm^3\ s^{-1}$

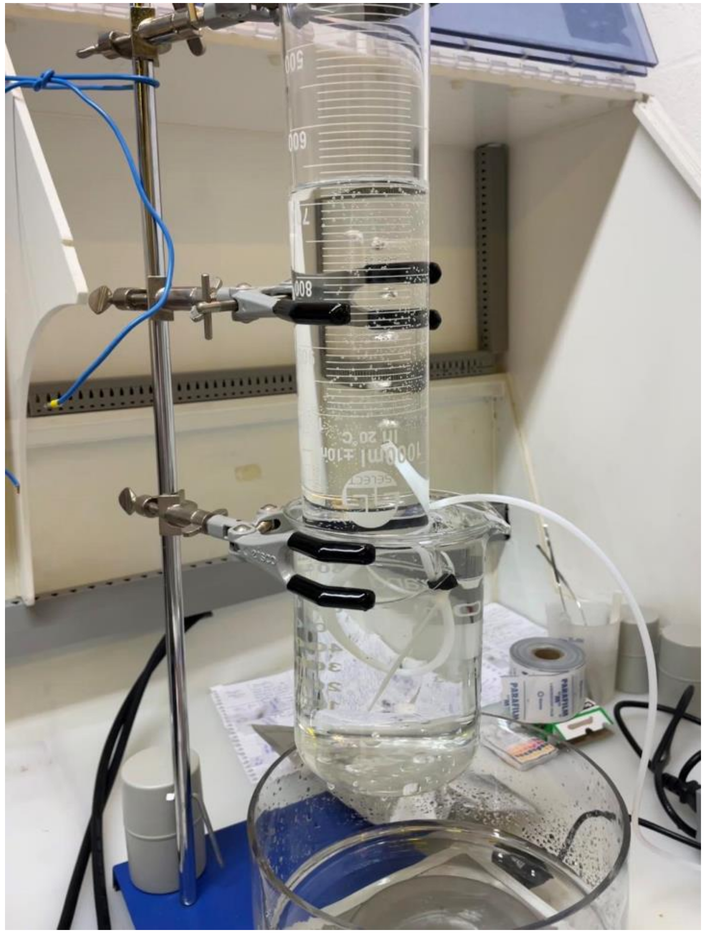
= 32.76 ± 1.02 $cm^3\ min^{-1}$

Average rate of H_2 production = 1.207 ± 0.024 $cm^3\ s^{-1}$

= 72.42 ± 1.44 $cm^3\ min^{-1}$

Electrolysis PSOC testing – 2.9 V starting at 50 % SOC





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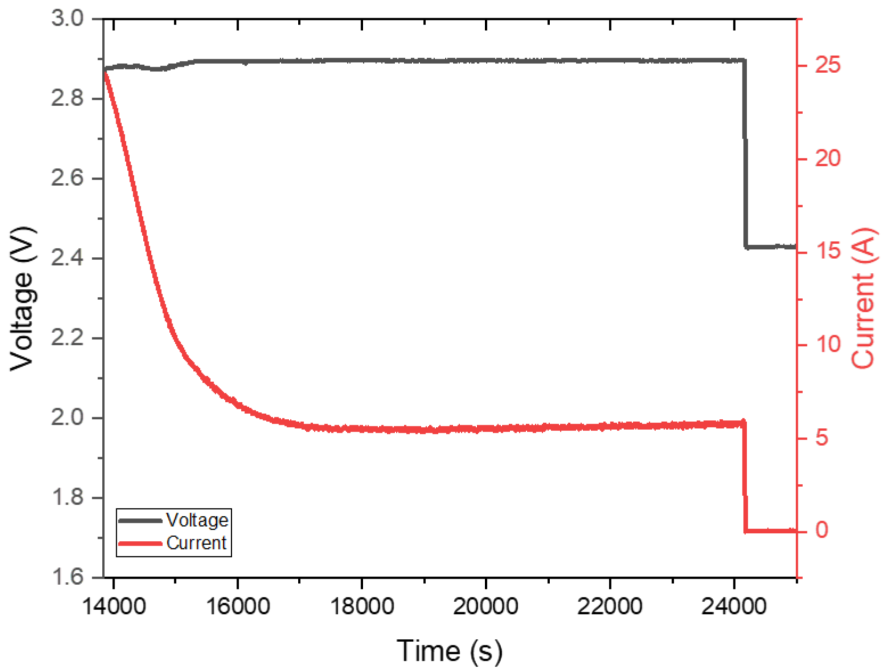
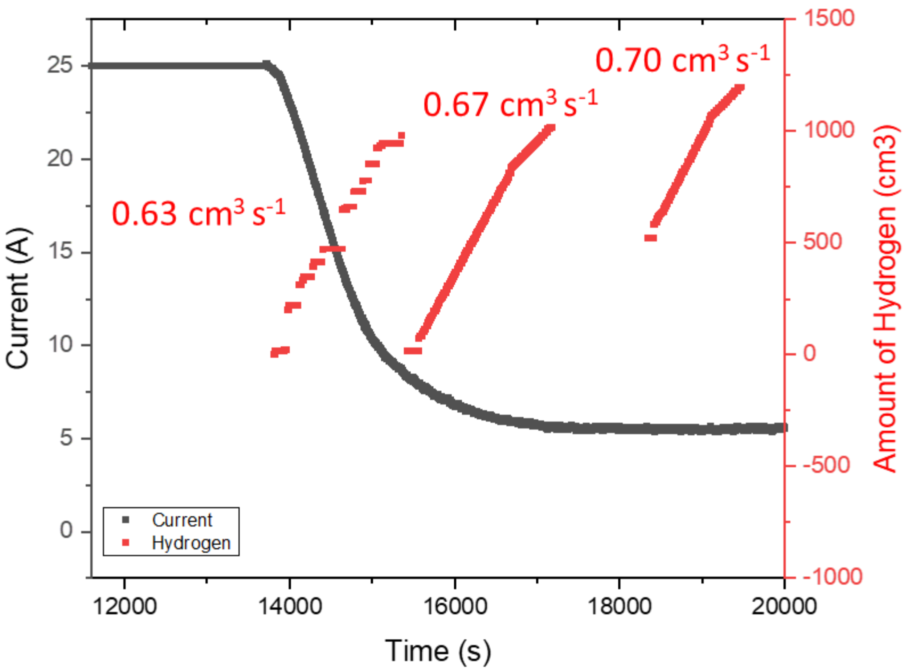
Electrolysis PSOC testing – 2.9 V starting at 50 % SOC





