Imperial College London

The role of hydrogen in supporting a low carbon transition of the UK economy: key drivers and challenges

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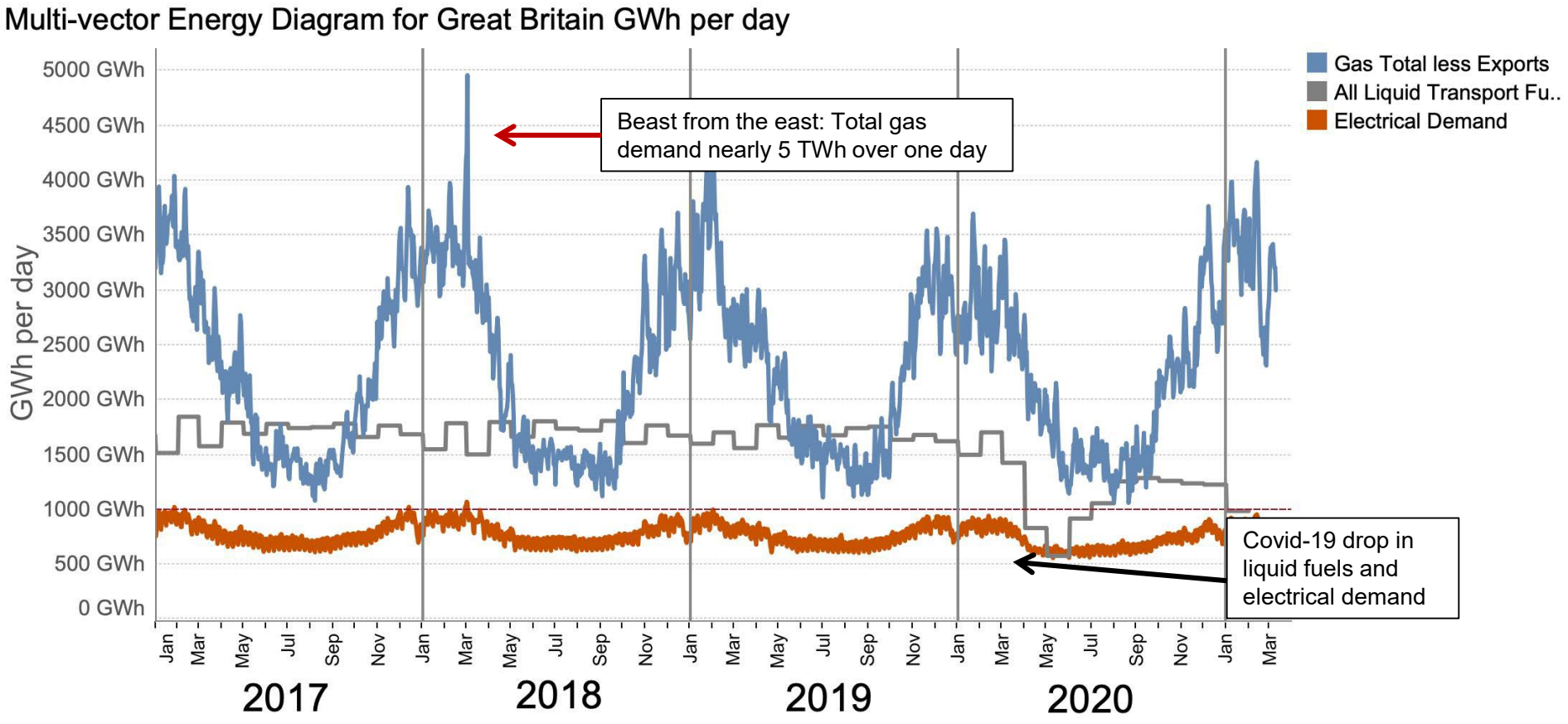
Daily UK total gas, all liquid transport fuels, and electrical demand



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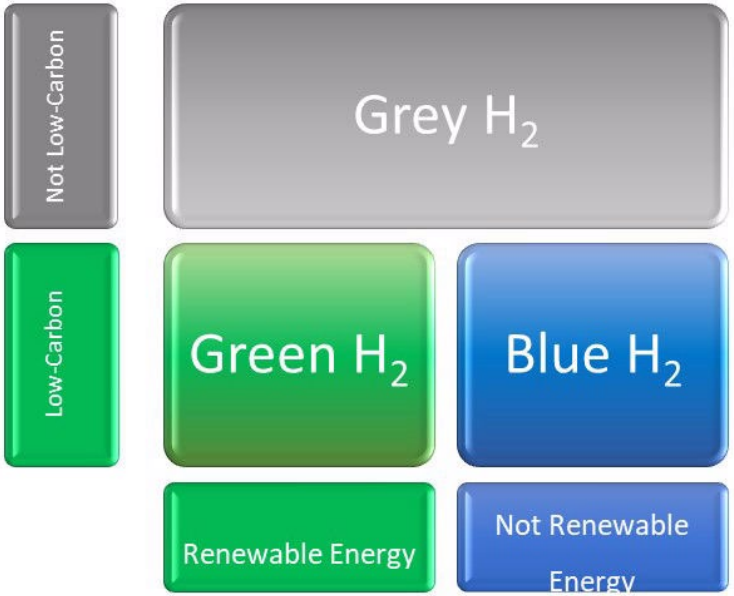
Underlying data are from National Grid, Elexon and BEIS
Figure created by Dr Grant Wilson: i.a.g.wilson@bham.ac.uk
Energy Informatics Group, University of Birmingham
slidepack available from https://doi.org/10.5281/zenodo.3930970

The colours of hydrogen

Grey = hydrogen made from fossil fuels (96% of current production)

