Hydrogen: The Missing Piece of the Clean Energy Puzzle?

An Introduction to IHS Markit's Hydrogen Initiatives

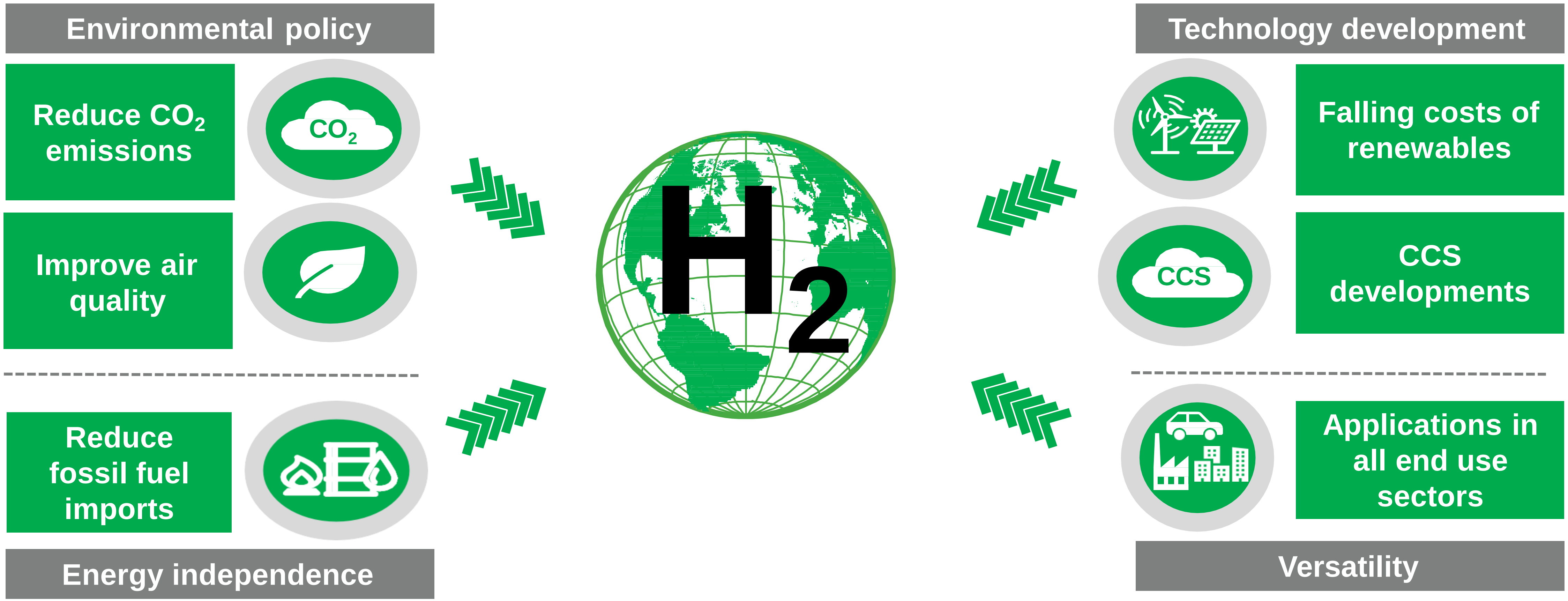
2019

Why Hydrogen Today?

Why hydrogen today?

In recent years multiple factors have come together to drive interest in hydrogen

- **Drivers of increasing interest in hydrogen**



Environmental policy

Reduce CO_2 emissions

Improve air quality

Reduce fossil fuel imports

Energy independence

Technology development

Falling costs of renewables

CCS developments

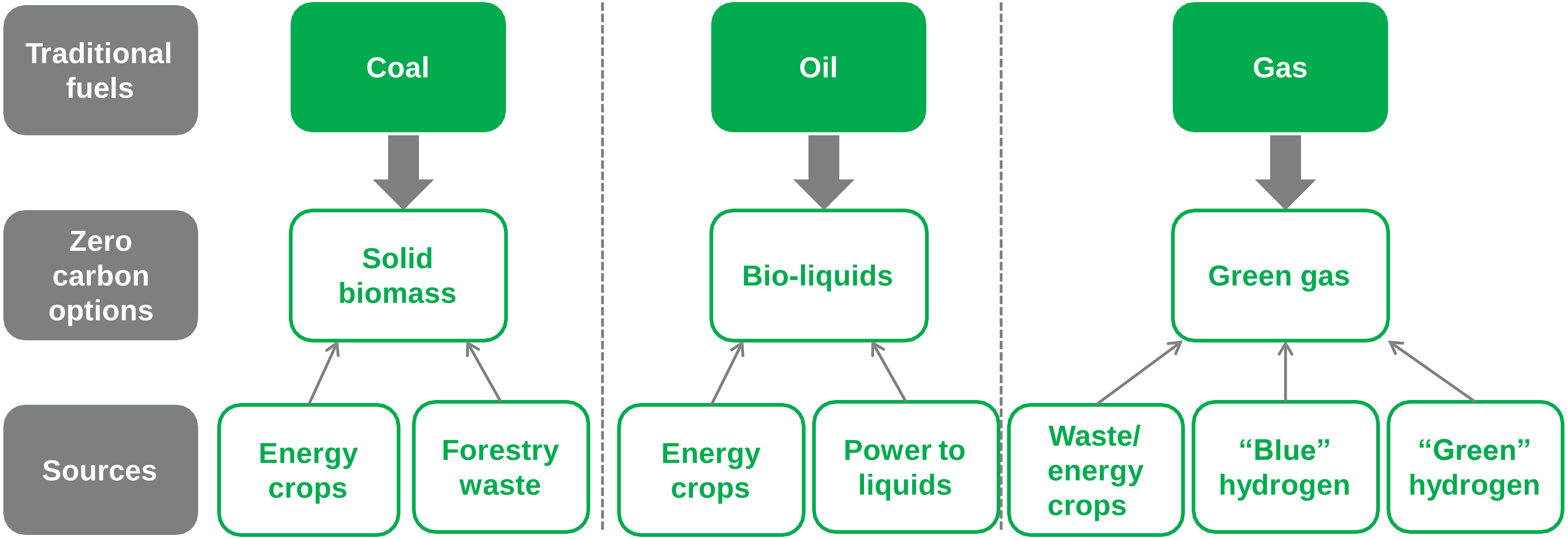
Applications in all end use sectors

Versatility

Source: IHS Markit

Global climate targets require the replacement of fossil fuels with storable, low-carbon alternatives

Storable energy: From high to zero carbon options



Note: "Blue" hydrogen is hydrogen created from steam reforming of natural gas combined with CCS. "Green" hydrogen is from electrolysis with the electricity provided by renewable sources

Source: IHS Markit

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Hydrogen's versatility allows it to play a role in all sectors of the economy…

- End use applications of hydrogen for energy use

Transport

Displace batteries or fossil fuels

Industry

Residential Commercial

Displace natural gas in pipelines and end uses

Displace coal used for direct heat in industrial and commercial applications

Power

Intra-day balancing of renewable generation and power demand

Seasonal balancing of renewable generation and power demand

Reduced fossil generation

Source: IHS Markit

…but there are significant hurdles to overcome

- Hydrogen will have ***competition***—from batteries, demand side management (DSM), and other forms of low carbon heat

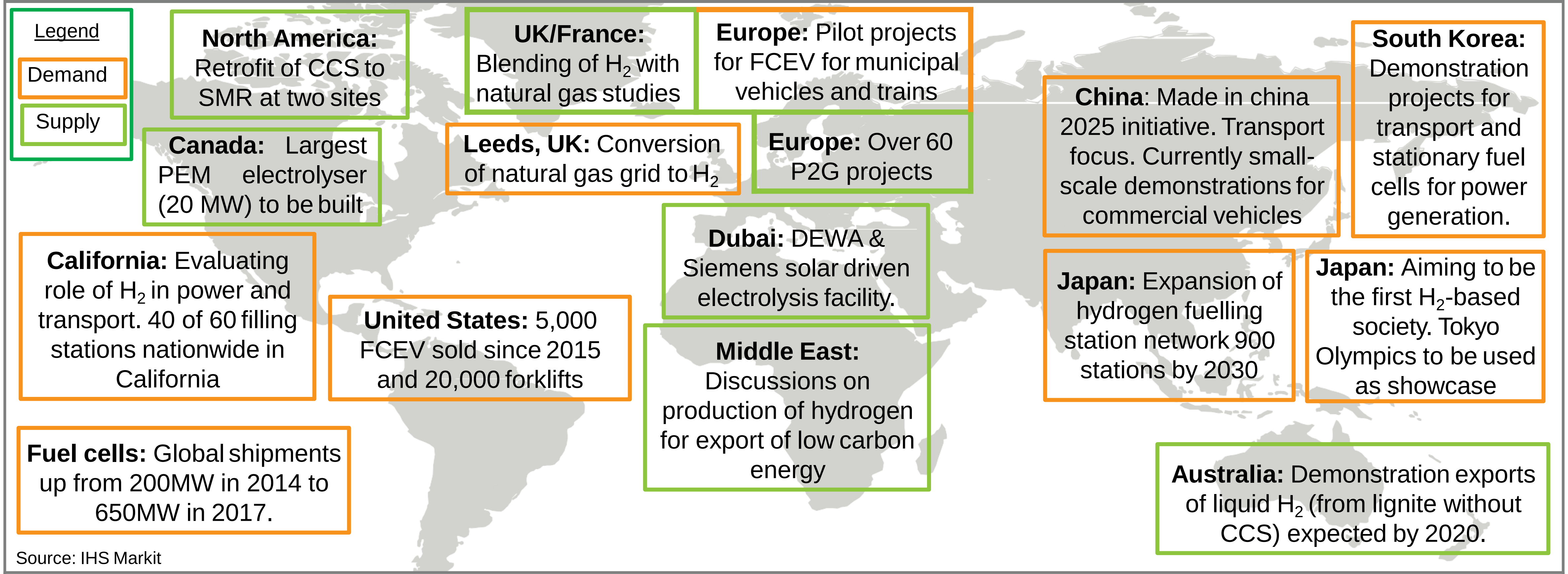
- Potentially significant ***infrastructure/logistical investments*** will be needed

- The ***source*** of the hydrogen matters—production from unabated natural gas or coal is carbon intensive. To play a role in the energy transition low-carbon hydrogen is essential

- ***Cost*** reductions associated with scaling up low-carbon hydrogen production uncertain

Turning point: Are we reaching a critical mass of pilot projects?

Current status of hydrogen in the energy transition



Legend
- Demand
- Supply

North America: Retrofit of CCS to SMR at two sites

UK/France: Blending of H_2 with natural gas studies

Europe: Pilot projects for FCEV for municipal vehicles and trains

South Korea: Demonstration projects for transport and stationary fuel cells for power generation.

Canada: Largest PEM electrolyser (20 MW) to be built

Leeds, UK: Conversion of natural gas grid to H_2

Europe: Over 60 P2G projects

China: Made in china 2025 initiative. Transport focus. Currently small-scale demonstrations for commercial vehicles

California: Evaluating role of H_2 in power and transport. 40 of 60 filling stations nationwide in California

United States: 5,000 FCEV sold since 2015 and 20,000 forklifts

Dubai: DEWA & Siemens solar driven electrolysis facility.

Japan: Expansion of hydrogen fuelling station network 900 stations by 2030

Japan: Aiming to be the first H_2-based society. Tokyo Olympics to be used as showcase

Middle East: Discussions on production of hydrogen for export of low carbon energy

Fuel cells: Global shipments up from 200MW in 2014 to 650MW in 2017.

Australia: Demonstration exports of liquid H_2 (from lignite without CCS) expected by 2020.

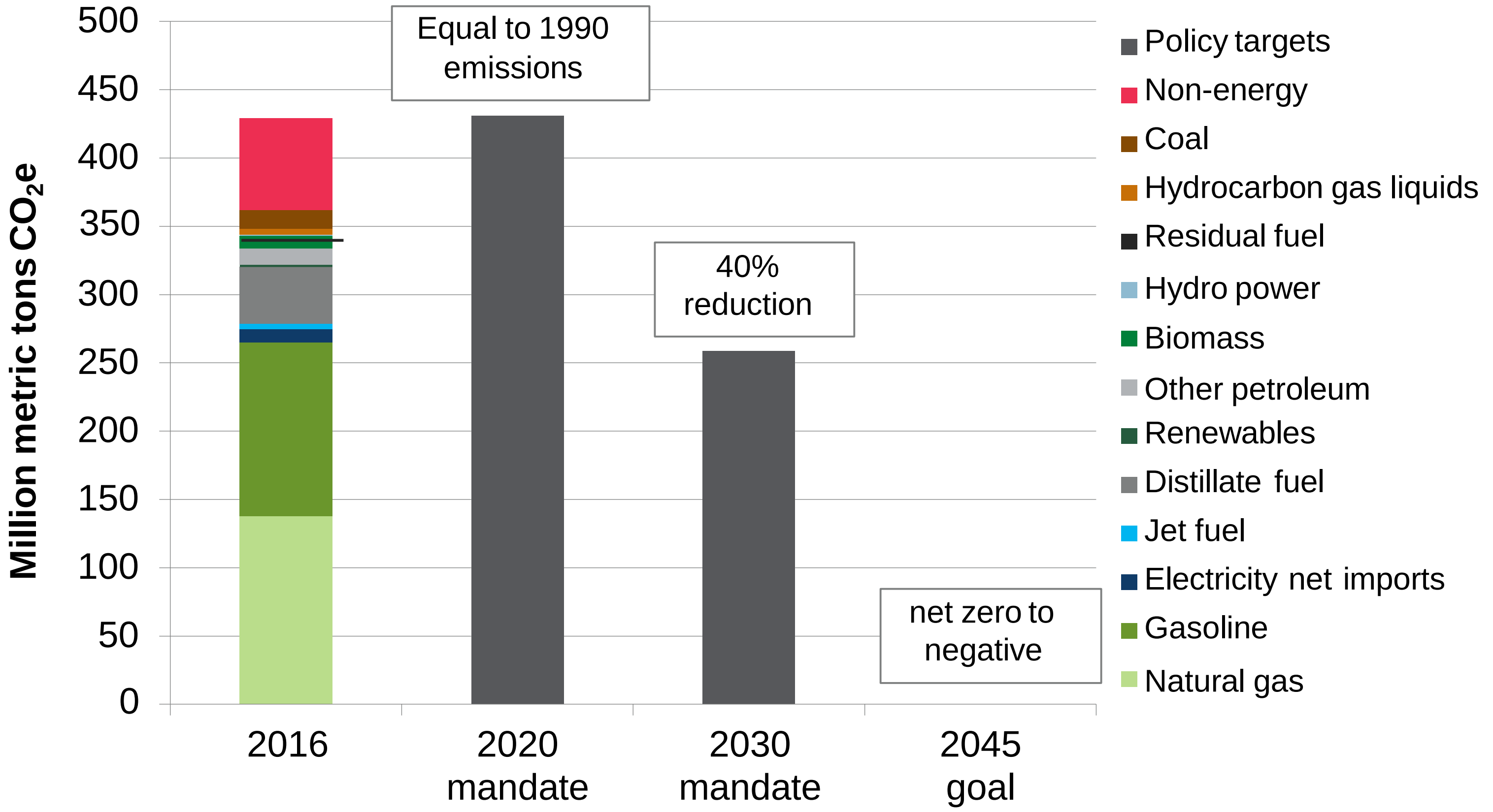
Source: IHS Markit

IHS Markit Hydrogen studies:
Why focus first on California, Europe and China?