Average current (A)	Rate of Hydrogen production ($cm^3\ s^{-1}$)
17	0.63
7	0.67
5.5	0.70

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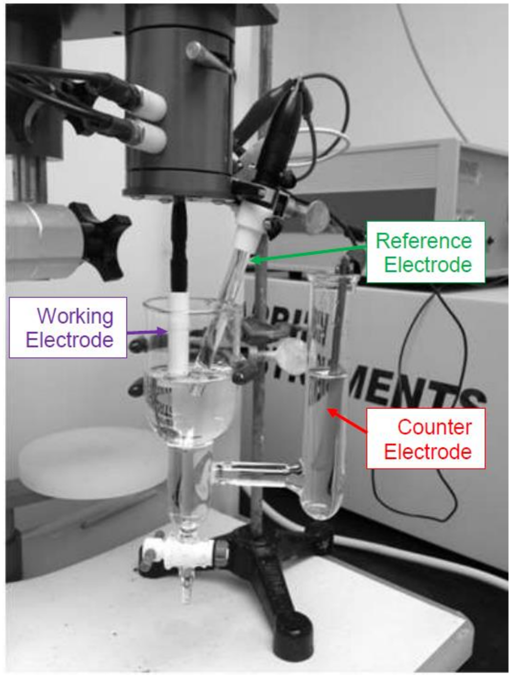
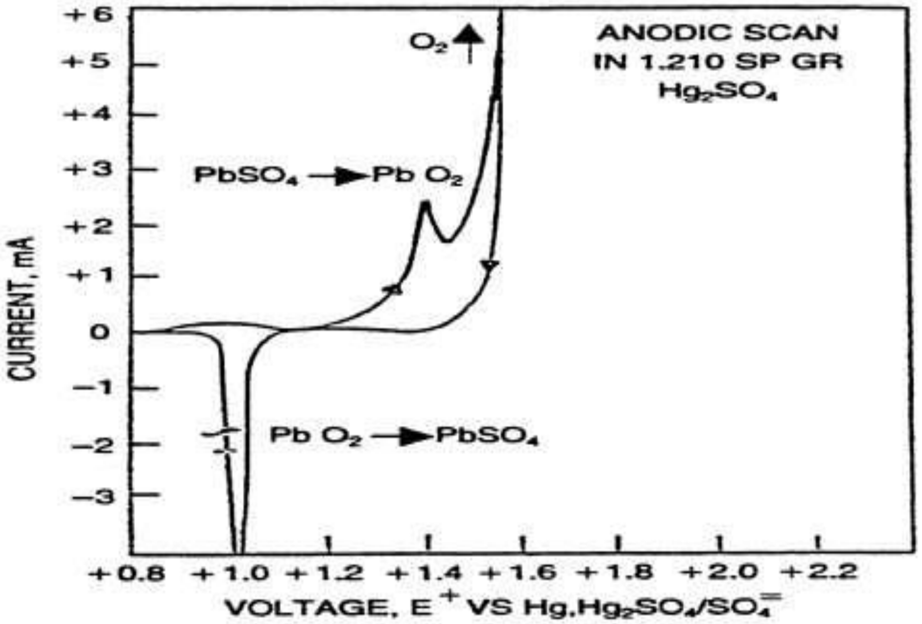
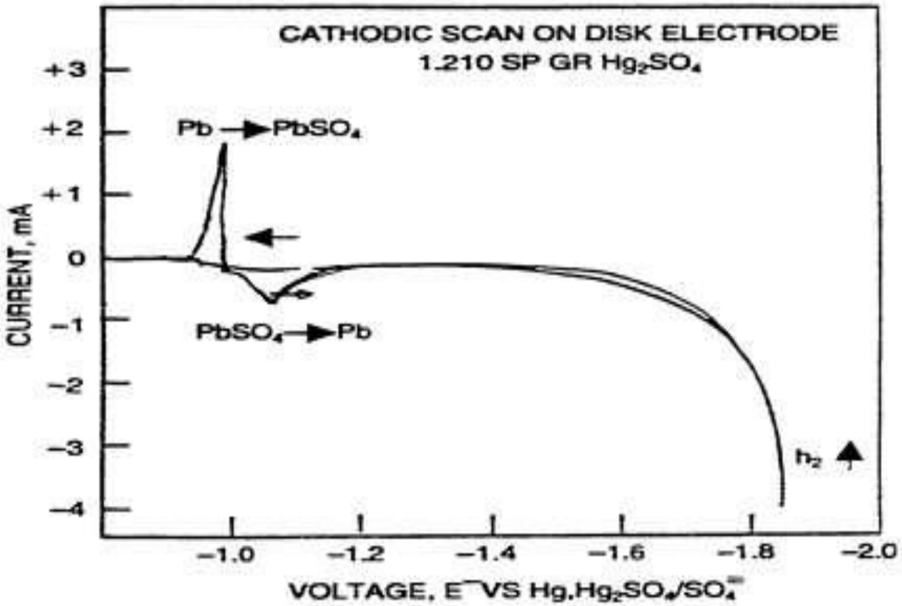
Visit to West Groton – H&V

