McKinsey & Company

Hydrogen
An opportunity to reduce pressure on critical materials in the long term?

World Materials Forum | Nancy, 26.-27 August 2020

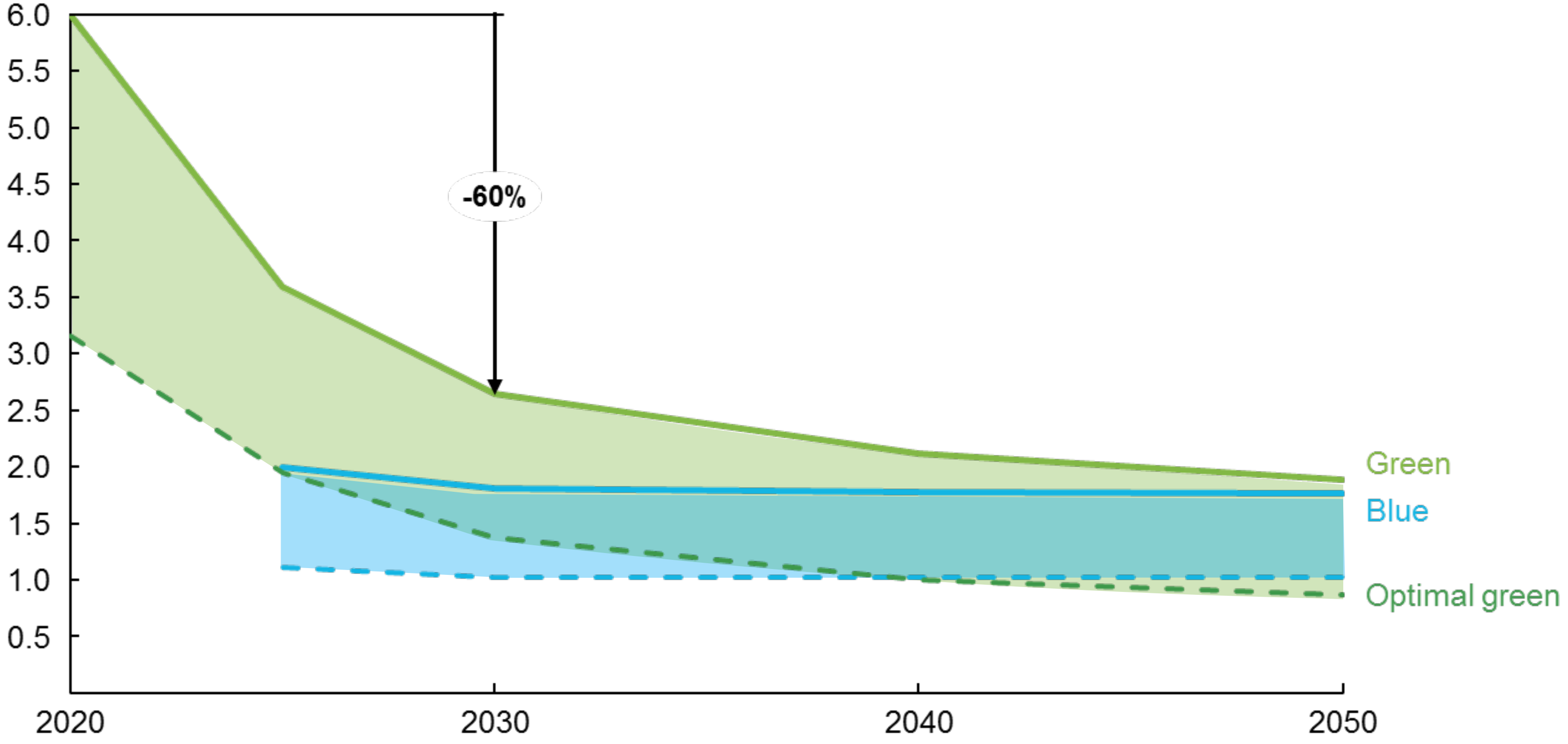
WORLD MATERIALS FORUM

The potential for hydrogen

1. **Hydrogen/ fuel cells can be a competitive substitute to electrical vehicles/ in other areas**
   if we are serious about mobility solutions (and implications on decarbonization)
2. **Low-carbon, green hydrogen can be competitive in selected applications**
   by 2030 driven by rapid cost reductions in renewable energy and electrolysers
3. **There is unprecedented global momentum**
   reflected by 4 underlying trends – substitution for (H)EV (decarbonization), strategic government push, industry coordination and translation in to projects
4. **Demand for hydrogen could increase 10x by 2050**
   in a two-degree scenario, with most growth coming from green hydrogen
5. **Power demand increases by 50% relative to Reference Case demand**
   by 2050 due to production of green hydrogen