Regional context: California

California is now looking towards reducing GHG emissions 40% by 2030 and eliminating them by 2045

California, total GHG emissions by fuel in 2016 and policy targets, 2020, 2030 and 2045



Equal to 1990 emissions

40% reduction

net zero to negative

Source: IHS Markit, CARB

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- The first column shows CARB's most recent GHG inventory, which is total included emissions subject to California's policies. Emissions are shown as CO2-equivalent (CO2e).
- California's first GHG emission reduction goal is to return to 1990 emission levels by 2020. The state reached this goal in 2016.
- The next goal is lowering emissions to 40% below 1990 levels by 2030 (Senate Bill 32). Much needs to be done to reach this goal.
- The long-term goal, set by the governor's executive order at the end of 2018, is a net zero GHG emitting economy by 2045.
- Our analysis will focus on the opportunity for hydrogen in a decarbonized California, which will come about from strong policy.

California regulates a majority of GHGs emitted in the state, referred to as "included," but some emission sources are outside the state's scope

California's included and excluded GHG emissions

Included emissions:

429 million metric tons (CO_2-equivalent) in 2016

- Transportation fuels
- Electricity generation and imports
- Manufacturing
- Oil & gas production
- Refining
- Cement production
- Natural gas combustion
- Natural gas storage and transmission
- Chemicals
- Propane combustion
- Agriculture (short-lived climate pollutants)
- Wastewater treatment
- Landfills

Excluded / not specified emissions:

59 million metric tons (CO_2-equivalent) in 2016

- Aviation and marine fuel when destination is outside California
- Some oil and gas production & processing emissions
- Some military sources
- Fugitive emissions from municipal landfills and livestock manure
- Sources below annual minimum thresholds (e.g., 10,000 metric tons CO_2-equivalent)

Notes: Lists do not include every included or excluded / not specified emission source.
Source: IHS Markit, California Air Resources Board (CARB)

California is not alone: many US states and municipalities have low carbon ambitions

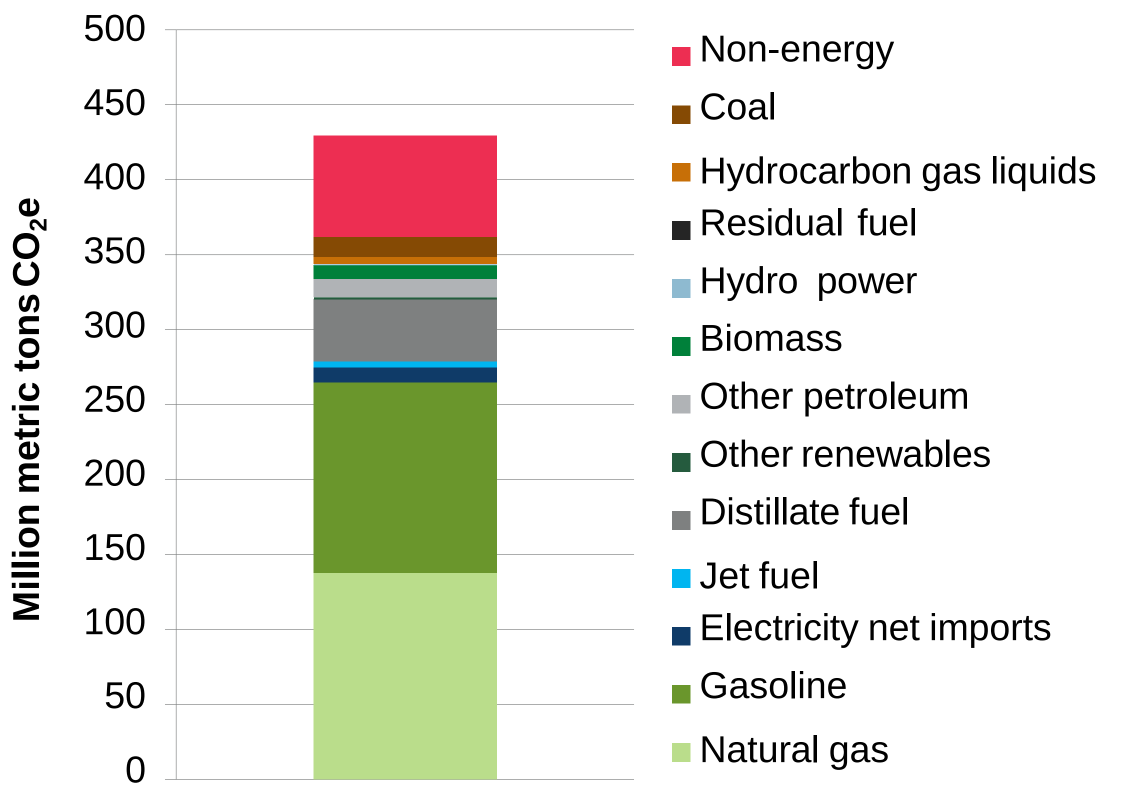
State and local level climate commitments

State climate goals	**20 states** are now part of the US Climate Alliance, committed to reducing emissions consistent with goals of the Paris Agreement – and 22, plus Washington DC, have GHG targets **10 states** currently place an explicit price on CO_2 emissions (and likely to grow to 13)
Municipal targets	**Hundreds of cities** have declared commitments to stand by the Paris Agreement
Power	**29 states** have renewable portfolio standards for electricity - representing 55% of total US electricity sales
Transport	**2 states** have clean fuel standards on top of the federal Renewable Fuels Standard. **22 states** have financial incentives for EV or PHEV vehicles. **9 states** currently designing joint cap on transportation emissions.

Source: IHS Markit

More than 70% of included GHG emissions come from natural gas, gasoline, and diesel; transport and industry emit 2/3 of included GHGs

California, included GHG emissions by fuel



Notes: Data from CARB’s emission inventory program, 2016
Sources: IHS Markit, CARB

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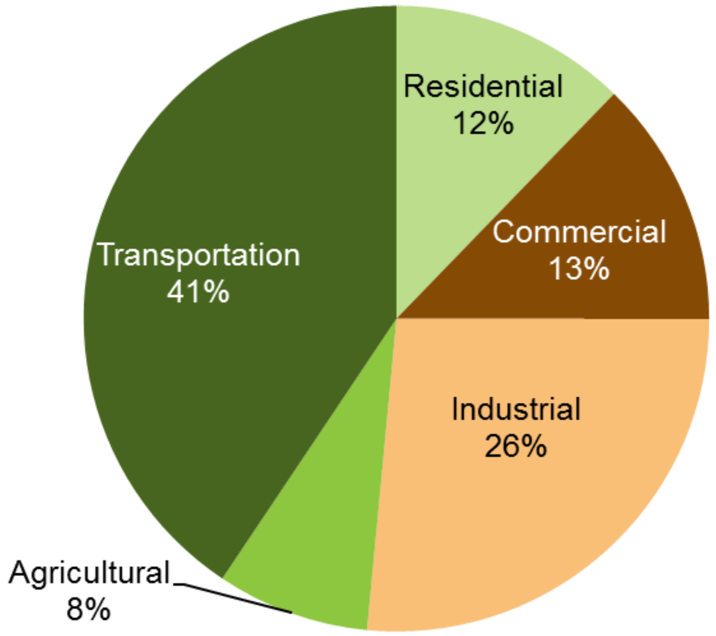
California, included GHG emissions by sector



Nearly 50% of non-energy emissions come from agriculture and 25% come from industry.

Notes: Data from CARB's emission program,2016
Source: IHS Markit, CARB

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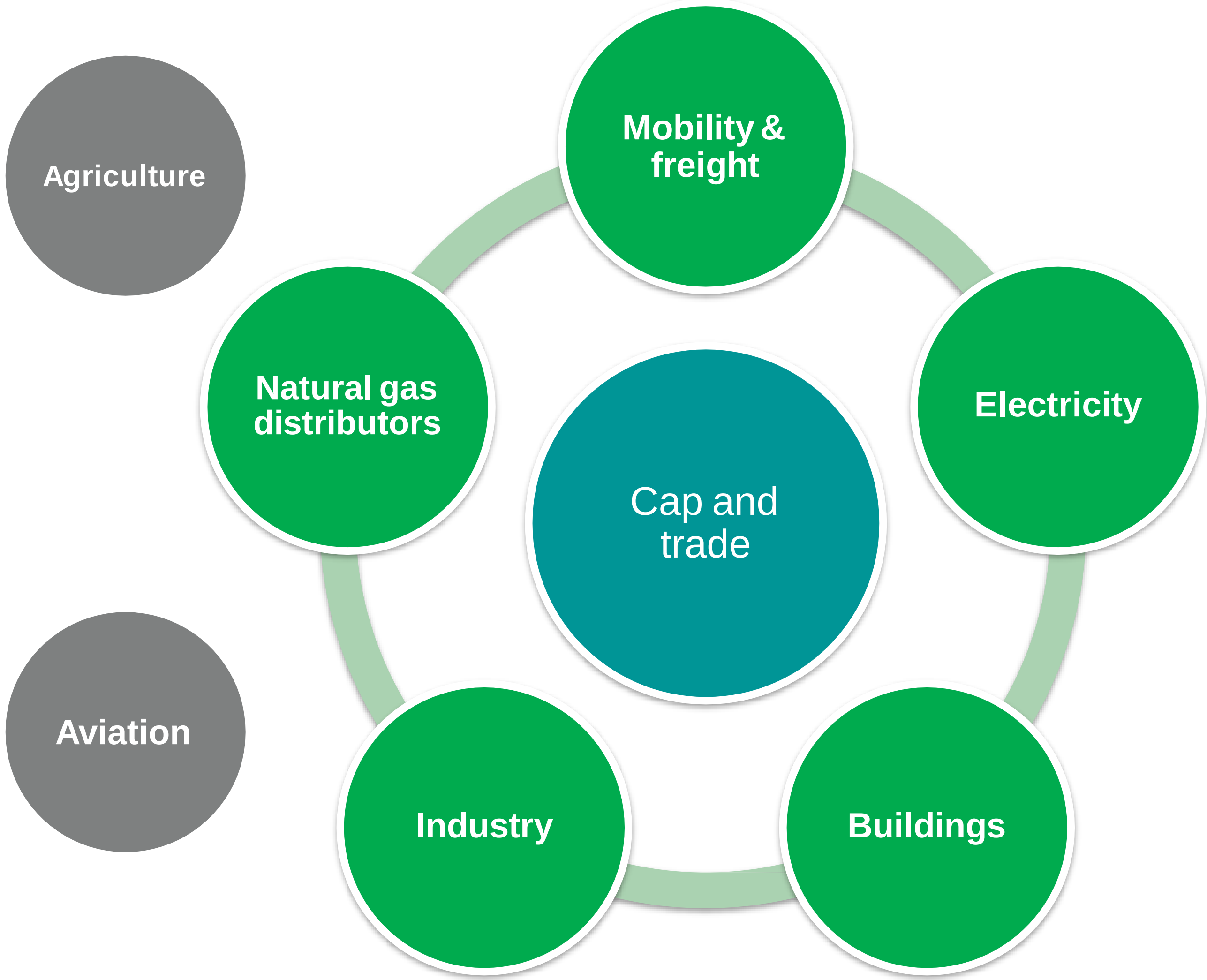
Sector-specific policies drive most of the GHG emission reductions



- **Power:** Renewable portfolio standard (60% by 2030), a phase-out of any remaining use of coal, and a 100% carbon-free power supply mandate by 2045
- **Buildings:** Energy efficiency savings in natural gas and electricity end uses, rooftop solar PV requirement, net zero energy buildings goal
- **Mobility & freight:** Low Carbon Fuel Standard, which seeks a 10% reduction in emissions intensity by 2020 and ratchets up to a 20% reduction by 2030 (all relative to 2010); zero emission vehicle requirements; and rebates for electric and hydrogen vehicles.
- **Industry:** Few focused policies implemented to date, but some offset availability under cap-and-trade
- **Natural gas distributors:** Biomethane procurement targets, clean heat market development, methane leakage policies

Source: IHS Markit

Regional context: Europe

Europe has committed aggressive long-term climate targets

The road to 2050

2020

Targets

- 20% GHG reduction versus 1990
- 20% share of renewable energy
- -20% versus baseline (13% primary energy reduction versus 2005)

Progress*

- Expected reduction: 23% in 2016 26–27% by 2020
- 16.9% share of renewable energy in 2016
- 10.2% fall in primary demand versus 2005 in 2016

Expectation is that emission target will be met, although some trading between member states will be required

2030

Targets

- 40% GHG reduction versus 1990
- 32% share of renewable energy
- 32.5% energy savings versus baseline

Current trajectory**

- 30–32% GHG reduction versus 1990
- Clean Energy package has been adopted setting policy framework until 2030. Renewables and Energy Efficiency directives and Governance regulation came into force on 24 December 2018.

Significant additional action required—Member state action plans for 2030 submitted by end 2018

2050

Target

- Options = 80% GHG reduction to "2050 net carbon neutrality"
- 55–75% share of renewable energy

Strategy to be submitted to the UNFCCC by early 2020.