Testing of Nickel sulphate, Cobalt sulphate, Iron sulphate and Manganese sulphate and antimony sulphate 1-500 ppm







3 weeks of testing

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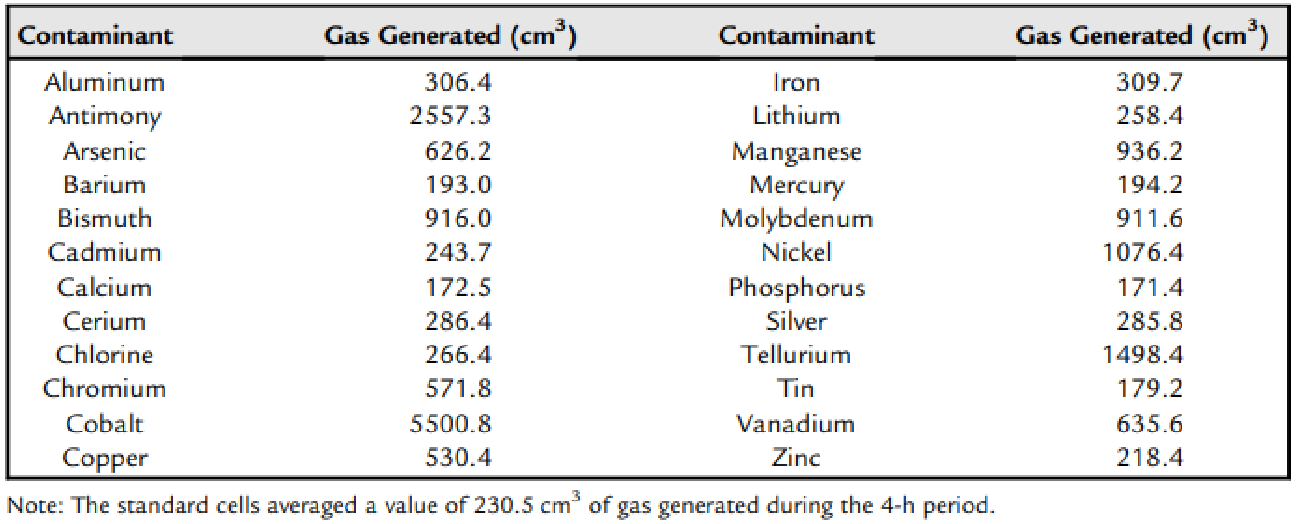
Visit to West Groton – H&V

Testing of Nickel sulphate, Cobalt sulphate, Iron sulphate and Manganese sulphate and antimony sulphate 1-500 ppm

1. below 1 ppm for tellurium, antimony, arsenic, cobalt, and nickel;
2. 2. below 3 ppm for manganese;
3. 3. below 160 ppm for iron;
4. 4. below 500 ppm for aluminum, bismuth, cerium, chromium, copper, molybdenum, silver, and vanadium;
5. 5. below 5000 ppm for barium, cadmium, calcium, chlorine, lithium, mercury, phosphorus, tin, and zinc.