Blue = hydrogen made from fossil fuels with CCS

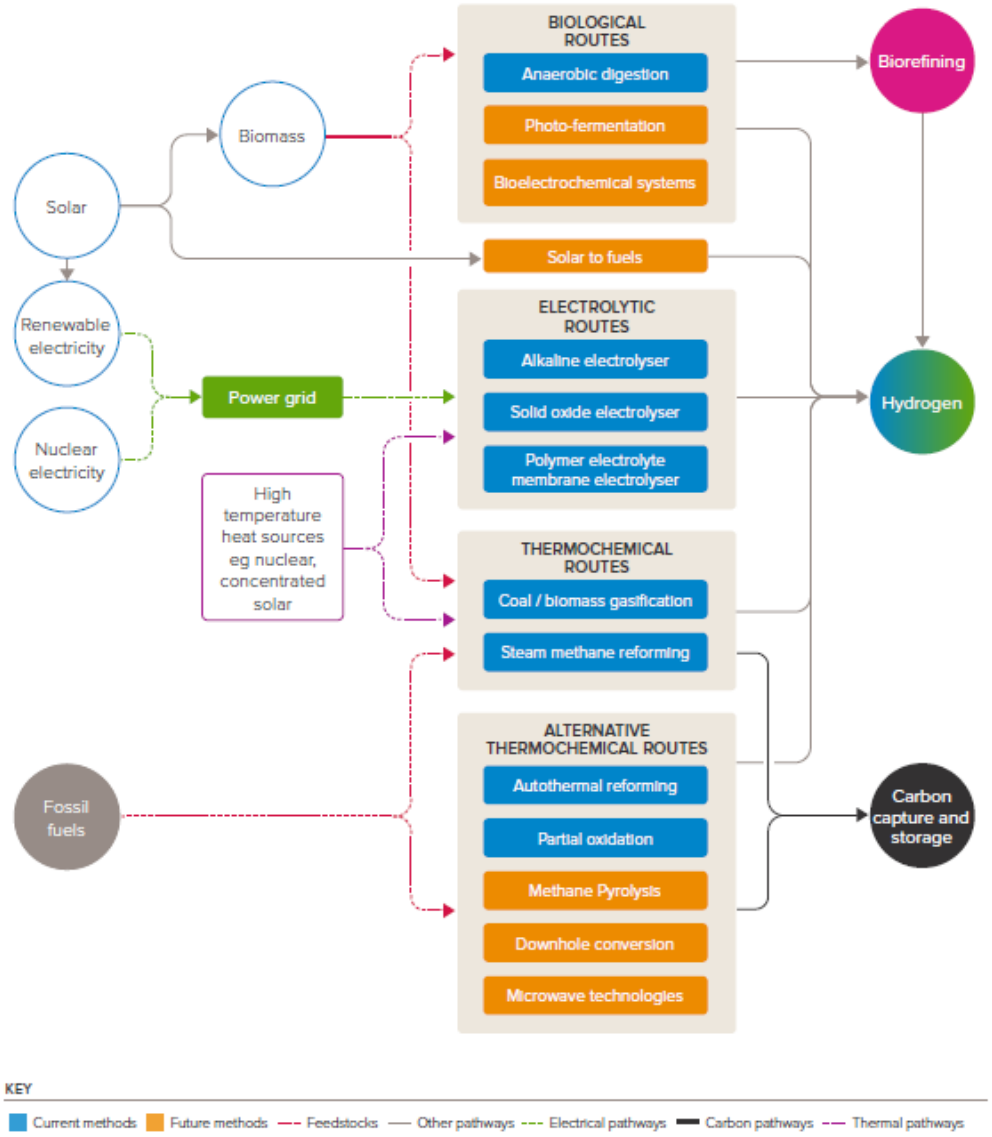
Green = hydrogen made from renewables

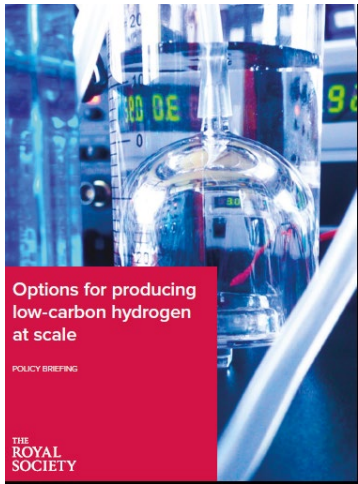


Low Carbon Hydrogen Production

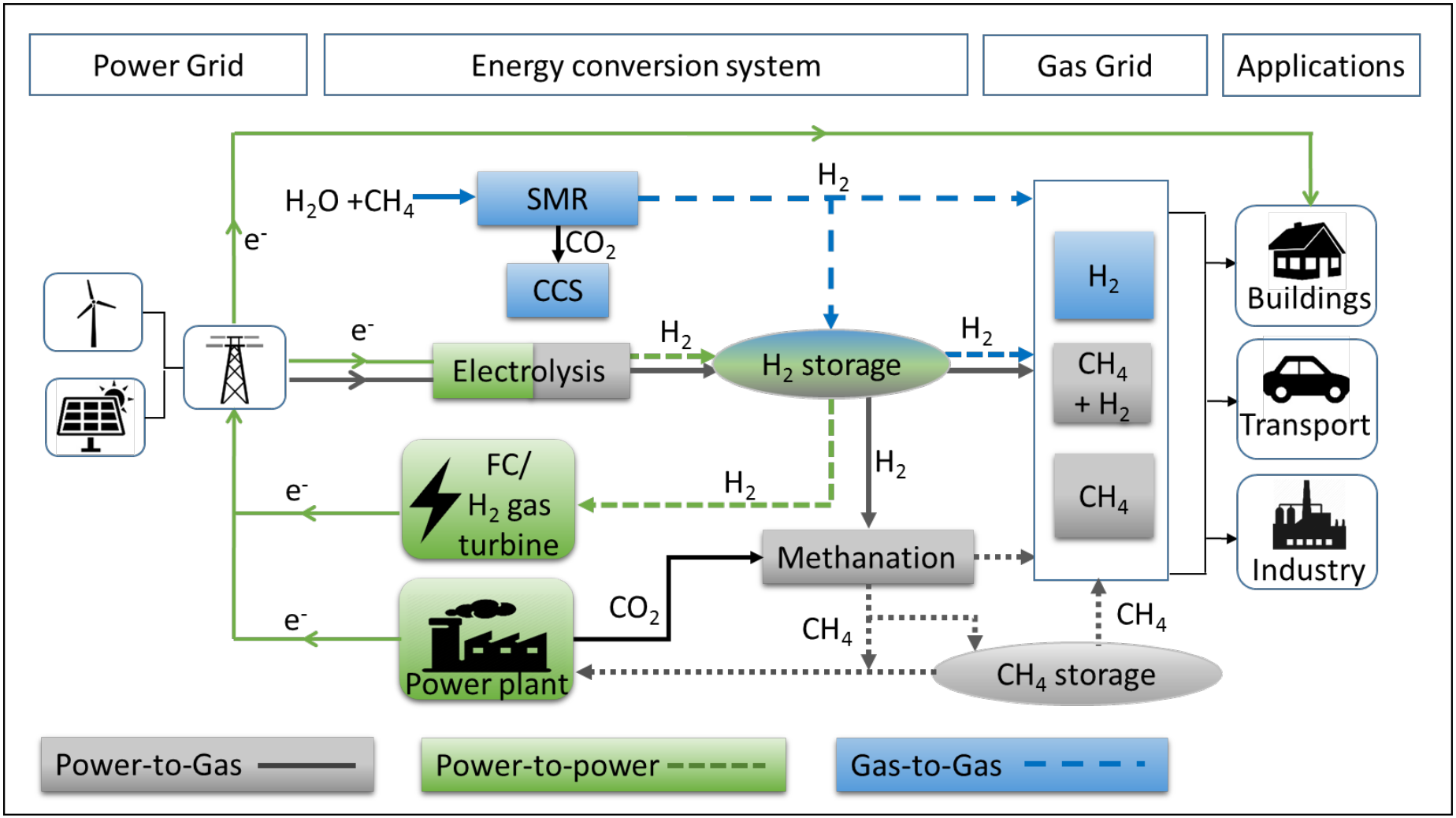
FIGURE 1

Schematic of the production options for low-carbon hydrogen[1].





The Role of Hydrogen in the Economy



PHILOSOPHICAL TRANSACTIONS A

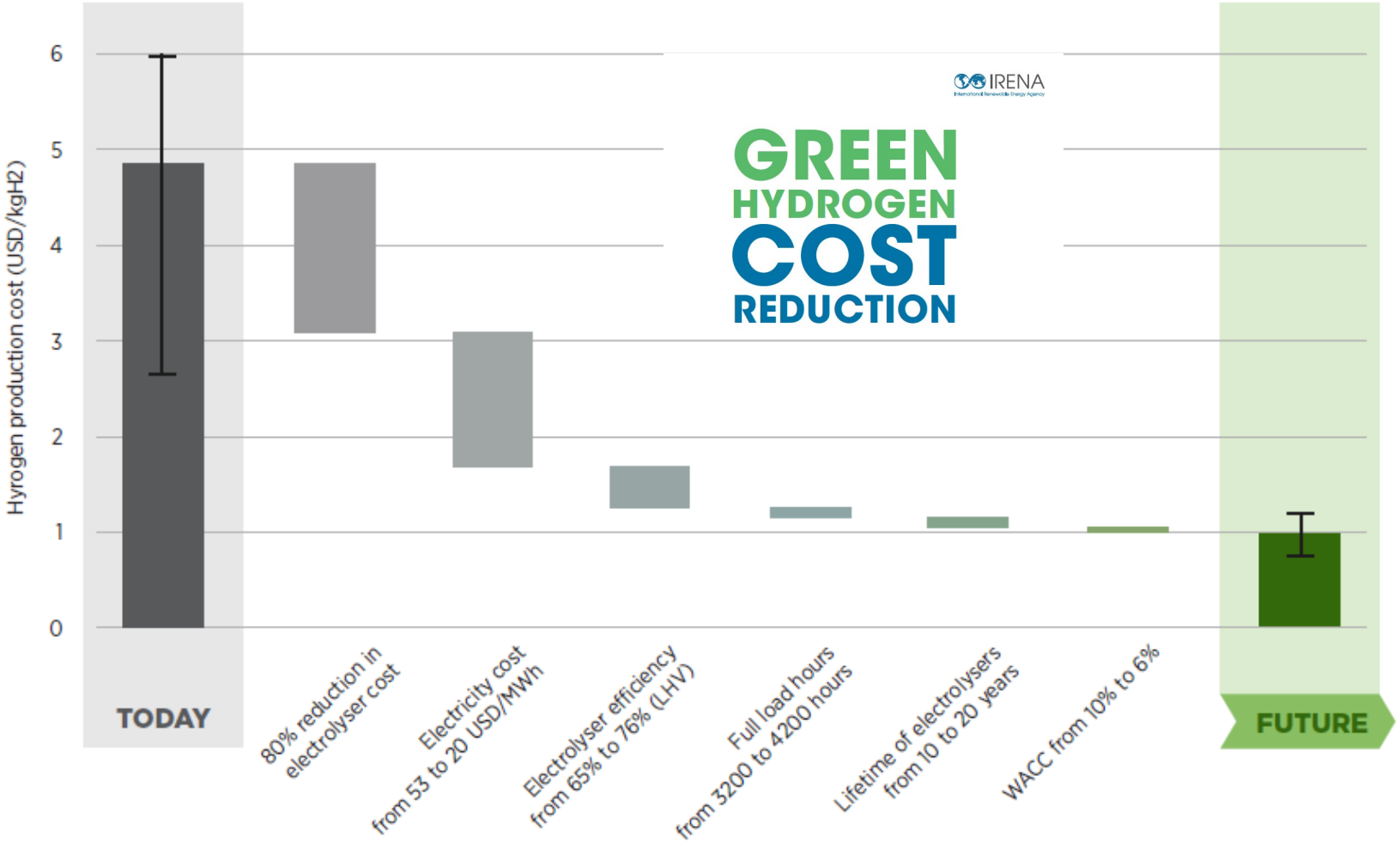
rsta.royalsocietypublishing.org

Clean energy and the hydrogen economy

N. P. Brandon and Z. Kurban

Cite this article: Brandon NP, Kurban Z. 2017 Clean energy and the hydrogen economy. *Phil. Trans. R. Soc. A* **375**: 20160400.
http://dx.doi.org/10.1098/rsta.2016.0400

Hydrogen production costs



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

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Hydrogen Fuel Cell Electric Buses

USA: 40 FCEBs in public service. AC Transit's fleet of 13 vehicles have logged 2.8 million miles, with one fuel cell clocking 30,000 hours

South Korea: 1,000 buses, and associated fuelling infrastructure, will be operating by 2022.