*Indicative 2016 numbers from Trends and Projections 2017, published November 2017.
**View of expected progress based on current and proposed legislation—European Commission.
Note: GHG = greenhouse gas; RES = renewable energy sources; EE = energy efficiency.
Source: IHS Markit, European Environment Agency

▭ European target, binding
⬚ European target, nonbinding
⬚ Long-term target range

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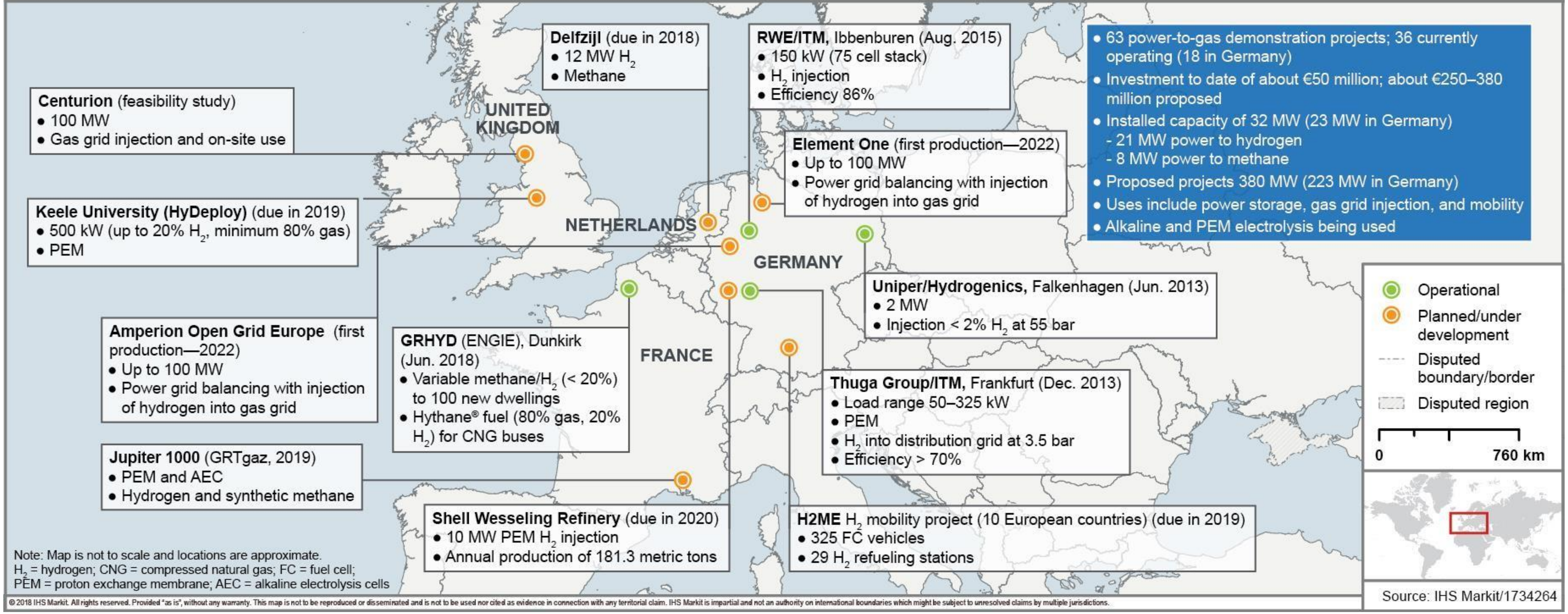
Europe has >60 power-to-gas demonstration projects-1/2 in Germany

Recently announced projects would move P2G to entirely new level

Selected examples of power-to-gas demonstration projects in Europe



Centurion (feasibility study)
- 100 MW
- Gas grid injection and on-site use

Keele University (HyDeploy) (due in 2019)
- 500 kW (up to 20% H_2, minimum 80% gas)
- PEM

Amperion Open Grid Europe (first production—2022)
- Up to 100 MW
- Power grid balancing with injection of hydrogen into gas grid

Jupiter 1000 (GRTgaz, 2019)
- PEM and AEC
- Hydrogen and synthetic methane

Delfzijl (due in 2018)
- 12 MW H_2
- Methane

GRHYD (ENGIE), Dunkirk (Jun. 2018)
- Variable methane/H_2 (< 20%) to 100 new dwellings
- Hythane® fuel (80% gas, 20% H_2) for CNG buses

Shell Wesseling Refinery (due in 2020)
- 10 MW PEM H_2 injection
- Annual production of 181.3 metric tons

RWE/ITM, Ibbenburen (Aug. 2015)
- 150 kW (75 cell stack)
- H_2 injection
- Efficiency 86%

Element One (first production—2022)
- Up to 100 MW
- Power grid balancing with injection of hydrogen into gas grid

Uniper/Hydrogenics, Falkenhagen (Jun. 2013)
- 2 MW
- Injection < 2% H_2 at 55 bar

Thuga Group/ITM, Frankfurt (Dec. 2013)
- Load range 50–325 kW
- PEM
- H_2 into distribution grid at 3.5 bar
- Efficiency > 70%

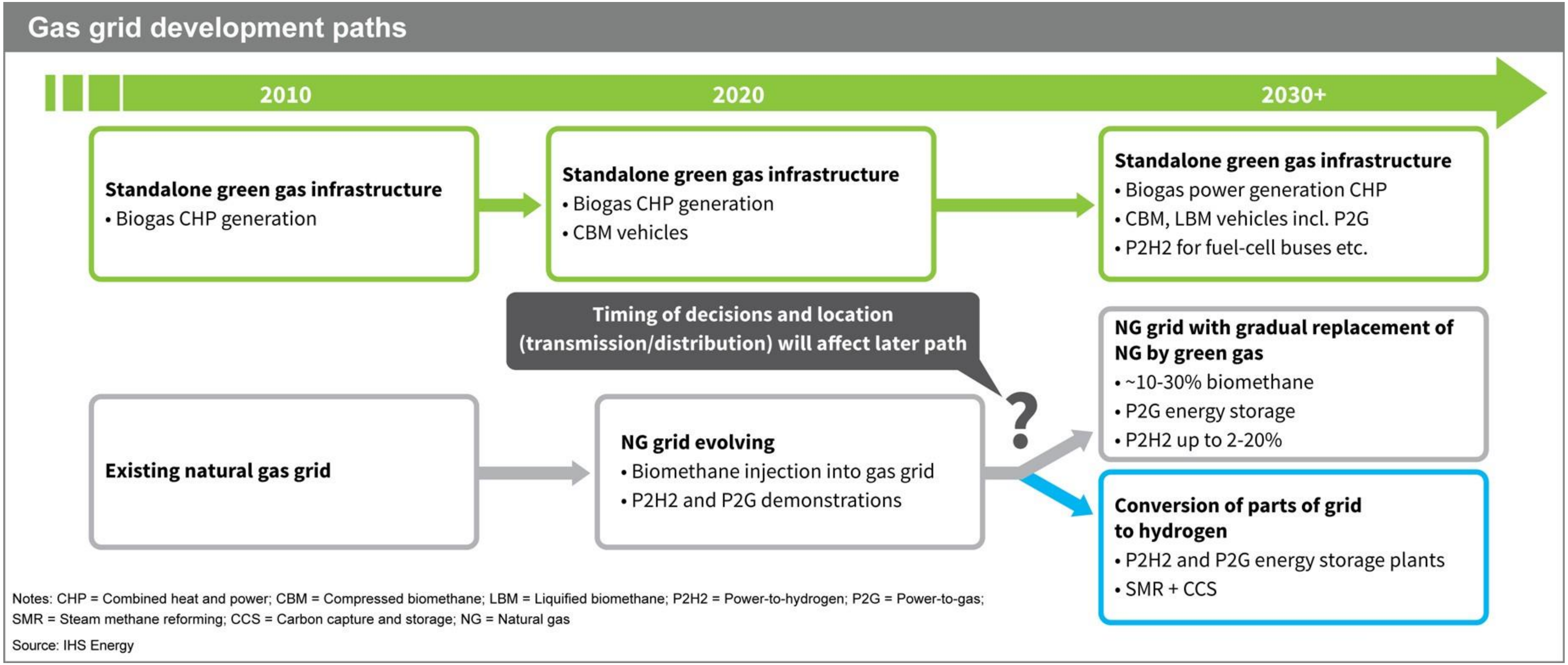
H2ME H_2 mobility project (10 European countries) (due in 2019)
- 325 FC vehicles
- 29 H_2 refueling stations

- 63 power-to-gas demonstration projects; 36 currently operating (18 in Germany)
- Investment to date of about €50 million; about €250–380 million proposed
- Installed capacity of 32 MW (23 MW in Germany)
  - 21 MW power to hydrogen
  - 8 MW power to methane
- Proposed projects 380 MW (223 MW in Germany)
- Uses include power storage, gas grid injection, and mobility
- Alkaline and PEM electrolysis being used

Note: Map is not to scale and locations are approximate.
H_2 = hydrogen; CNG = compressed natural gas; FC = fuel cell;
PEM = proton exchange membrane; AEC = alkaline electrolysis cells

Source: IHS Markit/1734264

As Europe seeks to decarbonize gas, consideration is being given to choosing between a methane/hydrogen mix and hydrogen-only



Gas grid development paths

2010 | 2020 | 2030+

Standalone green gas infrastructure
- Biogas CHP generation

Standalone green gas infrastructure
- Biogas CHP generation
- CBM vehicles

Standalone green gas infrastructure
- Biogas power generation CHP
- CBM, LBM vehicles incl. P2G
- P2H2 for fuel-cell buses etc.

Timing of decisions and location (transmission/distribution) will affect later path

?

Existing natural gas grid

NG grid evolving
- Biomethane injection into gas grid
- P2H2 and P2G demonstrations

NG grid with gradual replacement of NG by green gas
- ~10-30% biomethane
- P2G energy storage
- P2H2 up to 2-20%

Conversion of parts of grid to hydrogen
- P2H2 and P2G energy storage plants
- SMR + CCS

Notes: CHP = Combined heat and power; CBM = Compressed biomethane; LBM = Liquified biomethane; P2H2 = Power-to-hydrogen; P2G = Power-to-gas; SMR = Steam methane reforming; CCS = Carbon capture and storage; NG = Natural gas

Source: IHS Energy

The H21 North of England project shows what would be needed

H_2 production close to a North Sea CO_2 sequestration site; dedicated transmission pipe

- 3.7million gas-heated homes converted to H_2
  - Local industry and power generation
  - Household conversion starting summer 2028
- 9 1.35 GW ATRs with 94.2% carbon capture
  - CO_2 storage in North Sea
  - Seasonal H_2 storage in salt caverns
  - Dedicated H_2transmission system
- Sufficient capacity in medium and low pressure system for conversion to 100% H_2
- FEED—2019/2023, FID—2023

Supplying hydrogen to Leeds

Source: H21 Leeds City Gate

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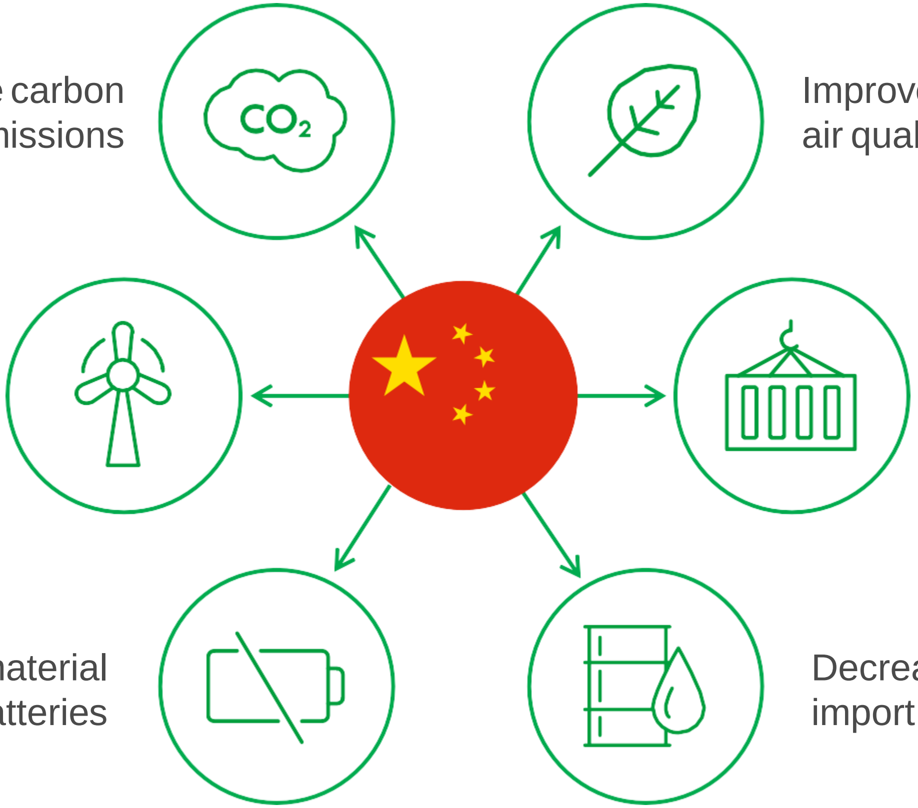
World's largest CO2 emission reduction project. £23 billion capital investment
Partnership between Cadent, Equinor, and Northern Gas Networks