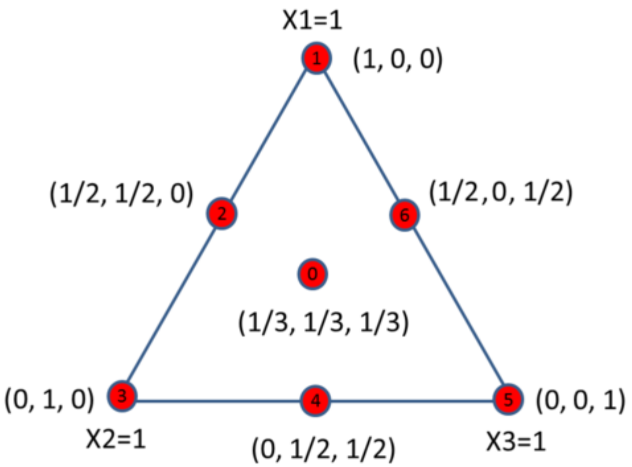
Contaminant	Gas Generated (cm^3)	Contaminant	Gas Generated (cm^3)
Aluminum	306.4	Iron	309.7
Antimony	2557.3	Lithium	258.4
Arsenic	626.2	Manganese	936.2
Barium	193.0	Mercury	194.2
Bismuth	916.0	Molybdenum	911.6
Cadmium	243.7	Nickel	1076.4
Calcium	172.5	Phosphorus	171.4
Cerium	286.4	Silver	285.8
Chlorine	266.4	Tellurium	1498.4
Chromium	571.8	Tin	179.2
Cobalt	5500.8	Vanadium	635.6
Copper	530.4	Zinc	218.4

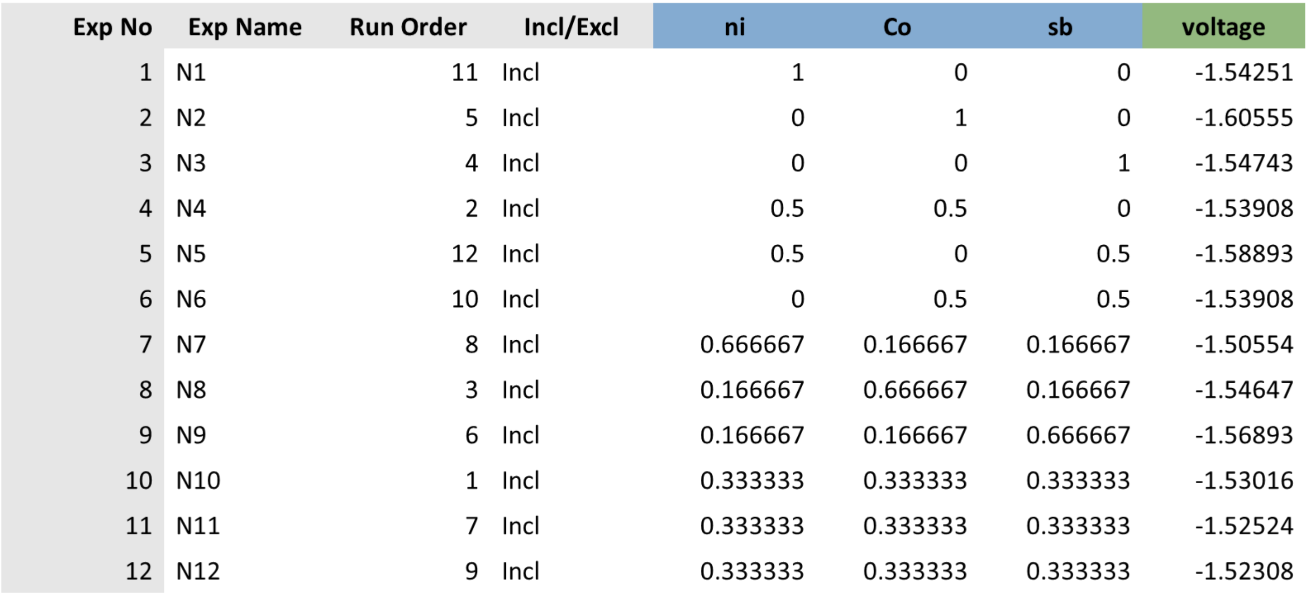
Note: The standard cells averaged a value of 230.5 cm^3 of gas generated during the 4-h period.

Reference: J.R. Pierson, C.E. Weinlein, C.E. Wright, in: D.H. Collins (Ed.), Power Sources 5, Academic Press, London, UK, 1975, p. 97

Design of Experiments – Simple Centroid Design

Design of Experiments (DOE) – testing mixtures of the additives to determine any combination effects using Simplex Centroid Design.





