...giving Hydrogen the green light?

16th April 2021

FUTURE OF TECHNOLOGY SERIES

SHARING IDEAS

UNLOCKING OPPORTUNITIES

ADVANCED PROPULSION CENTRE UK

How hydrogen can help us to Net Zero?

13th April, 2021

Sam French

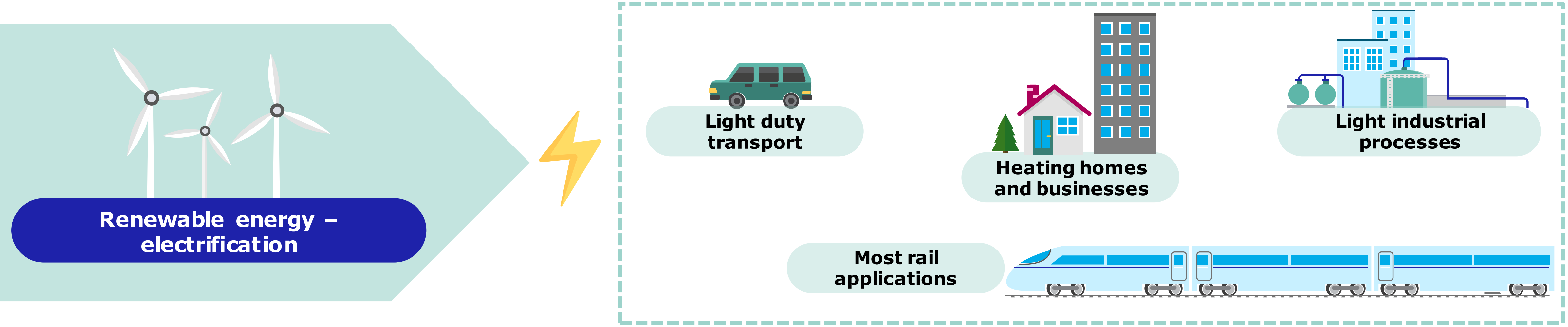
Johnson Matthey
Inspiring science, enhancing life

The move to net zero is accelerating: “building back greener”

Source: Energy and Climate Intelligence Unit, December 2020.

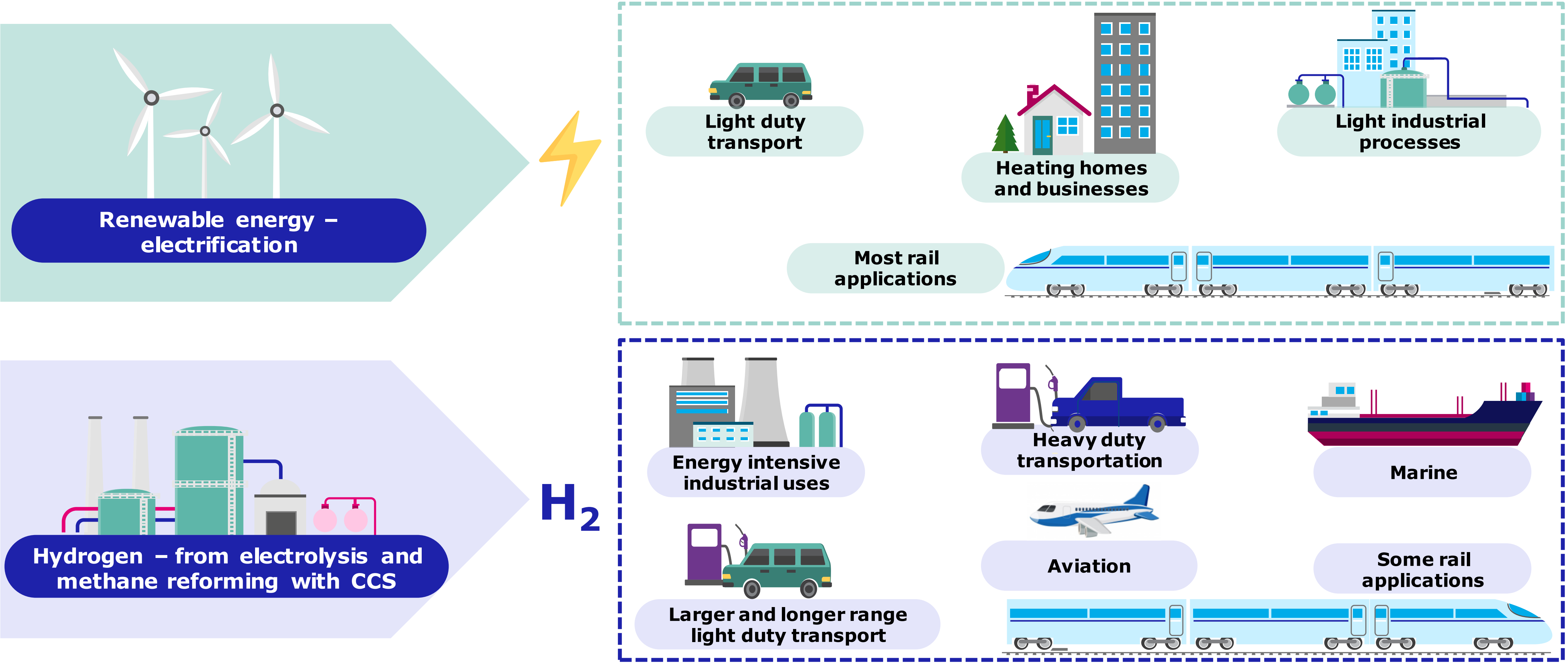
Clean electricity will play a critical role in decarbonisation

We should use renewables to electrify what makes sense – it’s often the most energy efficient route



Clean hydrogen will play a critical role in decarbonisation

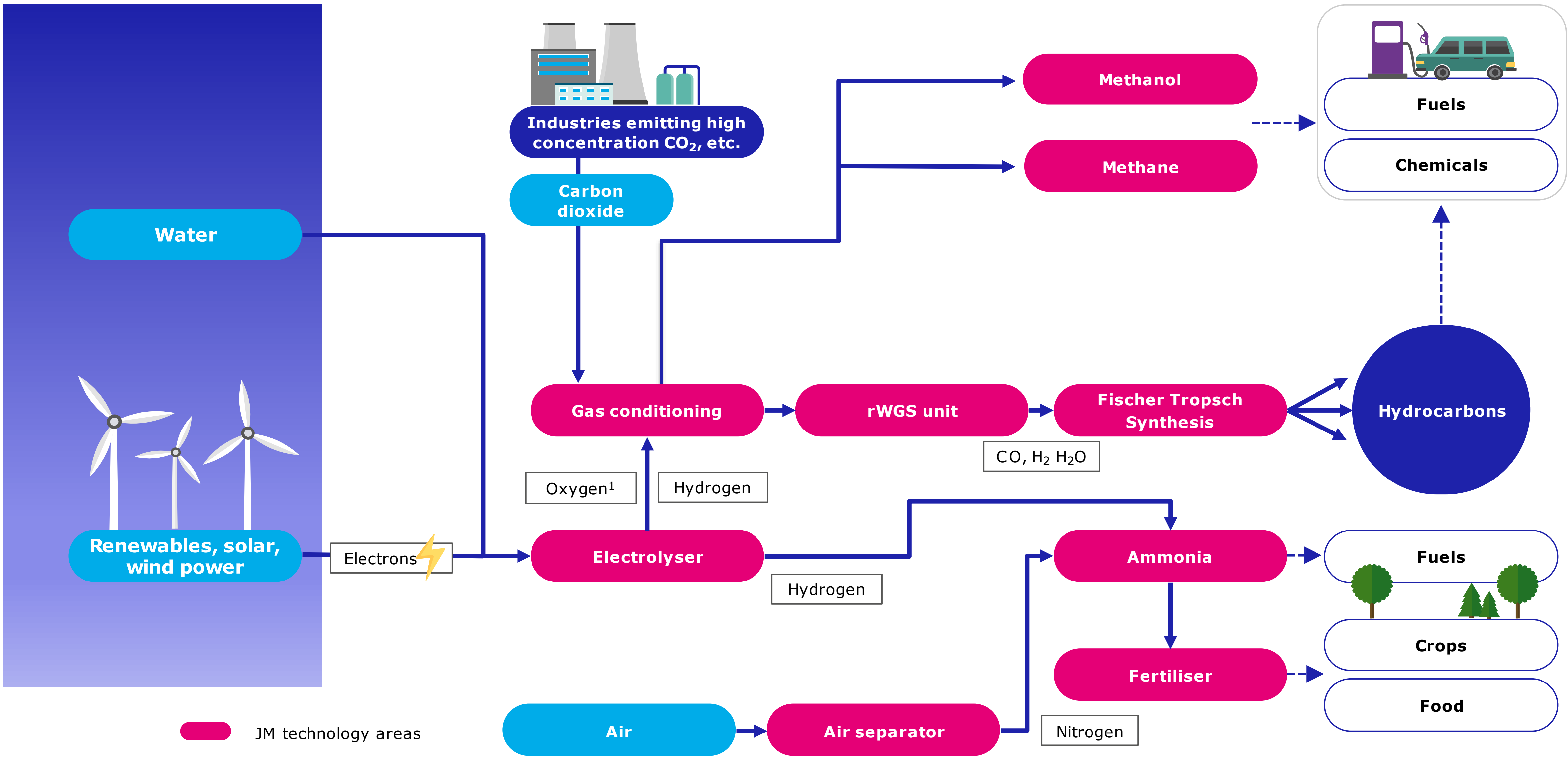
Particularly in hard-to-abate sectors. Hydrogen is transitioning from a chemical feedstock into an energy vector – storing and transporting renewable energy for a range of applications



Note: CCS – carbon capture and storage.

Turning green hydrogen into chemical building blocks: a vision

Upgrading renewable feedstocks (eg biomass, CO_2) into the sustainable fuels & chemicals of the future



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Note: rWGS – reverse water-gas shift reaction

1. Oxygen produced opens up new value streams for electrolyser operators as oxygen is another important chemical widely used by industry. This is not covered in this presentation.

JM has a strong presence across hydrogen production technologies

JM's technologies (Grey, Blue, Green)

Brown	Grey	Blue	Green
Coal	Natural gas	Natural gas	Renewable electricity
-	Leading catalyst supplier 40% segment share[1]	Differentiated technology and catalyst supplier	Expect to supply catalyst coated membrane
Gasification No CCS	Steam methane reforming No CCS	Advanced gas reforming CCS	Electrolysis
Highest GHG emissions (19 tCO_2/tH_2)	High GHG emissions (11 tCO_2/tH_2)	Low GHG emissions (0.2 tCO_2/tH_2)	Potential for zero GHG emissions
\$1.2 to \$2.1 per kg H_2	\$1 – \$2.1 per kg H_2	\$1.5 – \$2.9 per kg H_2	\$3 – \$7.5 per kg H_2

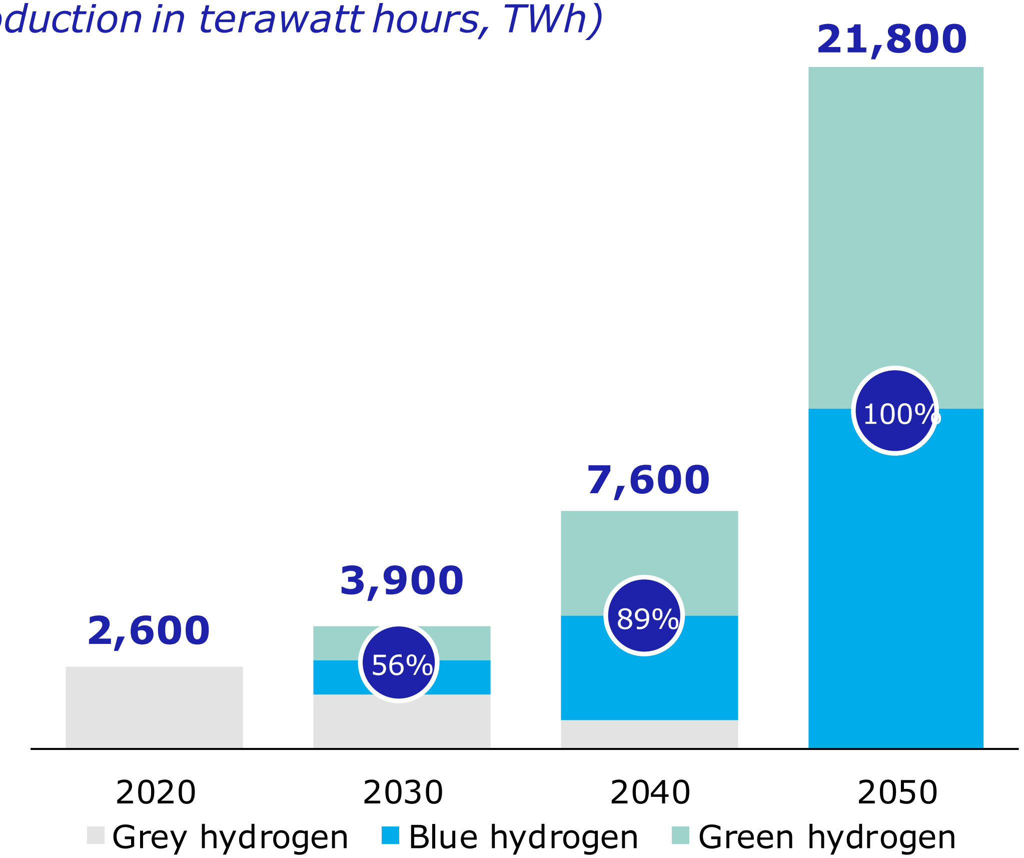
Note: GHG – greenhouse gas; CCS – carbon capture and storage; tCO_2/tH_2 – tonne of carbon dioxide per tonne of hydrogen.
Source: IEA, The Future of Hydrogen, Karuizawa, Japan, June 2019.
1. Based on Johnson Matthey data.

