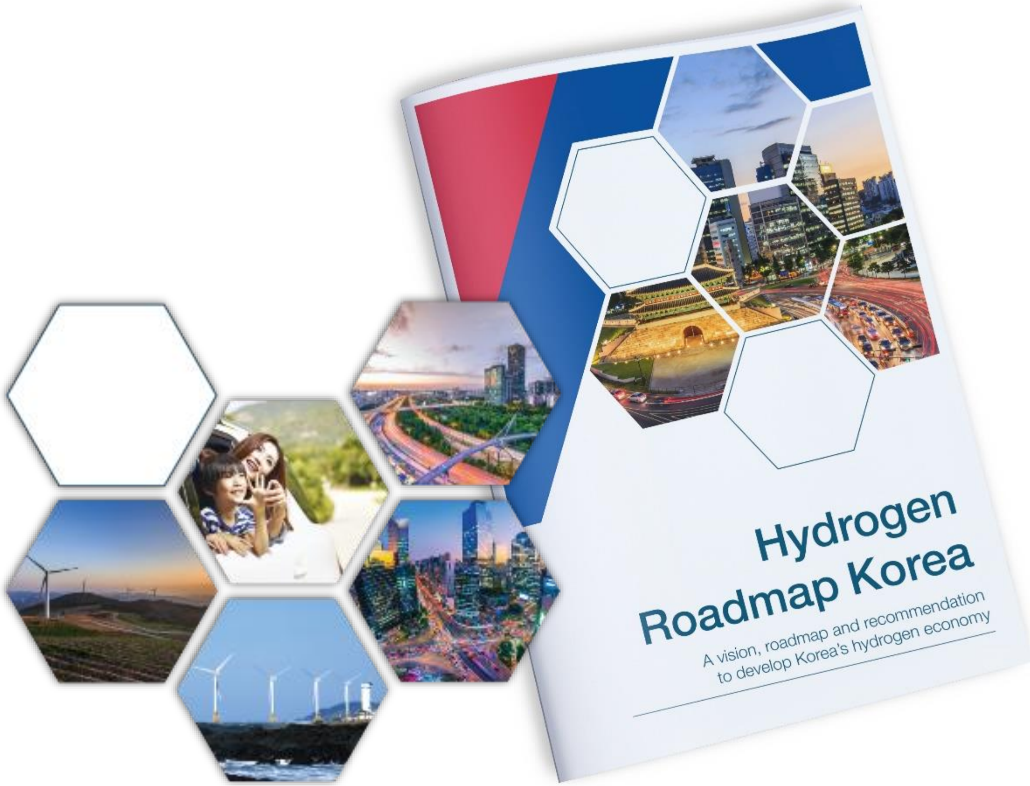
Hydrogen Roadmap Korea

A vision, roadmap and recommendation to develop Korea’s hydrogen economy

November 2018

This study is a comprehensive and actionable hydrogen roadmap for Korea



Objectives of the study

- **Comprehensive quantified vision** and **roadmap** for deployment of hydrogen applications, infrastructure and supply
- **Ambitious yet realistic**
- **Integrated study** of an industry coalition consisting of leading Korean industry players and organizations
- **Provide actionable recommendations** to implement the hydrogen roadmap for Korea

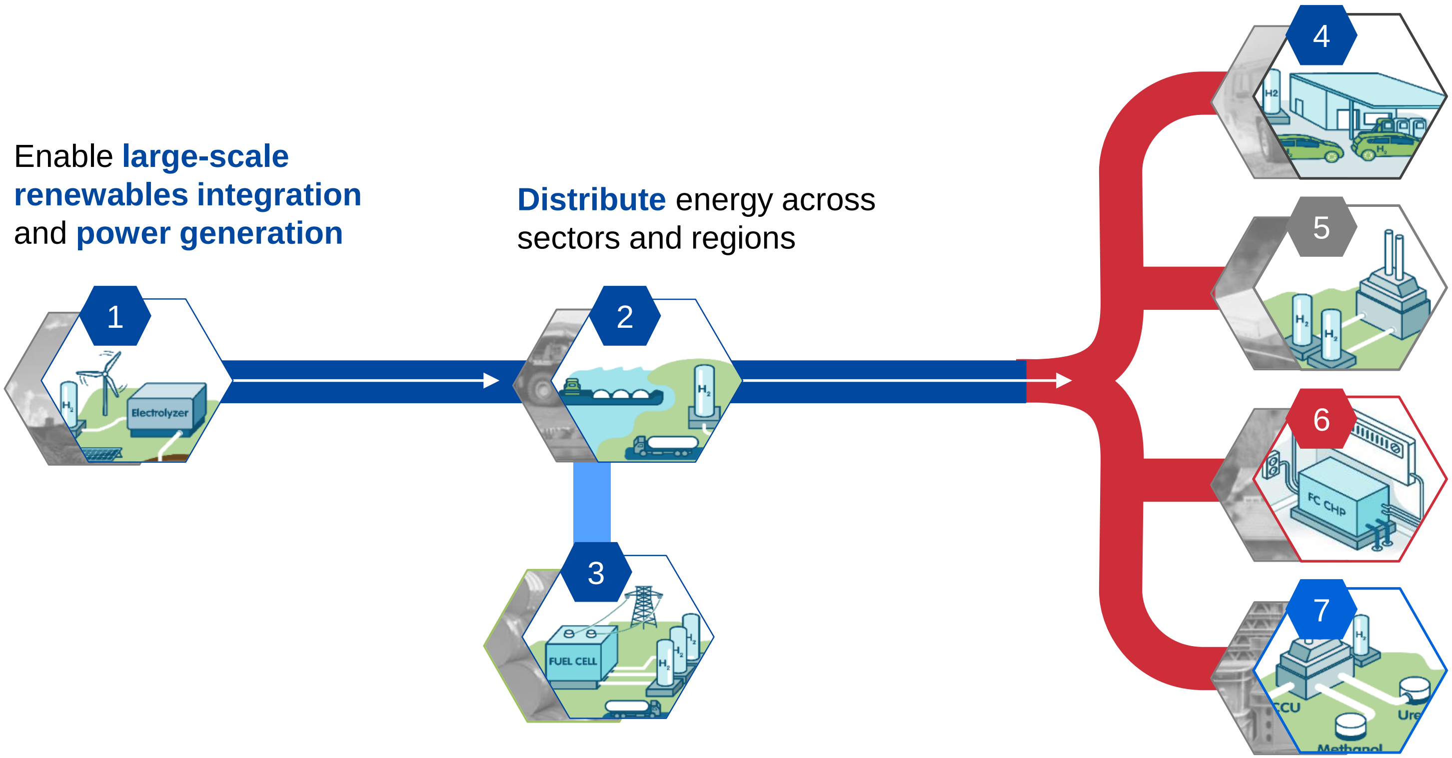
Participating partners:

HYUNDAI, KOGAS, KOLON INDUSTRIES, INC., Air Liquide, Shell, WWF 세계자연기금, LOTTE CHEMICAL, Korea Investment & Securities Co., Ltd., SAMSUNG SECURITIES, DOOSAN, H2KOREA, HYUNDAI MOTOR SECURITIES, Hyundai Oilbank, TOYOTA TSUSHO, UBS, EM SOLUTION CO., LTD., NH투자증권

SOURCE: Hydrogen Council; Hydrogen Korea Study team

Hydrogen is a key pillar for the energy transition in Korea

Enable the renewable energy system → Decarbonize end uses



Enable **large-scale renewables integration** and **power generation**

Distribute energy across sectors and regions

Act as a **buffer** to increase system resilience

Decarbonize **transportation**

Decarbonize **industrial energy** use

Help decarbonize **building heat and power**

Serve as renewable **feedstock**

SOURCE: Hydrogen Council; Hydrogen Korea Study team

Hydrogen has advantages for Korea's environment, industry and society

Industry

- Korea can become a **leader in hydrogen technology** and **build a new industry** around fuel cell electric vehicles (FCEVs), hydrogen production equipment, distribution infrastructure and end-use applications
- This will open **export opportunities,** fueling increases in revenues as well as jobs

Environment

- Hydrogen can decarbonize otherwise **hard-to-decarbonize sectors** (heavy transport, buildings, industry…)
- Total potential of **~150 million tons CO_2 emissions, closing 40%** of the CO_2 reduction gap in 2050
- Reduction of **local emissions**