Exp No	Exp Name	Run Order	Incl/Excl	ni	Co	sb	voltage
1	N1	11	Incl	1	0	0	-1.54251
2	N2	5	Incl	0	1	0	-1.60555
3	N3	4	Incl	0	0	1	-1.54743
4	N4	2	Incl	0.5	0.5	0	-1.53908
5	N5	12	Incl	0.5	0	0.5	-1.58893
6	N6	10	Incl	0	0.5	0.5	-1.53908
7	N7	8	Incl	0.666667	0.166667	0.166667	-1.50554
8	N8	3	Incl	0.166667	0.666667	0.166667	-1.54647
9	N9	6	Incl	0.166667	0.166667	0.666667	-1.56893
10	N10	1	Incl	0.333333	0.333333	0.333333	-1.53016
11	N11	7	Incl	0.333333	0.333333	0.333333	-1.52524
12	N12	9	Incl	0.333333	0.333333	0.333333	-1.52308

Total of 100 ppm e.g 66.7ppm Ni 16.7ppm Sb 16.67ppm Co

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Catalysts for hydrogen evolution

Table 1: H_2 production from lead acid batteries when metal impurities are present at 5000 ppm or saturations level[3]

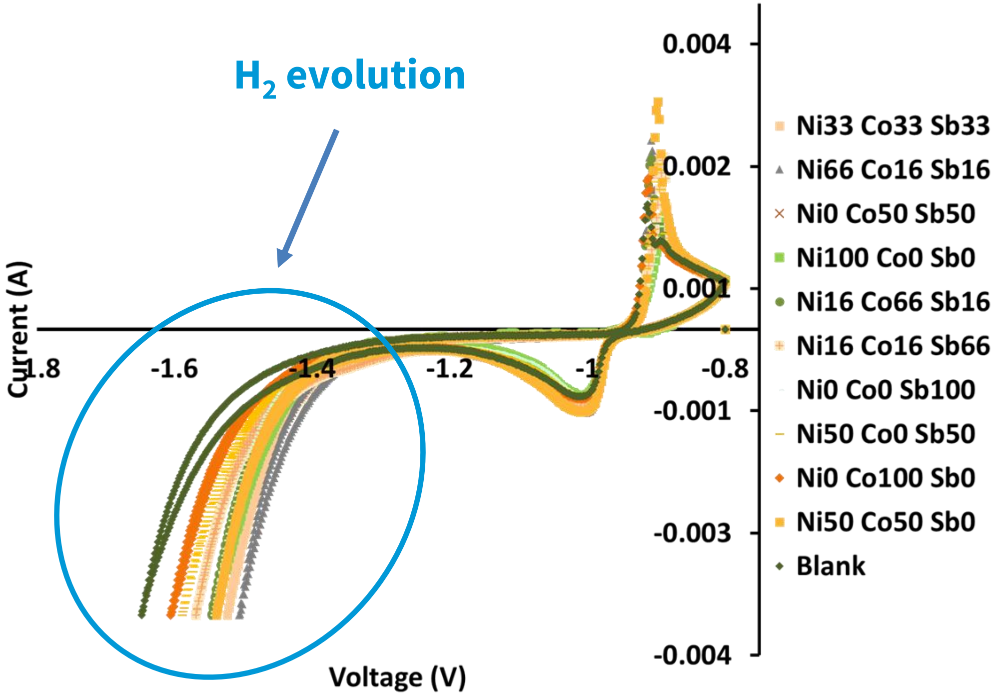
Elements	Maximum allowance	Gas generated
	(ppm)	(cm^3)
Ni	**1**	**1076.4**
Co	**1**	**5500.8**
Sb	**1**	**2557.3**
Fe	**160**	**309.7**
Mn	**3**	**936.2**
Te	**1**	**1498.4**

Note: The standard cells averaged a value of 230.5 cm^3 of gas generated during the 4 h period.

🟧 Increasing cost with uptake of renewables

🟩 Cheap and abundant, non-toxic

⬜ Rate metals (not viable)



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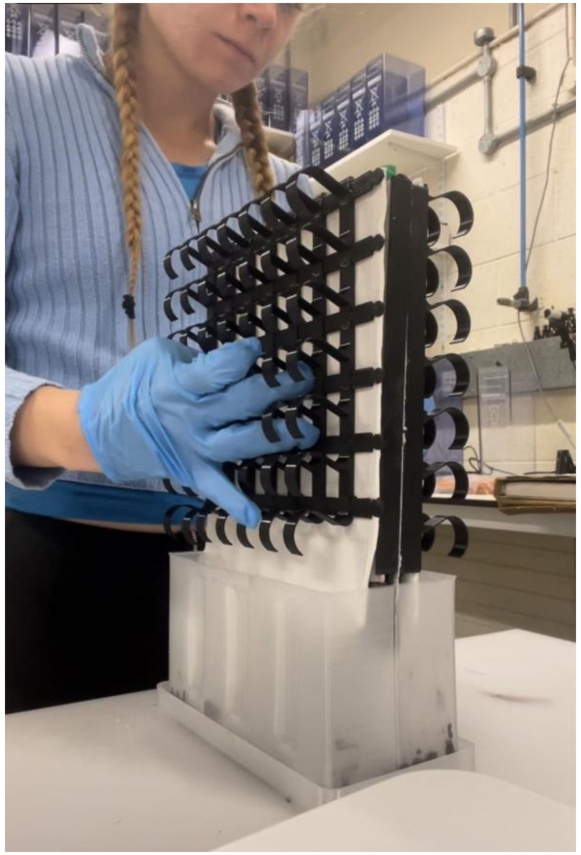
Manufacture of cell 004 – ABS separator and springs