We are going to need a lot more H_2 in future – and it must be clean

Both Blue and Green H_2 will be used as enabling business models are introduced

Split of hydrogen production methods

(Production in terawatt hours, TWh)



% indicates proportion of blue + green hydrogen production

Grey share declines with future carbon tax

Blue adoption driven by geology (carbon storage locations), infrastructure (pipelines) and high cost of alternative routes to low carbon hydrogen

Green adoption driven by geography, declining cost of renewable energy and incentives

Sources: Hydrogen Council, "Hydrogen, Scaling up" report, 2017, (total hydrogen demand); Johnson Matthey, IEA, BP (split of hydrogen production methods).

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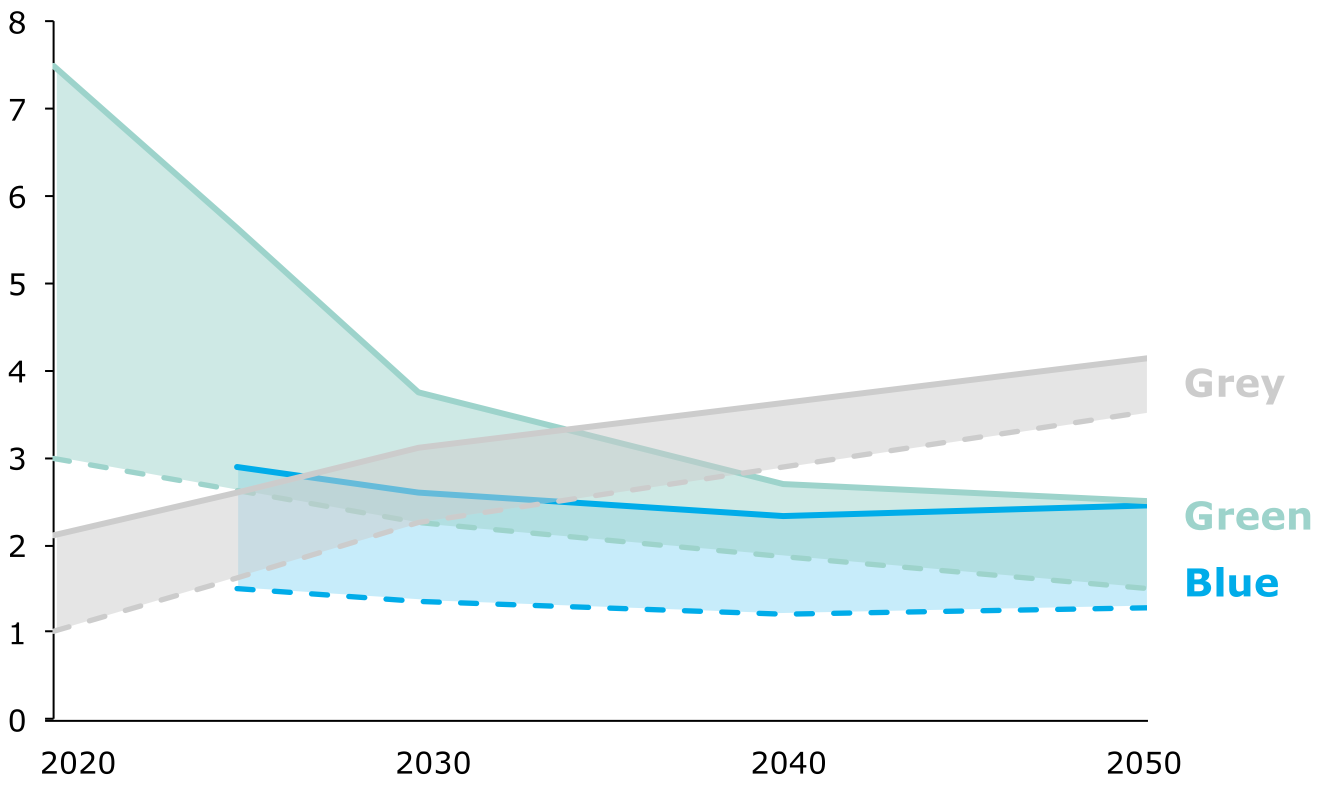
Green hydrogen becomes more competitive over the medium term

Estimated hydrogen cost

($ per kg H_2)



Blue hydrogen advantaged in certain regions and likely to be a long term solution in places with the right geology and infrastructure e.g. US and UK

Green hydrogen will be a solution in some regions as both renewable energy and capital costs decline

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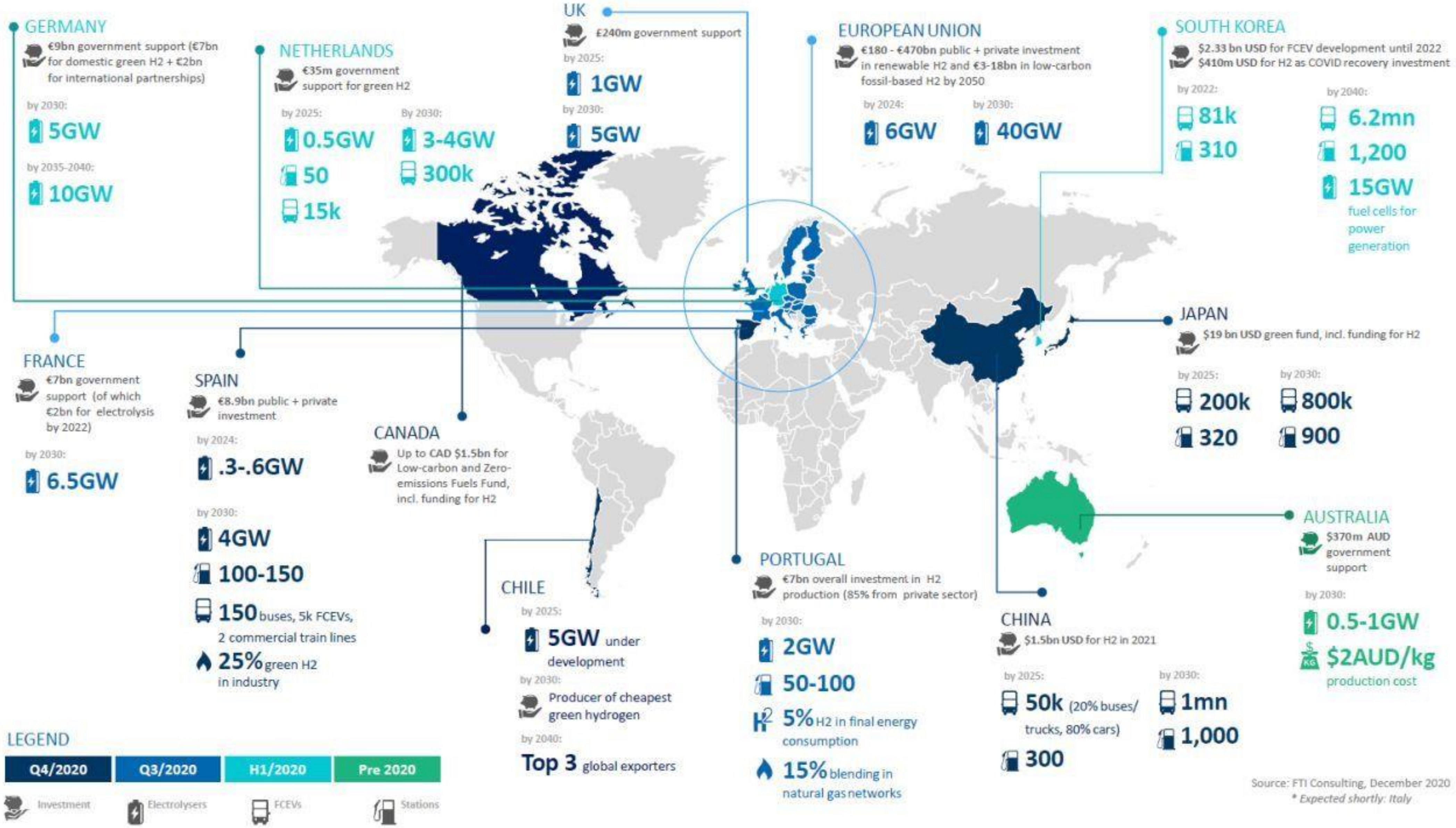
Source: IEA, The Future of Hydrogen, Karuizawa, Japan, June 2019; McKinsey; Johnson Matthey.


GERMANY
€9bn government support (€7bn for domestic green H2 + €2bn for international partnerships)
by 2030:
5GW
by 2035-2040:
10GW
NETHERLANDS
€35m government support for green H2
by 2025:
0.5GW
50
15k
By 2030:
3-4GW
300k
UK
£240m government support
by 2025:
1GW
by 2030:
5GW
EUROPEAN UNION
€180 - €470bn public + private investment in renewable H2 and €3-18bn in low-carbon fossil-based H2 by 2050
by 2024:
6GW
by 2030:
40GW
SOUTH KOREA
$2.33 bn USD for FCEV development until 2022
$410m USD for H2 as COVID recovery investment
by 2022:
81k
310
by 2040:
6.2mn
1,200
15GW
fuel cells for power generation
JAPAN
$19 bn USD green fund, incl. funding for H2
by 2025:
200k
320
by 2030:
800k
900
FRANCE
€7bn government support (of which €2bn for electrolysis by 2022)
by 2030:
6.5GW
SPAIN
€8.9bn public + private investment
by 2024:
.3-.6GW
by 2030:
4GW
100-150
150 buses, 5k FCEVs, 2 commercial train lines
25% green H2 in industry
CANADA
Up to CAD $1.5bn for Low-carbon and Zero-emissions Fuels Fund, incl. funding for H2
CHILE
by 2025:
5GW under development
by 2030:
Producer of cheapest green hydrogen
by 2040:
Top 3 global exporters
PORTUGAL
€7bn overall investment in H2 production (85% from private sector)
by 2030:
2GW
50-100
5% H2 in final energy consumption
15% blending in natural gas networks
CHINA
$1.5bn USD for H2 in 2021
by 2025:
50k (20% buses/ trucks, 80% cars)
300
by 2030:
1mn
1,000
AUSTRALIA
$370m AUD government support
by 2030:
0.5-1GW
$2AUD/kg
production cost
LEGEND
Q4/2020
Q3/2020
H1/2020
Pre 2020
Investment
Electrolysers
FCEVs
Stations
Source: FTI Consulting, December 2020
* Expected shortly: Italy