Regional context: China

Hydrogen is consistent with many of China’s long-term goals



Reduce carbon emissions

Improve air quality

Increase renewable deployment

Technology

leadership

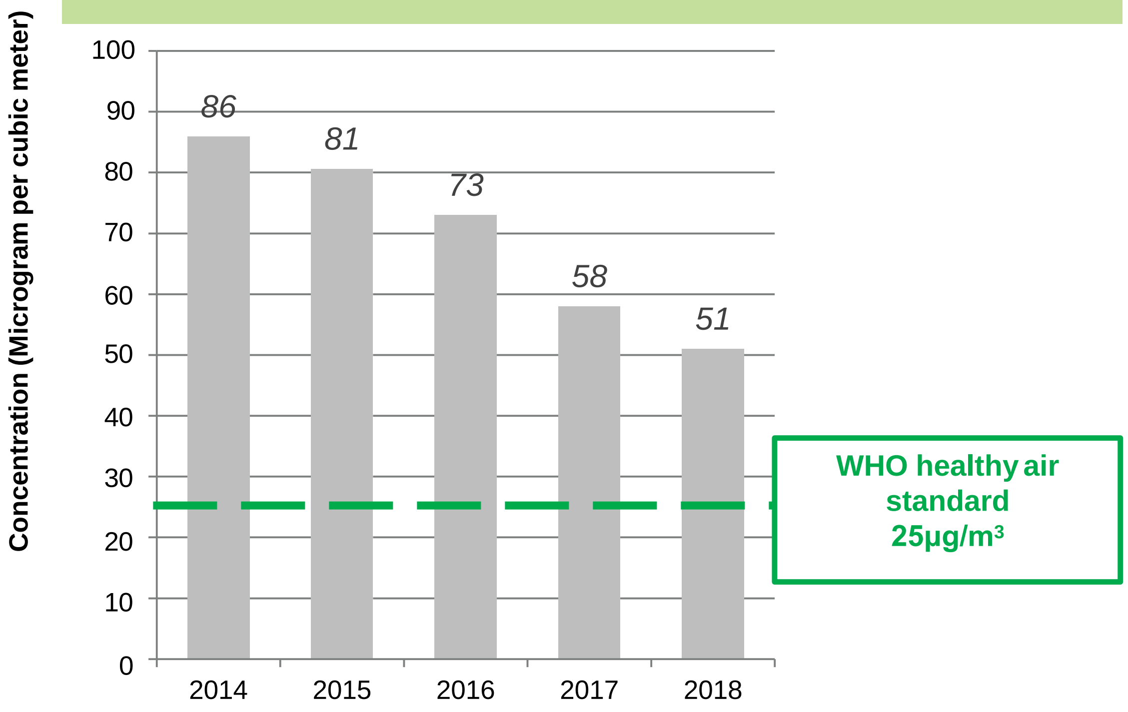
Lessen raw material imports for batteries

Decrease oil and gas import dependency

The use of hydrogen can accommodate air pollution control and CO_2 emissions reduction efforts

Beijing’s annual average PM2.5 index

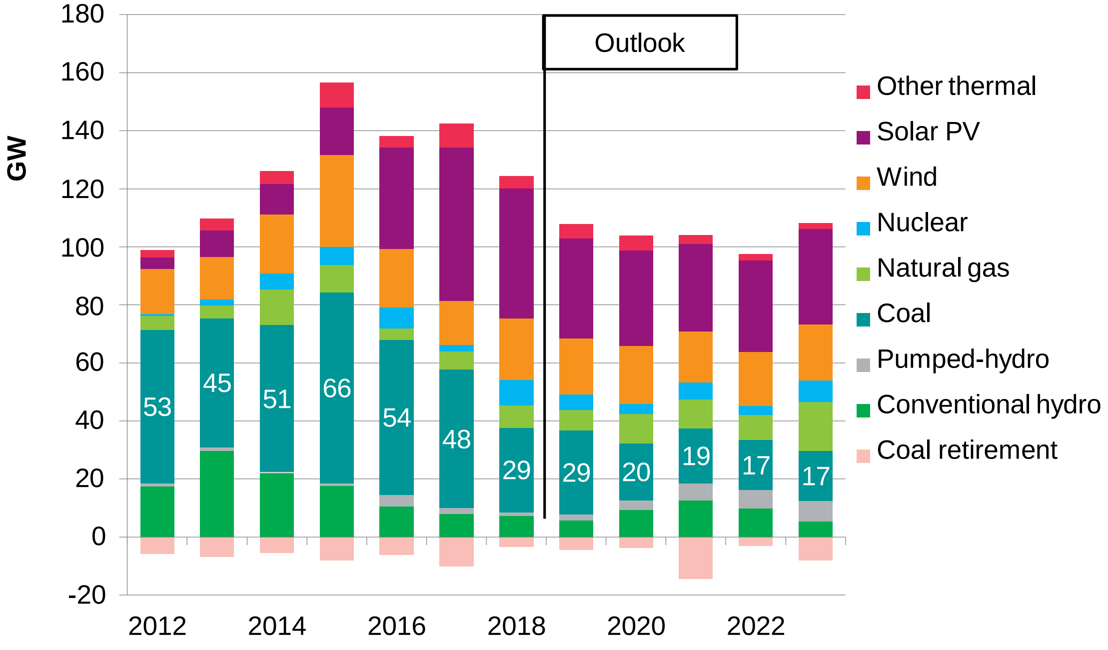
Air quality in key regions has improved recently but still requires more effort to reach a healthy level



Source: IHS Markit, Beijing Ecological Environment Bureau

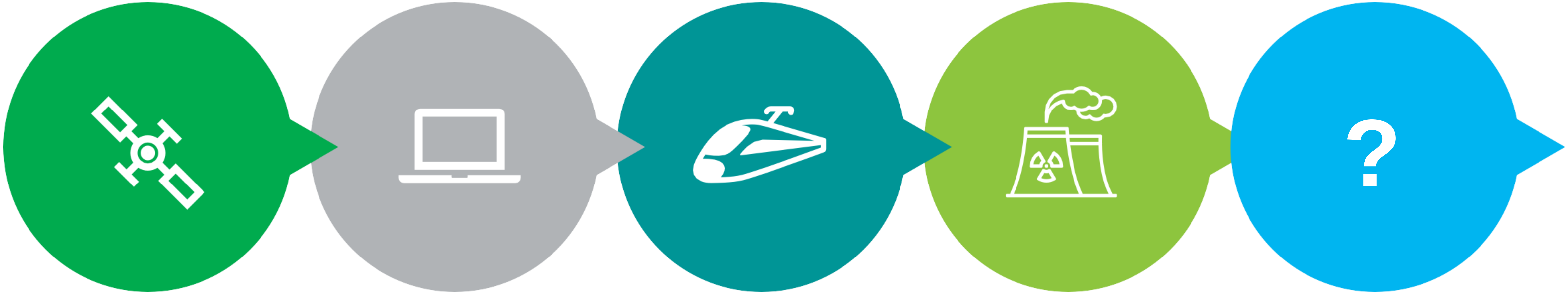
China's power capacity addition outlook

China’s coal-fired power capacity additions have declined rapidly but remain significant in absolute terms



Source: IHS Markit, China Electricity Council

Hydrogen and fuel cell can help advance China's plan to be a technology leader



Satellite

Computers

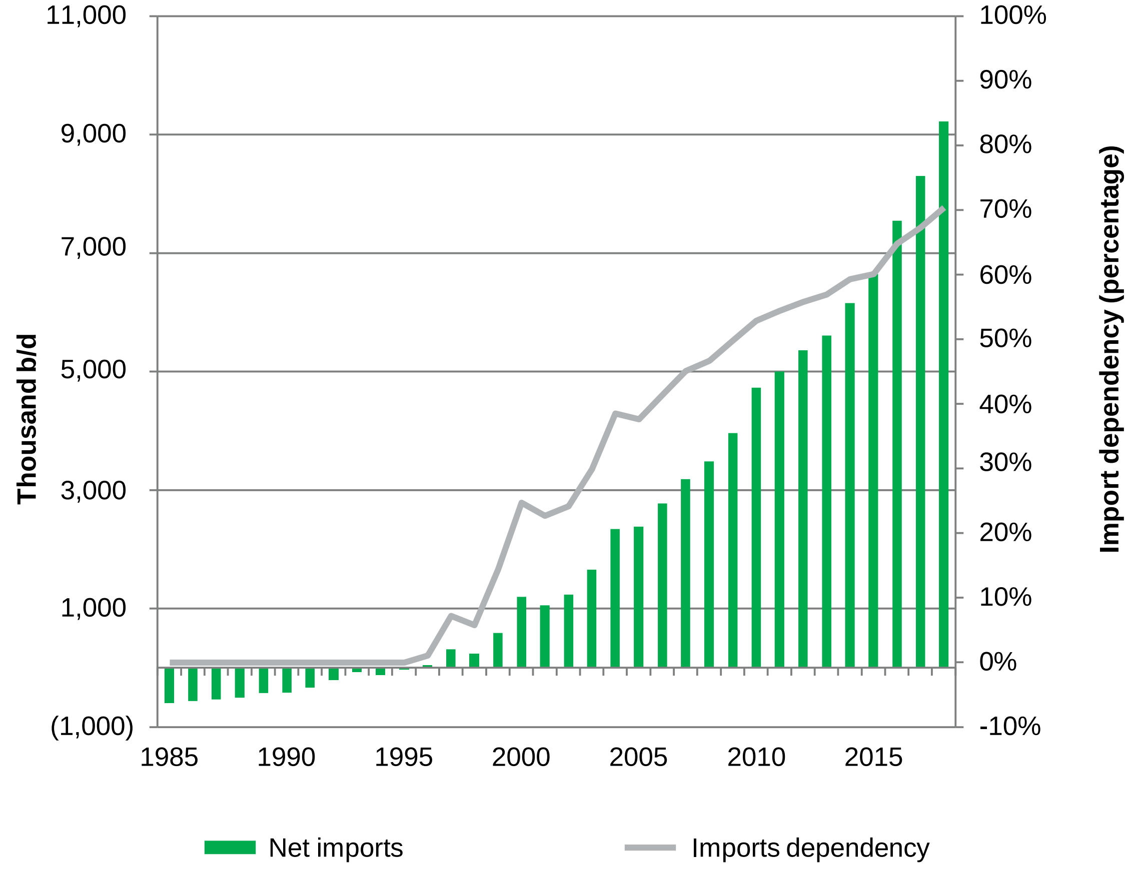
Railway

Nuclear power

Key strategic new industries such as fuel cell electric vehicles

In 2018, crude oil and natural gas import dependency has reached 70% and 45%, respectively, making supply security a key policy focus

China’s crude oil net imports and import dependency



Source: IHS Markit

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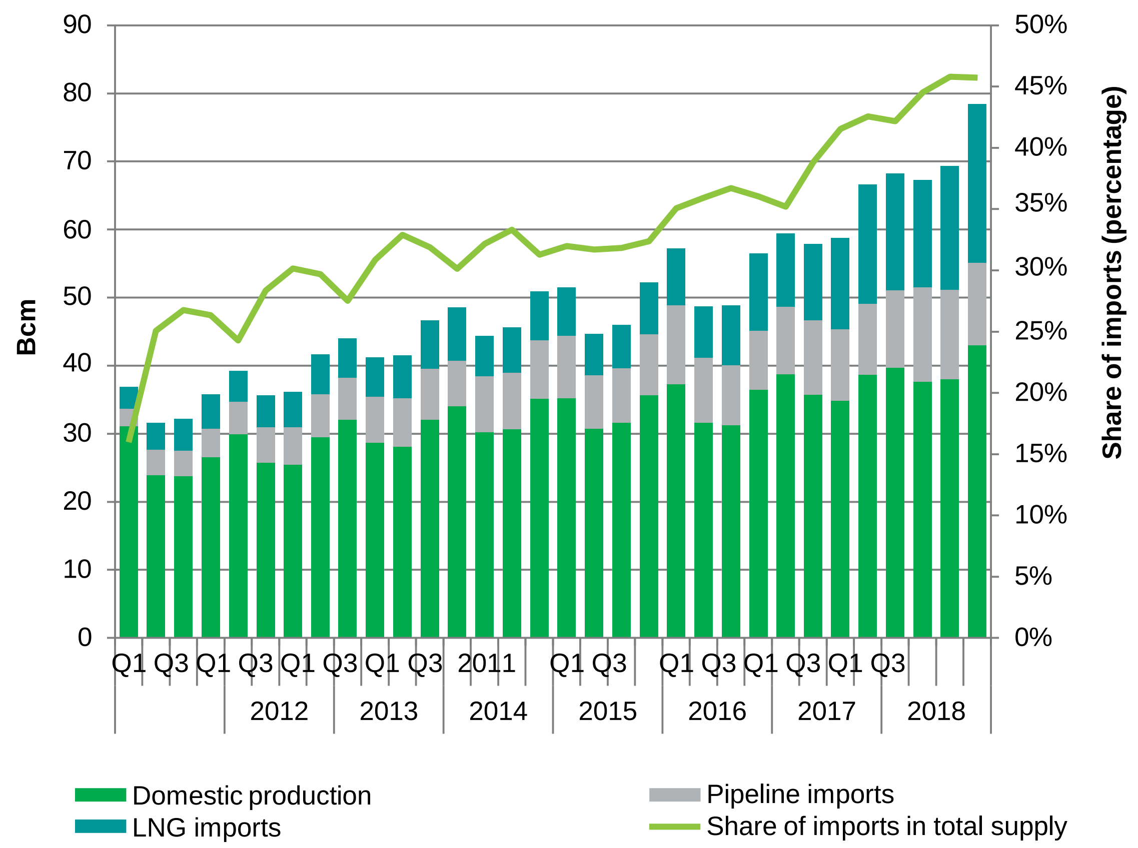
China’s natural gas supply and import dependency



Source: IHS Markit, National Bureau of Statistics (NBS), China Customs

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Hydrogen energy development is receiving increasing attention and support from the Chinese government