HyDEX



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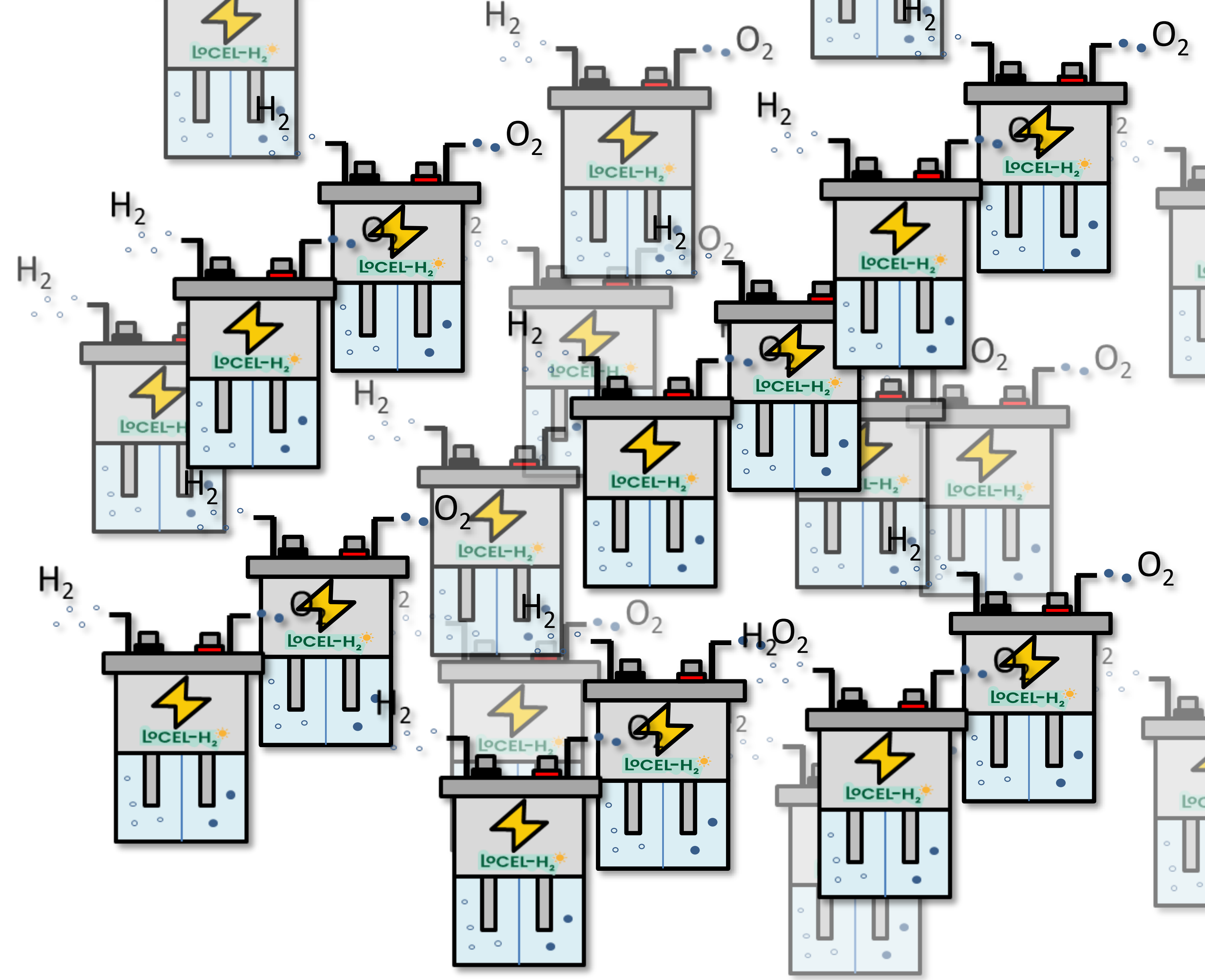
NEXT STEPS