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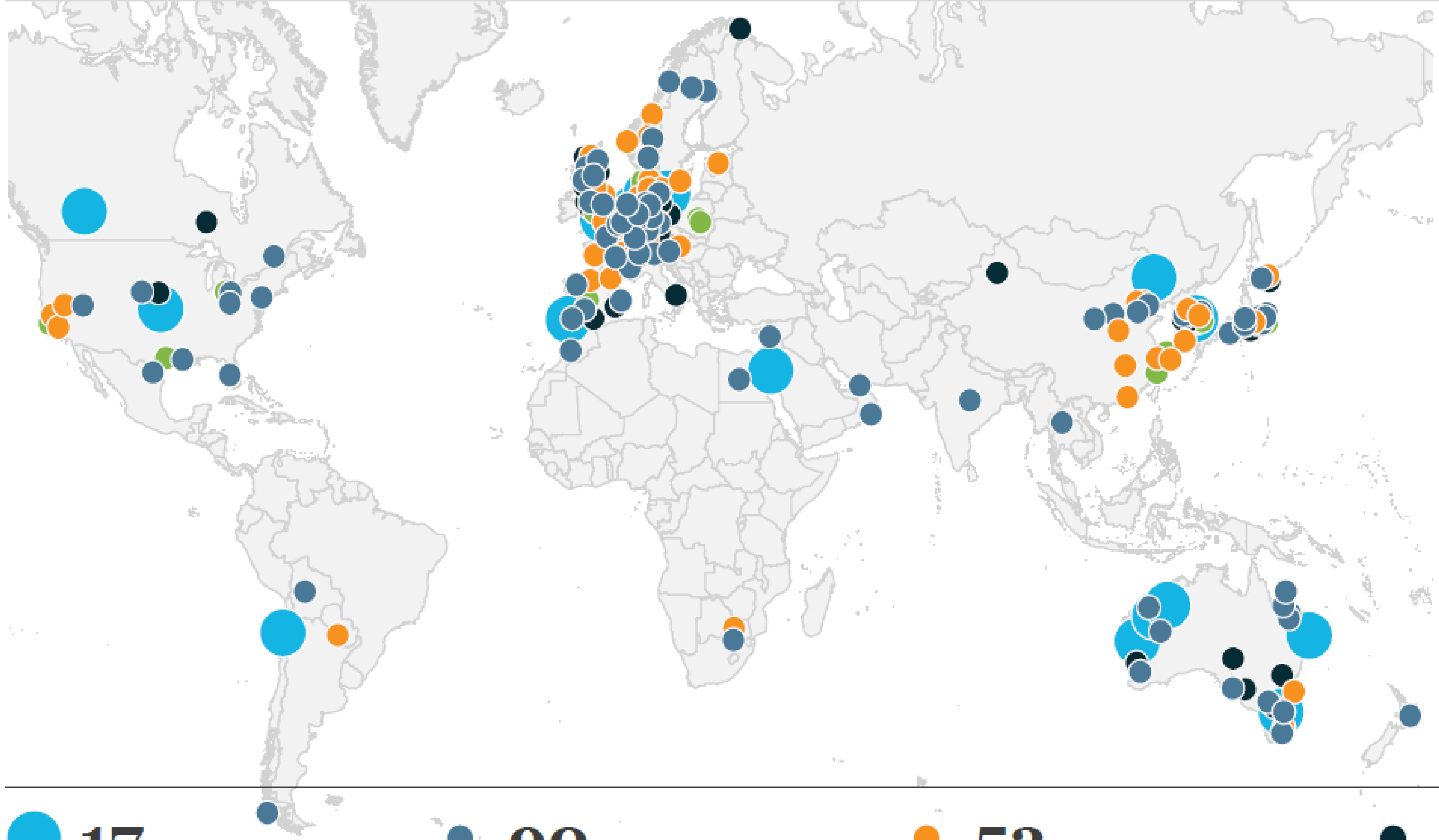
Around the world hydrogen projects of unprecedented scale are being announced across the entire value chain, with 85% located in Europe, Asia and Australia



228 announced projects

126 Europe

46 Asia and China

24 Oceania

19 North America

8 Middle East and Africa

5 Latin America

17

Giga-scale production
Renewable H_2 projects >1GW and low-carbon H_2 projects >200 kt p.a.

90

Large-scale industrial usage
Refinery, ammonia, methanol, steel, and industry feedstock

53

Transport
Trains, ships, trucks, cars and other hydrogen mobility applications

45

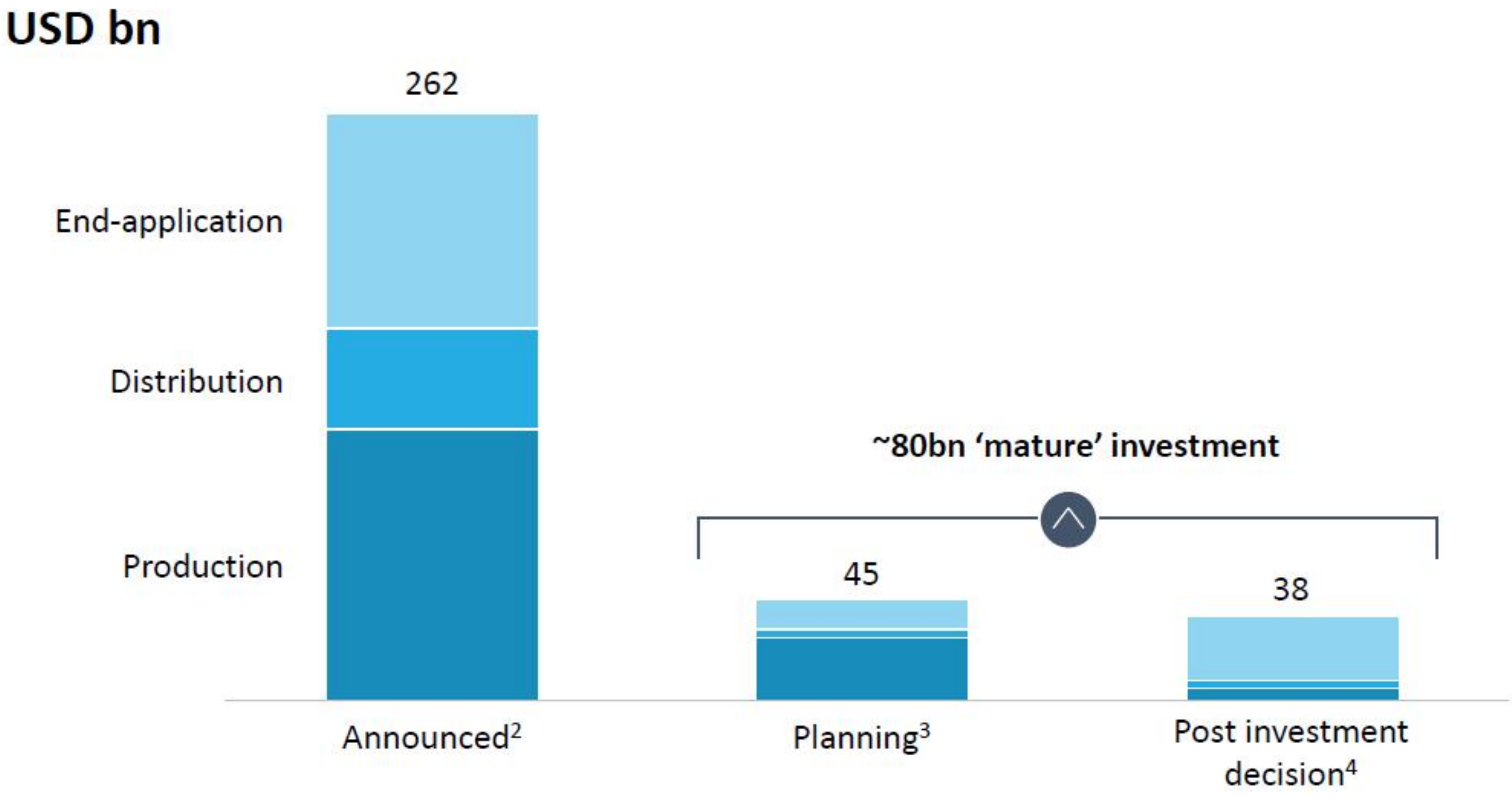
Integrated H_2 economy
cross-industry, and projects with different types of end-uses

23

Infrastructure projects
H_2 distribution, transportation, conversion, and storage

Hydrogen investments

Around 80bn of announced investments are considered mature, either in planning stages or post FID1



70bn of government funding has been announced to support project and technology development

6X increase in private investment until 2025 compared to 2019 spending. And x16 until 2030

80% of private investment allocated to capex, while the remaining is into R&D and M&A

1. Final Investment Decision
2. Includes projects at preliminary studies or at press announced stage. It also includes required investment to reach national targets and governments funding
3. Includes projects that are at the feasibility study or front-end engineering and design stage
4. Includes projects where are a final investment decision (FID) has been taken, under construction, commissioned-and operational

The UK has some world-leading initiatives to demonstrate clean H_2 at scale

- Trialling decarbonised hydrogen as a fuel and feedstock
- Phase 1: 80kt (350MW) of hydrogen p.a. Equivalent to world scale hydrogen plant
- Used in industry, homes and transport

- Renewable hydrogen from electrolysis of water using off-shore wind
- 100 MW electrolyser linked to Hornsea Two offshore wind farm
- Potential to supply up to 30% of the Phillips 66 Humber Refinery hydrogen demand

Great opportunity for the UK to learn by doing and drive further innovation - but we need to act quickly or we will become followers

Global H_2 market estimated at \$2.5tn in 2050[1]

UK targeting 5GW of clean H_2 (Green and Blue) by 2030

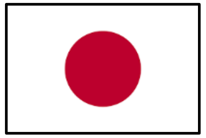
Strongly supports new skills development and levelling-up of UK communities

Note: CCS – carbon capture and storage.
1. Hydrogen Council, "Hydrogen, Scaling up" report, 2017

Fuel cell electric vehicle and hydrogen infrastructure development

- >1m FCEVs in 2030
- >1,000 hydrogen refuelling stations (HRS) by 2030

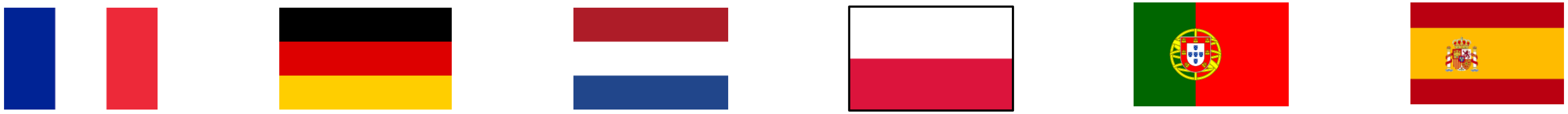
- >1.8m FCEVs in 2030
- >500 HRS in 2030
- $2.2bn investment by 2022



- Strong drive towards hydrogen economy
- 800k FCEVs by 2030
- 900 HRS by 2030

- Zero emission vehicle mandate
- 50k FCEVs by 2025
- 200 HRS by 2025

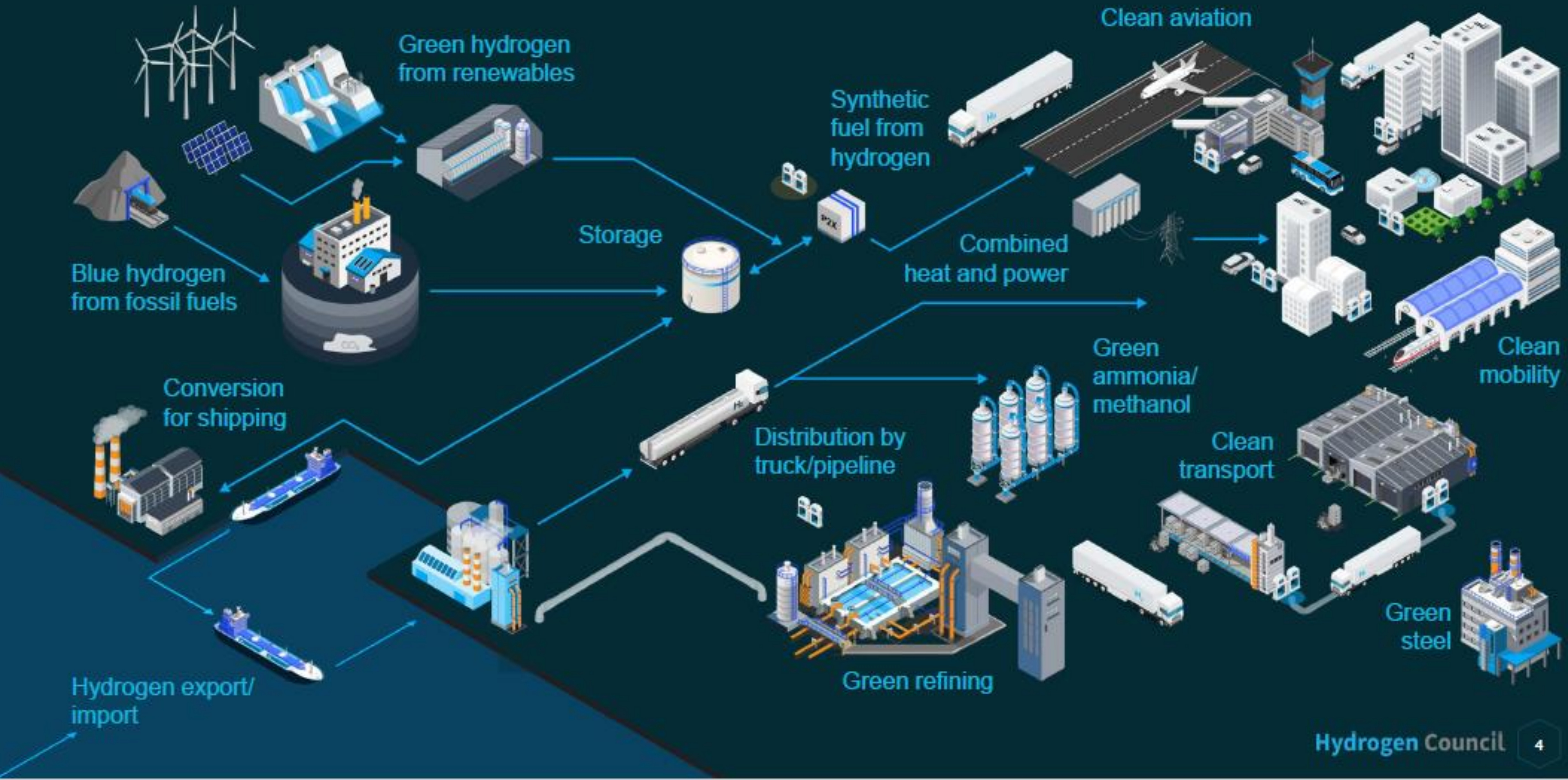
FCEV/HRS deployment by 2030 from European National Hydrogen Strategies



		Bavaria	North-Rhine Westphalia				
LCV	20-50k (2028)	80k	6k	15k (2025) 300k (2030)		5% of road transport powered by H_2	5-7.5k
HCV	0.8-2k (2028)	3k	15k	3k (2025)	2k		
HRS	400-1,000 (2028)	400	200	50 (2025)	150	50-100	100-150

Note: FCEV – fuel cell electric vehicle; HRS – hydrogen refuelling station

The hydrogen economy spans across sectors



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Johnson Matthey
Inspiring science, enhancing life

Q&A

HYDROGEN TASKFORCE

Hydrogen Taskforce

Clare Jackson - Ecuity

HYDROGEN TASKFORCE

Who is the Hydrogen Taskforce?