2: Green hydrogen production costs could drop 60% by 2030

Production cost of hydrogen,
USD / kg



1. Offshore wind in Germany, load factor 50%
2. Blend of wind / solar in Chile, load factor 75%
3. Average blue / grey assumes natural gas price of USD 6.8 USD/MMBtu / Optimal blue/grey assumes gas price of USD 2.0/MMBtu

Source: Hydrogen Cost Model

The optimal low-carbon hydrogen solution in 2030 depends on resources available in a specific region

Green[1] can be the most competitive alternative in markets with average resources, but there is an opportunity to leverage global hydrogen trading, e.g., EU

Optimal green hydrogen[2] can be achieved in places with good solar and wind conditions, e.g., Middle East, Chile, Australia

Blue[3] is the lowest cost alternative in areas with low-cost natural gas and CCS availability, e.g., the US, Russia. However, depending on CCS technology used it may not be close to zero-carbon hydrogen

3: There is unprecedented global momentum

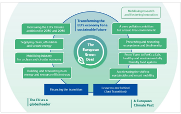
Detail follows

Stronger push to limit carbon emissions

185 Parties that have ratified the Paris Agreement to date out of 197 parties to the UNFCCC

66 Countries that have announced net zero emissions as a target by 2050

PARIS2015 UN CLIMATE CHANGE CONFERENCE COP21·CMP11



Strategic push in national roadmaps

10mn 2030 total target deployment of FCEVs announced by 30 countries

10,000 Hydrogen refuelling stations by 2030 in 30 countries, with over 3,000 announced to date

Industry alliances and momentum growing

81 Members of the Hydrogen Council today, up from 13 members in 2017

30+ Major investments announced[1] globally since 2017, including in new segments (e.g., heavy duty, rail, steel)