Political support

2015
Hydrogen included in the "Made in China 2025" initiative

2016
Hydrogen included in the 13th Five-Year Plan

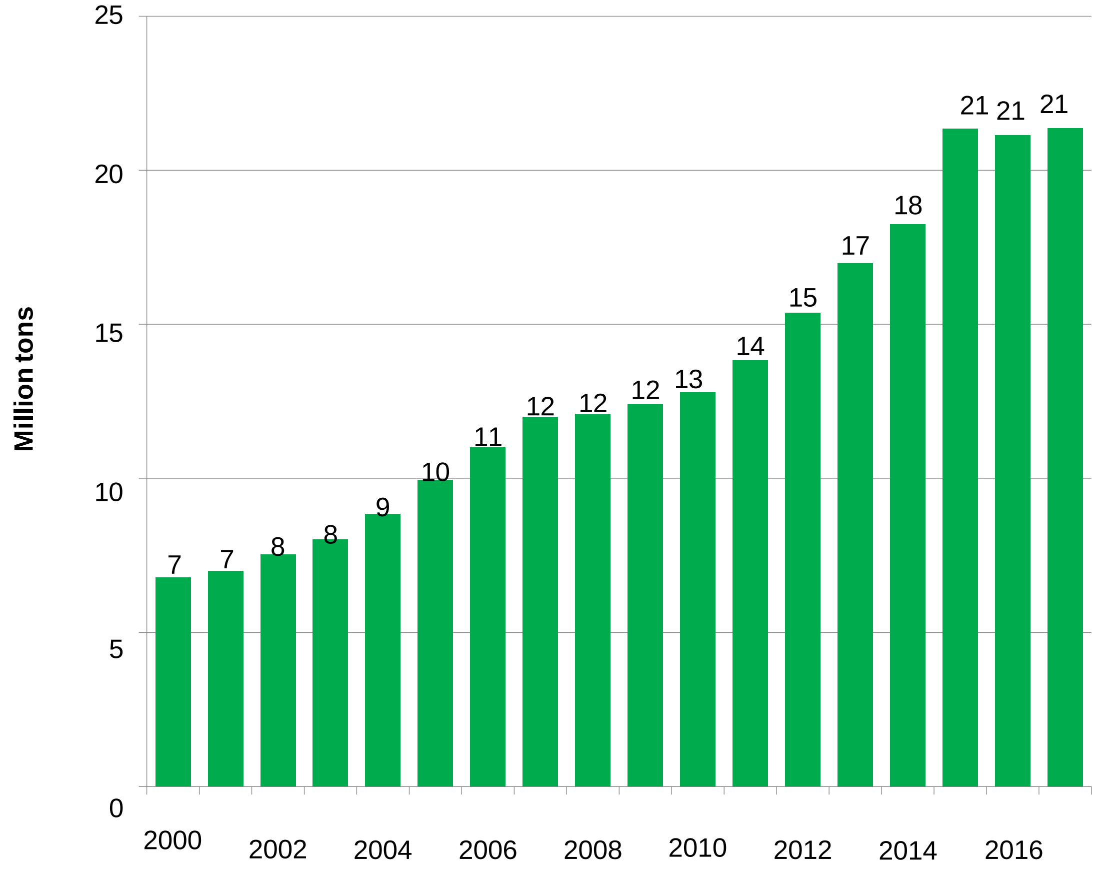
2018
China National Alliance of Hydrogen Energy and Fuel Cell established

Financial incentive

Subsidies on fuel cell vehicles ranging between 200,000 to 500,000 yuan per vehicle

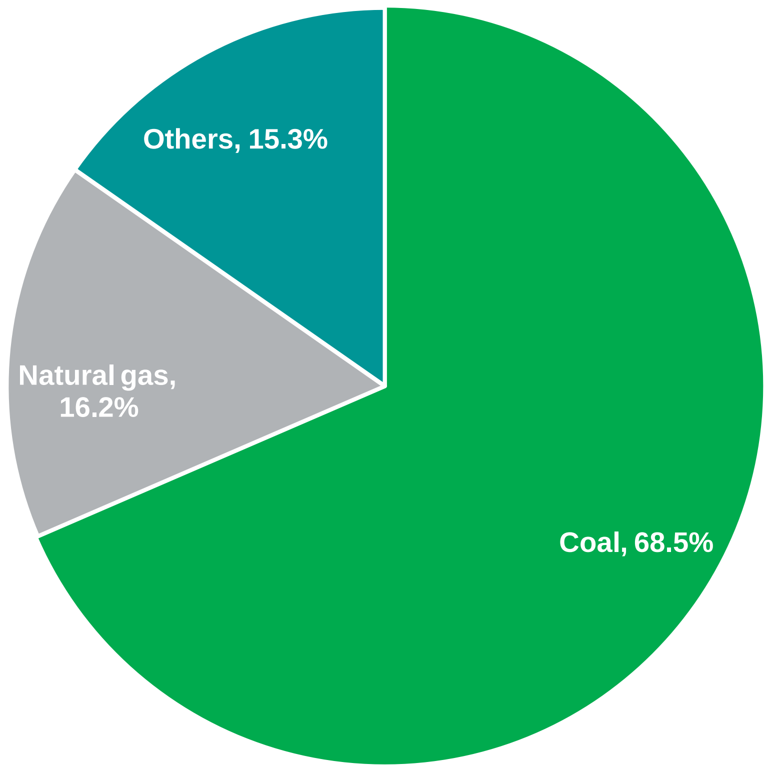
China is already the world’s largest hydrogen producer and consumer

China's hydrogen production



Source: IHS Markit

China’s hydrogen production by source (2017)



Source: IHS Markit

Understanding Hydrogen Supply:
The IHS Markit Levelized Cost of Hydrogen Model

Levelized cost of hydrogen methodology

- The IHS Markit levelized cost of hydrogen (LCOH2) model calculates hydrogen costs at the exit of the production facility,
  - Includes costs of carbon capture, transport and storage, and CO_2 emissions from the process when applicable.
  - Delivery to end user is considered a separate deployment step.

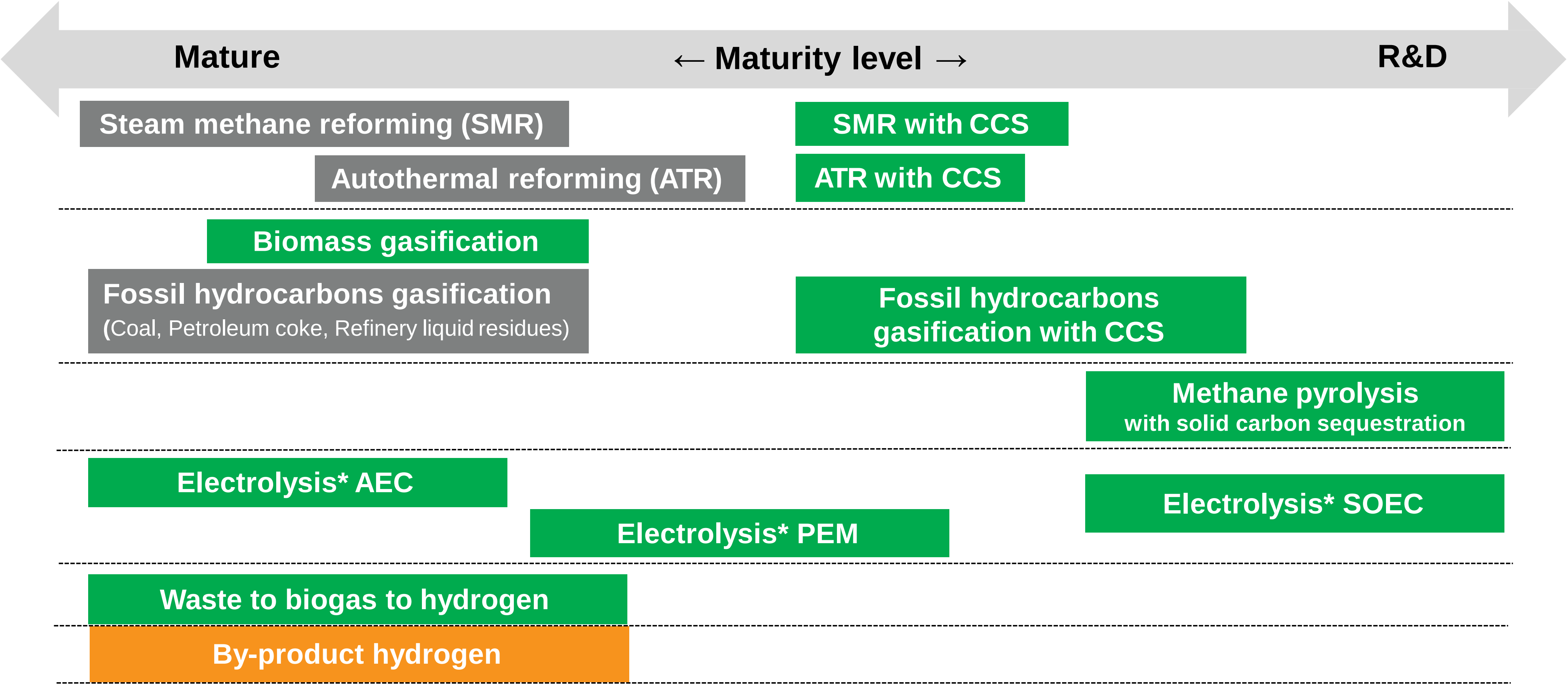
- The LCOH2 model calculates hydrogen costs via various pathways and multiple scales:
  - Steam methane reformation (SMR), with and without CCS
  - Hydrogen from biomass waste or coal gasification with and without CCS,
  - Three electrolysis technologies—varying scale and sources of power supply
  - Digestion of municipal solid waste, and
  - Methane pyrolysis

- Production costs provided for California, and selected European countries and Chinese regions

The studies consider a range of hydrogen production pathways

Pathways varying in terms of feedstock, scale, commercial availability, maturity and cost

Hydrogen production pathways



Source: IHS Markit

Unabated H_2 Low-carbon H_2

*** Assuming low carbon power supply**

AEC: Alkaline Electrolytic Cell / PEM: Proton exchange membrane/
SOEC: Solid oxide Electrolytic Cell / CCS: Carbon Capture and Storage
Byproducts of Chloroalkali industry, Refining (dehydrogenation)

Steam methane reforming dominates global hydrogen production

Interest in electrolysis is growing, current volumes are very small

Main sources of low-carbon hydrogen

	Technology status	Key uncertainties	Development model
Blue hydrogen	• SMR well understood and mature • Two examples of combining with CCS, but remains to be fully proven • Alternative processes under development to improve level of carbon capture and efficiency	• Natural gas price • Requires CCS to be low-carbon	• Large scale. Standard size 100,000 Nm^3/h. • 1 SMR makes enough H_2 to heat ~65,000 homes* • Scale growing, technology improving (ATR)
Green hydrogen	• Competing electrolysis options • Limited deployment to date • Significant cost reduction potential	• Scale / pace of process improvement • Source (and price) of electricity	• Existing $P2H_2$ capacity in Europe 21MW • Projects are scaling up—early projects <1MW, recent announcements 10-100MW

Note: *Adjusted for back up and seasonal variations in load

Source: IHS Markit

There are multiple options to provide electricity to electrolysis plants

Power generation for electrolysis

Local curtailment

Electrolysis next to renewable asset

Merchant / wholesale

Power bought from grid during periods of low prices

Potential to combine in some cases

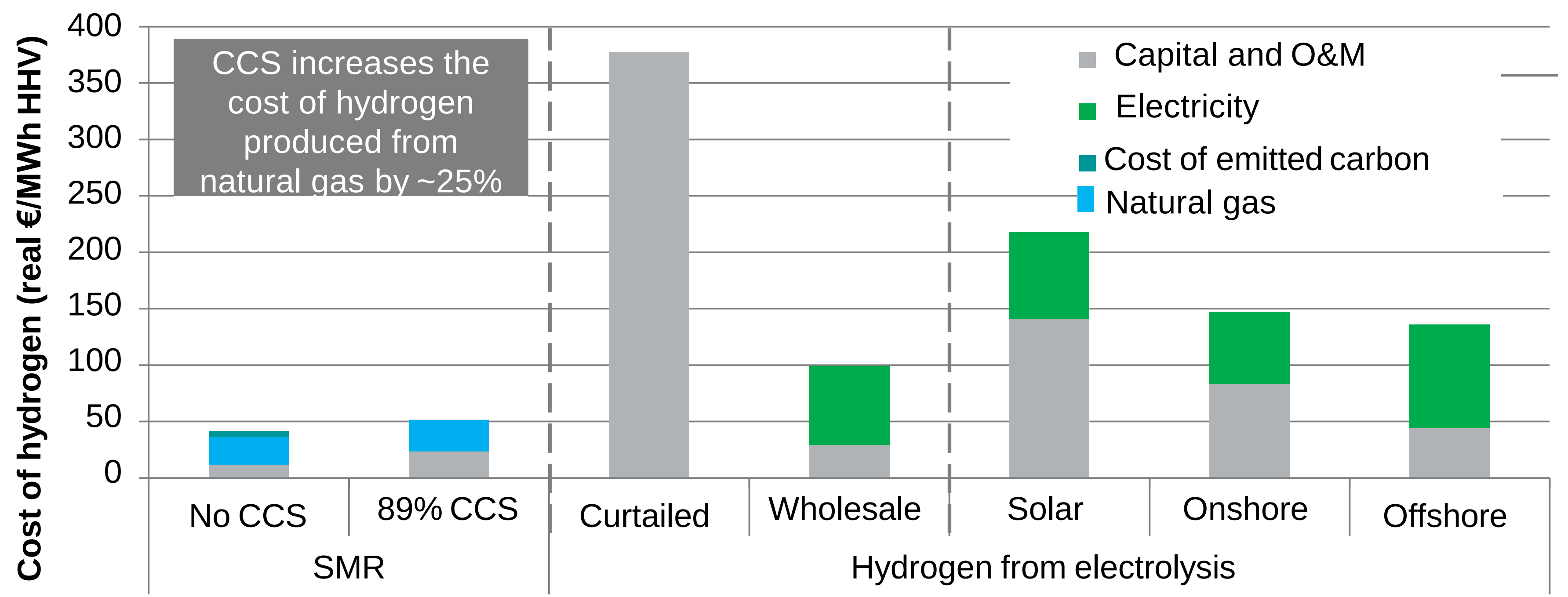
Dedicated / off grid

Renewable plant that primarily produces power for hydrogen production

Source: IHS Markit

Currently H_2 produced from natural gas is significantly lower cost than H_2 from electricity…but electrolyzer costs may fall rapidly

Levelized cost of hydrogen
(Current, at the boundary of the production facility / Germany)



CCS increases the cost of hydrogen produced from natural gas by ~25%

Notes: Hydrogen price at the boundary of the production facility. Natural gas price = €20/MWh, Carbon = €20/tonne, Curtailed = 5% (utilisation) / €0MWh, Wholesale = 95% / €50/MWh Solar: 15% / €55/MWh, Onshore wind: 25% / €46/MWh, Offshore wind: 54% / €66/MWh. Excludes electricity grid charges and taxes and levies

Source: IHS Markit

Carbon emissions per kWh of hydrogen

Fuel/ technology	**kg CO_2 per kWh(HHV) of natural gas/H_2**
Natural gas	0.18
SMR with no CCS	0.23
SMR with 89% CCS	0.03
Grid electricity (Germany 2020)	0.52

Source: IHS Markit

Key cost drivers for hydrogen production

Cost drivers for hydrogen

SMR	Electrolysis
Size of SMR	Electrolysis technology
% of CO_2 captured	Deployment/learning rate
Deployment/learning rate for CCS	Efficiency improvement
Natural gas price	Electricity price
Carbon price	Electricity supply: curtailed or dedicated?