China: World largest FCEB fleet. 30% of Shanghai's electric bus fleet to be FCEBs; Shangdong Heavy Industry's to make 2,000 buses; purchase of 300 FCEBs by Datong.

UK: 8 FCEBs in operation since 2011, 2 added in 2019. Arcola Energy and the Optare Group have announced the launch of a hydrogen fuel cell double-decker bus manufactured in the UK.

Fuel Cell Transport: Hydrogen FC Electric Trains

- The world's first fuel cell passenger train entered revenue service in 2018. Alstom's Coradia iLint has achieved more than 180,000 km in revenue service in Germany and Austria, with a high reliability of 95%.
- 41 trains have been sold with 30 year maintenance contracts.
- HydroFLEX began UK testing in Sep 2020.
- Alstom and Eversholt Rail have developed the Breeze for the UK market- a hydrogen fuel cell/battery hybrid – designed to replace diesel multiple units (DMUs). Range is >600 miles.

Hydrogen Fuel Cell Electric Trucks & Off-road

- Hyundai's has shipped hydrogen fuel cell trucks to Switzerland.
- 100's Medium-duty truck fleets are already delivering in China. 1000's have been manufactured.
- Toyota Class 8 truck in California.
- FedEx and UPS are trialling fuel cell range-extender Class 6 delivery vehicles.
- JCB has developed the construction industry's first ever hydrogen powered excavator.
- Bosch have announced plans to start production of hydrogen fuel cell powertrains, focusing initially on trucks.