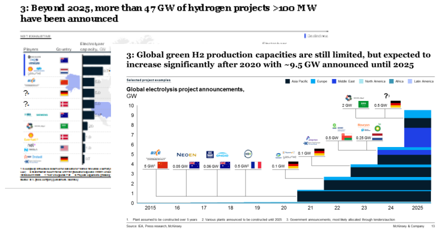
Hydrogen Council

Hydrogen Europe

Projects being announced

100x+ Expected increase in electrolysis capacity in 2025 versus 2015

33 GW Amount of co-located hydrogen-RES projects announced

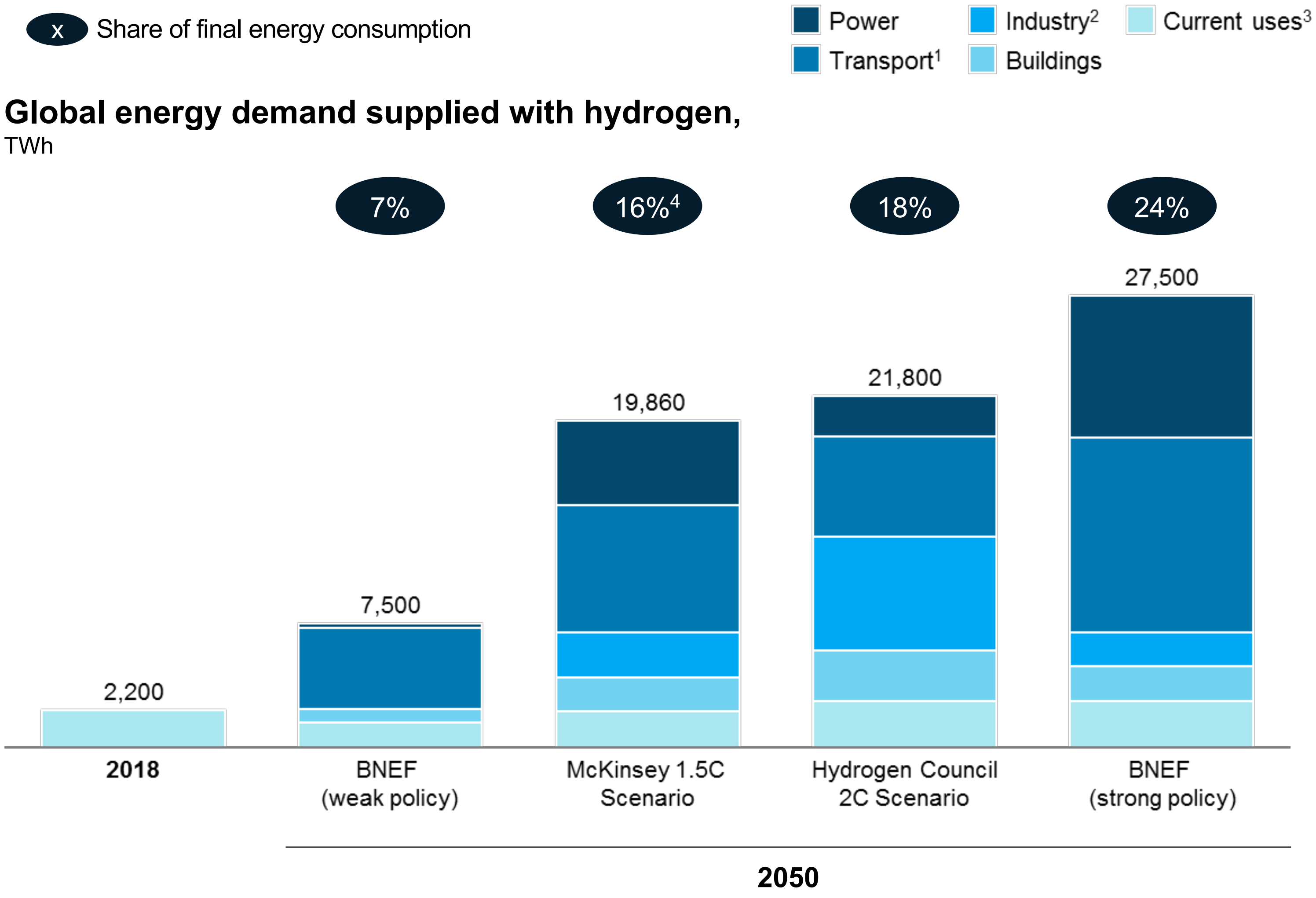


1. Not exhaustive

Source: McKinsey

3: Multiple scenarios point to strong growth in hydrogen demand

Global energy demand supplied with hydrogen,
TWh



1. Including synfuels 2. Including feedstock and heating 3. Primarily feedstock 4. Includes final energy consumption of H2 for power; 12% without