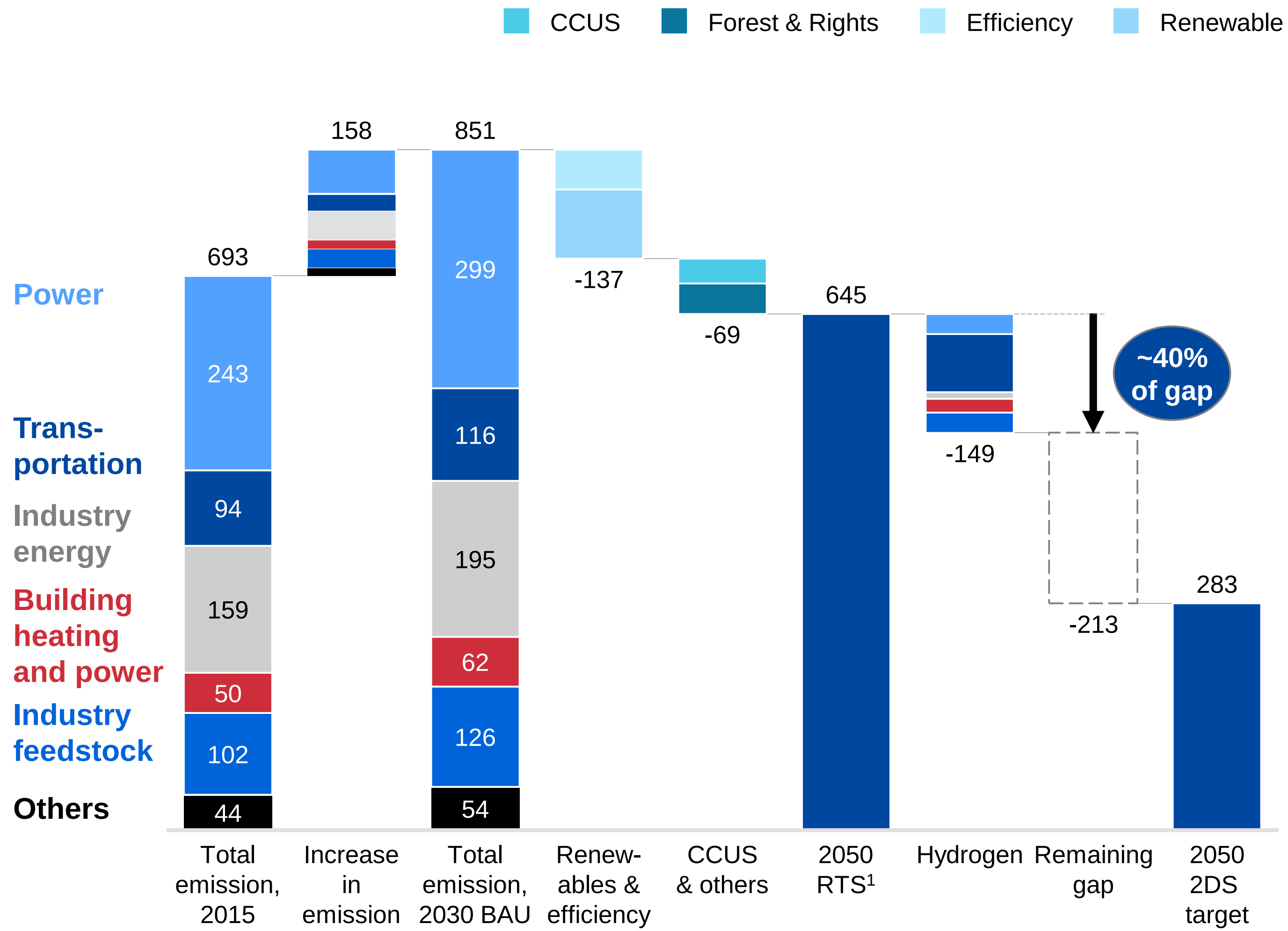
Energy mix

- Hydrogen can increase energy security by **diversifying its energy mix**, reducing the country's dependence on liquified natural gas (LNG) and oil imports
- **Importing low-carbon hydrogen** accelerates the switch to renewable and low-carbon energy carriers in Korea

SOURCE: Hydrogen Korea Study team

Hydrogen energy ecosystem can close gap to 2050 CO_2 emission reduction target by 40%

CO_2e emissions by segment, in million tons



- Hydrogen can close **40% of the gap to achieve the two degree target,** avoiding ~150 Mt CO_2e
- This is roughly equivalent to **double the planned contribution** from renewable energy
- Biggest contributor to reduction is the **transport segment**

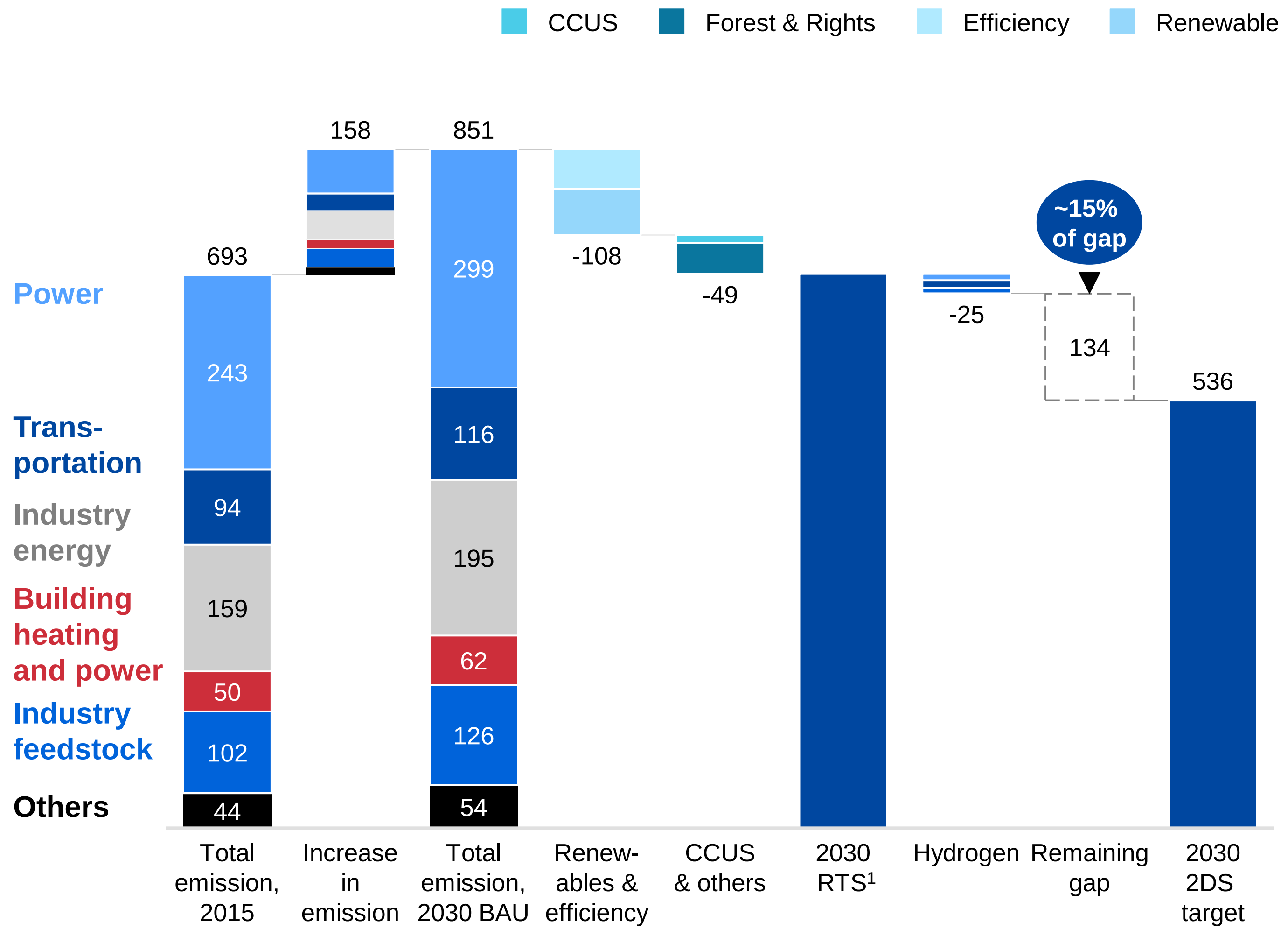
Total final energy demand assumed to stay constant between 2030 and 2050

1 Reference technology scenario

SOURCE: Ministry of Environment; MOTIE; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Hydrogen energy ecosystem can close gap to CO_2 emission reduction target by 15% already in 2030

CO_2e avoidance potential by segment in 2030, in million tons, hydrogen potential vis-à-vis BAU



- Hydrogen can close **15% of the gap to achieve the two degree target,** avoiding ~25 Mt CO_2e
- This is roughly equivalent to **half of the planned contribution** from renewable energy

1 Reference technology scenario

SOURCE: Ministry of Environment; MOTIE; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Macro-economic impact and social benefits of the hydrogen vision for Korea

2050 hydrogen vision, in approximate annual figures

30 %

Reduction of local emissions (NO_x, PM10)

20 %

Of final energy demand fueled with hydrogen[1]