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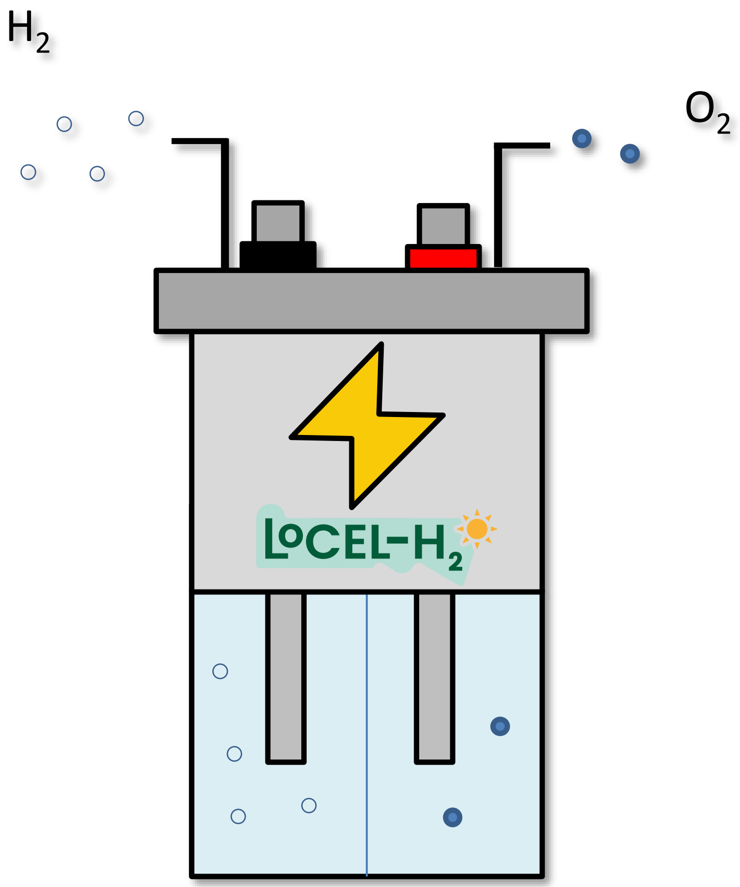
Manufacture of next 22 cells



Component	Parts made	Parts remaining
Plates soldered to terminals	44	0
lids	22	0
separators	14	30
Impaction separators	44	0
H&V separators	22	0
H&V AGM	22	0
Floats	2	42
Water fill	4	18
Logo and terminal ID	22	0
Pressure clips	28	412

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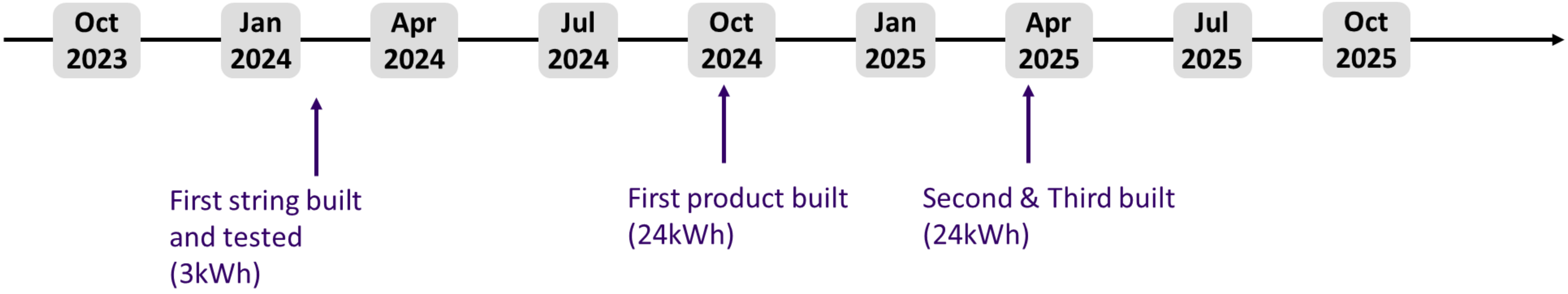
Future plans



First string built and tested (3kWh)

First product built (24kWh)

Second & Third built (24kWh)

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Arrival of the two 20ft containers