Source: BNEF, Hydrogen Council, McKinsey

Key drivers of assumptions

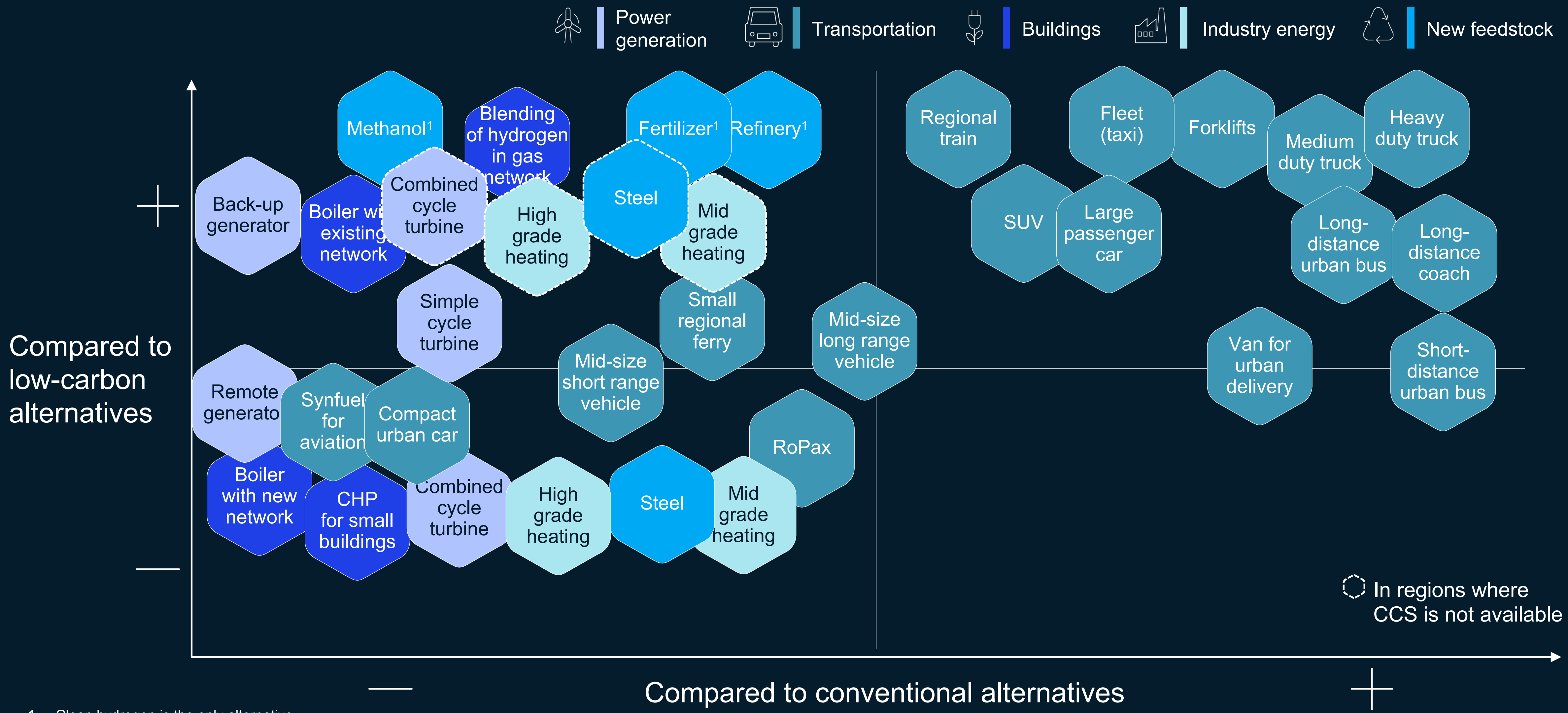
Decarbonization scenario

- BNEF (weak policy): 1.5C target is met
- McKinsey 1.5C scenario: 1.5C target is met
- Hydrogen Council: 2C target is met
- BNEF (strong policy): 1.5C target is met

Reliance on hydrogen vs. other decarbonization levers

- BNEF (weak policy): supportive but piecemeal policy for hydrogen in place
- McKinsey 1.5C scenario: cost and regulation-based scenario, medium reliance on hydrogen vs. other levers
- Hydrogen Council: high reliance on hydrogen across sectors
- BNEF (strong policy): strong and comprehensive policy in place in favor of hydrogen

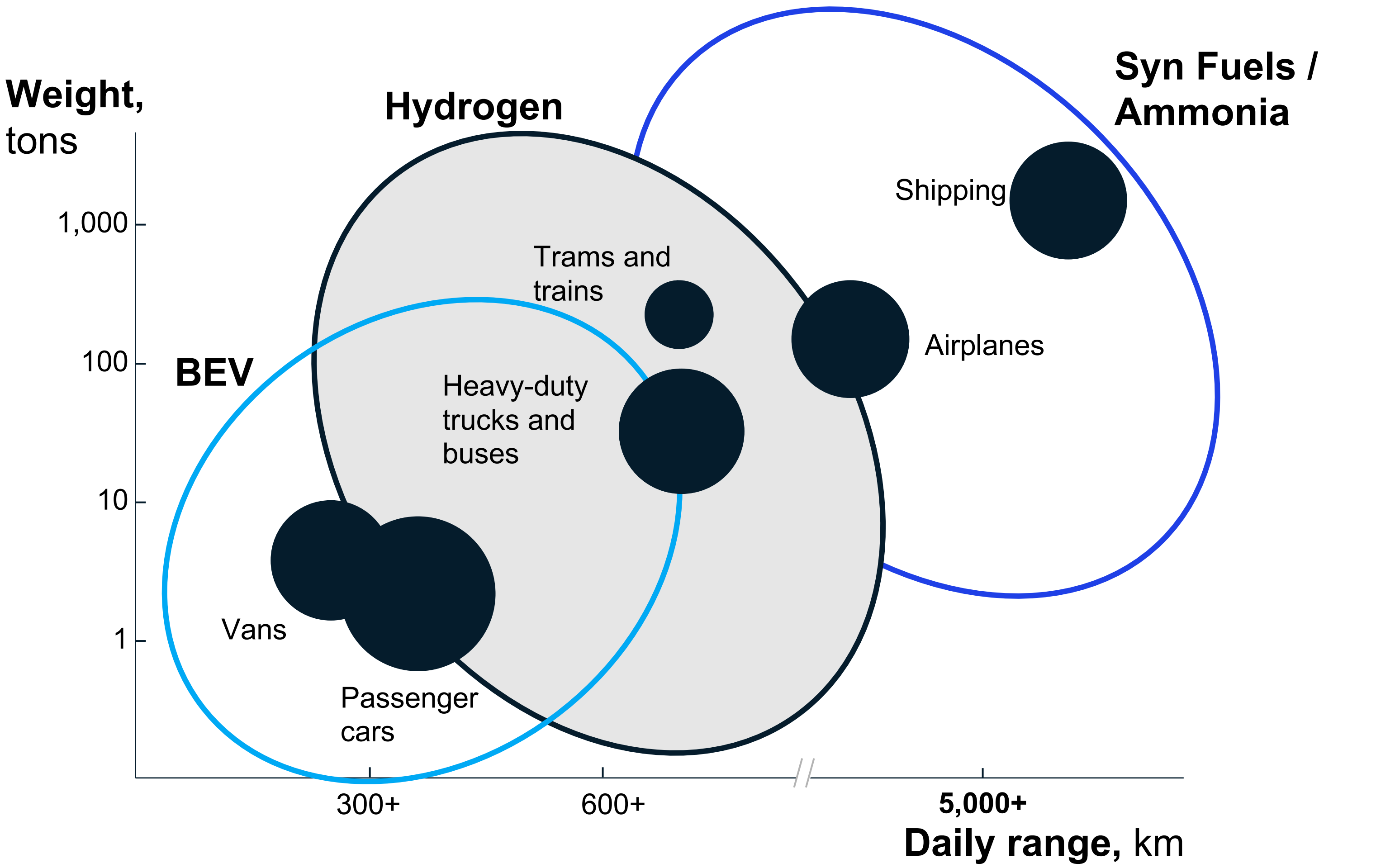
4: Competitiveness of hydrogen applications by 2030 shows that hydrogen can be the lowest-cost decarbonization technology