The Hydrogen Taskforce brings together the organizations leading on hydrogen across the value chain to make the high level energy system, economic and environmental case for hydrogen in the UK

ARUP
ARVAL BNP PARIBAS GROUP
Baker McKenzie.
BAXI HEATING
BNP PARIBAS The bank for a changing world
BOC A Member of The Linde Group
equinor
bp
Cadent Your Gas Network
centrica
DBD
ITM POWER
JM
eDF
Northern Gas Networks
Ørsted
SGN Your gas. Our network.
sse Thermal
uniper
DNV

Why hydrogen?

HYDROGEN TASKFORCE

- Enables greater deployment of renewables
- Reduces pressure on electricity transmission network
- Demand variation and storage
- Hard to abate sectors
- Energy System Resilience
- Global market opportunity

Key questions for 2021

What is the role of hydrogen in the UK?

What do we need to do now to achieve that?

Key questions for 2021

HYDROGEN TASKFORCE

How much hydrogen?

Where should it be used?

What economic benefit would this unlock?

What is the role of hydrogen in the UK?

How much carbon could we save?

What are the energy system implications?

What do we need to do now to achieve that?

What existing assets can we leverage?

Where can the UK take a global leadership position?

Key questions for 2021

What is the role of hydrogen in the UK?

How much hydrogen?

Where should it be used?

What economic benefit would this unlock?

What existing assets can we leverage?

Where can the UK take a global leadership position?

How much carbon could we save?

What are the energy system implications?

What do we need to do now to achieve that?

How do we ensure consumers are engaged?

What are the barriers?

What business models do we need?

What is the role of Government?

How do we encourage coordination across sectors?

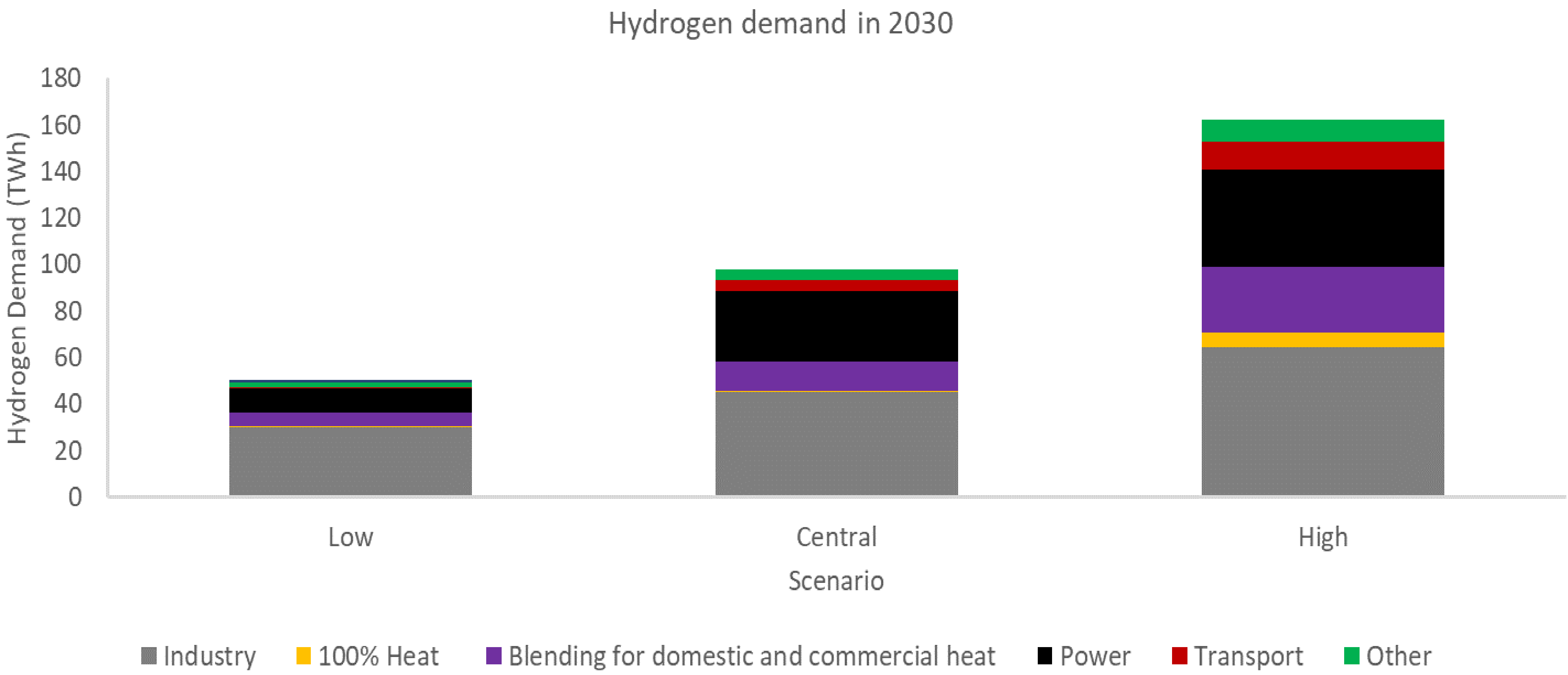
How do we ensure we have the right skills?

What infrastructure will we need?

Analysis| Production and Demand

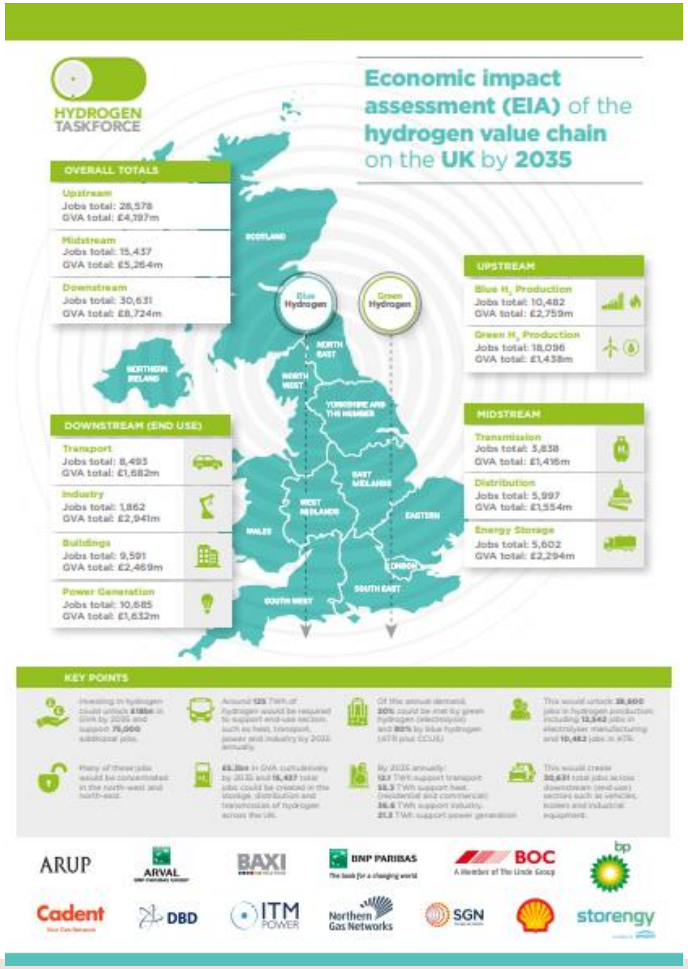
	10pt Plan	Low	Central	High
Production – installed capacity (GW)	5	**7.6**	**14.8**	**22.9**
Blue		5.2	9.1	14.0
Green		2.3	5.7	8.9
Demand - TWh		**49.7**	**97.9**	**161.9**
Industry		30.3	45.1	64.7
Blending for domestic and commercial heat		5.6	12.7	28.5
Power		10.4	30.1	41.6
Transport		0.8	4.6	12.1
100% domestic and commercial heat		0.2	0.7	6.1
Other (i.e. CHP, ammonia)		2.2	4.7	8.9
Impact				
Carbon abatement ($MtCO_2e$)	41	9.7	18.4	30.8
GVA - £bn		7.2	14.2	23.6
Jobs	8,000	29,700	58,500	96,800

Production/Demand figures



Making the case – Economic Impact Assessment

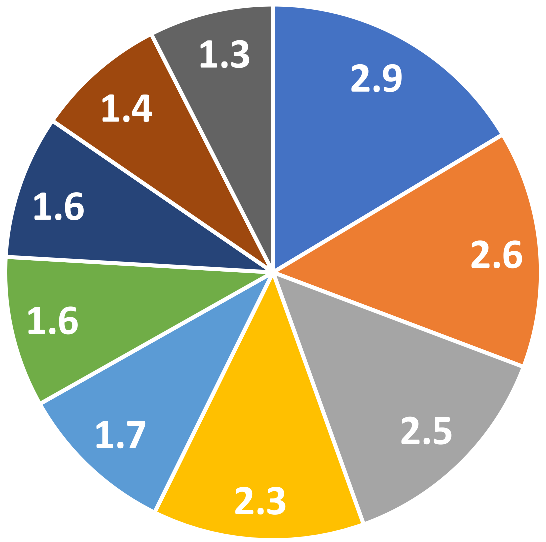
- Economic value and job creation estimated across the entire hydrogen value chain by 2035:
    - **Upstream**
        - Production – blue and green
    - **Midstream**
        - Transmission & distribution
        - Energy storage
    - **Downstream**
        - Power generation
        - Transport
        - Heat in Buildings and Industry