Source: IHS Markit

Hydrogen’s Potential End Uses

Hydrogen’s versatility allows it to play a role in all sectors of the economy

End use applications of hydrogen for energy use

Transport

Displace batteries or fossil fuels

Industry

Residential Commercial

Displace natural gas in pipelines and end uses

Displace coal used for direct heat in industrial and commercial applications

Power

Intra-day balancing of renewable generation and power demand

Seasonal balancing of renewable generation and power demand

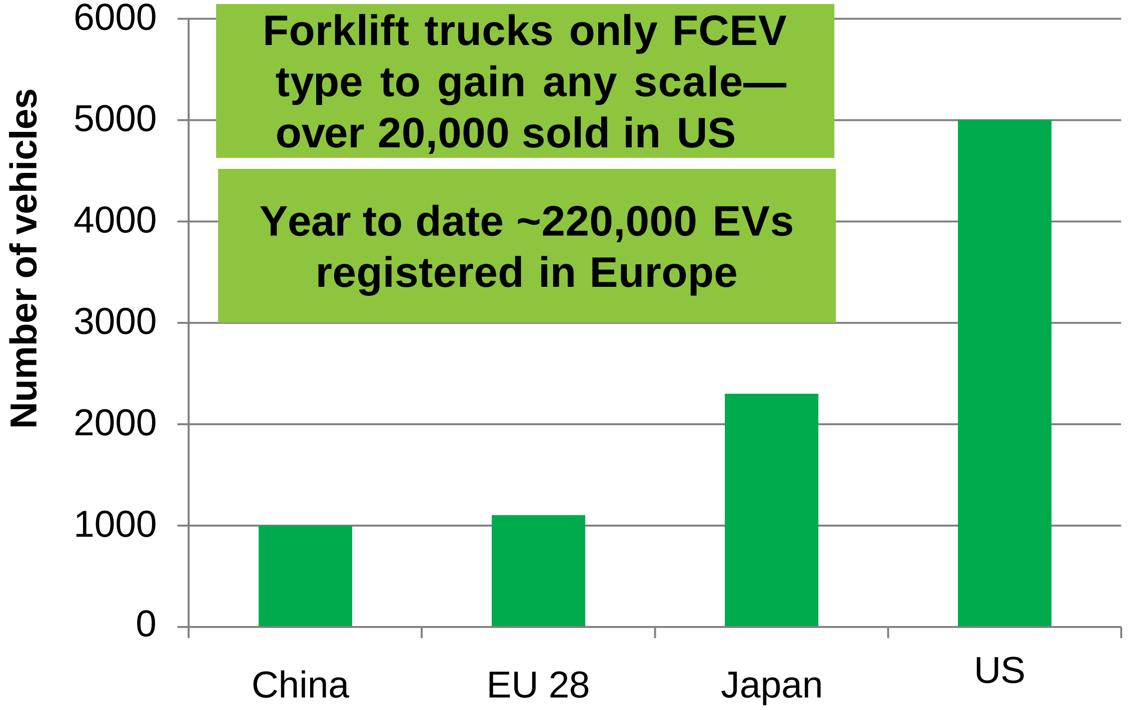
Reduced fossil generation

Source: IHS Markit

Early days for all alternative fuel vehicles…

…hydrogen has potential to significantly reduce emissions in over 60% of transport demand

Fuel cell electric vehicle fleet (road vehicles)

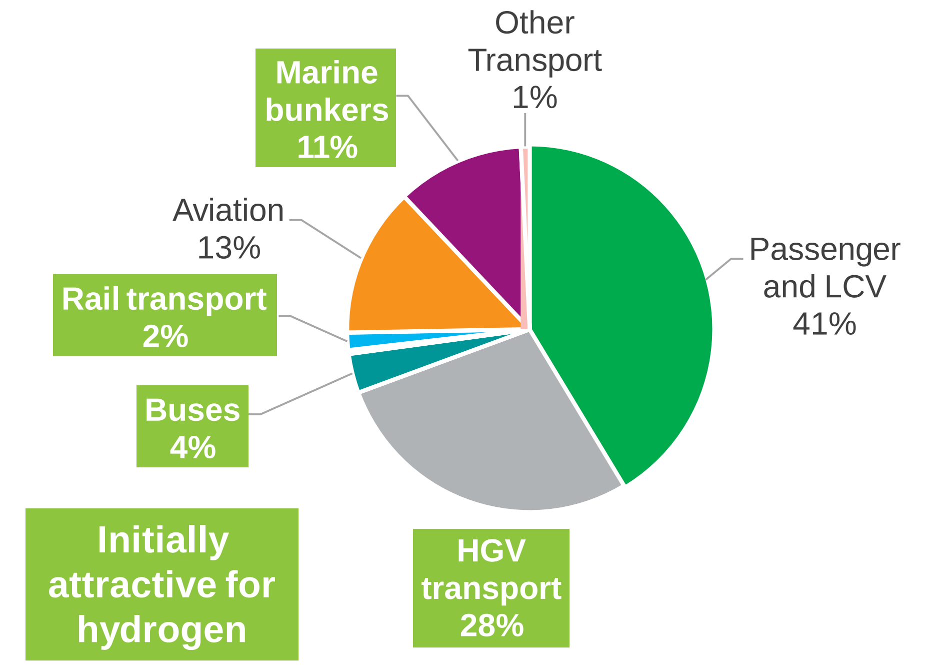


Forklift trucks only FCEV type to gain any scale—over 20,000 sold in US

Year to date ~220,000 EVs registered in Europe

Source: IHS Markit

Breakdown of transport energy use (European Union)



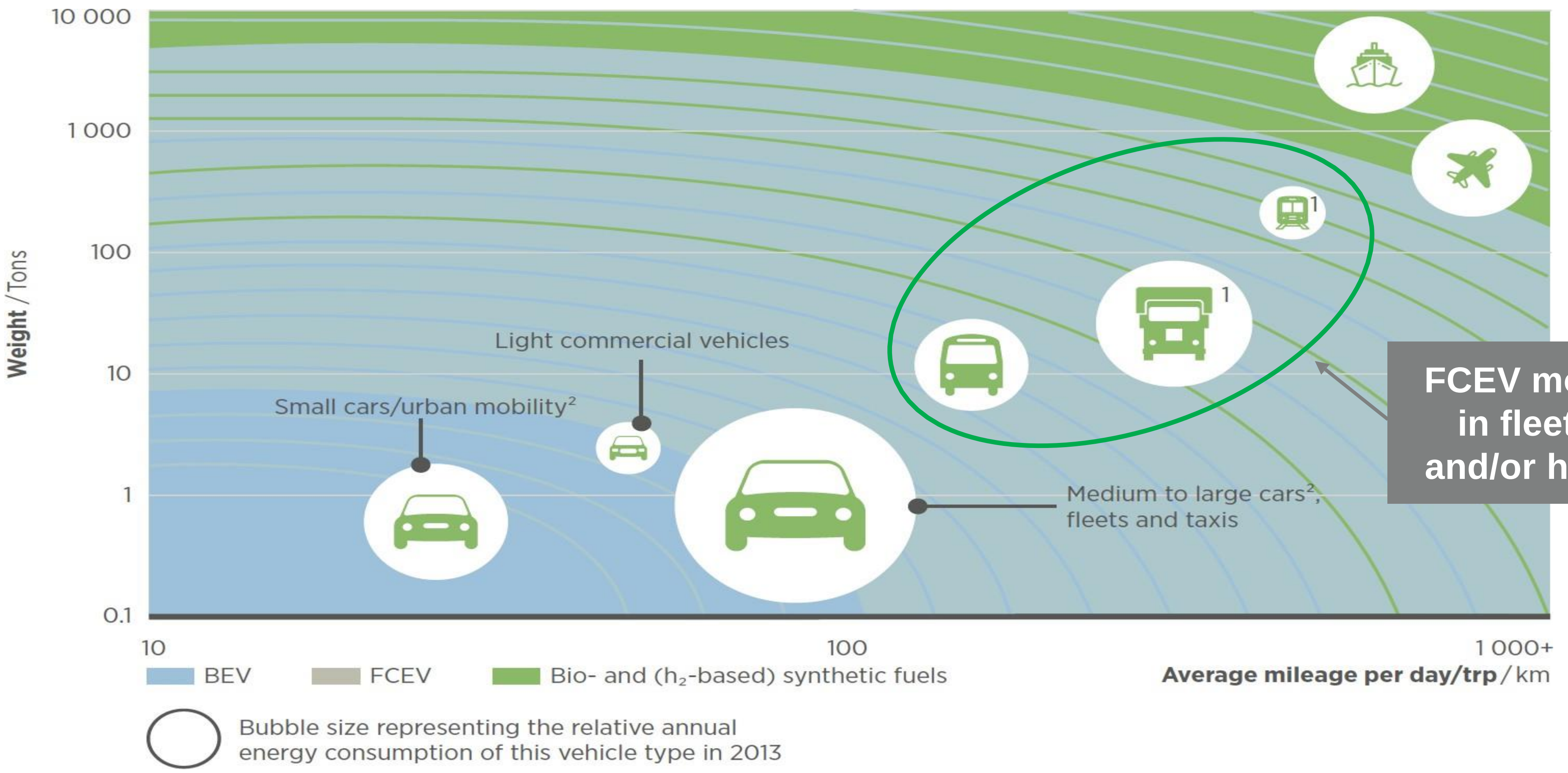
Initially attractive for hydrogen

Source: IHS Markit

Non-passenger vehicles have not had regulation to date for CO_2 emissions. However this is changing.

Trip length and weight determine competition between BEV and FCEV

Hydrogen advantage in HGV and fleet sector, BEV favoured in passenger car market

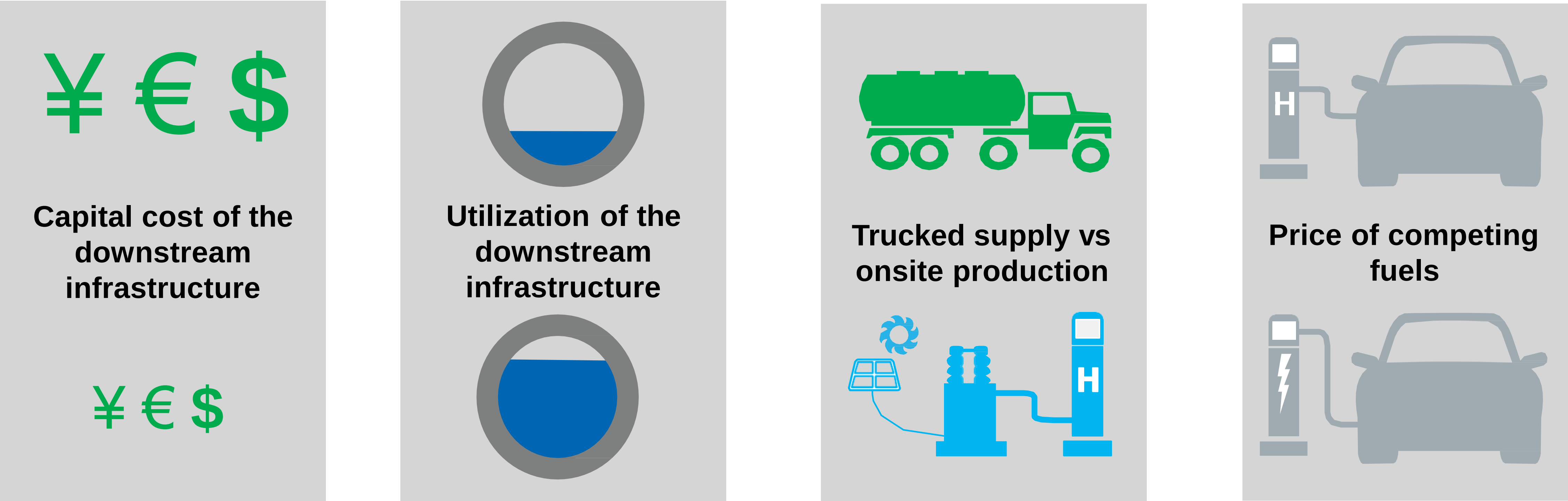


FCEV most likely to gain foothold in fleets with long single trips and/or high uptime requirements.