1. Clean hydrogen is the only alternative

Source: McKinsey

4: Hydrogen is the fuel of choice for trucks and long-distance transport



Synthetic fuel vs. hydrogen:

2.0x

cost per 100 km synthetic fuel vs. hydrogen

1.7x

more range per kWh of electricity converted to hydrogen vs. kWh converted to synthetic fuel

Source: McKinsey

4: OEMs have already started to move

Nikola One and Two for US market, Nikola Tre for EU market – focus on heavy-duty

IPO on June 4, current valuation USD ~25bn

Market launch 2023 in US, 2024 in EU

Carbon-free truck sales in 2039, 50% electric 2030

Heavy-duty truck series production in 2027

Joint venture to develop and manufacture fuel cells for heavy-duty applications at scale

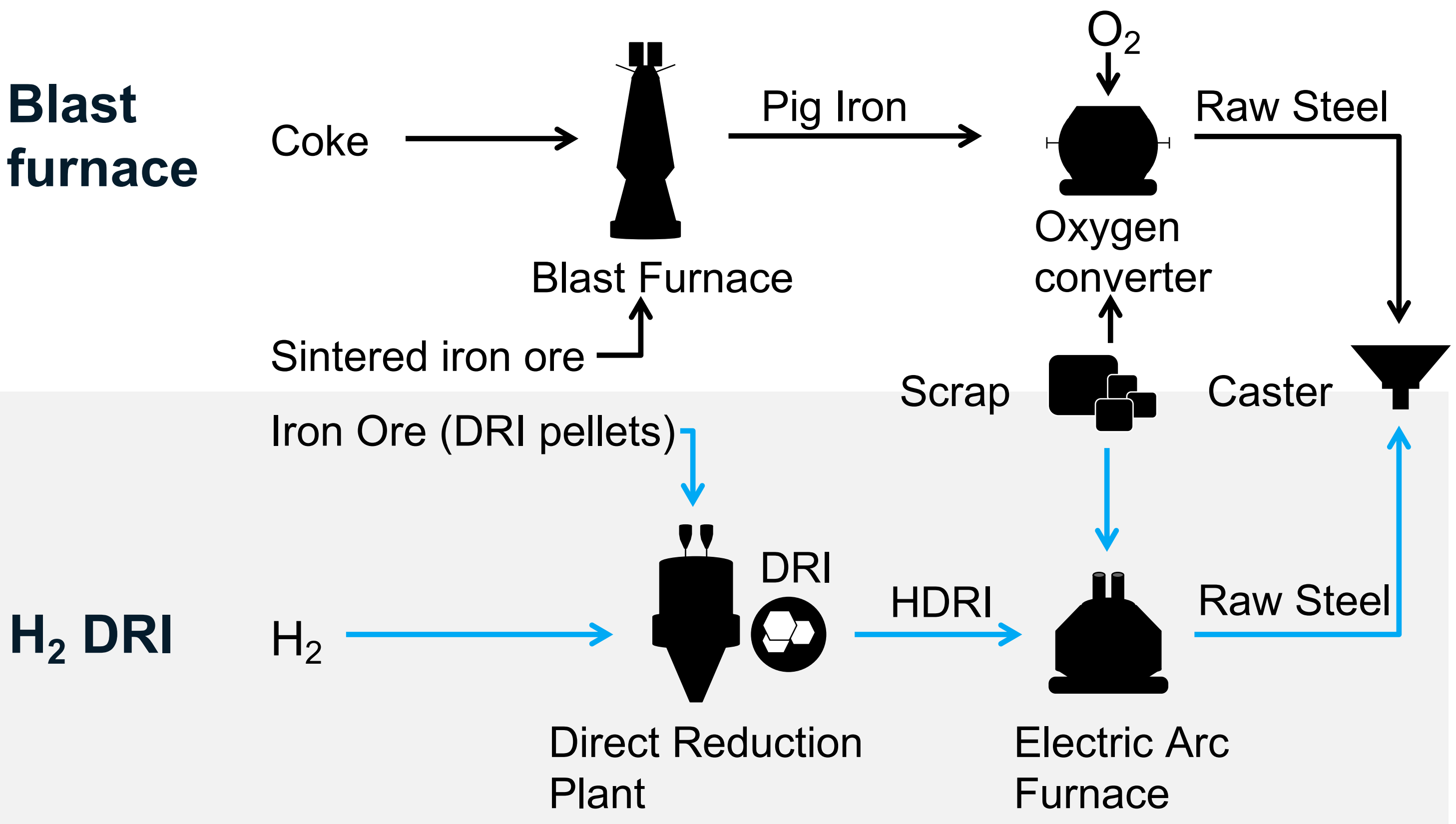
Investment of EUR 600m by Volvo (implied valuation 1.2bn), add. investments planned