Results and findings: GVA and jobs

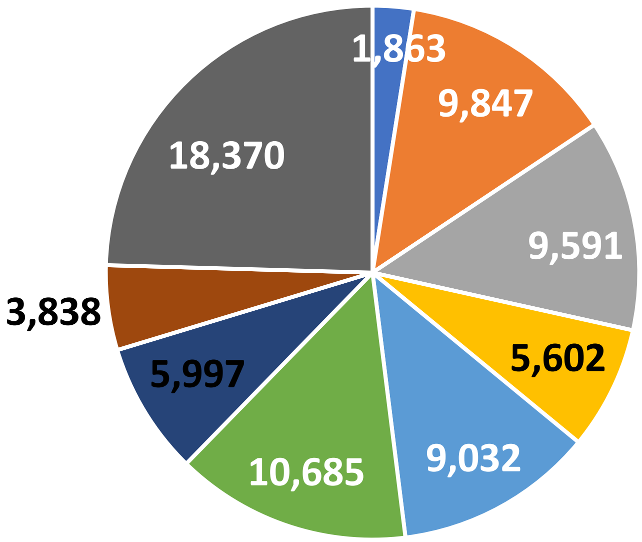
Unlock ~£18bn in GVA by 2035

GVA by sector - £bn



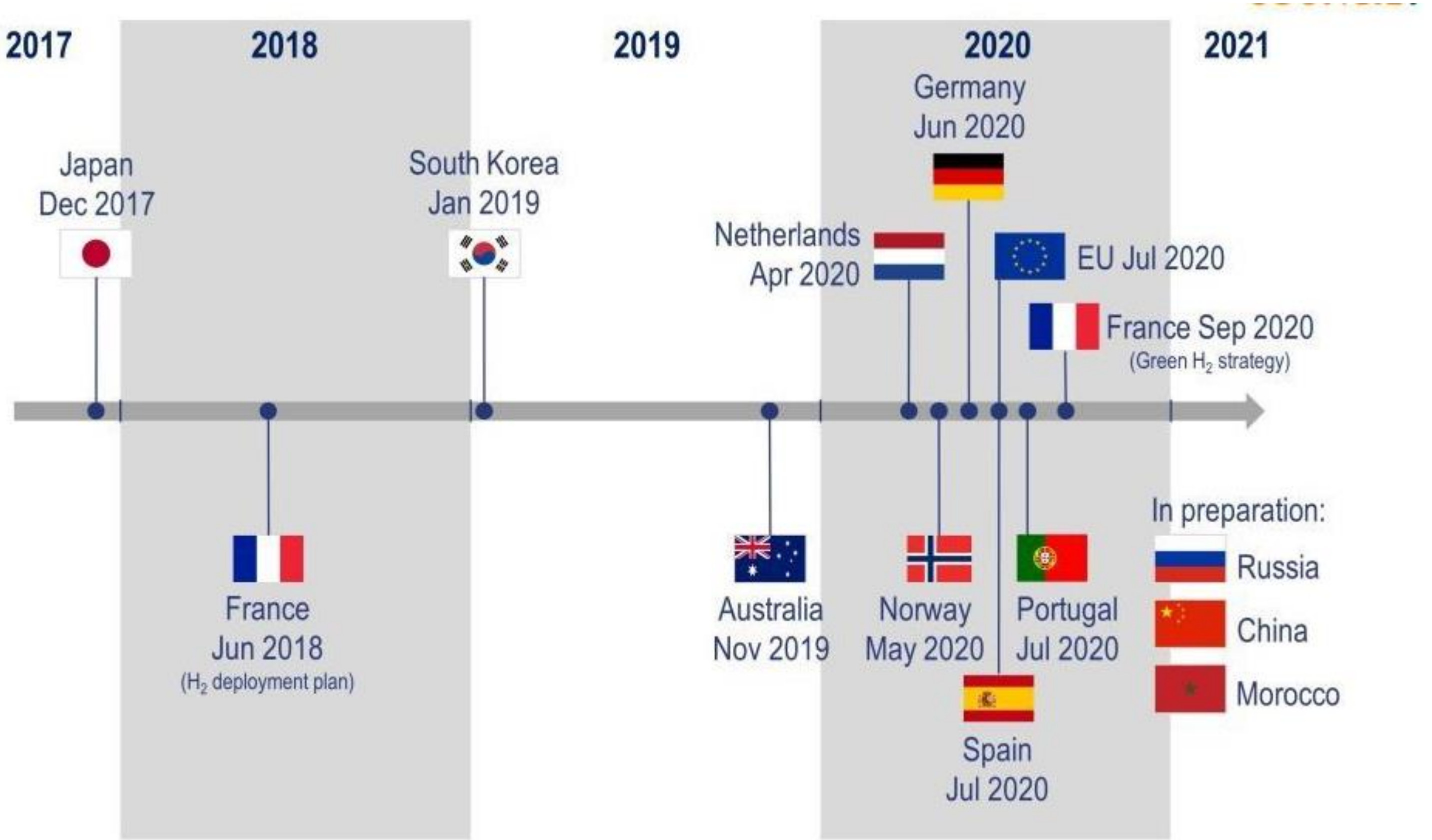
Create ~75,000 gross jobs by 2035

Jobs by sector



Industry · Blue Hydrogen · Buildings · Energy Storage · Transport · Power Generation · Distribution · Transmission · Green Hydrogen

The UK hydrogen strategy…



And business models…

Imperial College London
Corporate Partnerships

The role of hydrogen in the transition to net zero

Prof Nigel Brandon OBE FREng

n.brandon@imperial.ac.uk

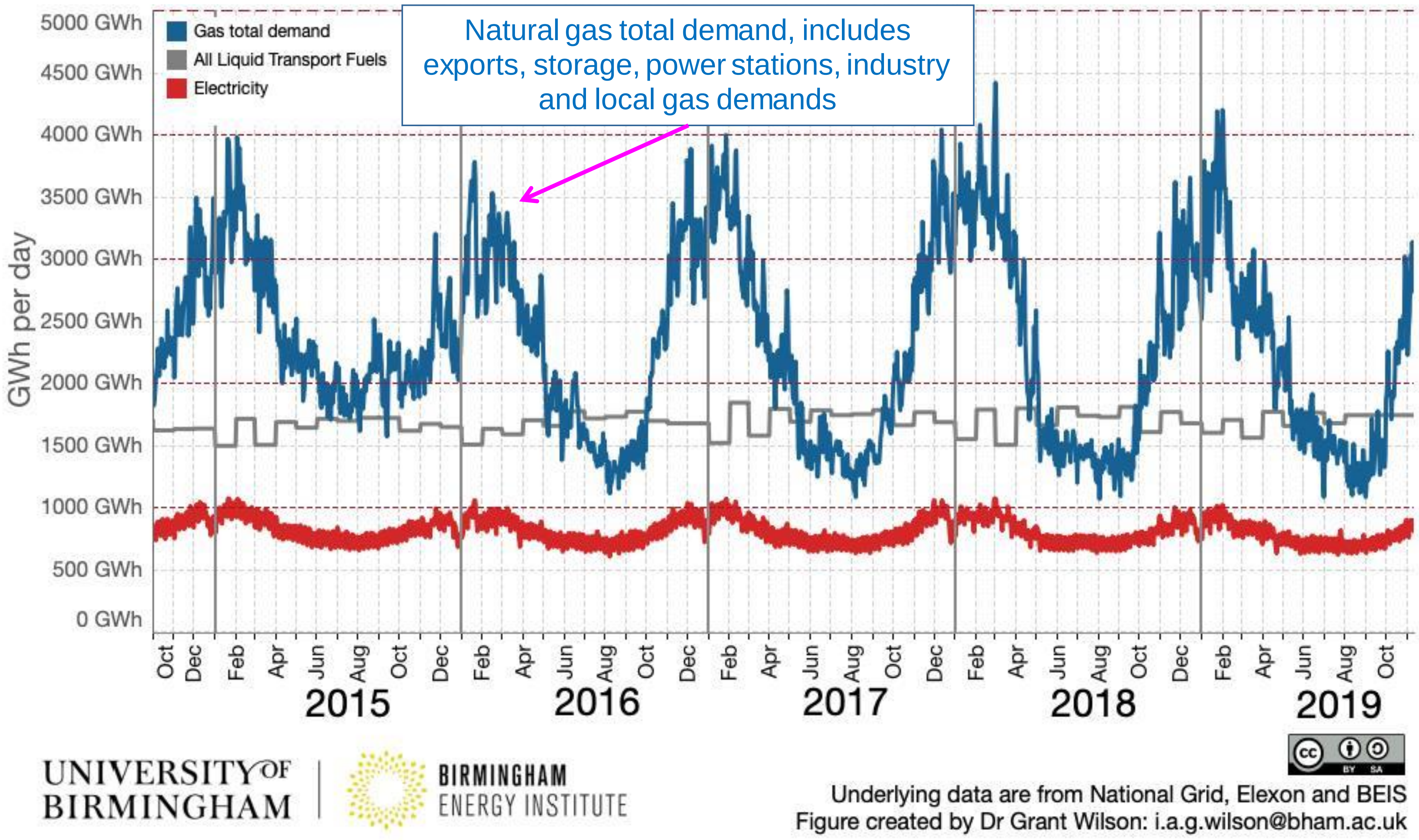
www.imperial.ac.uk/electrochem-sci-eng/

H2FC SUPERGEN
THE HYDROGEN AND FUEL CELL RESEARCH HUB

SUSTAINABLE GAS INSTITUTE

www.imperial.ac.uk/people/n.br

Great Britain’s Energy Vectors – in GWh per day



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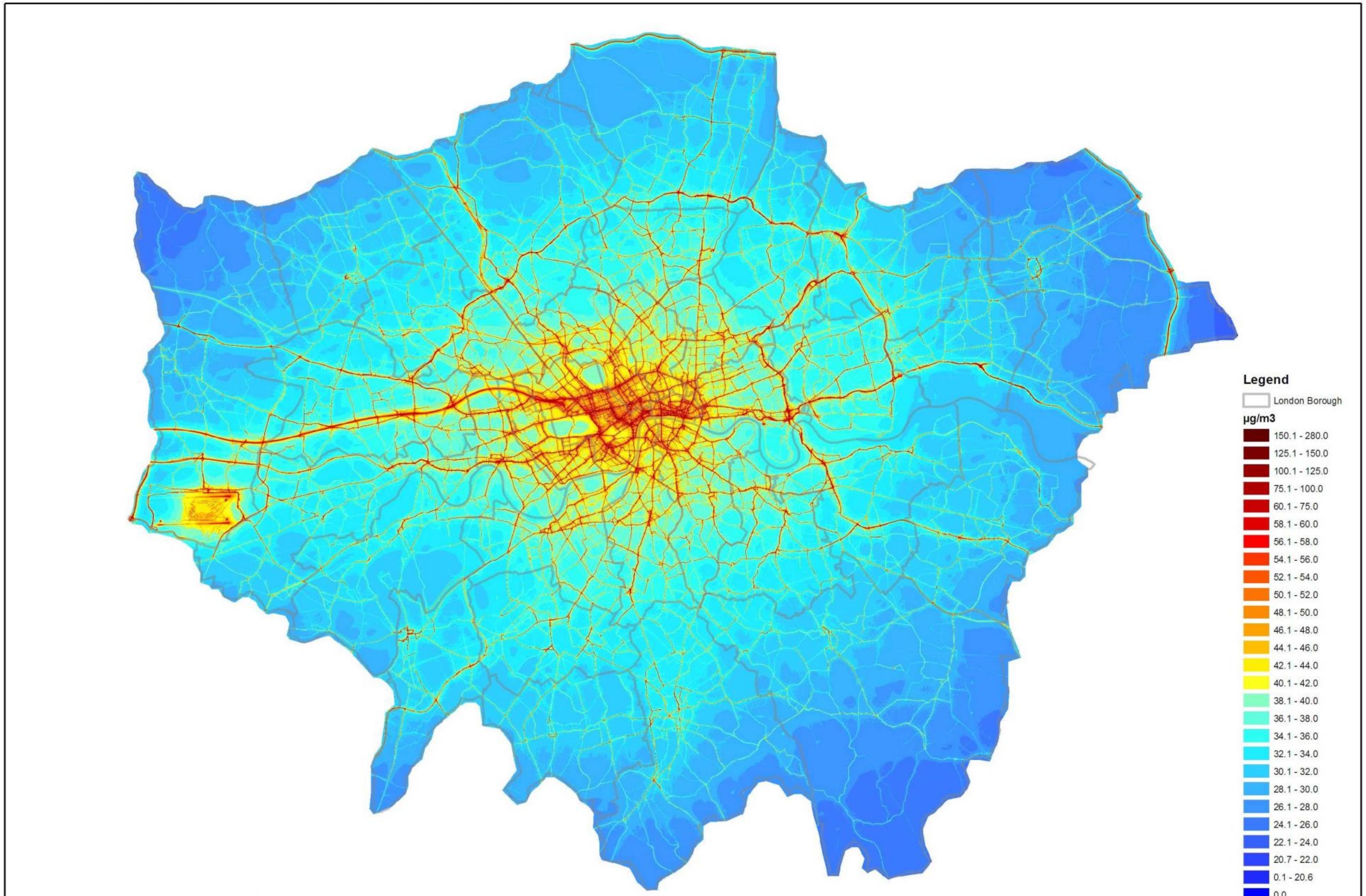
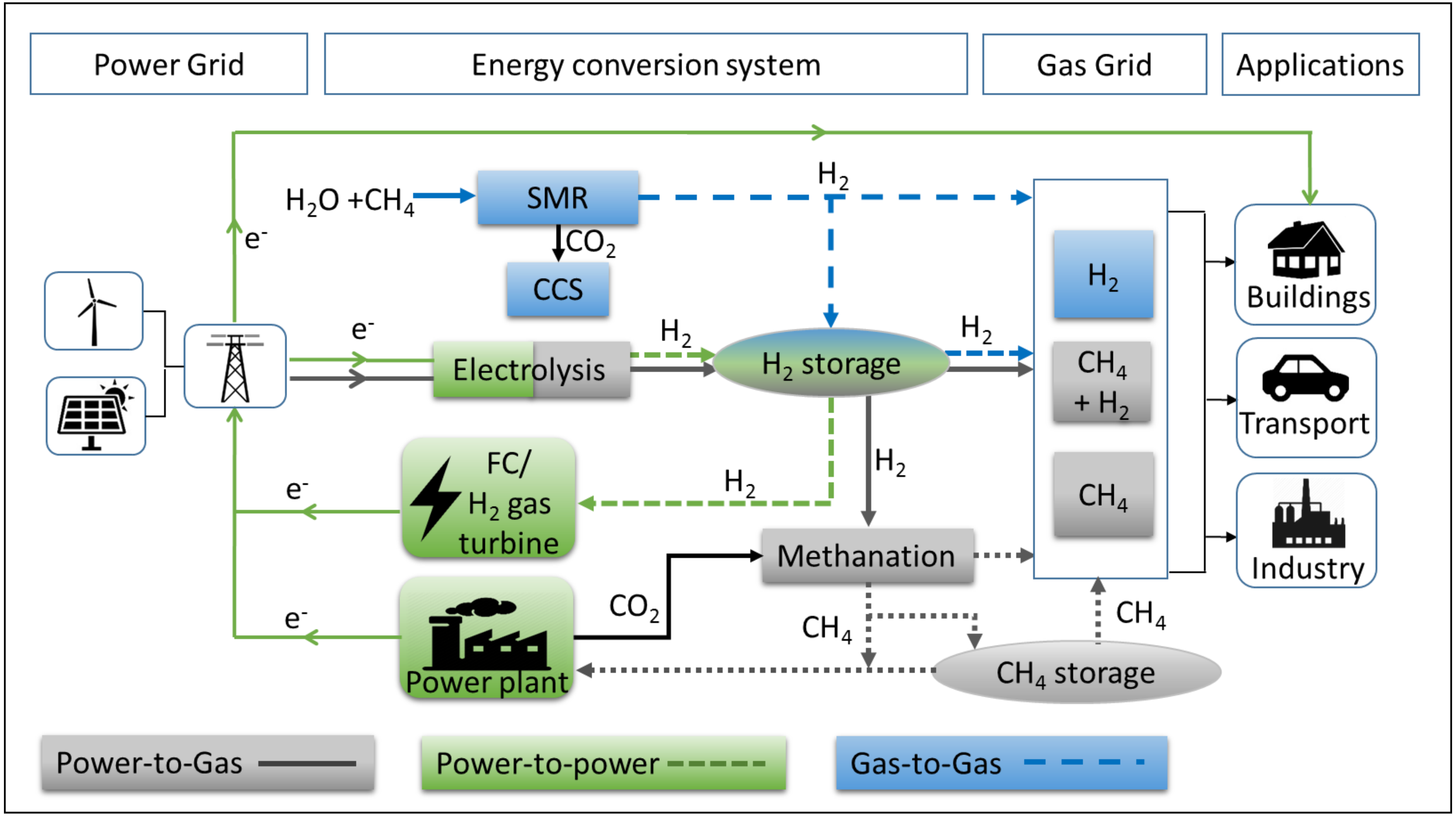
LAEI 2008: NO2 Annual Mean - 2008