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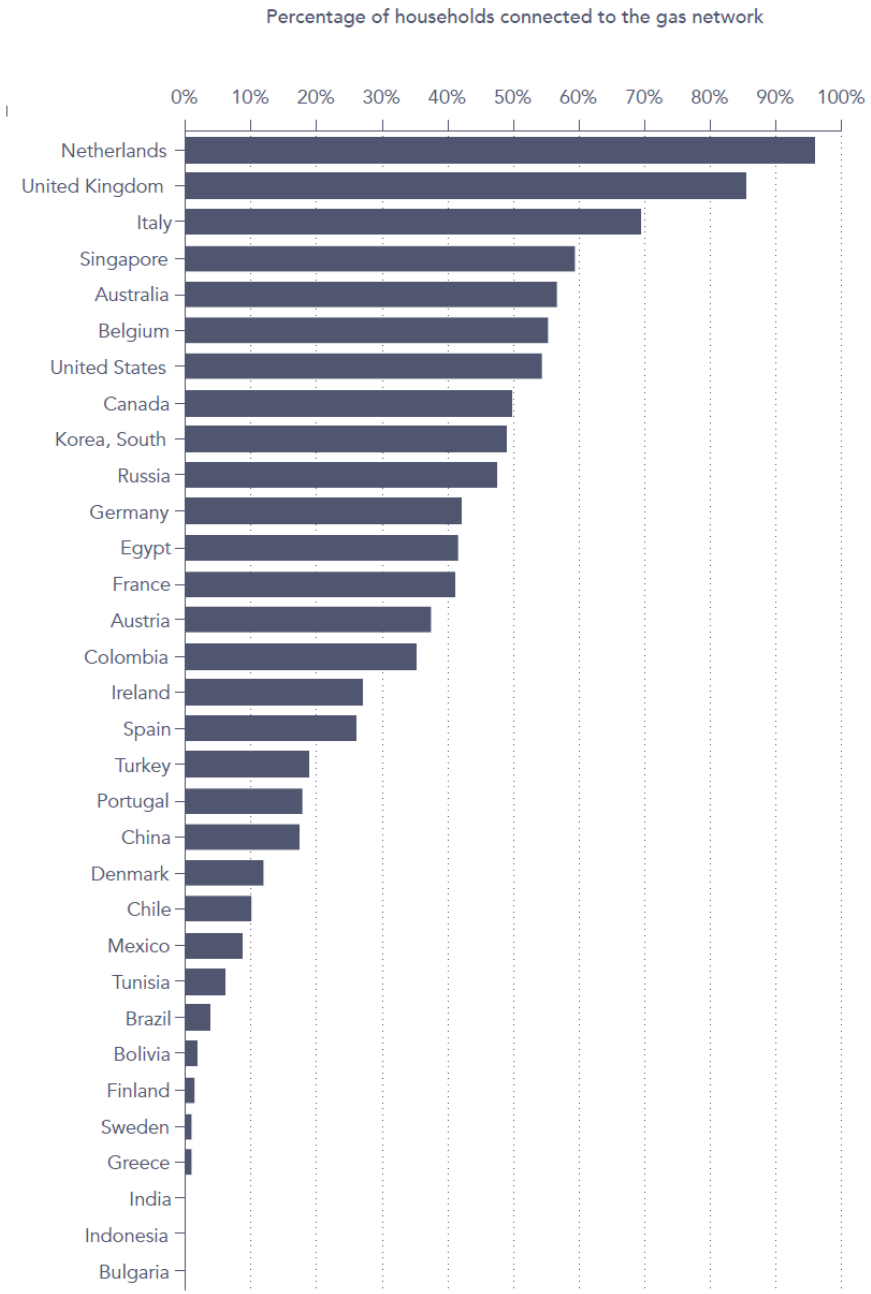
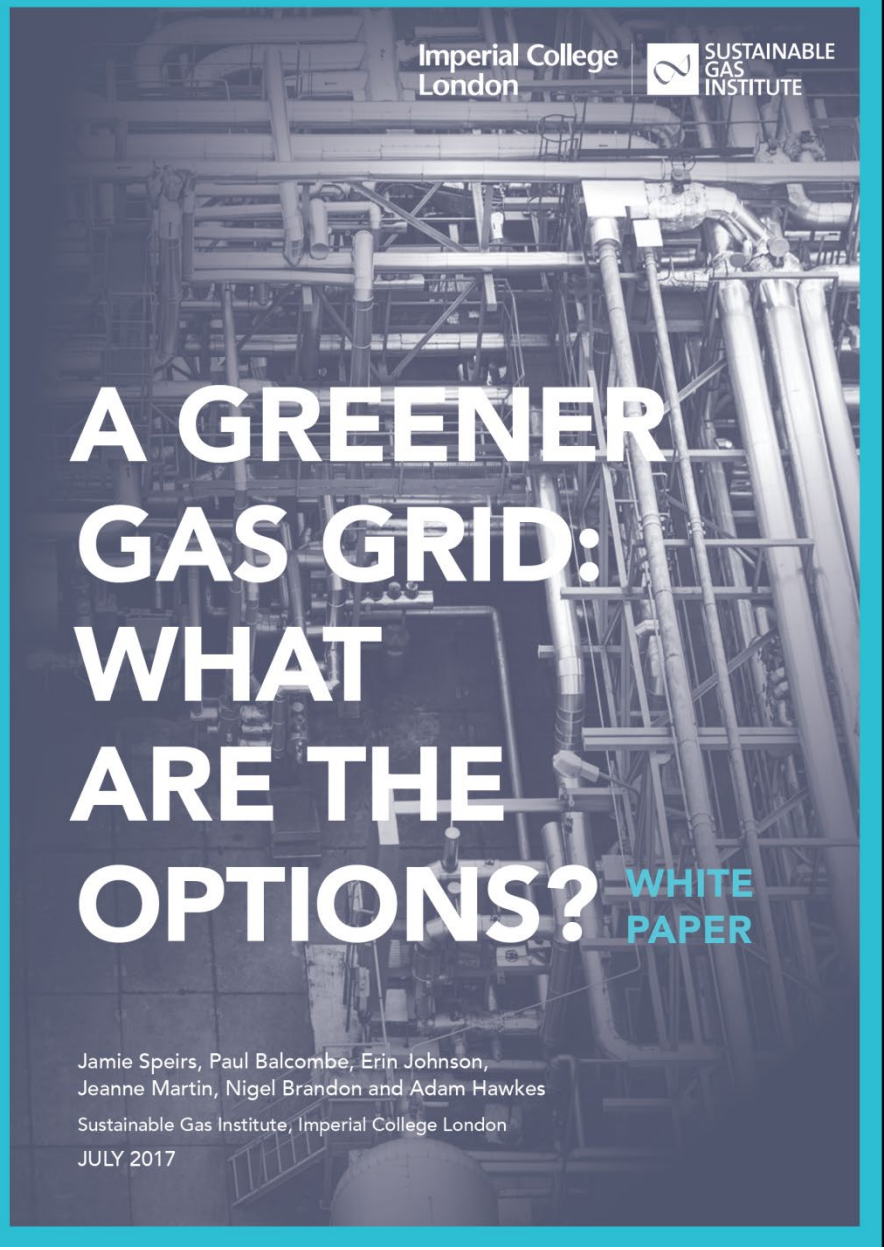
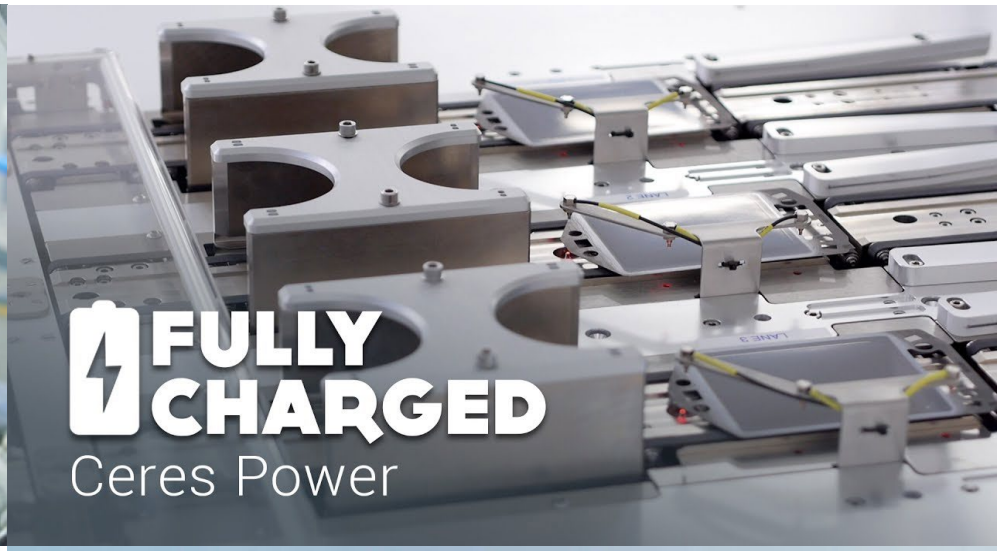
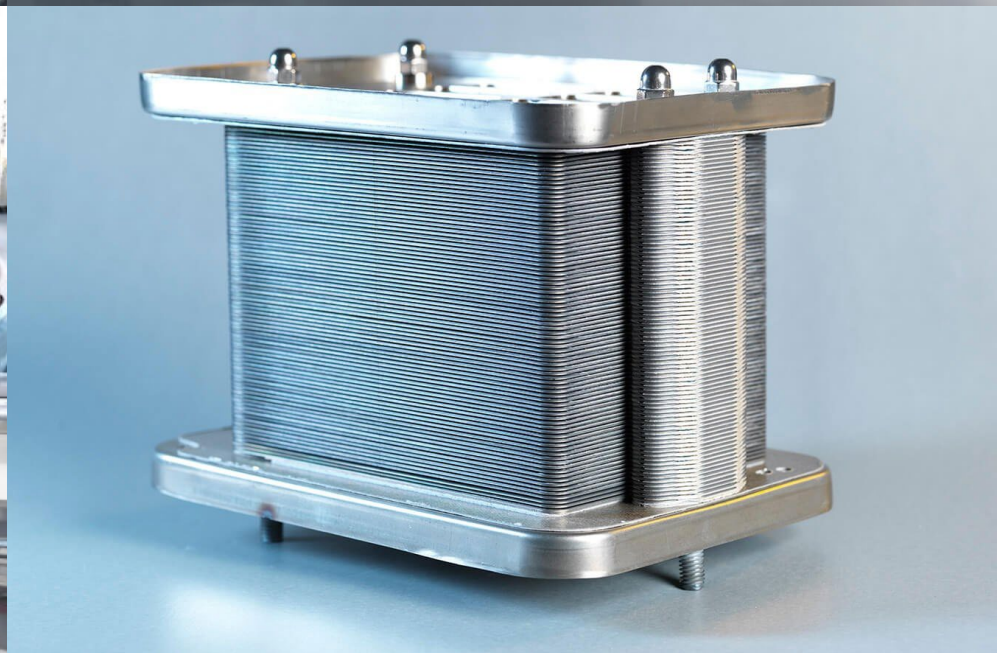