Source: Hydrogen Council

Drivers of the competitiveness of retail hydrogen

Drivers of the competitiveness of retail hydrogen



Capital cost of the downstream infrastructure

Utilization of the downstream infrastructure

Trucked supply vs onsite production

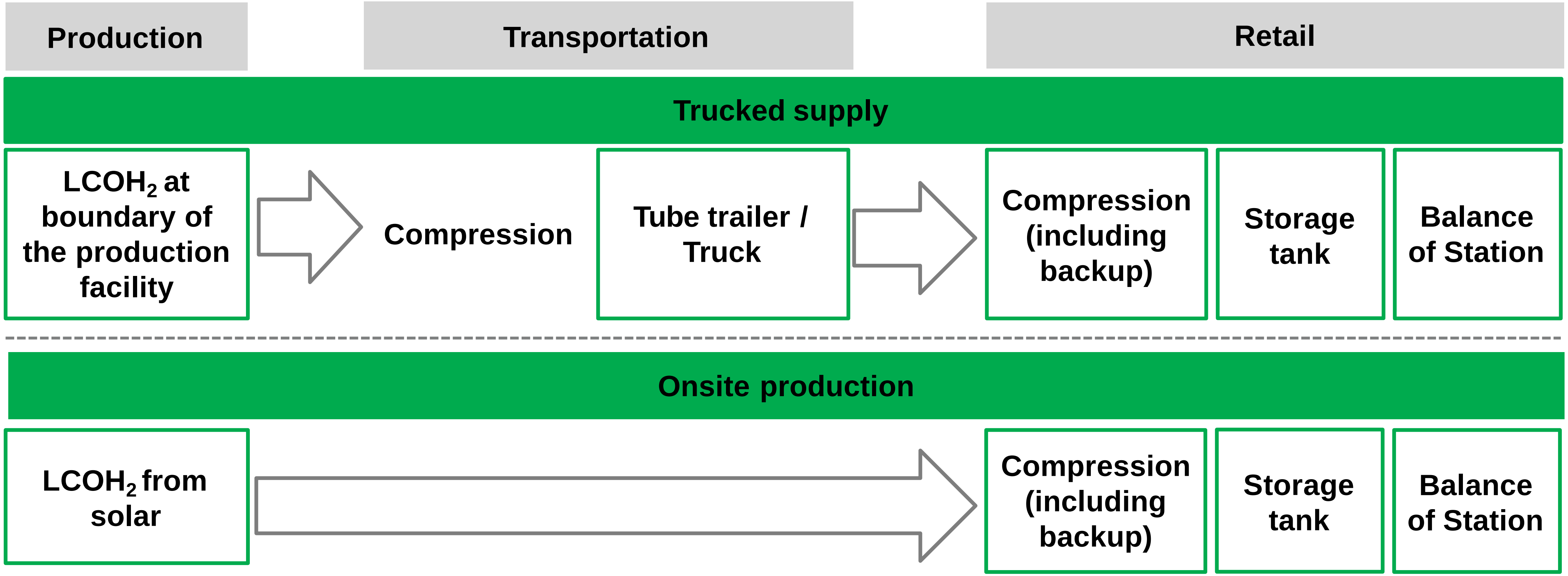
Price of competing fuels

Notes:
Source: IHS Markit

There are two options for the medium-term supply of H_2 for transport

Tube trailer or onsite production

Build up of hydrogen delivery costs (2020)



Production | **Transportation** | **Retail**

Trucked supply

$LCOH_2$ at boundary of the production facility → **Compression** → **Tube trailer / Truck** → **Compression (including backup)** | **Storage tank** | **Balance of Station**

Onsite production

$LCOH_2$ from solar → **Compression (including backup)** | **Storage tank** | **Balance of Station**

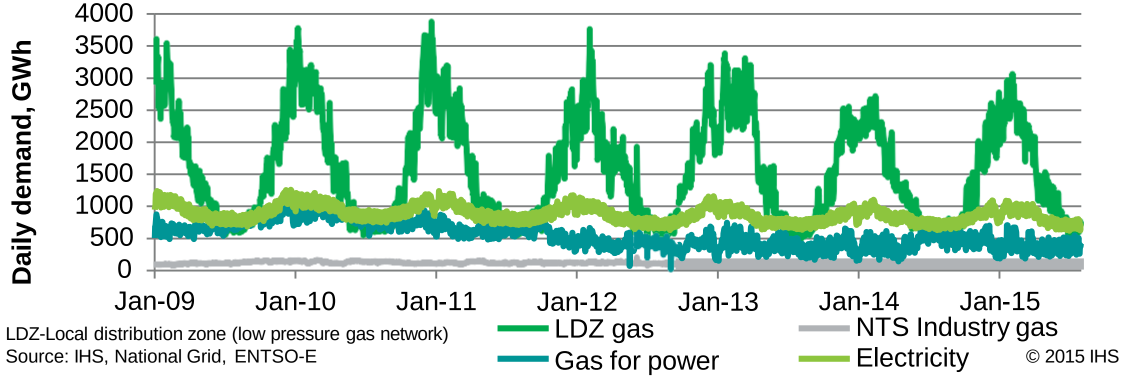
Notes: In the long-term hydrogen could be delivered via pipeline, but this is likely to require the deployment of hydrogen for energy use in the wider economy
Source: IHS Markit, US DOE

Variation in space heating demand limits potential for electrification

Storability of hydrogen can reduce the cost of decarbonising heat

- Space heating demand is extremely variable
  - Great Britain (GB): Maximum LDZ demand x 5-7 minimum LDZ demand
  - Netherlands (NL): Maximum ~x10 minimum
- Electricity demand is much less variable
  - GB: Max ~1.7 min (6% electric heating)
  - NL: Max ~1.6 min (2% electric heating)
  - France: Max ~2.2 min (13% electric heating)
- Range of French electricity demand is higher than in other markets, but still far less than variation in gas distribution system

Great Britain



LDZ-Local distribution zone (low pressure gas network)

Source: IHS, National Grid, ENTSO-E

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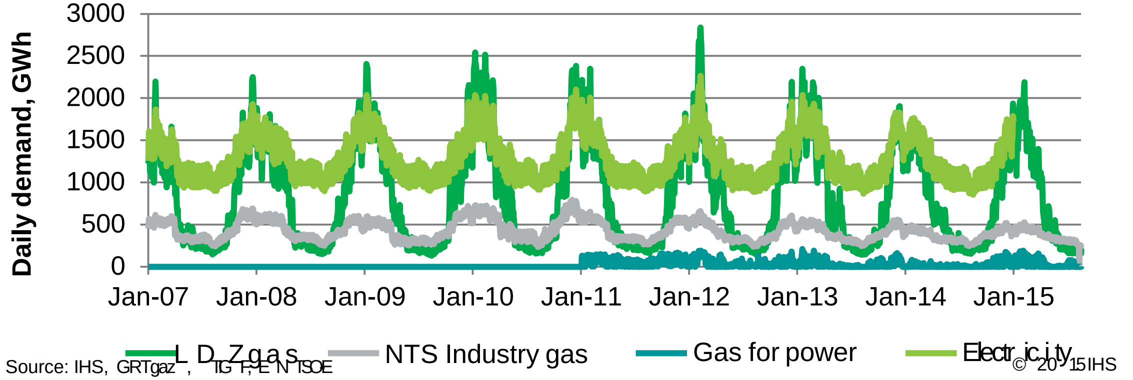
France



Source: IHS, GRTgaz, TIGF, ENTSOE

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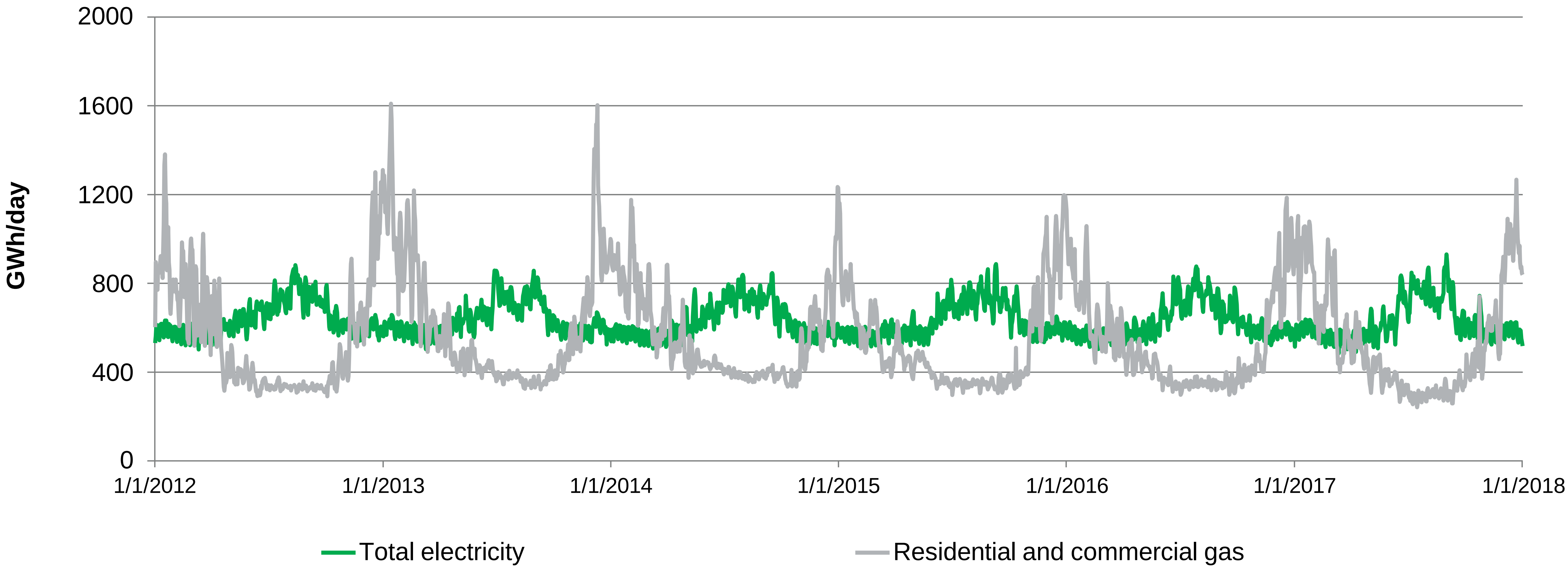
Key question from system perspective: How to manage variation in heat demand?

Even in warm climates, scale of peak heat load sets limits on level of electrification that is possible

California: Total daily electricity and domestic gas demand

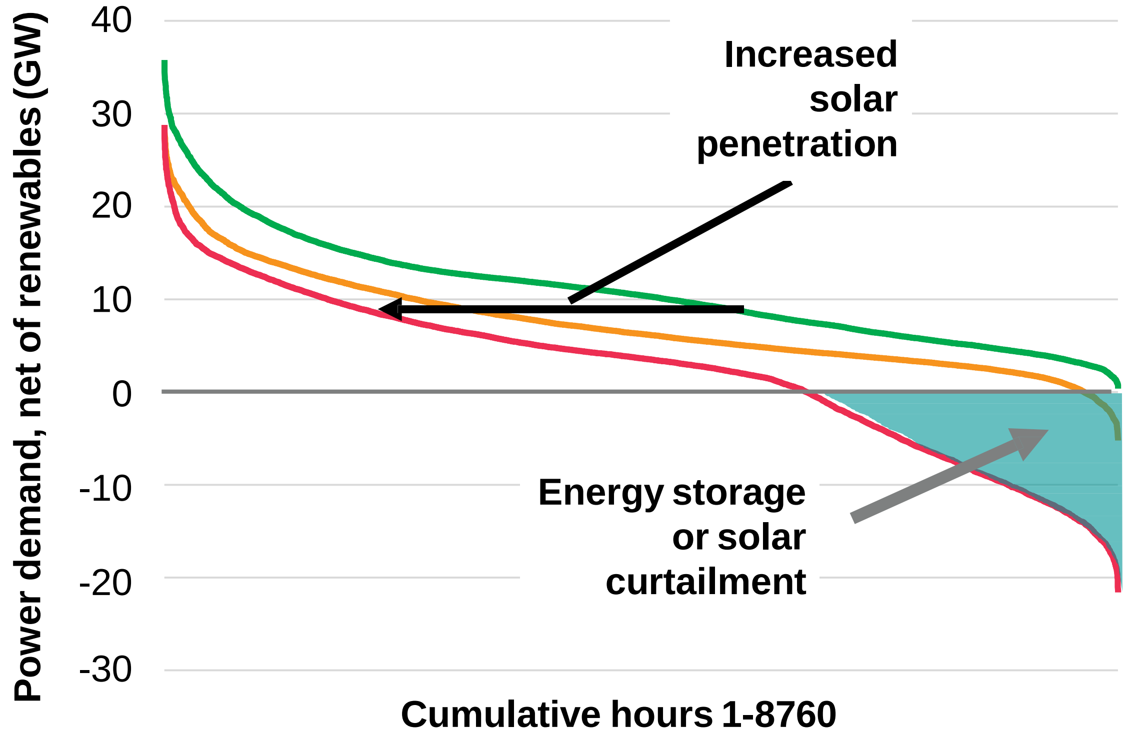


Source: IHS Markit

Energy storage is needed to match renewable generation with load

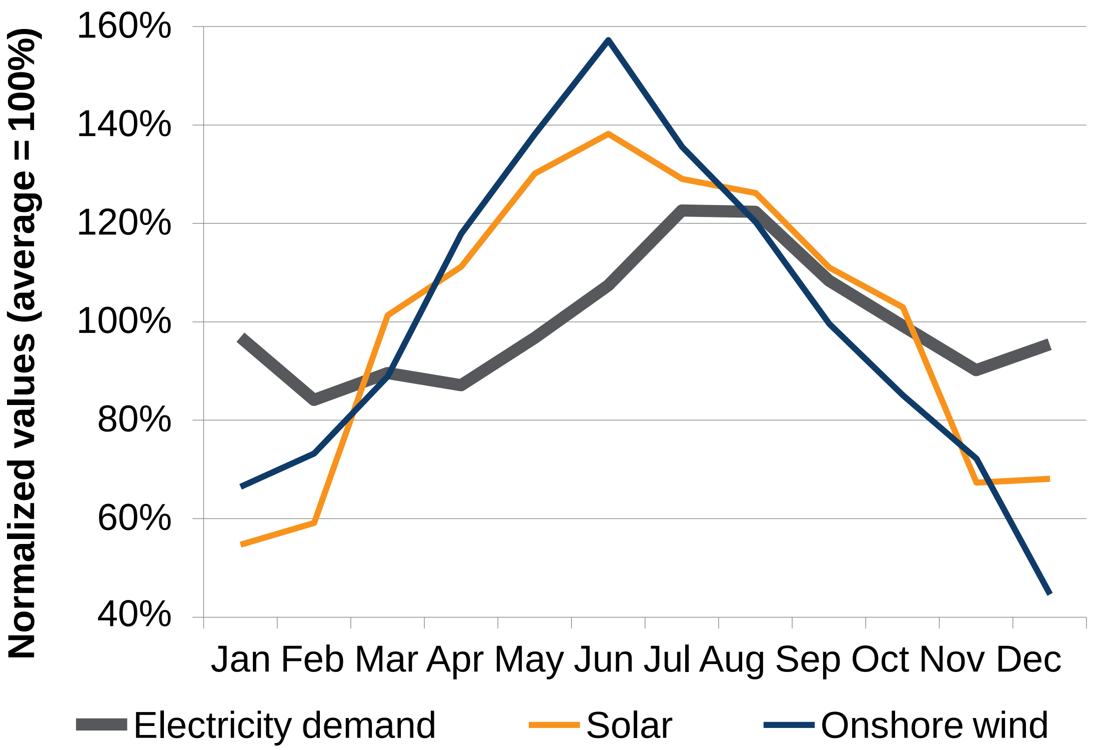
Mis-matches exist across hours, days, weeks, and months. Storage may also be necessary for year-to-year variations in climate.