GREATER**LONDON**AUTHORITY



The Role of Hydrogen in the Economy



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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

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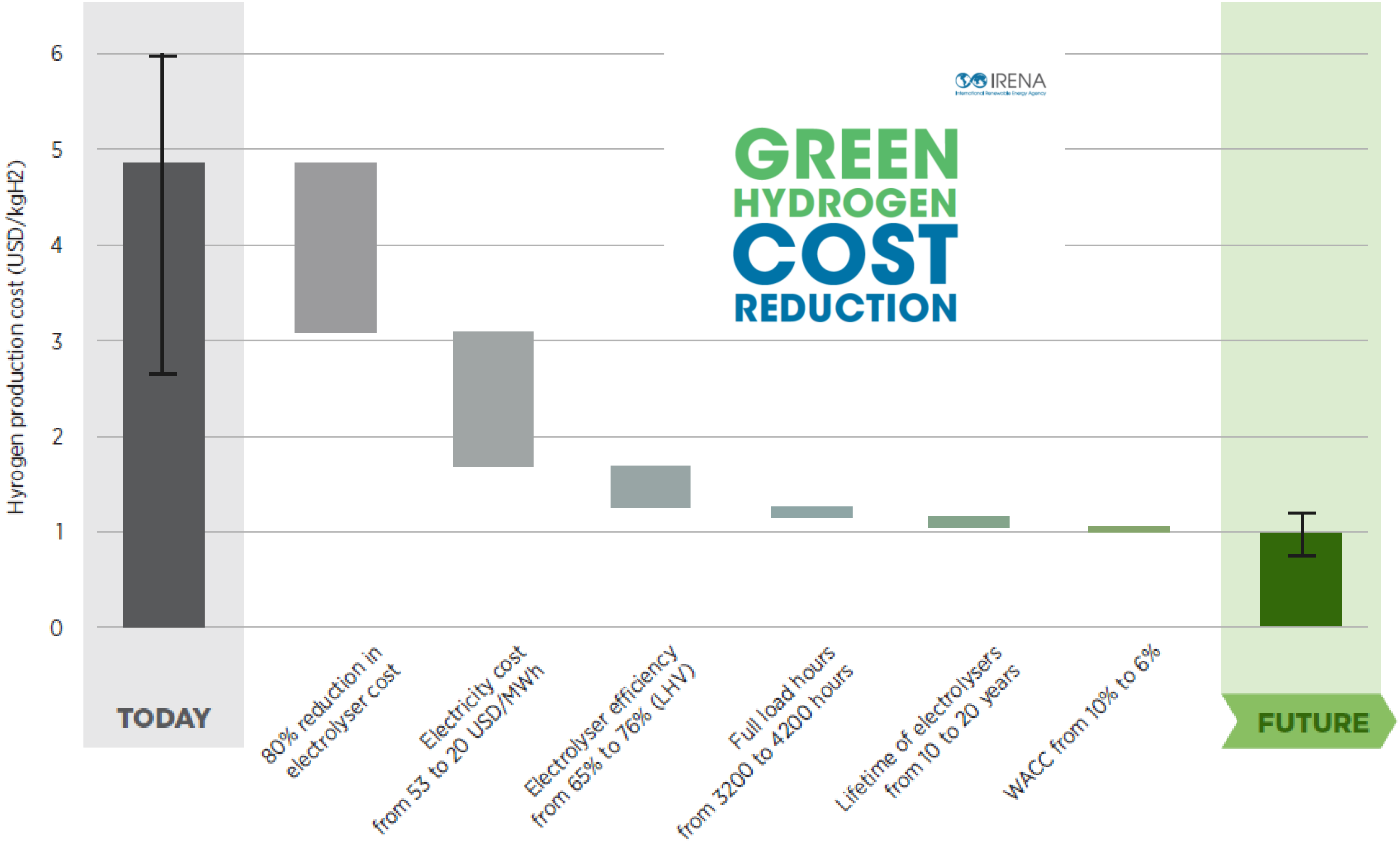
Green hydrogen production costs



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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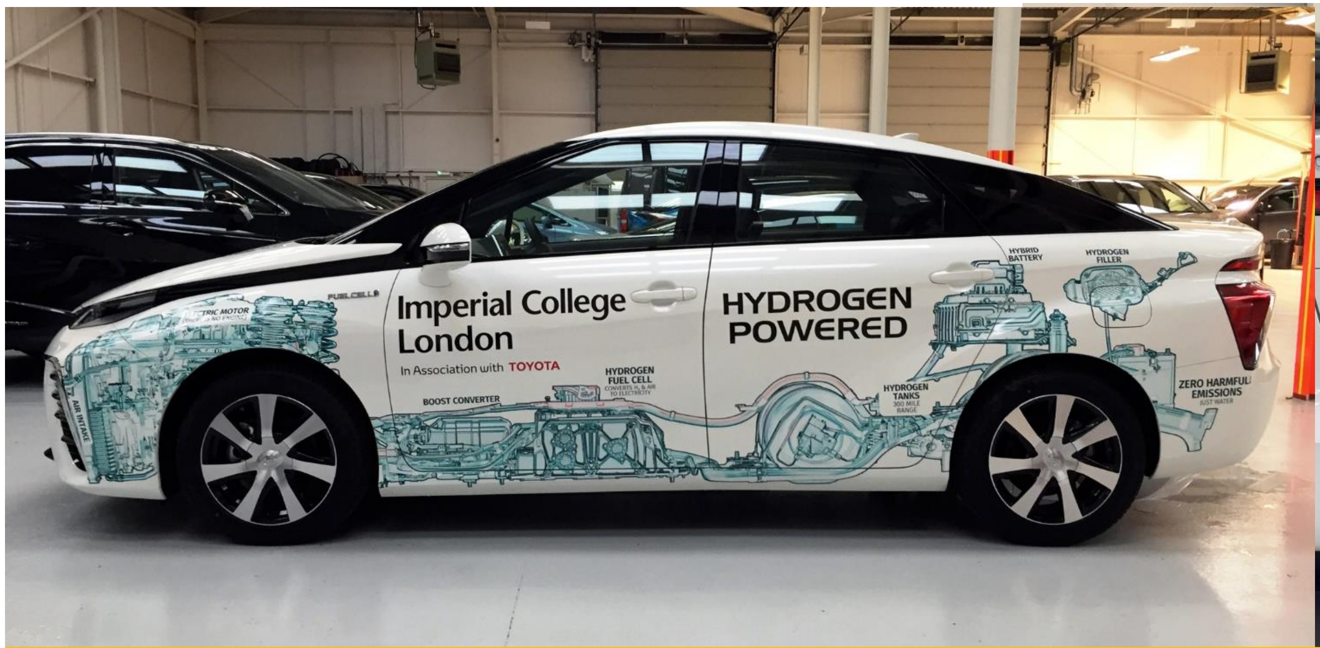
- Industry partnerships (BMW-Toyota), (Renault-Nissan-Daimler-Ford), (GM-Honda).
- Two FCEV models available to own in the UK - ***Toyota Mirai*** (£66k) (11,000 sales globally: 180 in the UK) and the ***Hyundai's ix35*** fuel cell. Hyundai's new FCEV Nexo retails as £70k. New ***Mirai*** in 2021 – 400 miles range, cost £50k.
- At the end of 2019, 470 hydrogen refuelling stations were in operation worldwide. Japan had 113 stations, Germany 81 and the United States 64.



Toyota Mirai 114 kW fuel cell, 3-5 minute refuel, 342 mile range, 0-60mph 9s

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.

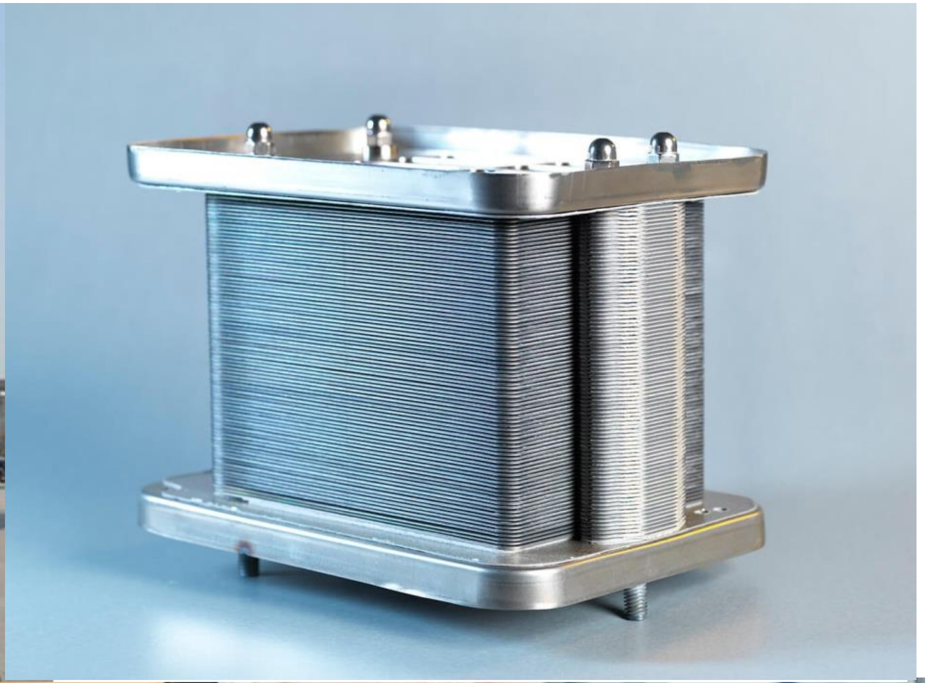
China: World largest FCEB fleet. 30% of Shanghai's electric bus fleet to be FCEBs; Shangdong Heavy Industry's to make 2,000 buses; purchase of 300 FCEBs by Datong.

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.

- 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.

- 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.

Metal supported SOFC from Ceres Power

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 n.brandon@imperial.ac.uk

...giving Hydrogen the green light?