“We are on the fuel cell truck… you will be surprised” – Traton CEO

Rumours of access to Toyota fuel cell stack through Hino

4: H2 DRI steel production can be cost competitive compared to blast furnaces

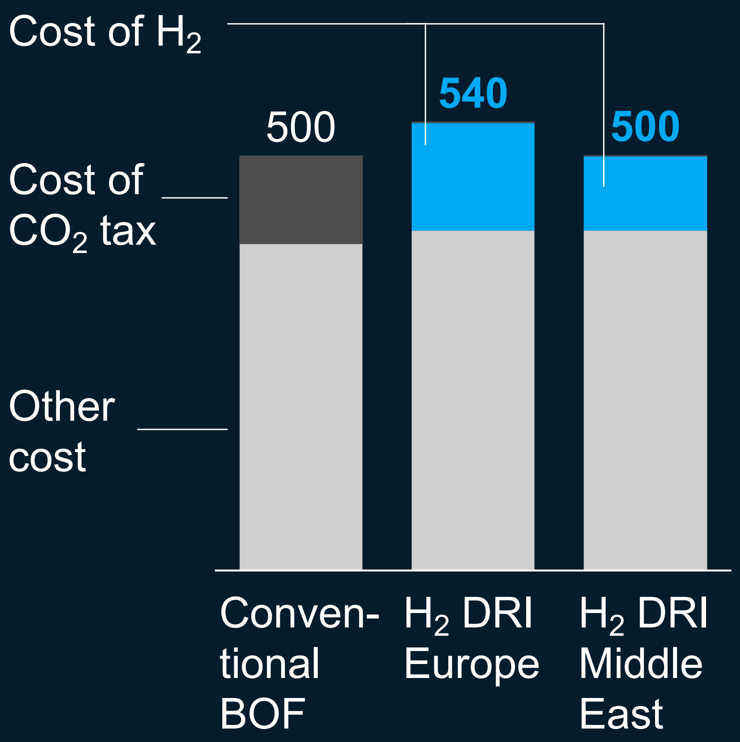
Example comparison of blast furnace and H_2-direct reduced iron steel making



Top global steel producers test H_2 DRI steel making processes

TATA STEEL, voestalpine, ArcelorMittal, thyssenkrupp, SSAB

Cost of steel making, in USD/ton



H_2 DRI steel making can be cost competitive in 2030 with blue H_2 in the Middle East

5: Key challenges for the uptake of a hydrogen economy

Key challenges for green hydrogen supply

High costs of green hydrogen production

Based on recent developments, **electrolysis is expected to reach cost parity** with SMR within the next 5-10 years since both key cost drivers (electrolyzer CAPEX and cost of electricity) are expected to decline significantly

Hydrogen storage required in a hydrogen economy

Storage of gaseous/compressed hydrogen feasible in **geological formations** (depleted gas fields, salt caverns, etc.)