600 K

jobs in hydrogen production, distribution and end-use applications

KRW 70 trn

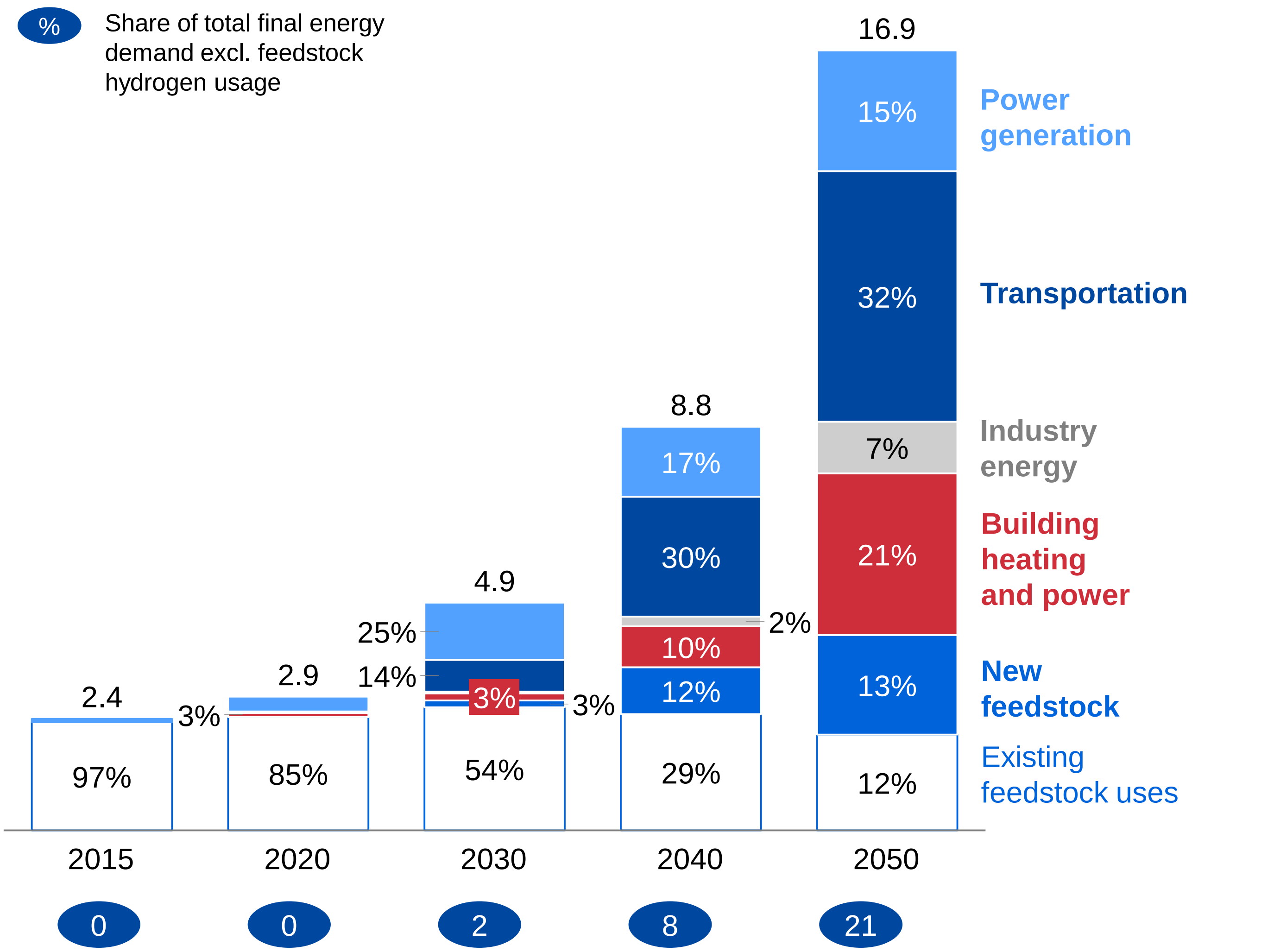
Sales (hydrogen and equipment)

1 Excluding hydrogen usage in feedstock

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Hydrogen demand is expected to reach 17 million tons in Korea in 2050

Hydrogen vision for Korea, 2015-2050, in Mt of hydrogen demand



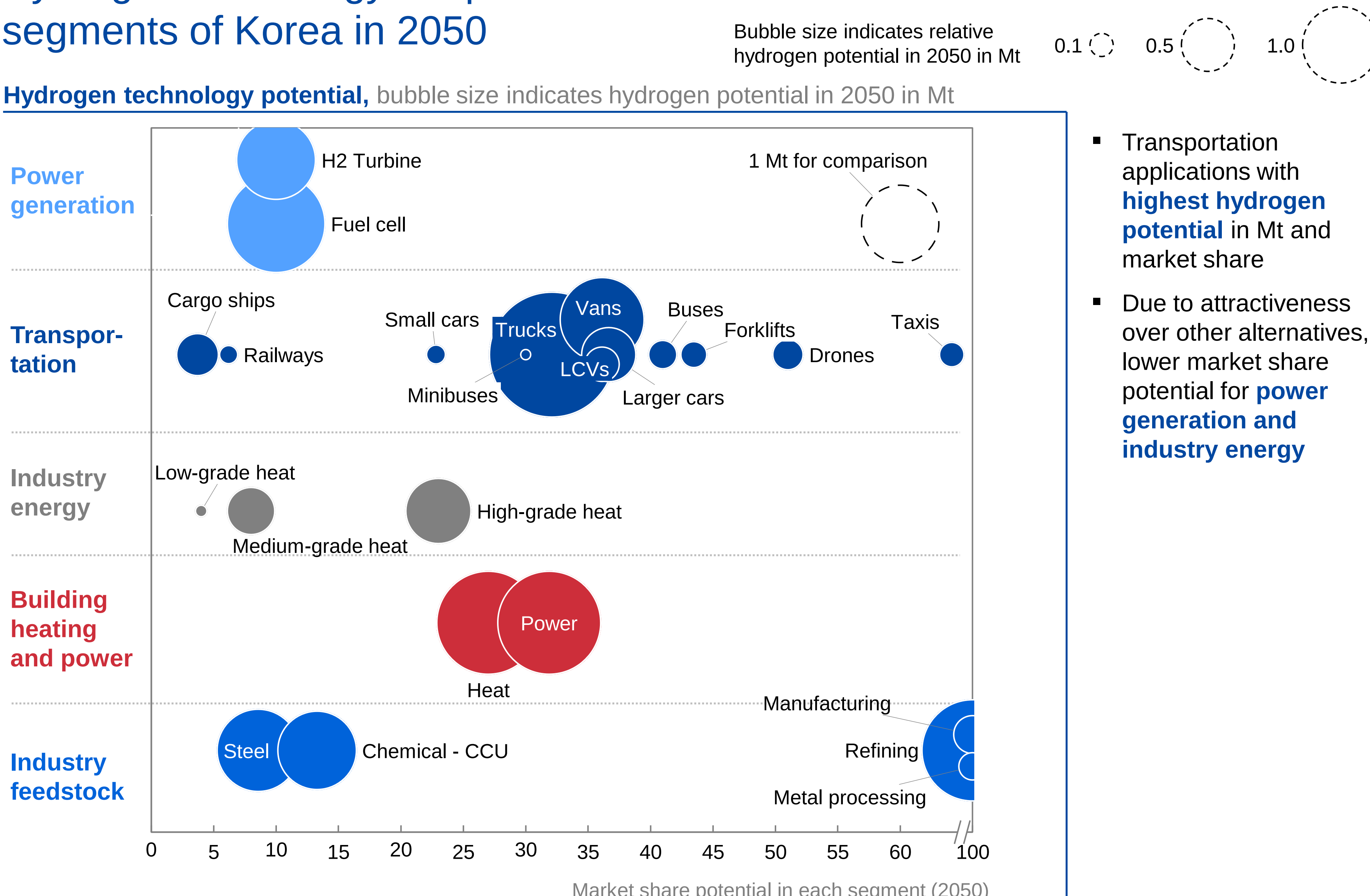
- Power generation assumes both fuel cell and H_2 turbine, **the latter ramping up post-2030**
- **Transportation accounts for the largest share** due to high uptake rates as Korea is considered a leading country
- Building heating and power is expected to grow **driven by the adoption of micro-CHP** in new built buildings
- High share of feedstock (~25% of total H2 demand) due to high adoption rates and large baseline in new applications (e.g., steel)

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Hydrogen technology adoption rates and demand vision across different segments of Korea in 2050

Bubble size indicates relative hydrogen potential in 2050 in Mt

Hydrogen technology potential, bubble size indicates hydrogen potential in 2050 in Mt



- Transportation applications with **highest hydrogen potential** in Mt and market share
- Due to attractiveness over other alternatives, lower market share potential for **power generation and industry energy**