13th-16th April 2021

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ADVANCED PROPULSION CENTRE UK

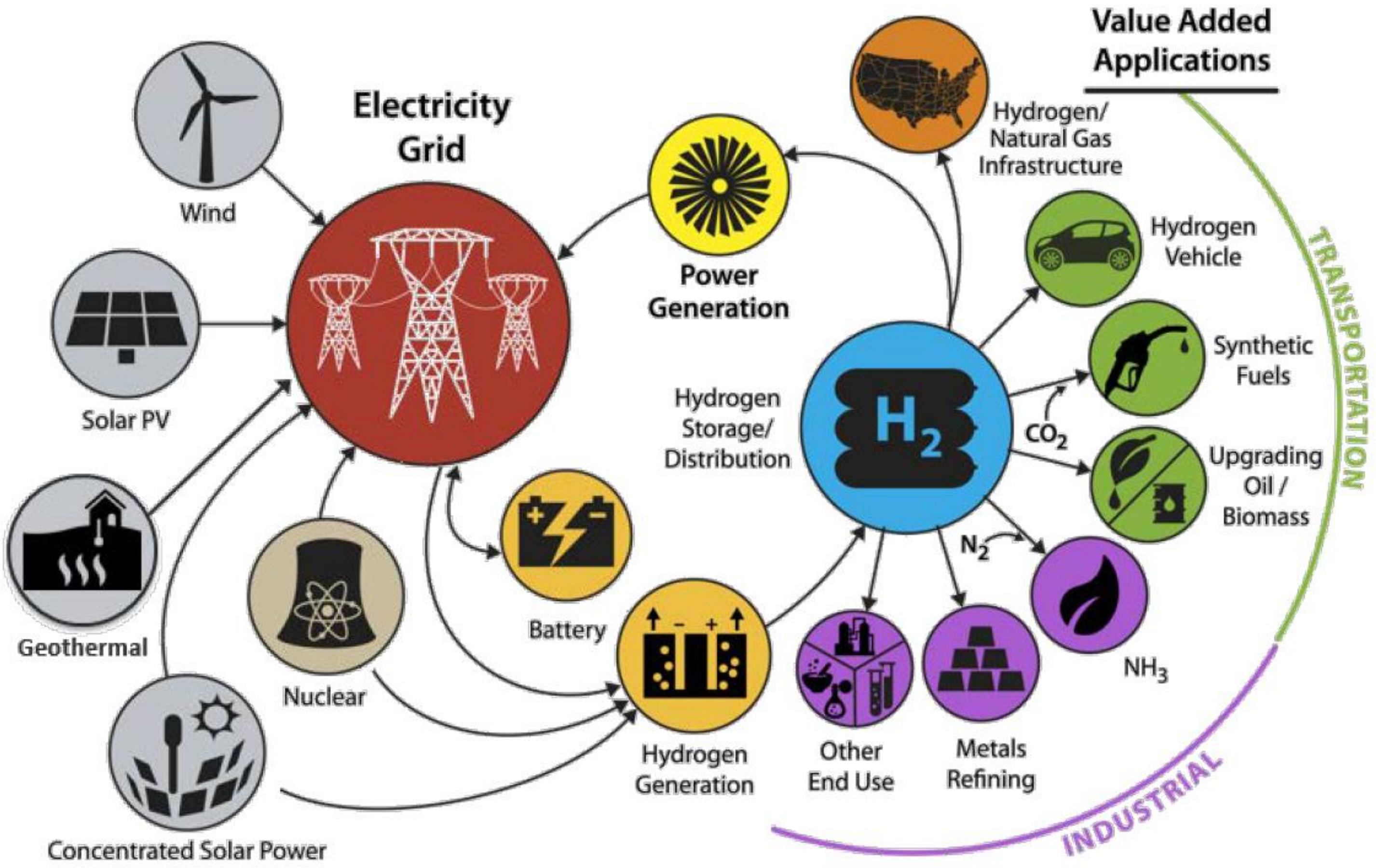
RALPH CLAGUE
HYDROGEN IN AUTOMOTIVE

13 April 2021

HYDROGEN IN THE ECONOMY

Hydrogen is a flexible energy vector for multiple end uses

- Need to decarbonise hydrogen already used in industry for fertiliser, refining hydrocarbon fuels, plastics, foods, etc (~65M tonnes/yr globally).
- Need to decarbonise heating, in the UK the natural gas grid delivers 3 times the ‘power’ of the electricity grid.
- fully renewable electricity grids depend on enormous energy storage capacity, hydrogen offers weeks to months of storage.
- Heavy industrial processes like steel making, can be decarbonised with hydrogen.
- Heavy duty transport applications (large vehicles, trucks, trains, ships) require more on-board energy than can be effectively (mass or cost) stored in batteries.

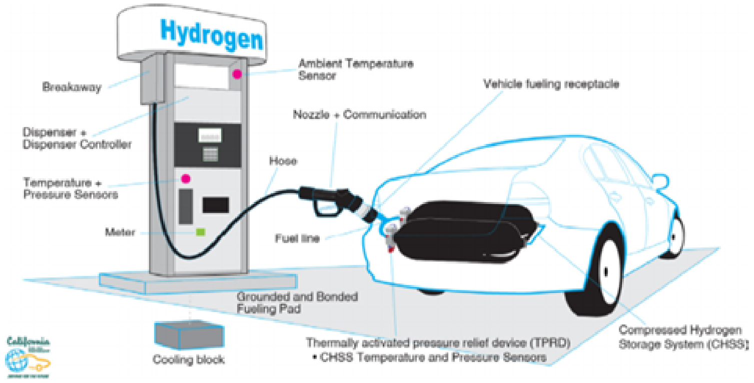


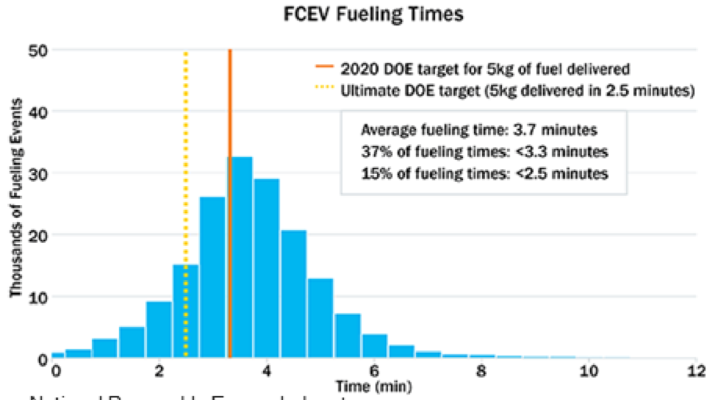
https://www.hydrogen.energy.gov/pdfs/htac_dec18_01_satyapal.pdf

Customer convenience

Battery vehicles are appearing and credible, why are auto makers still considering hydrogen?

Fast fill up convenient to customer, EV charging at home requires off street parking.

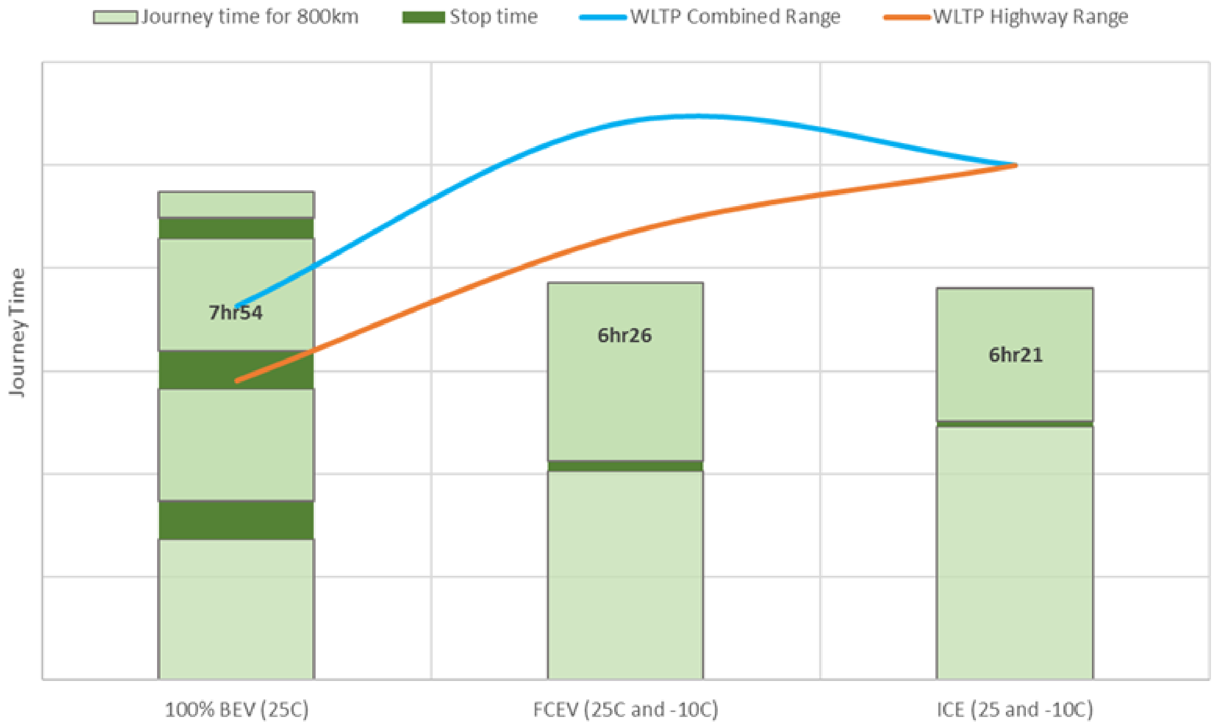




National Renewable Energy Laboratory
https://afdc.energy.gov/fuels/hydrogen_basics.html

Low residence time at H_2 stations, fewer public 'charging' stations needed

Long journey travel times for FCEV and ICE are comparable: 800km journey at 25°C, takes 1.5hrs longer in BEV than FCEV or ICE.



Range of BEV is reduced at low temperature (40% lower at -7C). FCEV range not affected by low temperature, FC heat used in cabin.

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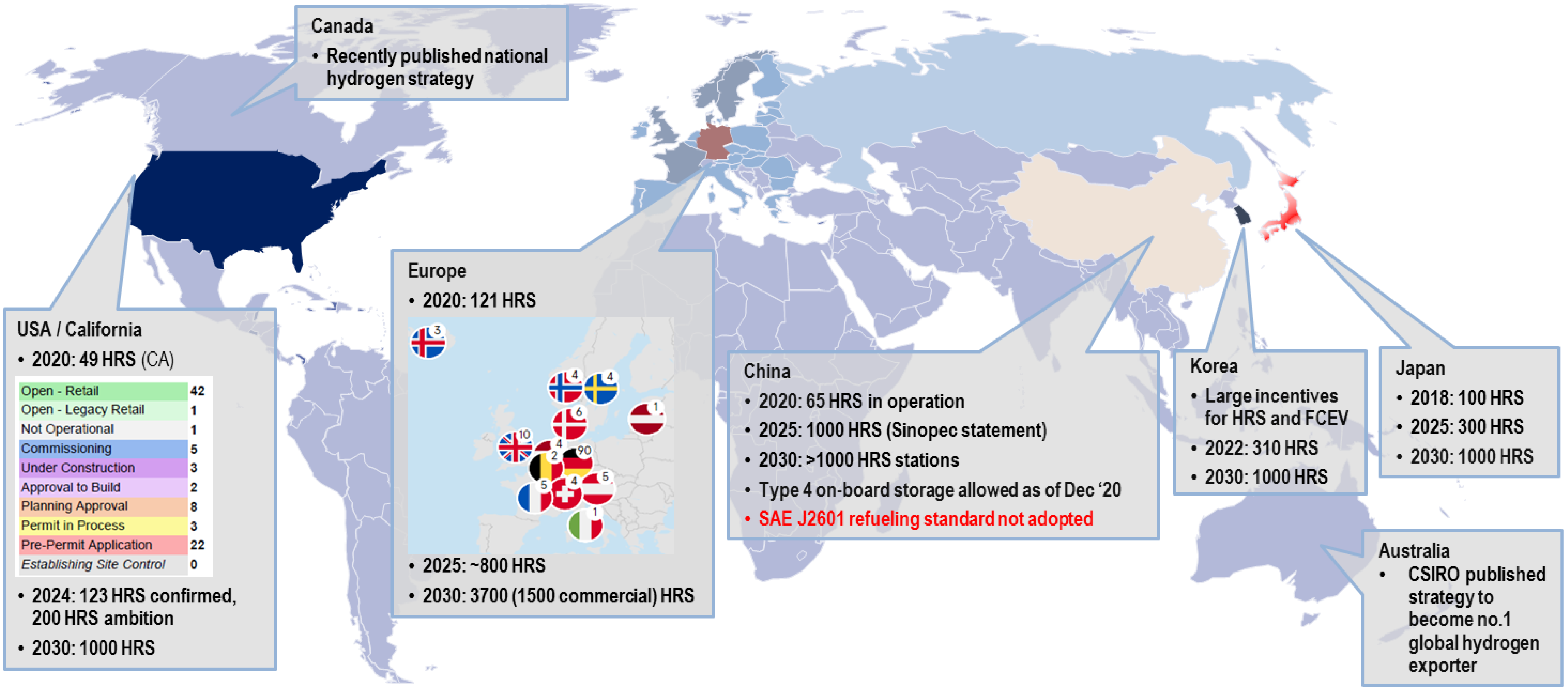
No hydrogen filling stations



Canada
- Recently published national hydrogen strategy

USA / California
- 2020: 49 HRS (CA)

Open - Retail	42
Open - Legacy Retail	1
Not Operational	1
Commissioning	5
Under Construction	3
Approval to Build	2
Planning Approval	8
Permit in Process	3
Pre-Permit Application	22
Establishing Site Control	0

- 2024: 123 HRS confirmed, 200 HRS ambition
- 2030: 1000 HRS

Europe
- 2020: 121 HRS

- 2025: ~800 HRS
- 2030: 3700 (1500 commercial) HRS

China
- 2020: 65 HRS in operation
- 2025: 1000 HRS (Sinopec statement)
- 2030: >1000 HRS stations
- Type 4 on-board storage allowed as of Dec '20
- SAE J2601 refueling standard not adopted