Storage in **salt caverns** expected to offer **lowest cost for large volumes**, (case example shows $0.24/kg by 2030)

Key challenges for hydrogen applications

Hydrogen distribution network yet to be developed

As of today, major countries already plan to build **more than 5,000 hydrogen refueling stations by 2030 globally**

3,700 large hydrogen refueling stations are sufficient to cover the hydrogen demand in Europe in 2030

Hydrogen is not yet a cost competitive fuel

FCEV trucks and passenger cars can become **cost competitive before 2030**, based on cost of green hydrogen below USD 2.5 per kg, even when assuming zero CO_2 cost (i.e. no tax or penalties on CO_2 emissions)

Source: McKinsey

National targets now amount to more than 4 million FCEVs and 3,200 refueling stations (HRS) in Asia (and California) – opportunity for Europe to catch up?

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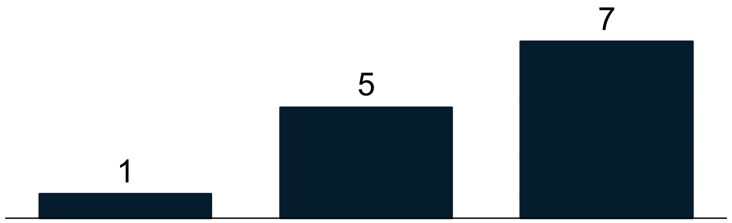
National targets for FCEVs[1]
millions



National targets for HRS[1]
thousands

China	Japan	California	South Korea
Dec 2016	Dec 2017	Jul 2018	Jan 2019
1 mn FCEV	**0.8 mn** FCEV	**1 mn** FCEV	**1.8 mn** FCEV by 2030
1,000+ HRS by 2030	**900** HRS by 2030	**1,000** HRS by 2030	**1,200** HRS by 2040
			6.2 mn target production capacity for FCEVs by 2040

1.China, Japan, US, South Korea
2.Primarily due to announcements made by Chinese regions - Plans of just 3 cities alone (Suzhou, Wuhan, and Shanghai) are 140% of China's national plans by 2025; other regions have announced similar ambitions

Source: Government announcements

China is aggressively accelerating in hydrogen with ambitious mid-term goals and incentives

Public roadmap

Central government policy support for decarbonization with explicit role for hydrogen

Roadmap set out in **Hydrogen infrastructure development blue book**

Supportive **local government goals**:

- UNDP Global Environment Facility Program (2016-2020): **≥100 FCEVs in five cities**, incl. Beijing, Shanghai, Zhengzhou, Foshan and Yancheng
- UNDP-China **Hydrogen Economy Pilot in Rugao** (2016-2020) with 5bn RMB funding
- Shanghai Fuel Cell Vehicle Development Plan: **3,000 FCEVs annually** by 2020

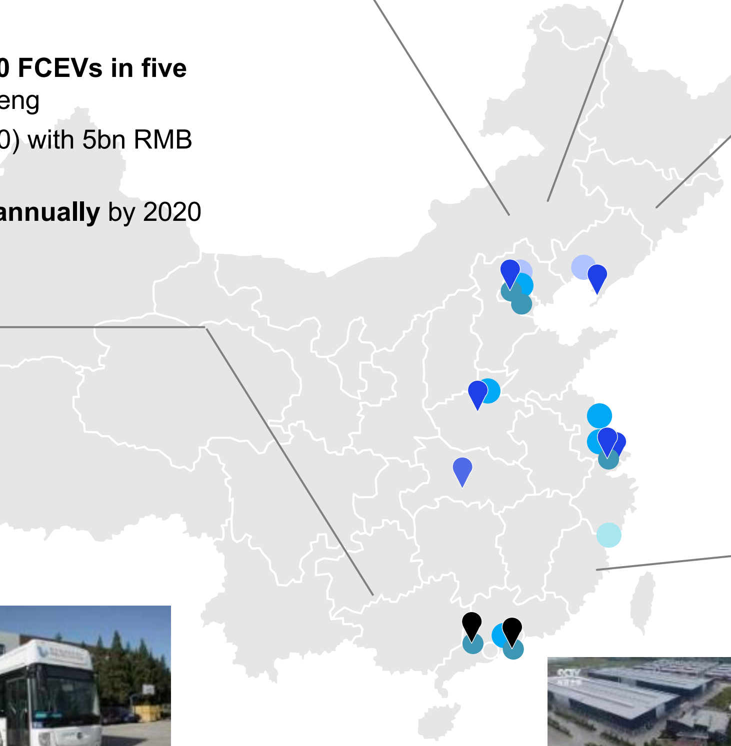
Mobility

Central government Goal: 5,000 FCEVs by 2020 (60% commercial and 40% passenger cars), **1 million FCEV by 2030**