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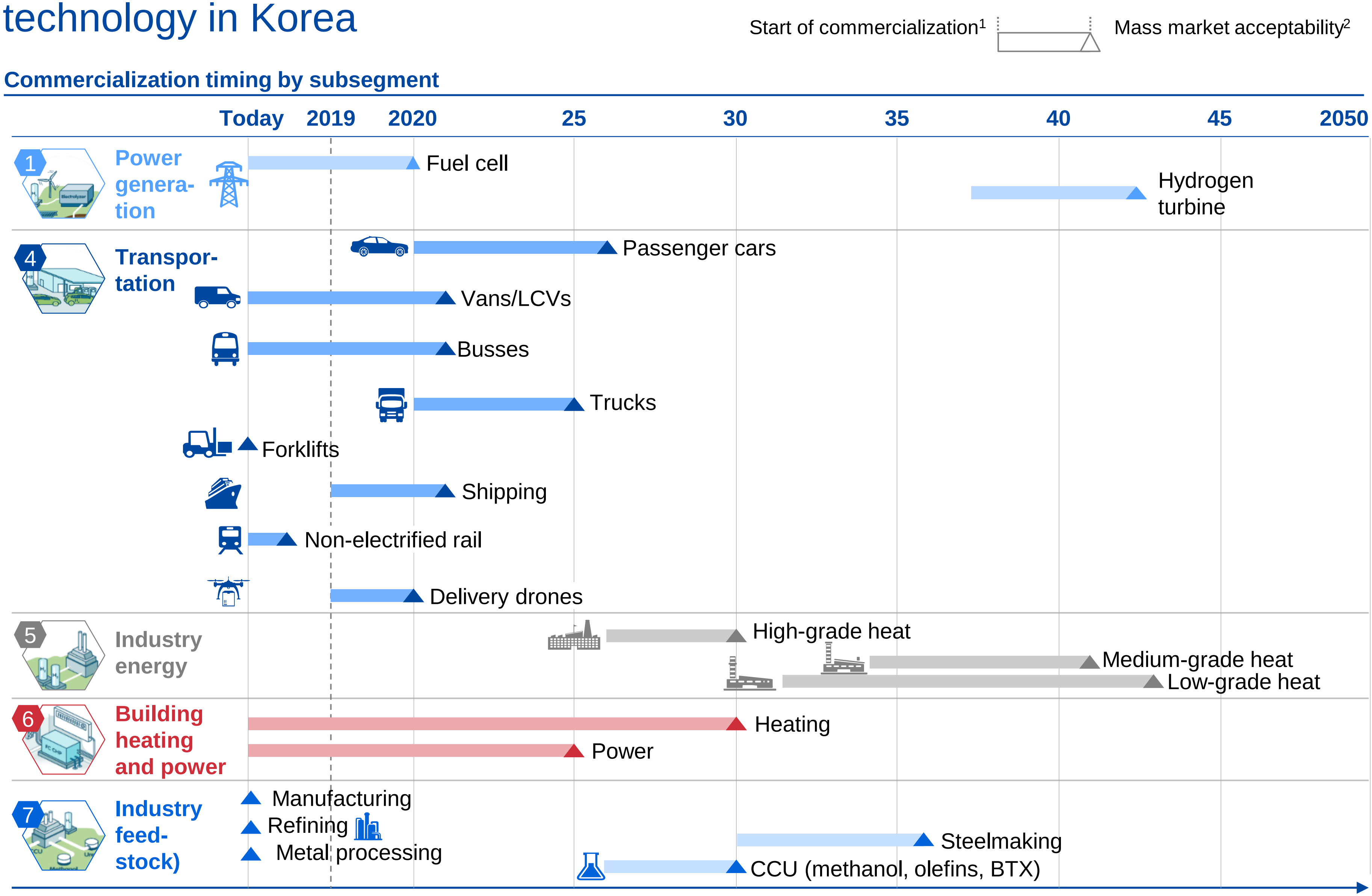
SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Start of commercialization and mass market acceptance of hydrogen technology in Korea

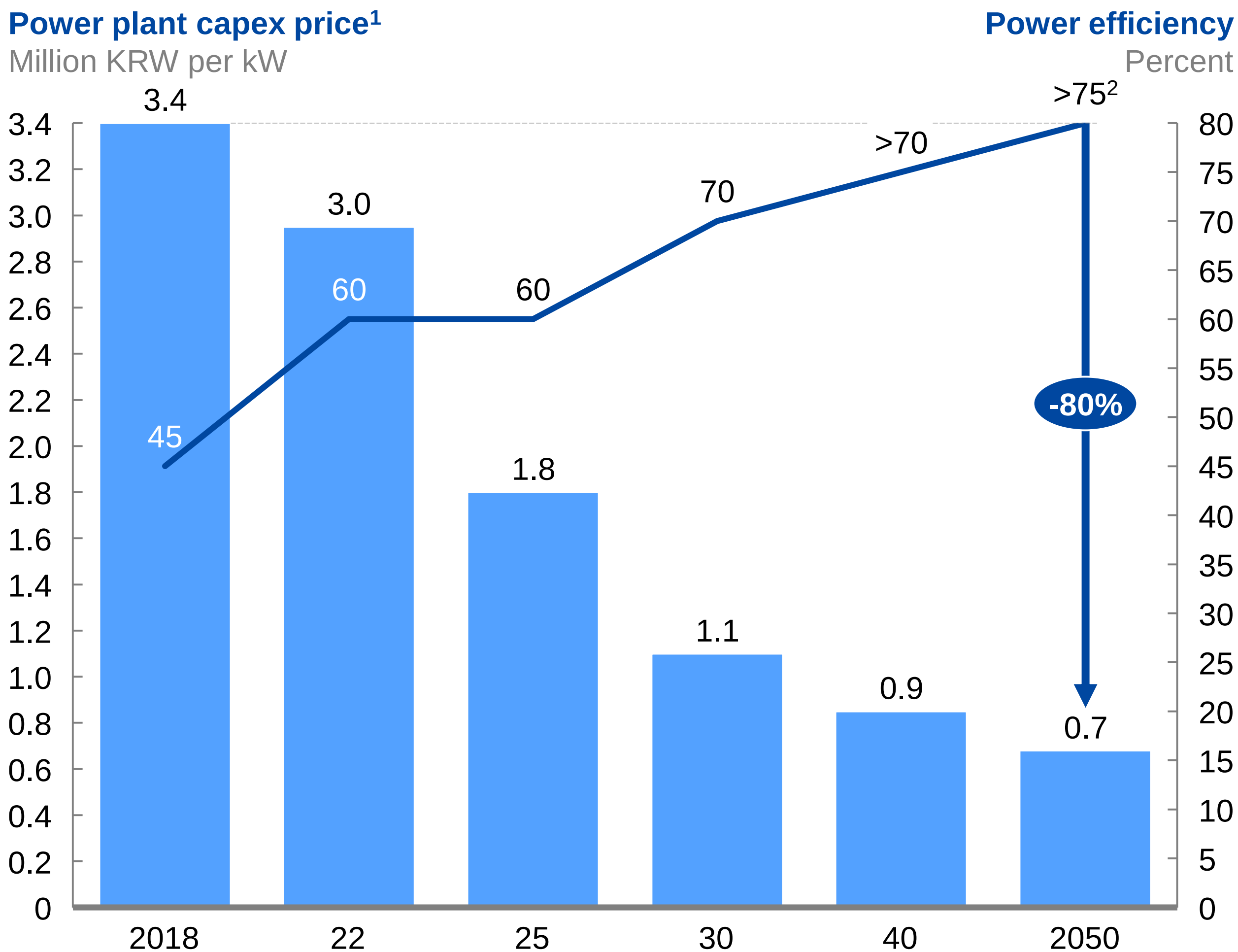


1 Defined as adoption rate ≥0.1% (market share of sales adoption rate for transport) ; 2 Defined as adoption rate ≥1% within the segment (market share of sales adoption rate for transport)

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Adoption of fuel cell power generation can increase with rapidly improving cost efficiency

Historical and estimated metrics on fuel cell power plant in Korea



Key observations

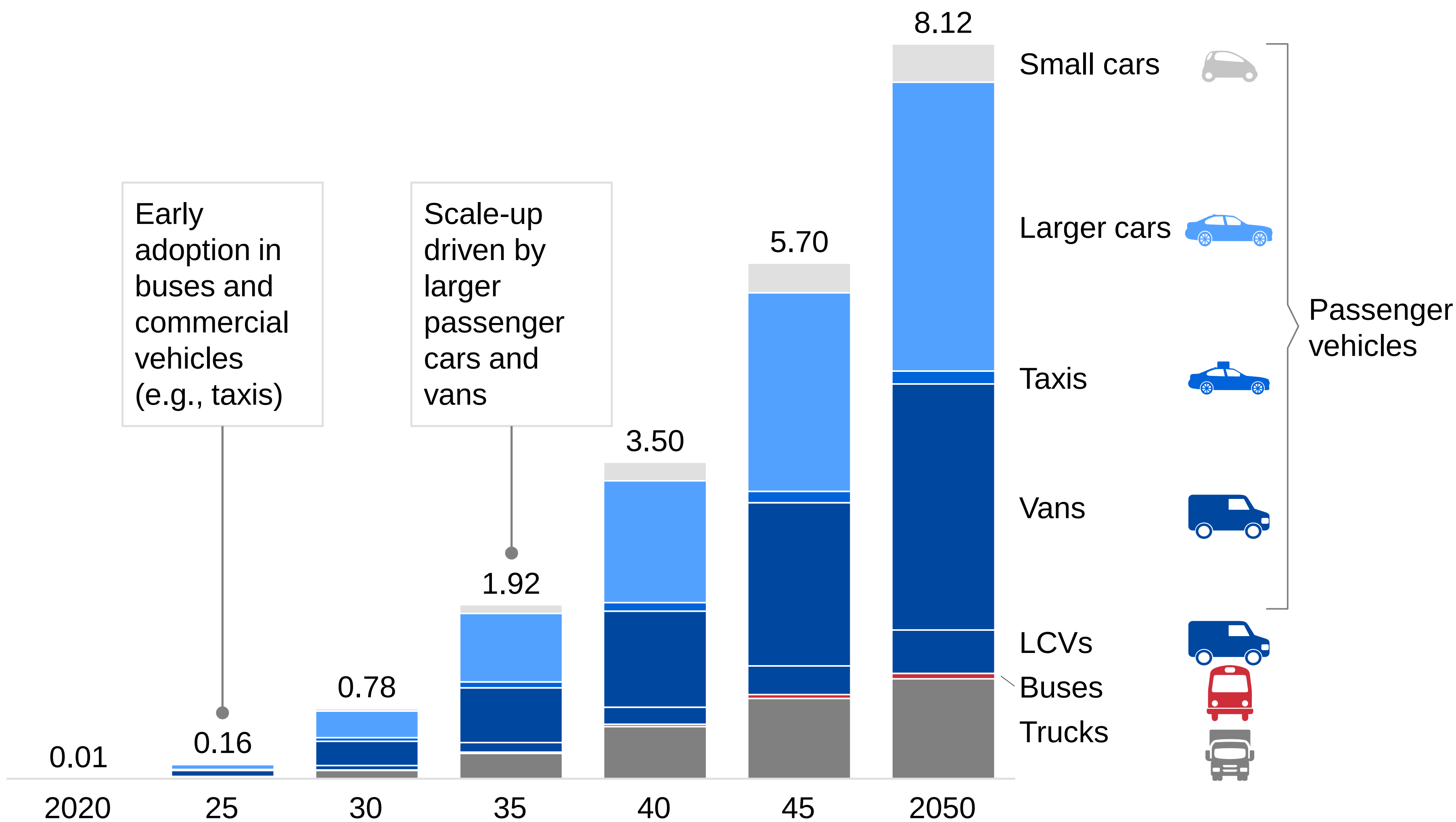
- Fuel cell power generation is **already commercialized** but will be followed by **further improvements** with continuous efficiency growth and capex cost reduction
- It also offers unique value propositions beyond improving economics:
  - **Reduce T&D cost** by enabling on-site distributed generation
  - **Reduce carbon emission and other air pollutants** (assuming green hydrogen use)