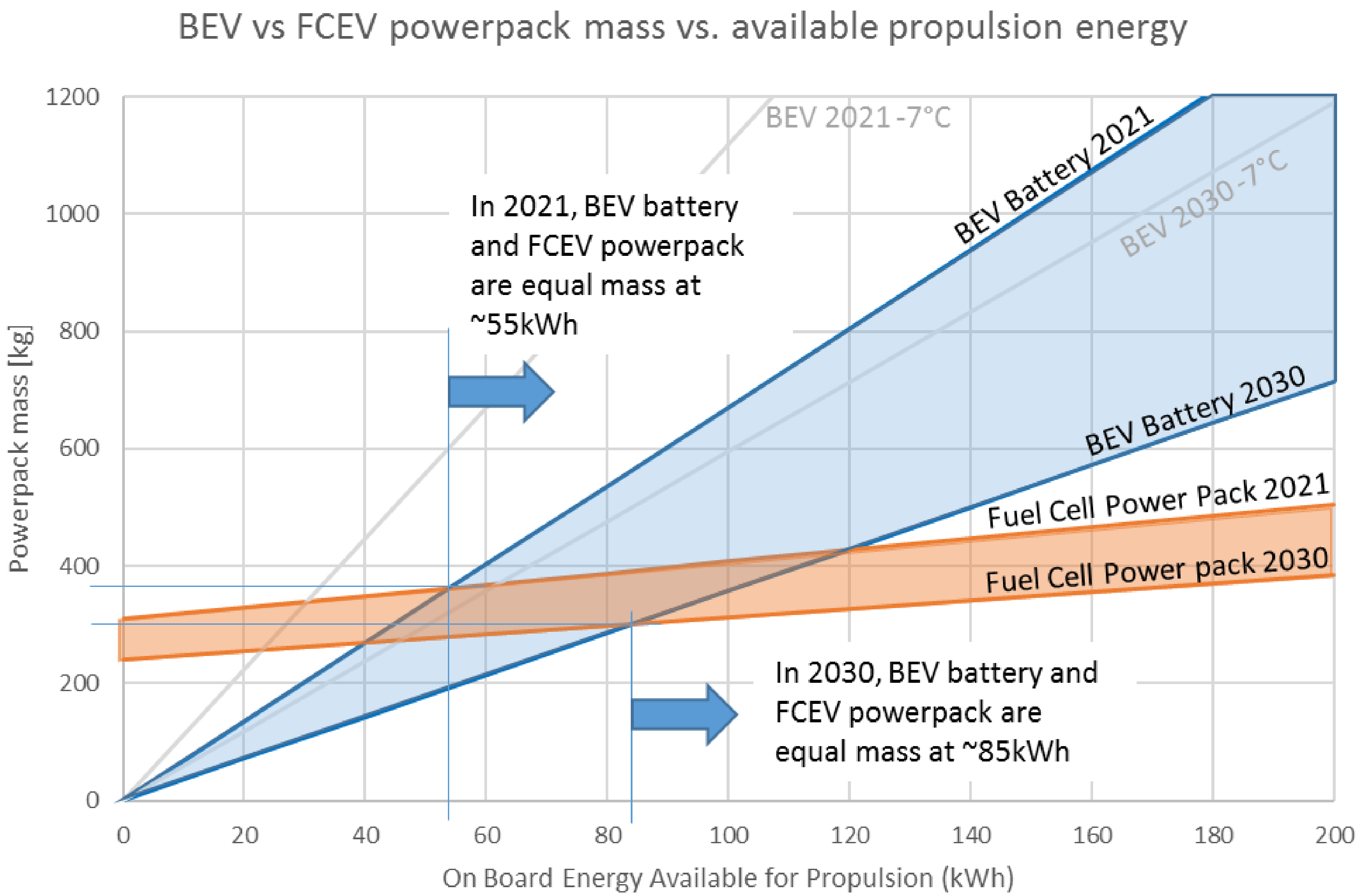
Korea
- Large incentives for HRS and FCEV
- 2022: 310 HRS
- 2030: 1000 HRS

Japan
- 2018: 100 HRS
- 2025: 300 HRS
- 2030: 1000 HRS

Australia
- CSIRO published strategy to become no.1 global hydrogen exporter

On board energy and mass

Where a lot of energy is needed on board, hydrogen fuel cell powerpacks are a lighter option



Lower powerpack mass (compared to BEV and PHEV) means:

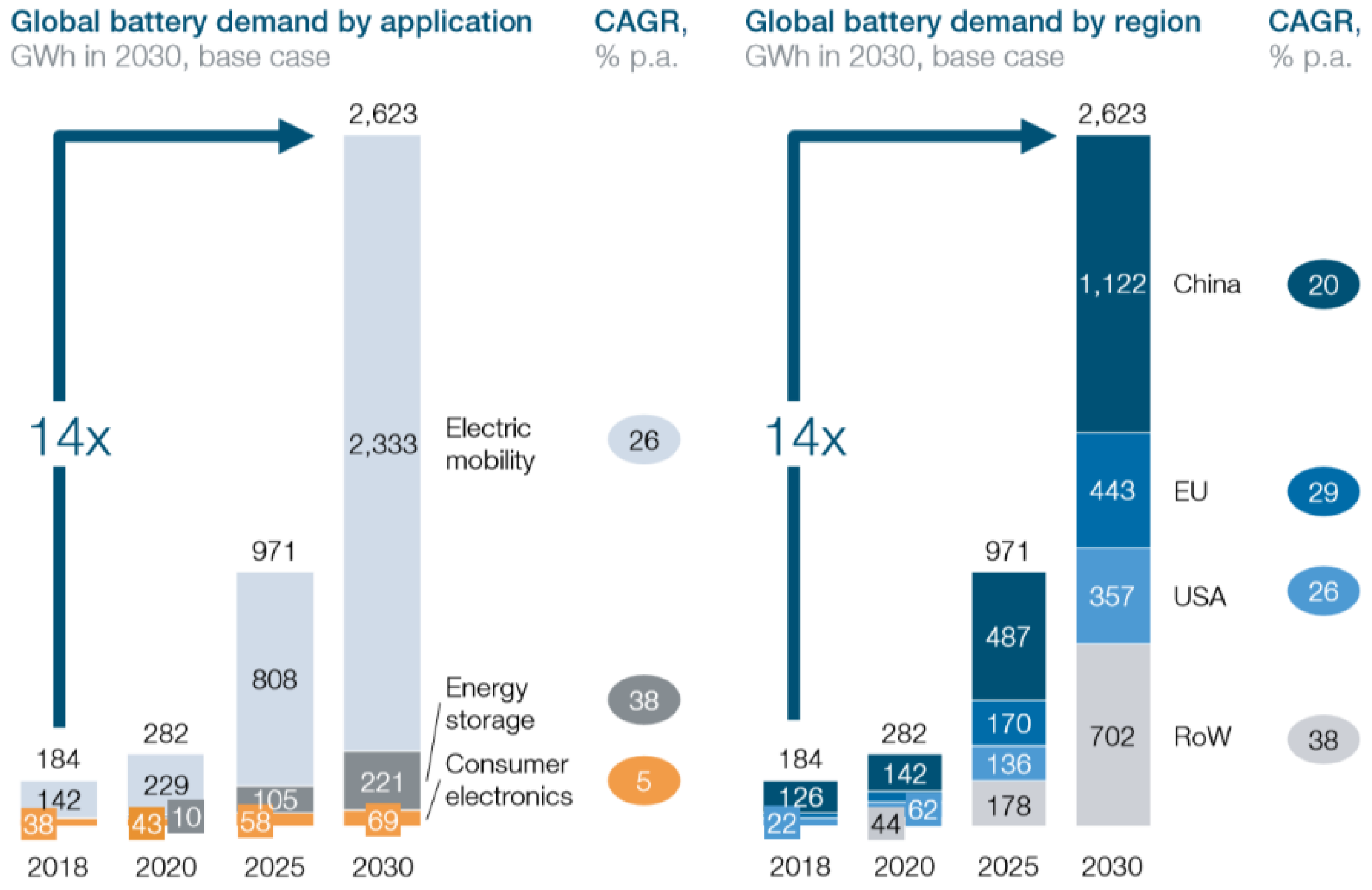
- Lower body/chassis mass
- Improved vehicle dynamic performance
- Higher vehicle payload capacity
- Lower cost to ship powerpack parts

Large automotive battery packs have a lot of embedded carbon,

JM

BATTERY MATERIALS Supply constraints

Huge increase in battery manufacturing capacity required by 2030, and beyond

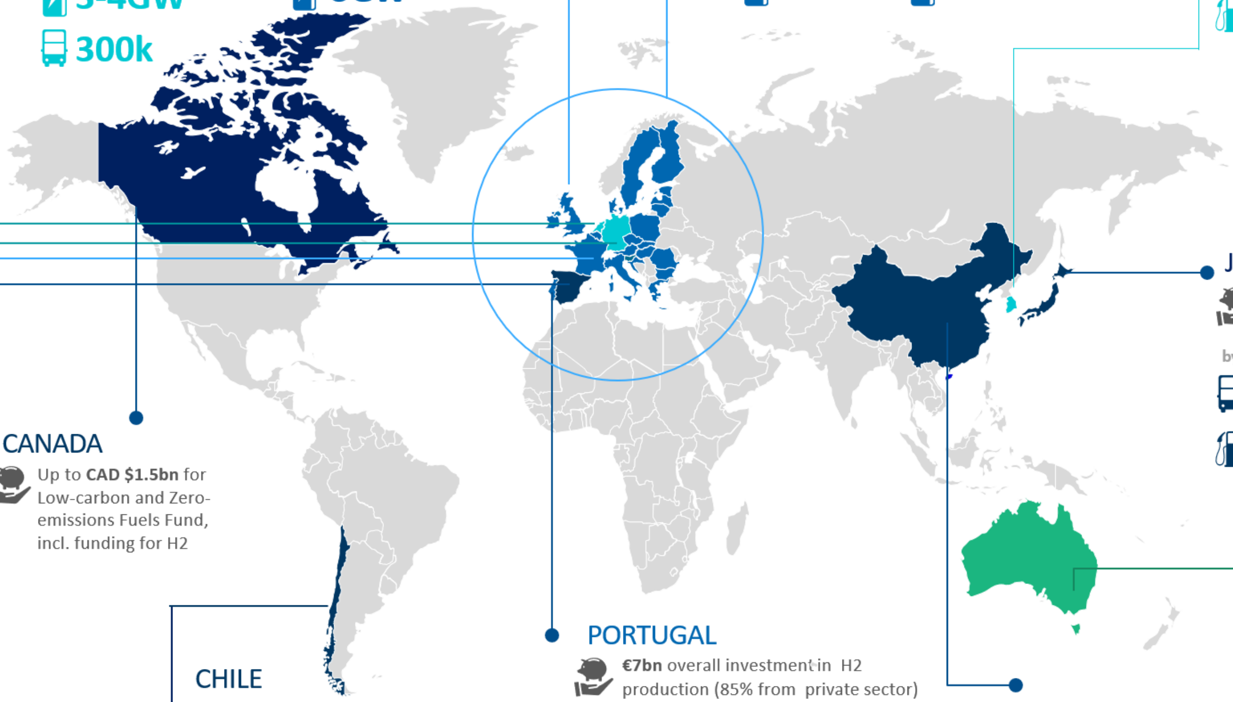


The challenge of decarbonizing transport is huge

Decarbonising transport with batteries alone is a big risk

Battery supply constraints are a critical concern, with vast investment needed.

In or out?



GERMANY
€9bn government support (€7bn for domestic green H2 + €2bn for international partnerships)

by 2030:
5GW

by 2035-2040:
10GW

NETHERLANDS
€35m government support for green H2

by 2025:
0.5GW
50
15k

By 2030:
3-4GW
300k

UK
£240m government support

by 2025:
1GW

by 2030:
5GW

EUROPEAN UNION
€180 - €470bn public + private investment in renewable H2 and **€3-18bn** in low-carbon fossil-based H2 by 2050

by 2024:
6GW

by 2030:
40GW

SOUTH KOREA
$2.33 bn USD for FCEV development until 2022
$410m USD for H2 as COVID recovery investment

by 2022:
81k
310

by 2040:
6.2mn
1,200
15GW
fuel cells for power generation

JAPAN
$19 bn USD green fund, incl. funding for H2

by 2025:
200k
320

by 2030:
800k
900

FRANCE
€7bn government support (of which €2bn for electrolysis by 2022)

by 2030:
6.5GW

SPAIN
€8.9bn public + private investment

by 2024:
.3-.6GW

by 2030:
4GW
100-150
150 buses, 5k FCEVs, 2 commercial train lines
25% green H2 in industry

CANADA
Up to **CAD $1.5bn** for Low-carbon and Zero-emissions Fuels Fund, incl. funding for H2

CHILE
by 2025:
5GW under development

by 2030:
Producer of cheapest green hydrogen

by 2040:
Top 3 global exporters

PORTUGAL
€7bn overall investment in H2 production (85% from private sector)

by 2030:
2GW
50-100
5% H2 in final energy consumption
15% blending in natural gas networks

CHINA
$1.5bn USD for H2 in 2021

by 2025:
50k (20% buses/ trucks, 80% cars)
300

by 2030:
1mn
1,000

AUSTRALIA
$370m AUD government support

by 2030:
0.5-1GW
$2AUD/kg production cost

LEGEND

Q4/2020	Q3/2020	H1/2020	Pre 2020

Investment
Electrolysers
FCEVs
Stations

Source: FTI Consulting, December 2020 * *Expected shortly: Italy*

Collaboration is key

The success or failure of hydrogen as a sustainable transport option requires action by all players