Percentage of households connected to the gas network
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Netherlands
United Kingdom
Italy
Singapore
Australia
Belgium
United States
Canada
Korea, South
Russia
Germany
Egypt
France
Austria
Colombia
Ireland
Spain
Turkey
Portugal
China
Denmark
Chile
Mexico
Tunisia
Brazil
Bolivia
Finland
Sweden
Greece
India
Indonesia
Bulgaria


Imperial College London
SUSTAINABLE GAS INSTITUTE
A GREENER GAS GRID: WHAT ARE THE OPTIONS?
WHITE PAPER
Jamie Speirs, Paul Balcombe, Erin Johnson, Jeanne Martin, Nigel Brandon and Adam Hawkes
Sustainable Gas Institute, Imperial College London
JULY 2017

Metal supported SOFC at Ceres Power





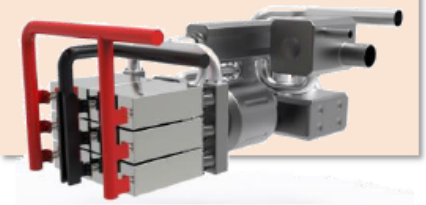
Progress with key commercial partnerships

BOSCH

- First partner to manufacture Ceres' core cell technology under licence
- Now scaling up to 200MW production by 2024 across multiple sites in Germany

WEICHAI

- 30kW range extender for electric buses progressing to field trials
- Establishment of the JV in Shandong province now likely to be H1 2021



DOOSAN

- Ambition to supply efficient fuel cells to meet Korean government renewable energy plan
- Good progress on initial CHP development deal
- Recent manufacturing licence signed for an initial 50MW facility by 2024

MIURA

- First units operating over one year; 90% efficient CHP for commercial buildings delivers energy savings and a lower carbon footprint
- Growing specialist team to support long-term deployment

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Additional H2 storage to deal with a prolonged low/no wind periods – *H2 enhances the resilience effectively*

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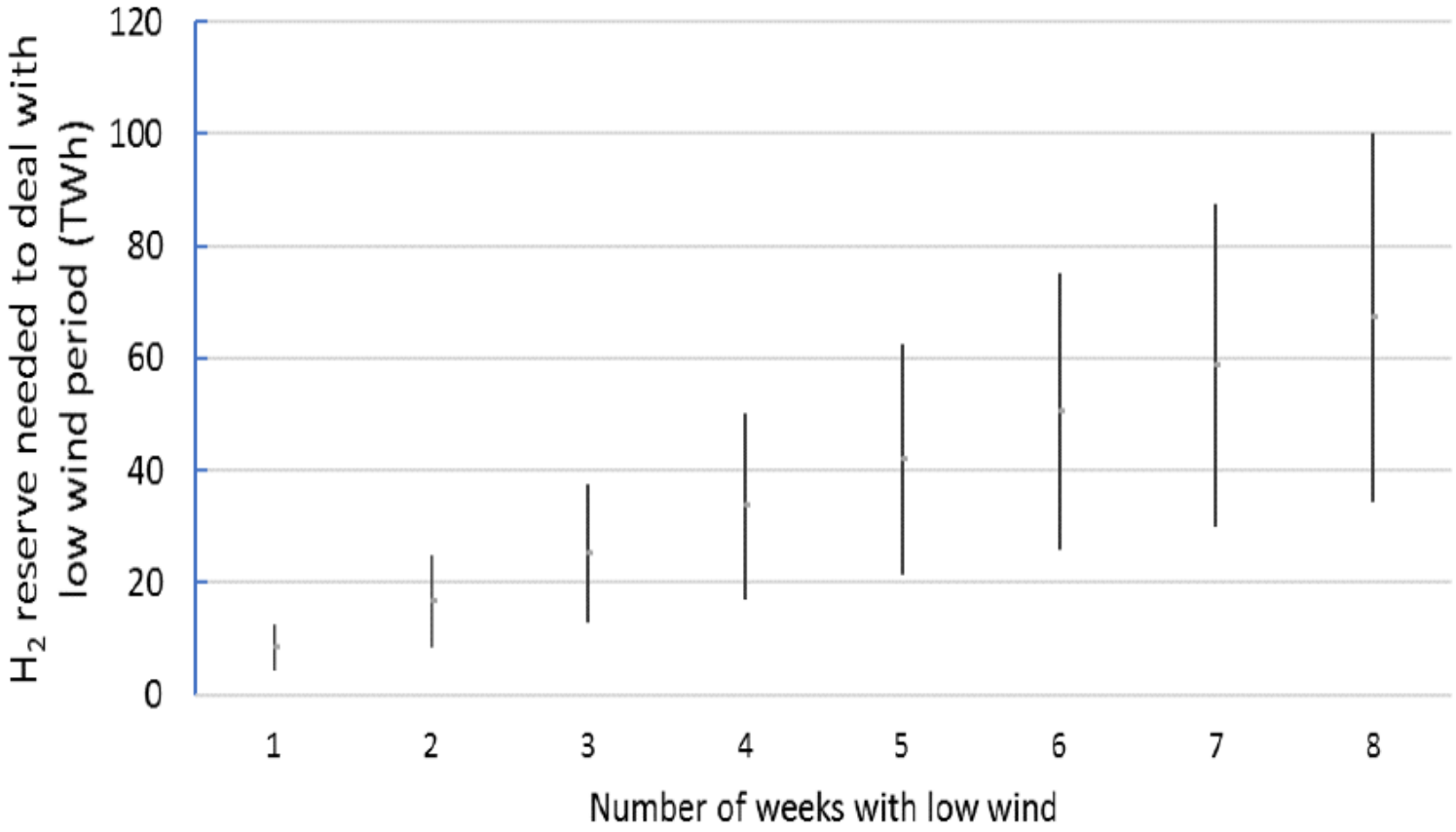