1 Cost of Fuel cell power plant construction (fuel cell system costs the majority of the power plant cost) | 2 ~80% of maximum power efficiency is expected which could significantly narrow the gap in electricity generation cost with other power generation methods currently available

SOURCE: Industry data; Literature search; Expert interviews; Hydrogen Korea Study team

Early adoption in buses and commercial vehicles followed by large cars and vans can drive deployment to ~2 Mio. FCEVs by 2030, 8 Mio. by 2050

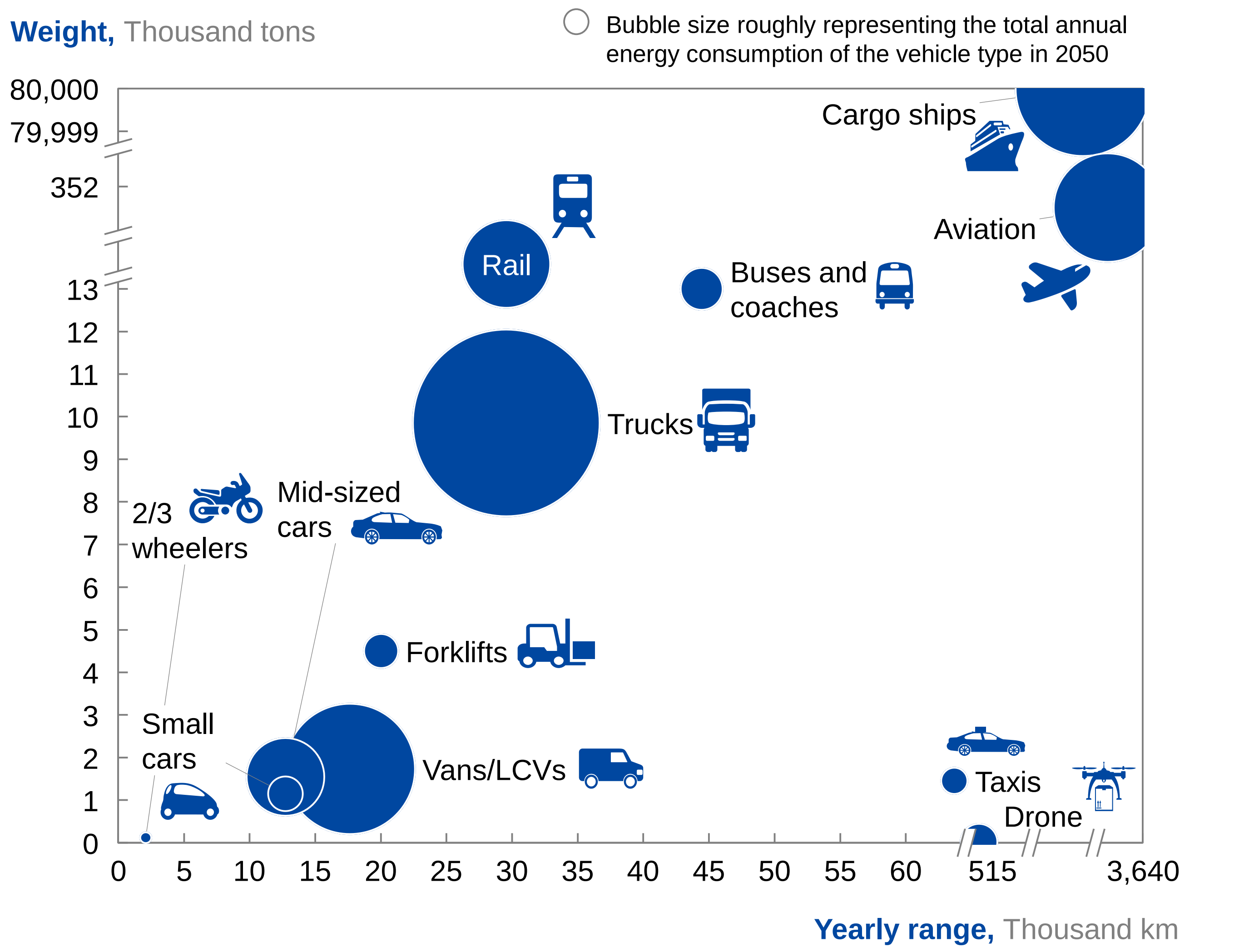
FCEV adoption for transportation, million of vehicle units



SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Hydrogen fuel cell can be the most efficient decarbonization lever for long-distance, heavy payload, high utilization transport segments

Comparison of annual vehicle energy consumption, by transportation type



- Among on-road segments, **trucks, buses and vans/LCVs exhibit high potentials** of FC powertrain adoption
- Among off-road segment, **cargo ships have the highest potential**

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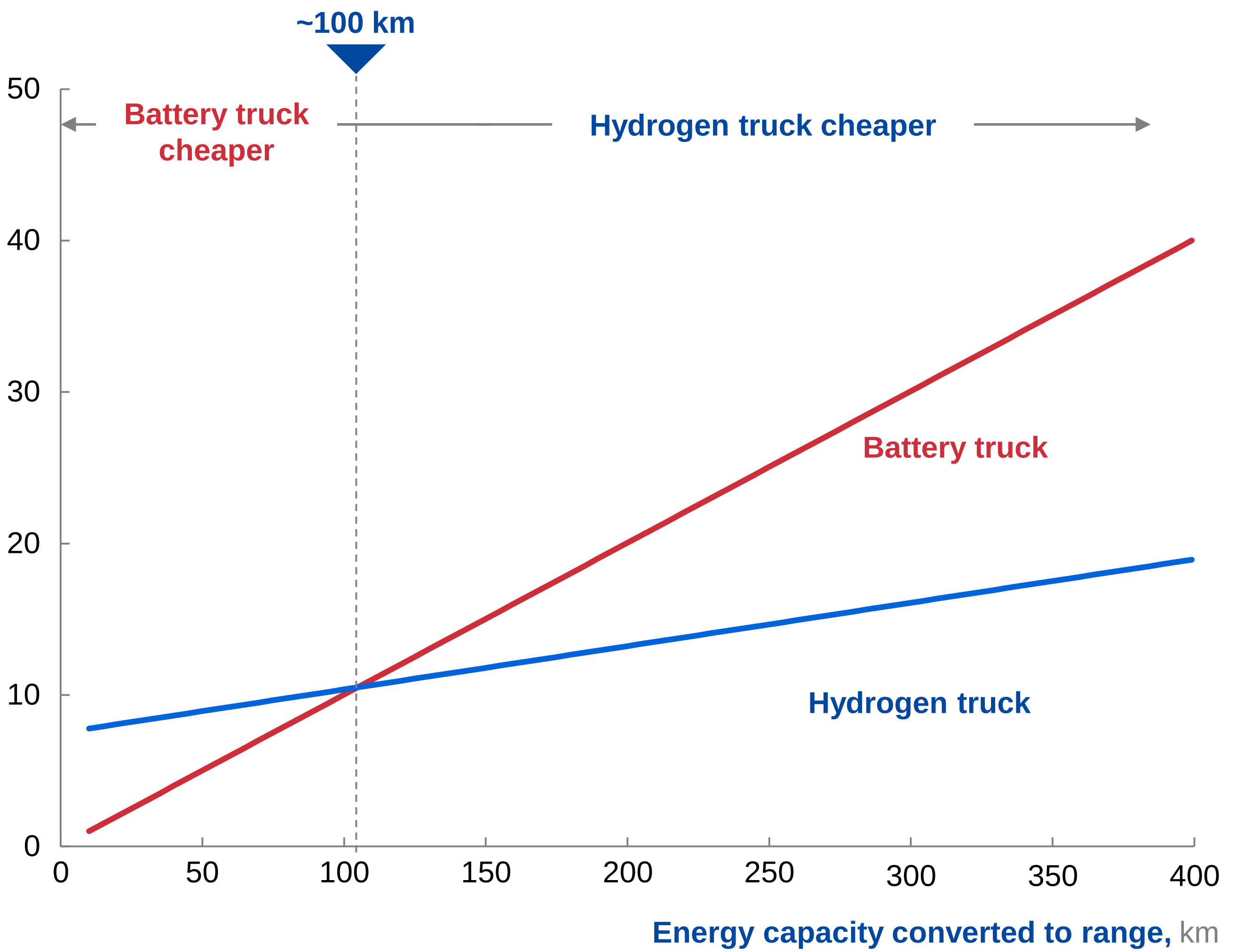
SOURCE: Literature search; Expert interviews; Hydrogen Korea Study team

System costs for hydrogen trucks are growing by a less margin than for battery trucks with increasing autonomy range