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Keele University

Midlands Innovation

Meet the team

Professor Dani Strickland
Professor of Electrical Power Engineering

Dr Jonathan Wilson
Lecturer in Systems and Mechanical Engineering

Dr John Barton
Senior Research Associate

Dr Elizabeth Ashton
Senior Research Associate

Matthew Brenton
PhD Researcher

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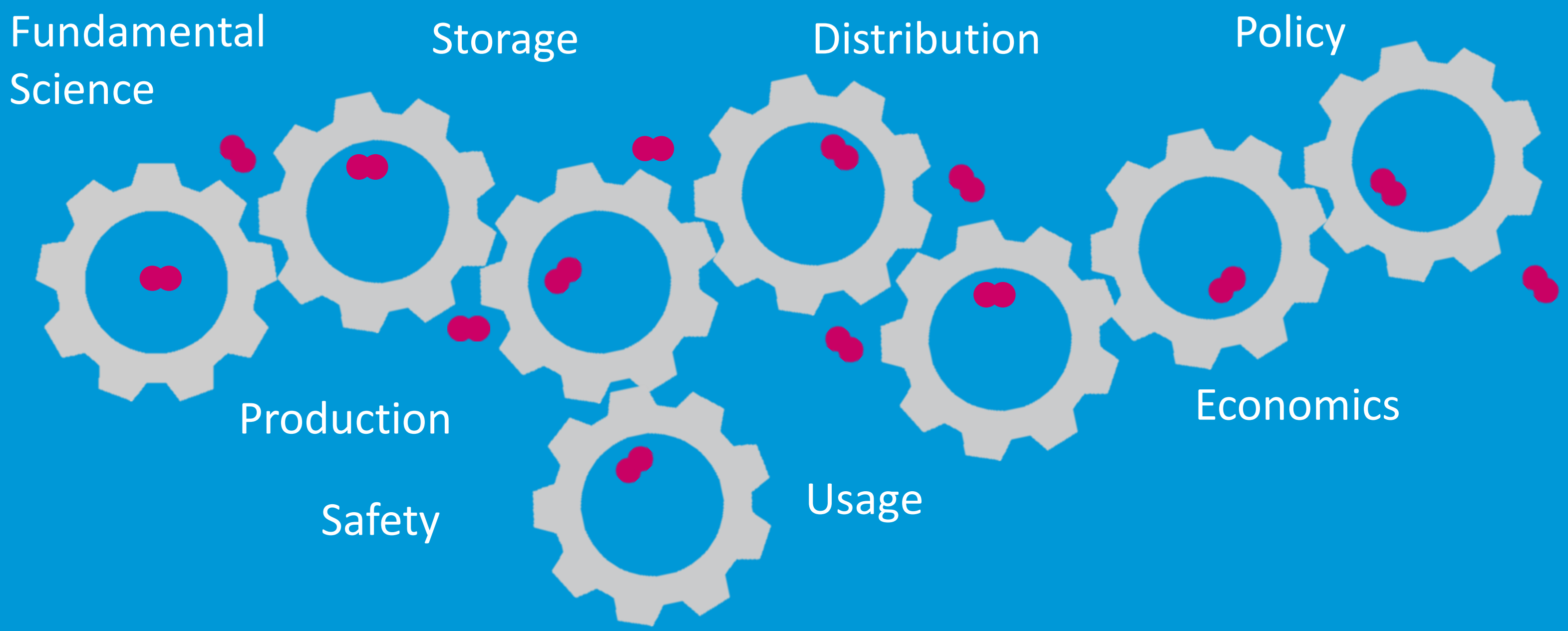
Multidisciplinary approach



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Conclusions

1 Battery technology

2 Green H_2

3 Manufacture

4 Pilot scale

- **Battery technology:** Using lead acid battery technology we have successfully develop a combined battery and electrolyser.
- **Green H_2:** excess renewable energy can be used to generate water via electrolysis when over charging the battery cell.
- **Manufacture**: We have developed the combine battery and electrolyser cell design from lab scale to full scale, using off the shelf and bespoke 3D printed parts.
- **Pilot scale:** We are now in the process of manufacturing the next 22 cells for testing, before deploying 168 cells in Zambia and the Ivory Coast.

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Co-funded by the European Union

LOCEL-H2

HyDEX

Thank you

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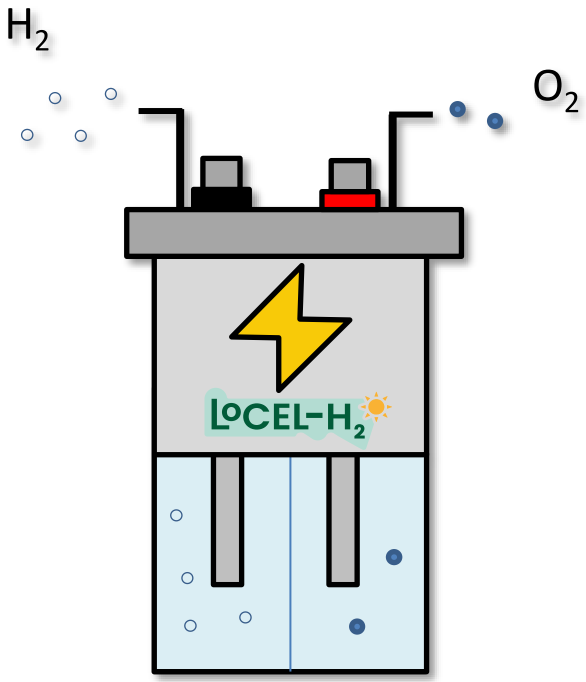
Elizabeth Ashton

Elizabeth Ashton
Research Associate at Loughborough University

Combined battery and electrolyser



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