Prog. Energy 2 (2020) 042001 https://doi.org/10.1088/2516-1083/abb216

Progress in Energy

TOPICAL REVIEW

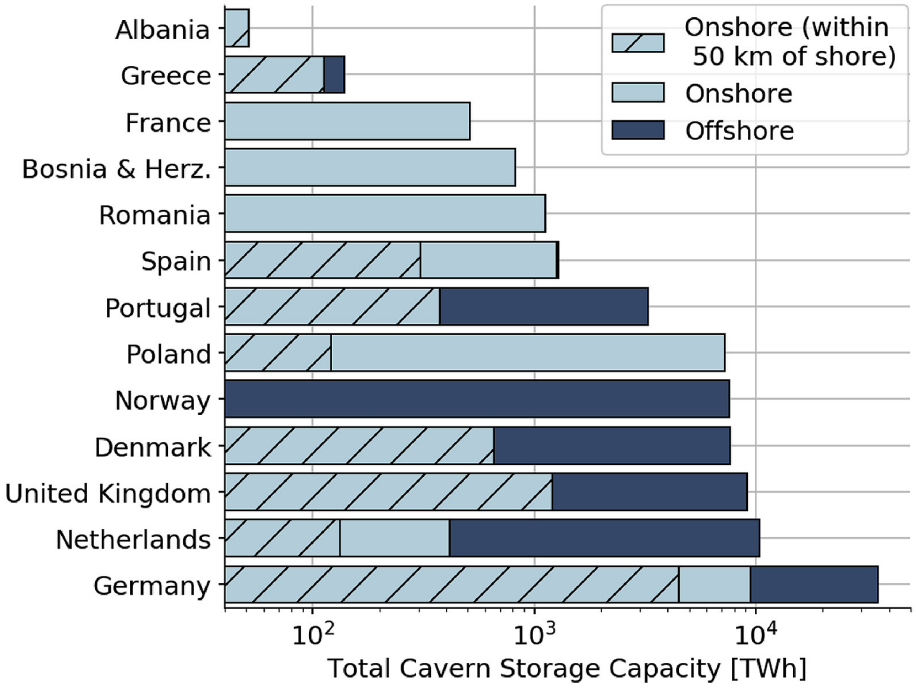
Role and value of flexibility in facilitating cost-effective energy system decarbonisation

Goran Strbac, Danny Pudjianto, Marko Aunedi, Predrag Djapic, Fei Teng, Xi Zhang, Hossein Ameli, Roberto Moreira and Nigel Brandon

UK Pumped Hydro @ Dinorwig – 9.1 GWh

1 million tonnes of hydrogen stored = 33 TWh or > 3600 pumped hydro facilities such as Dinorwig in the UK

Hydrogen for long term energy storage



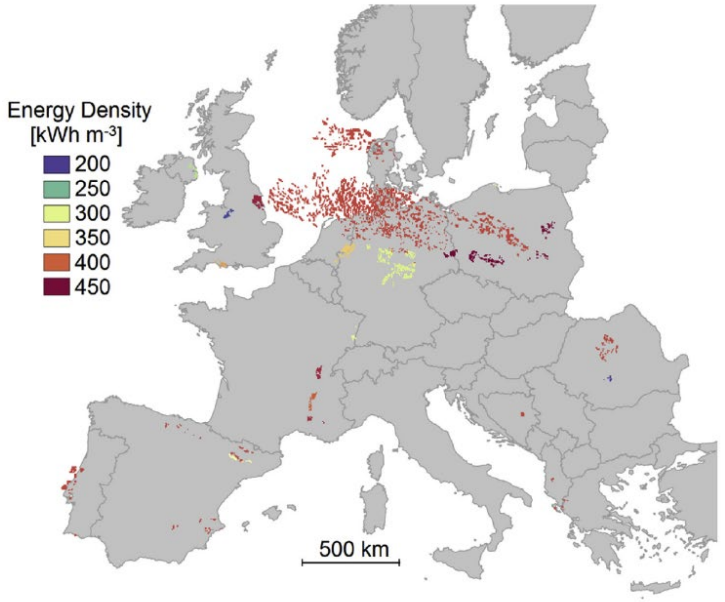


Fig. 7 – Distribution of potential salt cavern sites across Europe with their corresponding energy densities (cavern storage potential divided by the volume).