Solar generation's effect on California's power system



Notes: Chart is illustrative.
Source: IHS Markit

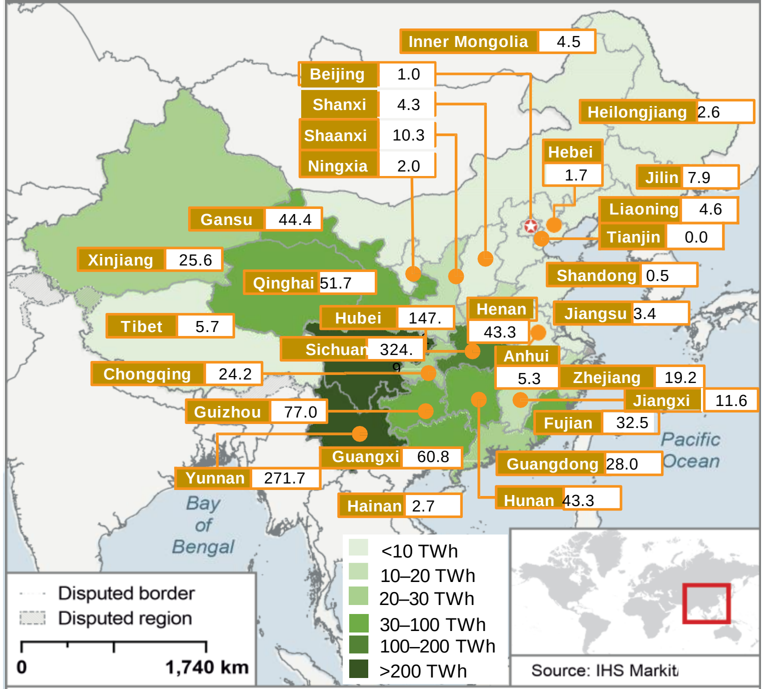
California, sample demand and generation profiles



Source: IHS Markit, ABB Velocity Suite

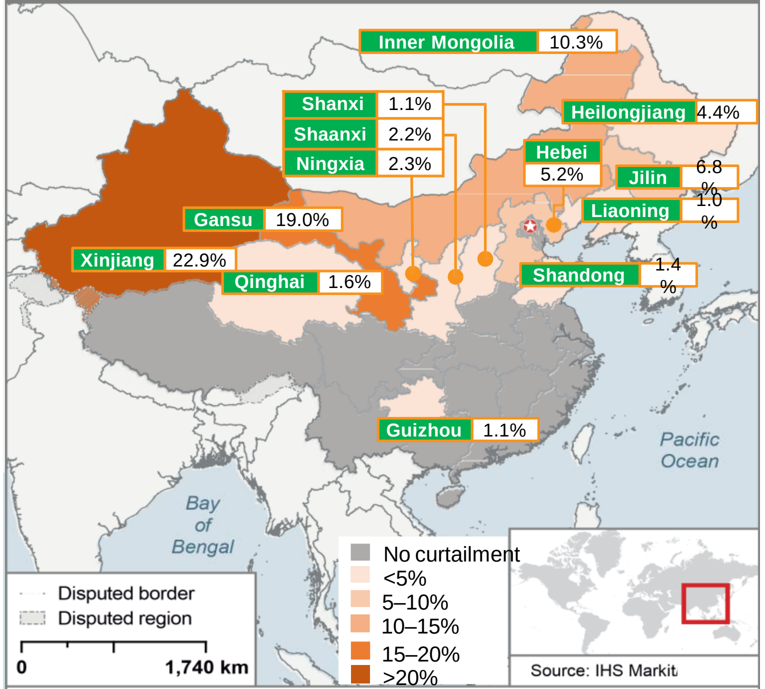
China’s curtailment problem: 97 TWh curtailed electricity can generate 2 MMt of hydrogen

Hydropower production in 2018



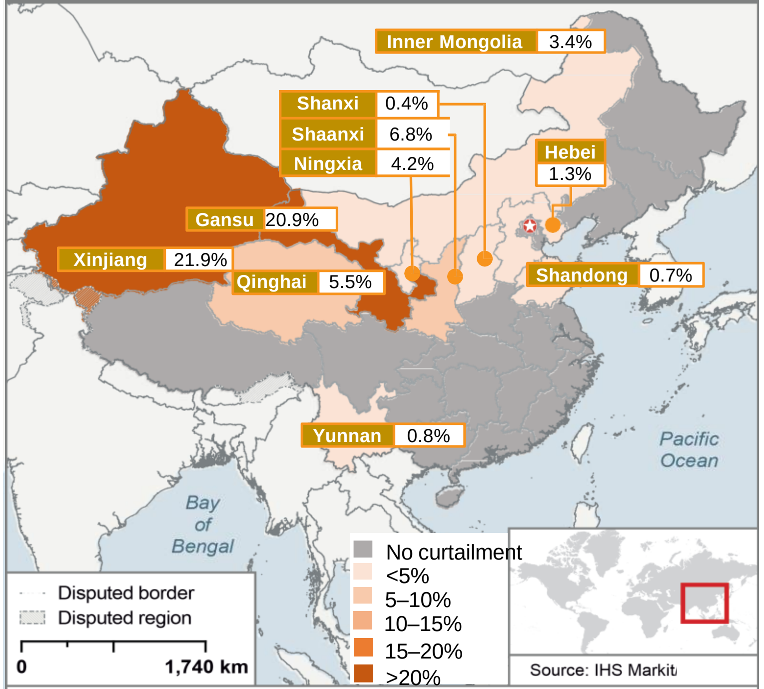
Source: IHS Markit

Wind curtailment by province in 2018



Source: IHS Markit

Solar curtailment by province in Q1-Q3 in 2017



Source: IHS Markit

Hydrogen can help transport energy resources to major demand centers

In China, energy resources are located far from coastal demand center

Major energy resources and regional power demand

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Major power transmission stream regional grids

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Source: IHS Markit

IHS Markit Hydrogen studies: Scope and detailed deliverables

Overall quantitative approach

Putting together costs and opportunities

Supply cost analysis: Green and other hydrogen production technologies analysis

Levelized cost of hydrogen under various technology starting points

- Green H_2 (electrolysis)
- Other H_2 technologies (coal, etc.)

Market potential

Plausible demand for hydrogen in each major end use given favorable costs and policy

- Power
- Space conditioning
- Industry
- Transportation

Tipping point analysis by end use sector

Identify the netback value or cost of hydrogen in each major end use under various sensitivity cases of future costs and policy.

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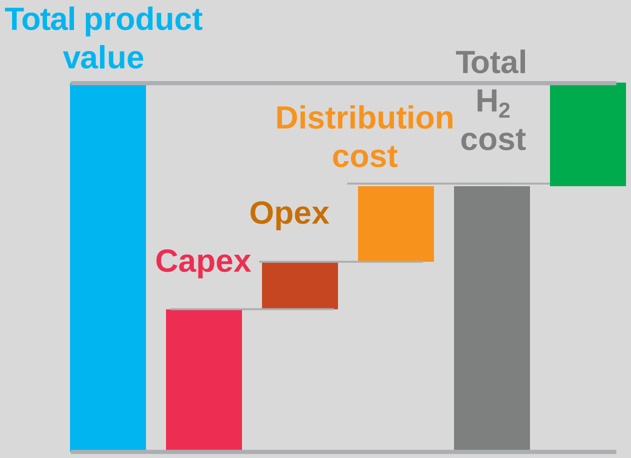

H_2 netback value = total product value – H_2 costs (could be negative)

- Power
- Space conditioning
- Industry
- Transportation

Source: IHS Markit

IHS Markit Hydrogen Studies: Topics Quantified

- Comparison of costs of producing low-carbon hydrogen
- Power to hydrogen from curtailed electricity—amount available to 2050
- The role of low-carbon hydrogen in space and water heating
- The tipping points for the use of hydrogen in heavy transport
- Defining the plausible demand for low-carbon hydrogen
- Matching low-carbon hydrogen production to demand
- Implications for hydrogen deployment in different segments of the energy business

Each study focuses on key questions in each region while providing a coherent global overview of prospects of hydrogen development

IHS Markit hydrogen studies - 2019

Hydrogen in the Golden State

Do policy measures change the economics of hydrogen use in transport?

How can hydrogen help California eliminate GHG emissions by 2045?

European Hydrogen Forum

How can hydrogen contribute to a net zero carbon Europe?

Role of low carbon gases: Synthetic methane vs hydrogen

Is there room for electrification and hydrogen?

Hydrogen as the Enabler: Meeting China’s Energy Challenge?

Could domestically produced hydrogen reduce fossil fuel imports?

Will China accelerate cost reductions for electrolysis?

Source: IHS Markit

Key Business Questions: What is the hydrogen opportunity for my company?

Upstream Oil and Gas Companies

- Can hydrogen produced with SMR and CCS offer a long term future for natural gas production?
- What is the competitive threat from hydrogen from electrolysis?

Electric Utilities

- What is the role of hydrogen storage in integrating renewables?
- Is large scale hydrogen power feasible?
- Is hydrogen electrolysis a major new power demand sector?

Natural Gas Utilities

- What is the potential for repurposing existing distribution assets to hydrogen delivery?

Transportation

- Could hydrogen be a major means to decarbonize cars, buses and trucks?
- What refueling infrastructure would be needed?

Industrial End Users

- Can hydrogen replace conventional sources of process heat?
- How would the hydrogen be produced and delivered to my facility?
- Could on-site renewable power generation be a source for hydrogen production?

Financial Institutions

- How will hydrogen infrastructure projects be financed?
- Will there be policy support for hydrogen?
- What are the technology and revenue risks?

Hydrogen in the Golden State: Project timeline and deliverables

Initial Workshop and Community Introduction
Los Angeles
30 October 2018

- **Why hydrogen now:** an overview of policy initiatives supporting hydrogen development in California.
- **Hydrogen supply analysis:** presenting the results and insights from the IHSM Levelized Cost of Hydrogen (LCOH$_2$) modeling and analysis.
- **Developing the project quantitative approach:** review of the components of the IHSM Autonomy scenario and a how to assess hydrogen’s role in a deeply decarbonized California.

Intermediate presentations: Community calls
November 2018 – May 2019

- **Intermediate community calls:** validation of the modelling and intermediate results, sectorial deep-dive, etc., in a webinar format.
- **California net zero greenhouse gas economy in 2050.** Provided the policy backdrop for the project’s analytics
- **Status of Analysis of the Transport Sector.** Quantification of transportation costs for hydrogen fuel cell vehicles and competing technologies.

Final workshop and presentation materials
Chicago
14-15 May 2019

- **Practicalities:** understanding the technical and policy issues impacting the potential role of hydrogen in power, industry, transport and heat in California.
- **Identifying the tipping points:** determining the triggers and conditions required for hydrogen to be used more widely
- **Costing:** quantifying indicative costs needed to move hydrogen from demonstration to commercial success in each principal end use.
- **The market potential for hydrogen:** quantification of the plausible and maximum potential demand for hydrogen in California.

Structure of the European Hydrogen Forum

Deliverables and scope of work can evolve based on participants feedback

- Two meetings during the year -- June and end October/November 2019

- Location: a ‘hydrogen-interesting’ location.
  - Suggested first meeting: June 12-13, 2019 Marseille, Jupiter 1000 hydrogen cogen plant and accompanying transmission line
  - Second meeting: to be determined

- A two-day session for each meeting – the first day will include a tour of a hydrogen facility followed by dinner, the second day is a workshop day with a presentation and discussion of analysis on specific topics.

- For the first session – suggested topics for analysis:
  - **Supply**:
    - ○ Comparison of a broader set of hydrogen production options from biomass/waste; a further review of costs
    - ○ Exploring options for hydrogen imports
    - ○ Costs of for example biomethane, synthetic gases

  - **Infrastructure**:
    - Comparison of the costs of transporting hydrogen compared with electricity and natural gas
    - Are synthetic methane or other synthetic fuels a better option than hydrogen?

European Hydrogen Forum: Client suggestions for topics

Hydrogen Supply Options

- Use of biomass to produce hydrogen
- Thermal methane pyrolysis or “Gas splitting” – Breaking methane molecule into hydrogen and solid carbon
- Conversion of hydrogen to methane by recycling CO_2 from the air
- Hydrogen plus a carbon source converted to liquid fuels for the transport sector e.g. methanol, biodiesel, ammonia (as a transport fuel)
- Import of hydrogen produced from renewable sources outside Europe in liquid form: liquefied hydrogen or ammonia
- Refineries could produce hydrogen by electrolysis instead of using SMRs
- **Transmission/Distribution**
- Cost and technical limitations of converting grid to hydrogen vs blending hydrogen with natural gas

Hydrogen Demand

- Opportunities in micro CHP
- Use in district heating
- Analysis of the light duty vehicle sector
- Comparison of the use of biomethane with hydrogen in all end-use sectors
- Altering the overall power generation mix—does using hydrogen imply a different power mix? e.g less renewable capacity required because hydrogen provides a storage option
- What is the route to market in the different sectors – is there a different risk profile?

Regular Tracking of Policies and Events

- Quarterly newsletter on hydrogen
- Review of policies on hydrogen in each of the countries in Europe and a global overview

Hydrogen the Enabler: Meeting China’s Energy Challenge?
Project timeline and deliverables

Study kick-off
March 2019

Intermediate workshop and presentation materials

Beijing
18 July 2019

Final workshop and presentation materials

Beijing
Fall 2019

- **Study kick-off**

- **Introduce the study participants.**

- **Overview of the project timeline and scope.**

- **Discuss the first workshop agenda and logistics.**

- **Why hydrogen now:** an overview of policy initiatives supporting hydrogen development.
- **Hydrogen supply analysis:** presenting the results and insights from the IHSM Levelized Cost of Hydrogen (LCOH$_2$) modeling from electrolysis, gasification and reforming.
- **Transmission comparison:** transporting hydrogen compared with electricity and natural gas

- **Practicalities:** understanding the technical and policy issues impacting the potential role of hydrogen in power, industry, transport, and heat in China.
- **Identifying the tipping points:** determining the triggers and conditions required for hydrogen to be used more widely.
- **Costing:** quantifying indicative costs needed to move hydrogen from demonstration to commercial success in each principal end use.

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