System costs of battery vs. hydrogen, in thousand USD



Fuel cell trucks have lower powertrain system costs than battery electric trucks already from autonomy ranges above ~100 km

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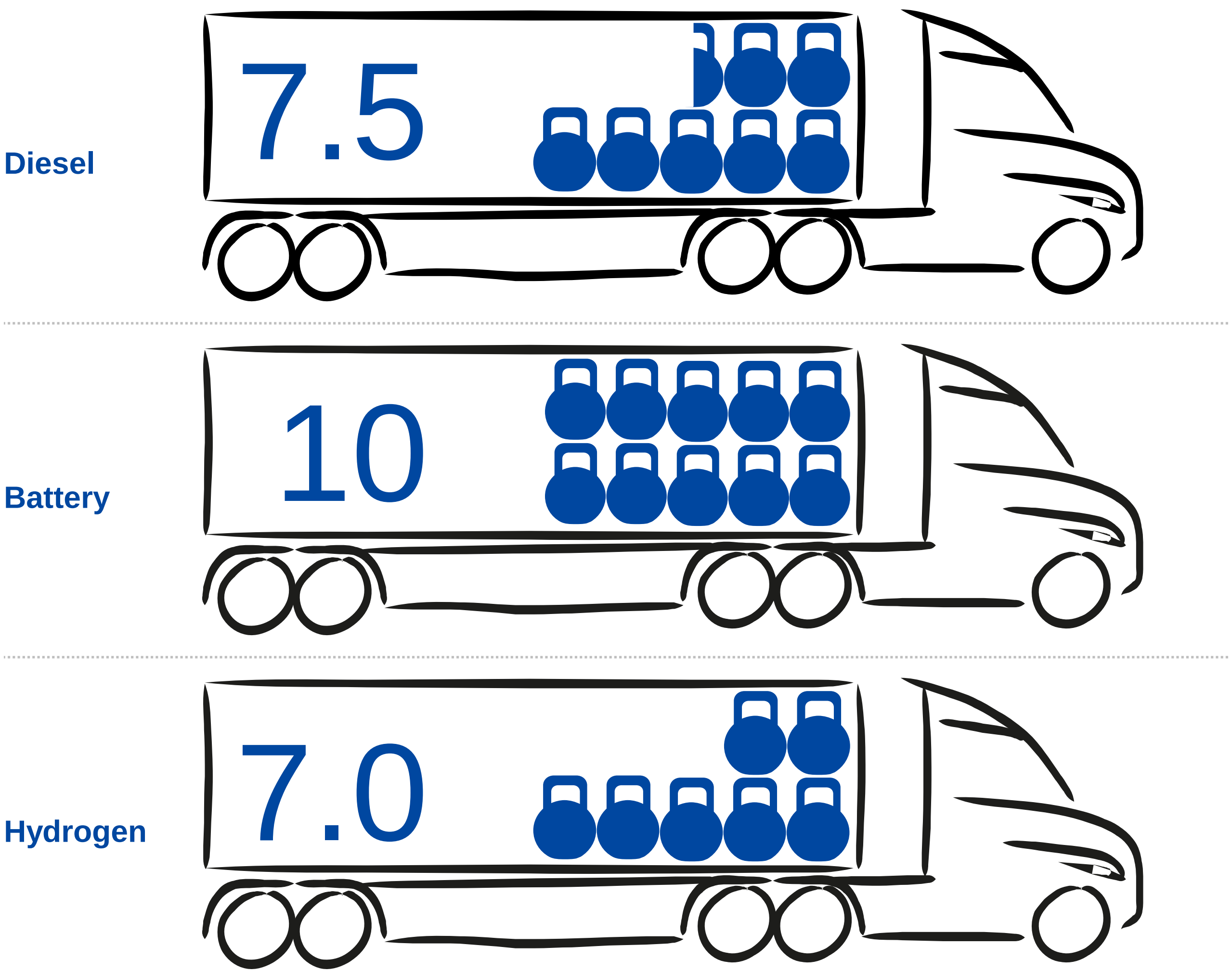
SOURCE: DOE; Tesla Semi; Nikola One; McKinsey; Hydrogen Korea Study team

FCEV powertrain for trucks weights 3 tons less than an equivalent BEV powertrain and is on par with diesel powertrains

Powertrain weight comparison, in tons for a 40 tons semi truck



FCEV powertrain system weight is **competitive compared to diesel powertrain weight and can even be superior**

Assumptions:

Component weight for diesel powertrain, in kg: ICE system 1,000; fuel system 1,050; transmission 200; exhaust 200

Component weight for BEV powertrain, in kg:
Transmission 50; E-motors 100; power electric 300; battery 4500

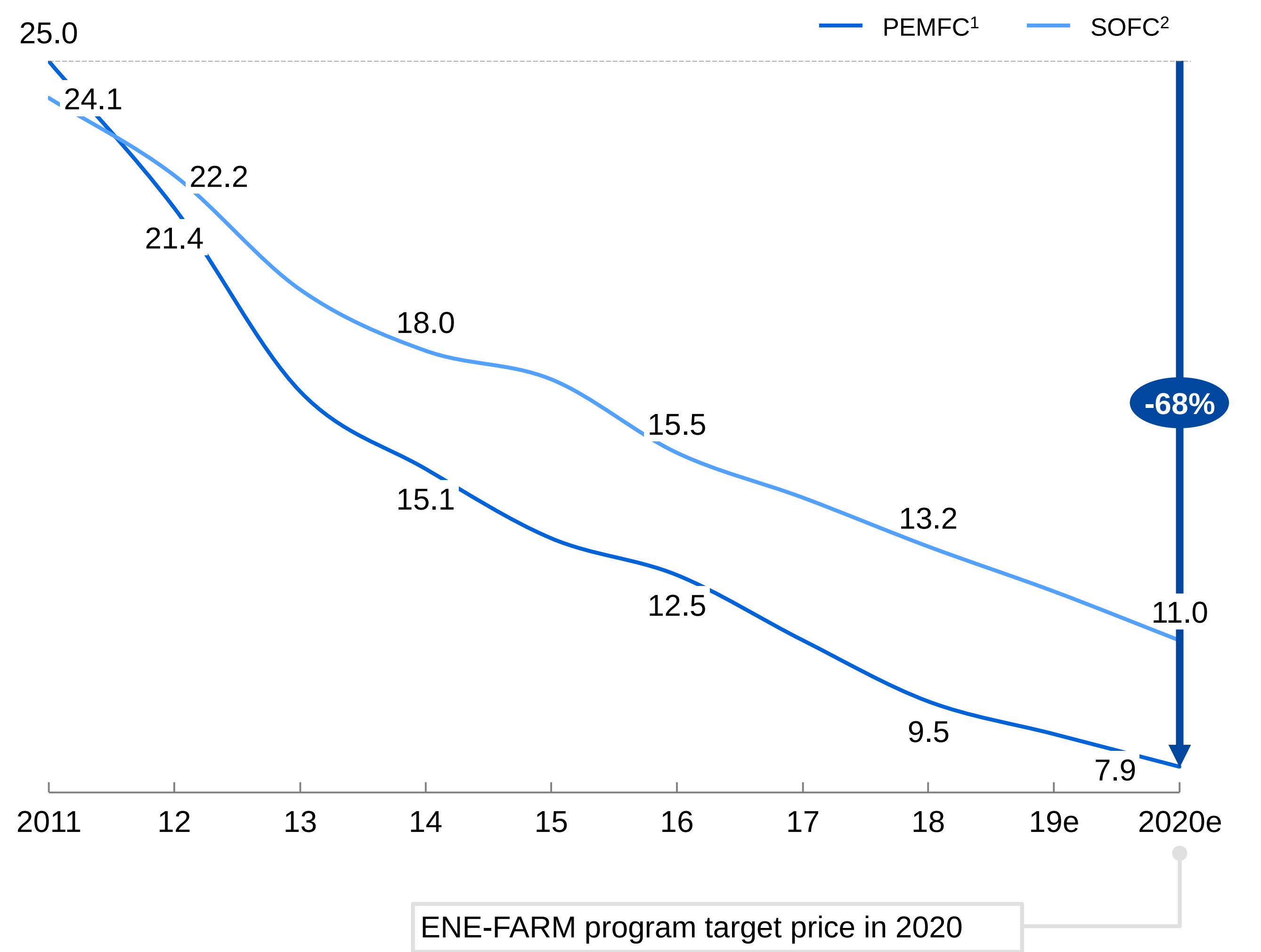
Component weight for FCEV powertrain, in kg:
Transmission 50; E-motors 100; power electric 300; battery 600; fuel cell 150; H_2 tank 800

Reference truck: 40 t semi truck with 18 t GVW truck tractor 4x2; FCEV truck with 120 kWh battery;
BEV truck with 900kWh battery;
FCEV and BEV battery with 5kg/kWh;
FCEV and BEV with two electric motors;
FCEV truck with 300 kW fuel cell weighing 150kg (2 kW/ kg)

SOURCE: DOE; Tesla Semi; Nikola One; McKinsey; Hydrogen Korea Study team

Building mCHPs are expected to become competitive against traditional technologies with rapid improvements in cost and efficiency