Over **400 billion m3 of natural gas is currently stored underground worldwide**. The **UK stores about 10,000 GWh of natural gas**

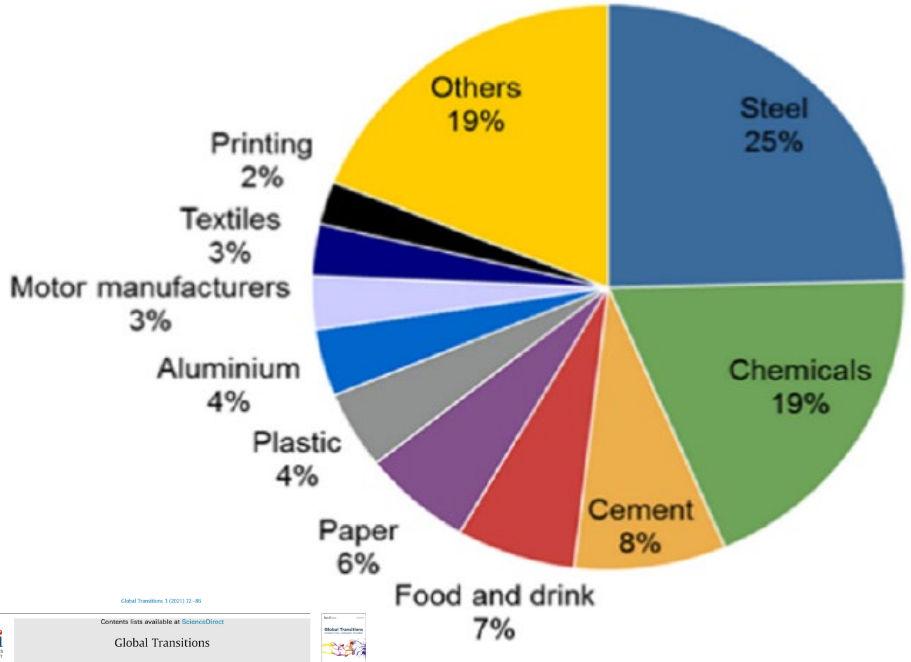
H2 is also currently **stored in a small number of salt caverns in the UK** and the USA, supporting chemical plants and oil refineries. The largest single store (USA) holds over 100GWh of H2

Technical potential of salt caverns for hydrogen storage in Europe, International Journal of Hydrogen Energy Volume 45, Issue 11, 2020, Pages 6793-6805.

Contents

Hydrogen for industrial decarbonisation

- Global ammonia production is 1.44% of global CO_2 emissions, with hydrogen production from fossil fuels being the dominant CO_2 source.
- World's Largest Green Hydrogen Project Unveiled in Saudi Arabia using 4 gigawatts of renewable electricity to produce 650 tons of green hydrogen daily. The fuel will be shipped as ammonia to end markets globally then converted back to hydrogen. Ammonia production is expected to start in 2025.
- Steelmaking produces 2.9 Gt CO_2 per year, and is on track to use 50% of)5



UK industrial GHG emissions

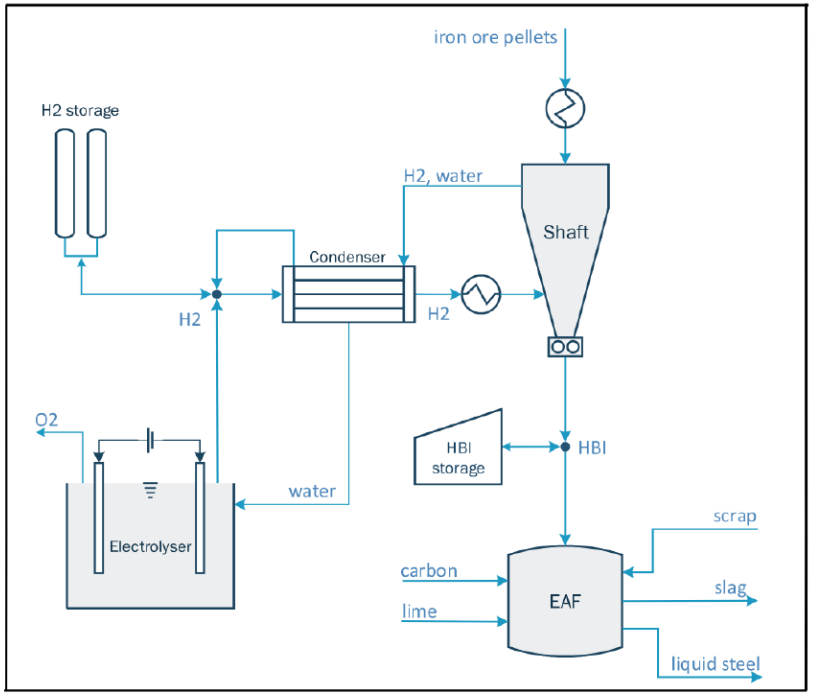


Fig. 1. Proposed process design for hydrogen direct reduction (H-DR) process.

The prospects for 'green steel' making in a net-zero economy: A UK perspective

Paul W. Griffin [a], Geoffrey P. Hammond [b, c, *]

Summary

- The use of low to zero carbon molecules alongside low to zero carbon electrons will be necessary to decarbonise all sectors of the economy.

- Hydrogen and its carriers such as ammonia are leading options.

- There are growing international commitments to green hydrogen and green ammonia production – there need to be equal commitments to their distribution, storage and end-use.

- The UK has a great science base in this field, and some highly innovative and successful companies, and some great examples of early adoption, and is therefore well placed to benefit from growing use of hydrogen in the energy system - and the economy more widely.

Further information

For more information on the electrochemical science and engineering group at Imperial College see
https://www.imperial.ac.uk/electrochem-sci-eng/

For further information on the Hydrogen and Fuel Cells Hub see
www.h2fcsupergen.com

For further information on the Sustainable Gas Institute see
www.imperial.ac.uk/sustainable-gas-institute/

For further information on the Energy Futures Lab see
www.imperial.ac.uk/energy-futures-lab/

We run a consultancy specialising in electrochemical technologies, hydrogen and the energy transition – Galvanic Energy – feel free to reach out
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