Strong development in **fuel cell buses, trams and light rail**

Local government with hundreds of buses, thousands of trucks planned for deployment – likely overshooting central government targets in 2020

Hydrogen-powered trams in Foshan, completed by end of 2018 and in Tangshan



H2 Infrastructure

HRS

~20 HRS in operation, plan to > 100 by 2020

>1,000 HRS by 2030

Stationary applications & power

World's first 2MW PEM fuel cell power plant installed on site at Ynnovate Shanzheng Fine Chemicals, in Yingkou by AkzNobel, MTSA and Nedstack

4 MW hydrogen production equipment for Power-to-Gas transformation in Guyuan, Hebei Province

Technology leadership

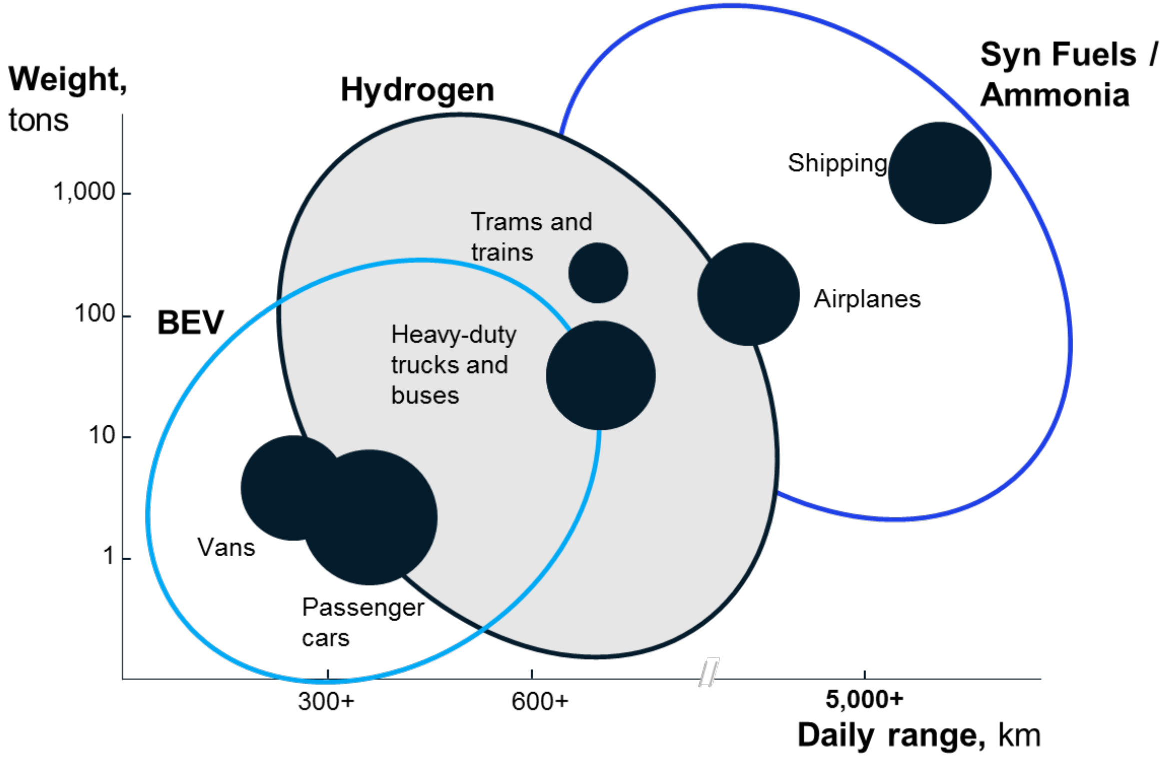
Strong **development of hydrogen industrial clusters**, e.g., Zhangjiakou FCEV factory, Yunfu FC bus factory

Largest **research output** on hydrogen alongside US

Hydrogen Town Taizhou in Zheijang with investments of 16bn RMB over 5 years

Source: McKinsey

Conclusion



- While Hydrogen **is unlikely to reduce the pressure on critical battery materials like Co and Ni short-term**, it is expected **it will do so medium/longer-term as Green Hydrogen becomes cost competitive** and substitutes part of battery-driven developments
- Growth of Hydrogen production and use will on the other hand **increase the pressure on PGM/ Platinum demand** (essential for efficient reactions)
- The need for renewable energy for Green Hydrogen can further **increase the pressure on REE materials** (current technology permanent magnets in wind turbines etc.)

Source: McKinsey