Historical trends in Japanese mCHP cost, Million KRW per 0.7 kW unit



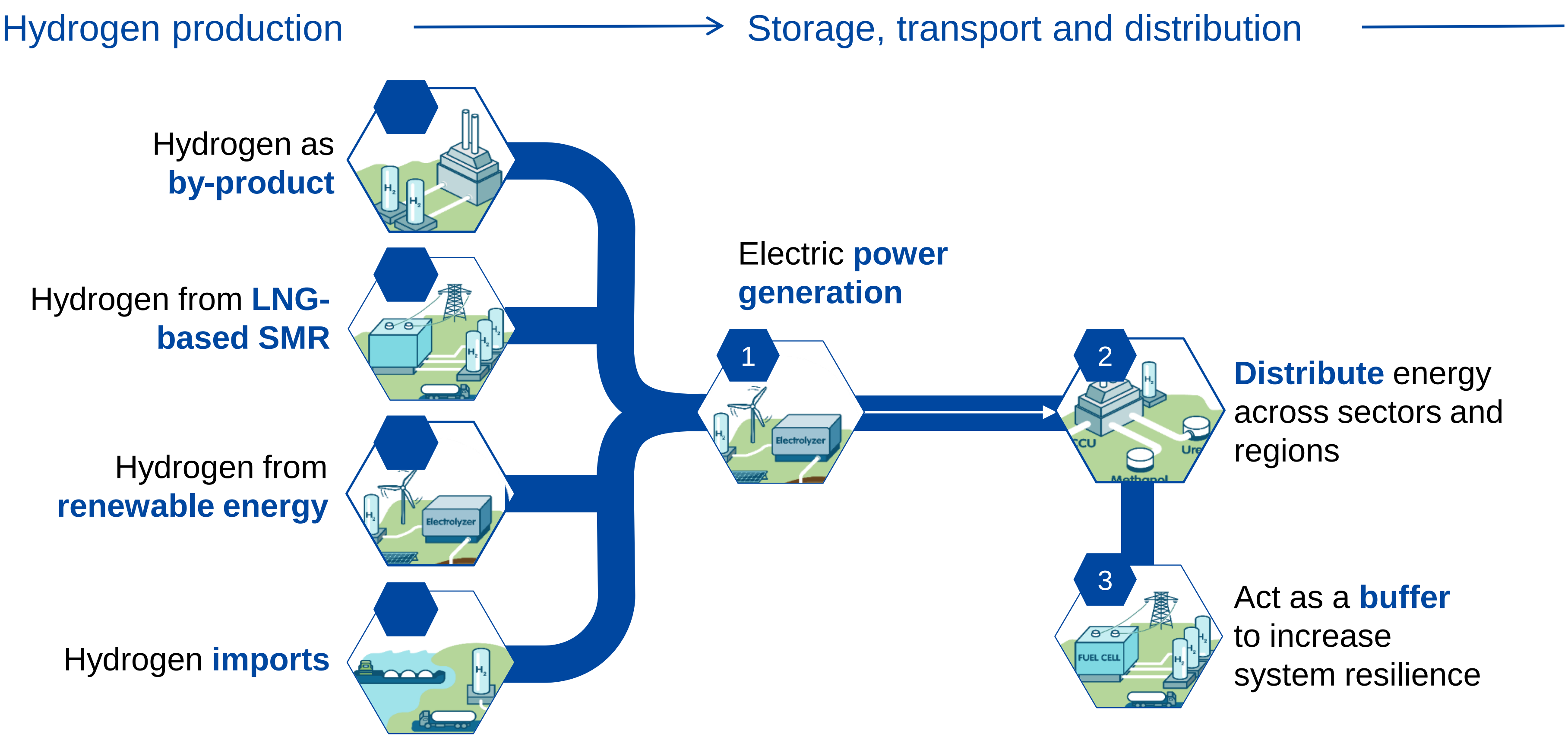
- Equipment cost of mCHP has been **dropping significantly** in last 5 years
- Heat and power **efficiency has increased** from 89% in 2009 to 95% in 2016
- Potential power price increase in Korea due to nuclear phase-out and increasing renewable **could make hydrogen mCHPs competitive** in the future

1 Proton-Exchange Membrane Fuel Cell

2 Solid Oxide Fuel Cell

SOURCE: ENE Farm Partners, literature search; Expert interviews; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Hydrogen makes import of renewable energy possible

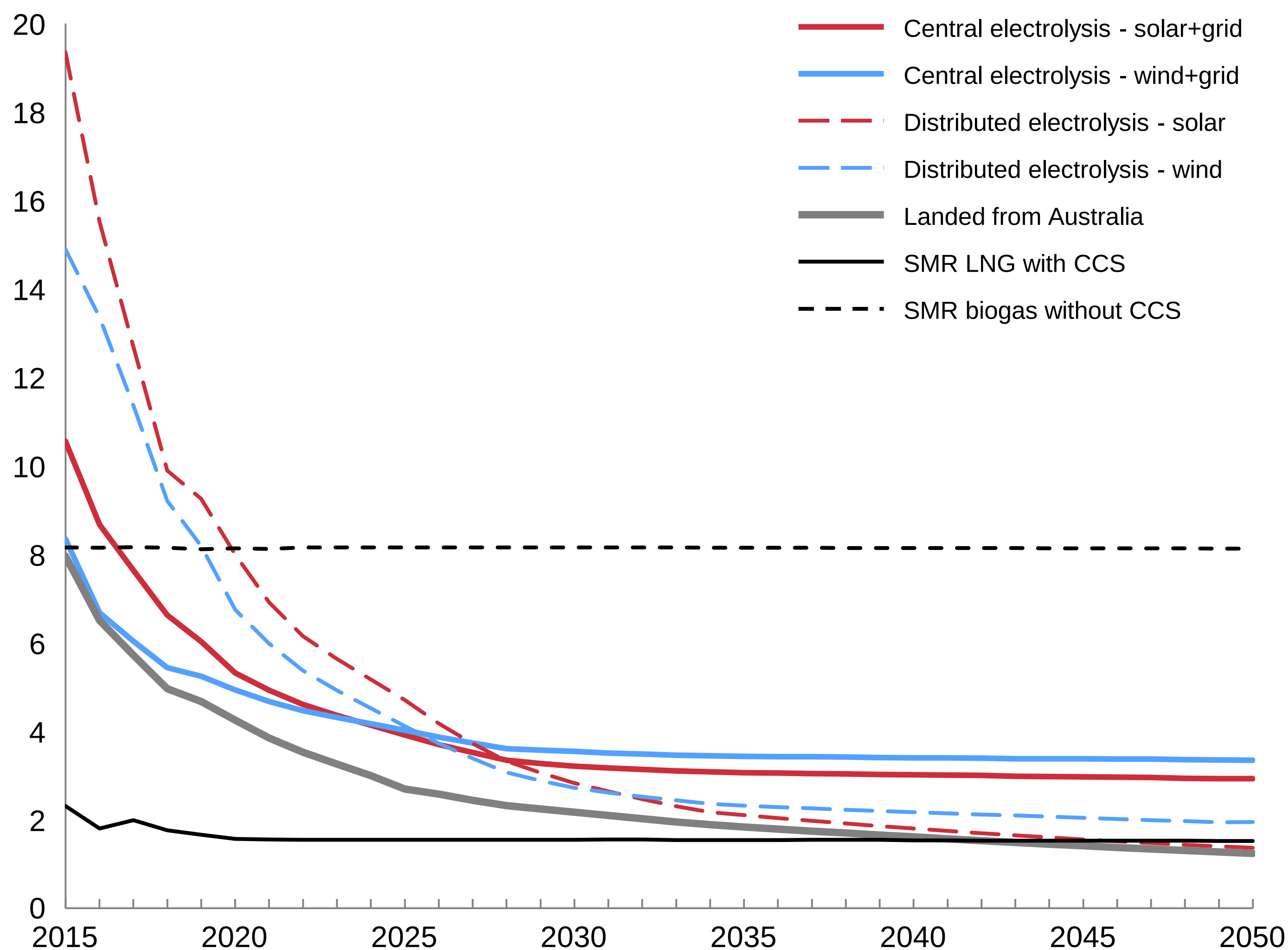


- In near future hydrogen production relies on hydrogen as by-product and hydrogen from LNG-based SMR
- Hydrogen from wind and solar power is required to decarbonize the hydrogen ecosystem
- Alternative pathway is the import of renewable energy (RE) in the form of hydrogen, as domestic RE is limited

SOURCE: Hydrogen Council; Hydrogen Korea Study team

Electrolysis-based hydrogen production could break even with SMR between 2025 and 2030

Cost of hydrogen production in Korea by method, 2015 US dollars per kg H2

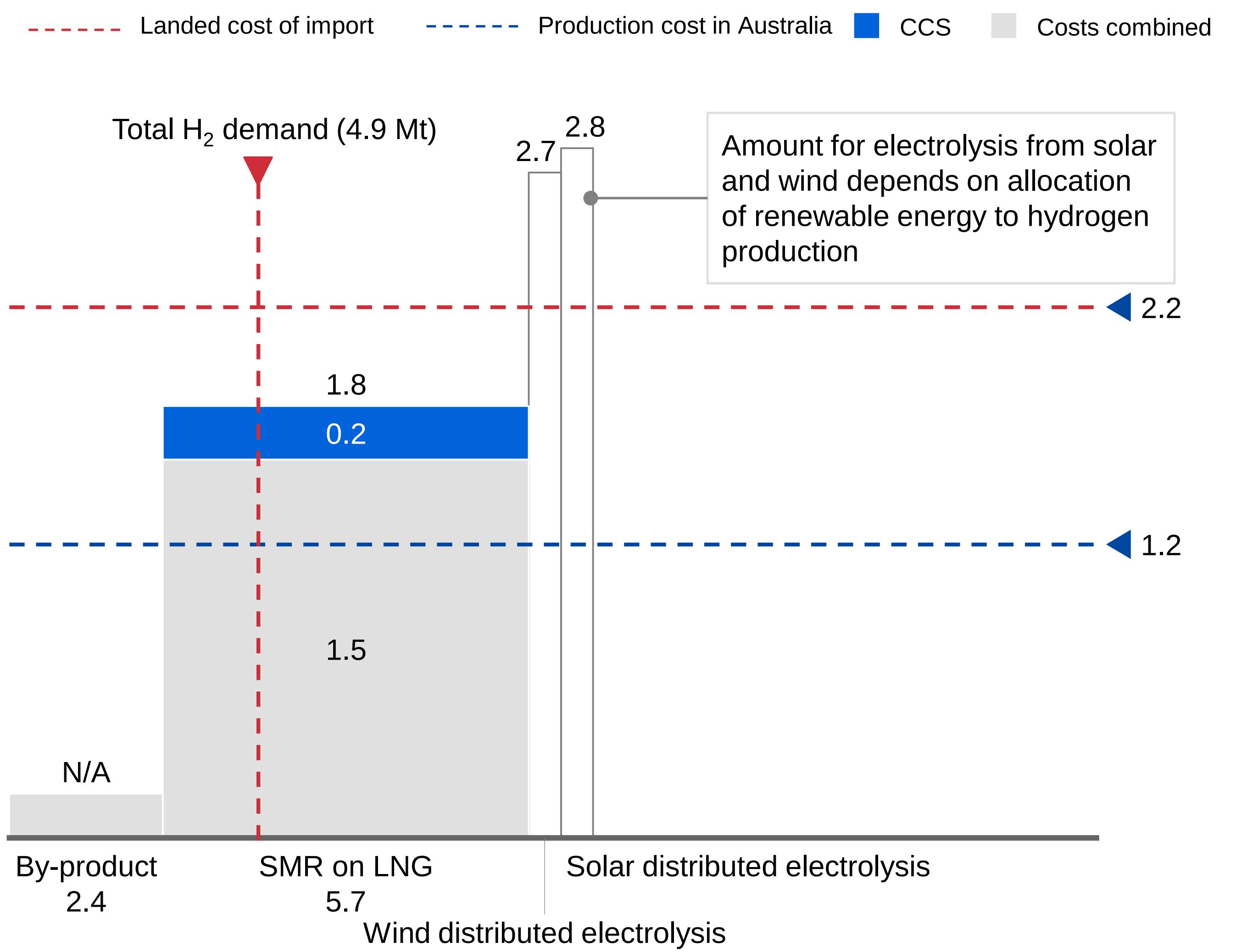


- Hydrogen from **SMR is more expensive than hydrogen from electrolysis** on the long run
- Central electrolysis costs at 90% utilization rate, using renewable energy as available and complemented with grid power
- Distributed electrolysis costs at utilization rate according to renewable energy availability
- All calculations exclude distribution costs from hydrogen production site to end consumer

SOURCE: McKinsey Energy Insights' Global Energy Perspective, Enerdata

In 2030 domestic hydrogen production is expected to be the most economic option to meet hydrogen demand

Hydrogen production costs over quantity in 2030, in Mt (x-axis) and USD per kg H_2 (y-axis)



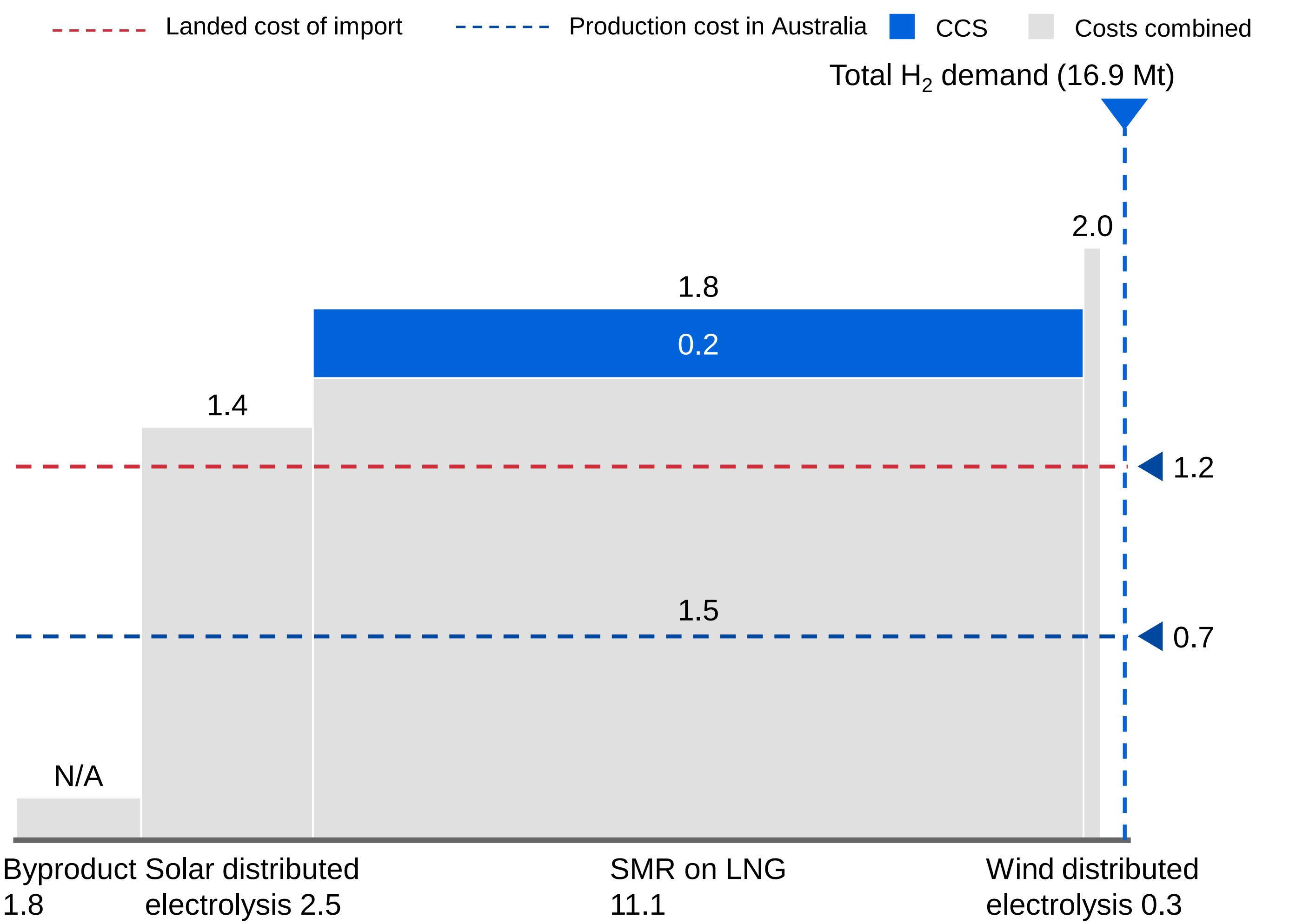
- Korean hydrogen **demand cannot be met fully by 2030 with by-product** in Korea
- There is **need for domestic SMR with carbon capture** and sequestration to meet total hydrogen demand
- **Electrolysis on renewable energy still more expensive** and will compete with direct feed-in of renewables into the grid

1 Distributed Electrolysis would compete with central electrolysis for the same energy source but costs more

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

In the long-term the import of renewable hydrogen could be the most economic source

Hydrogen production costs[1] over quantity in 2050, in Mt (x-axis) and USD per kg H_2 (y-axis)



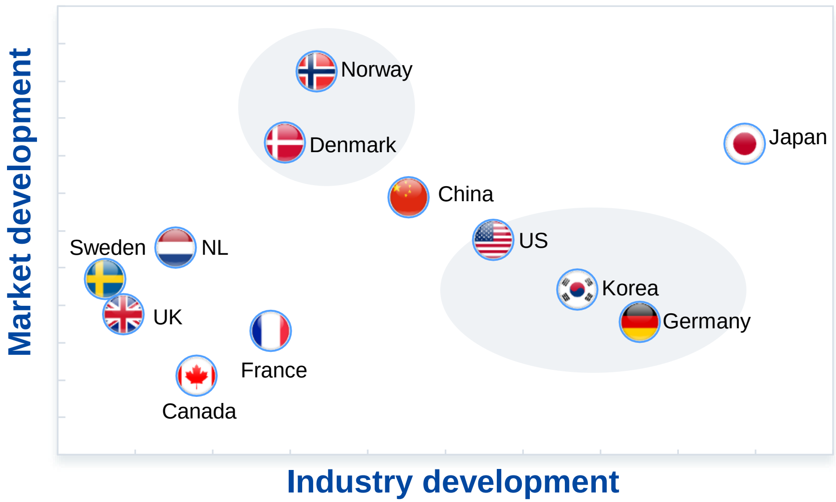
- Korean hydrogen **demand by 2050 exceeds domestically producible hydrogen**
- Electrolysis[2] on solar power **expected to become cheaper than SMR**
- Landed **cost of import expected to be lower than domestic solar electrolysis**

1 All calculations exclude distribution costs from hydrogen production site to end consumer
2 Distributed electrolysis would compete with central electrolysis for the same energy source; this graph shows distributed electrolysis to depict only electrolysis from renewables and not grid

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

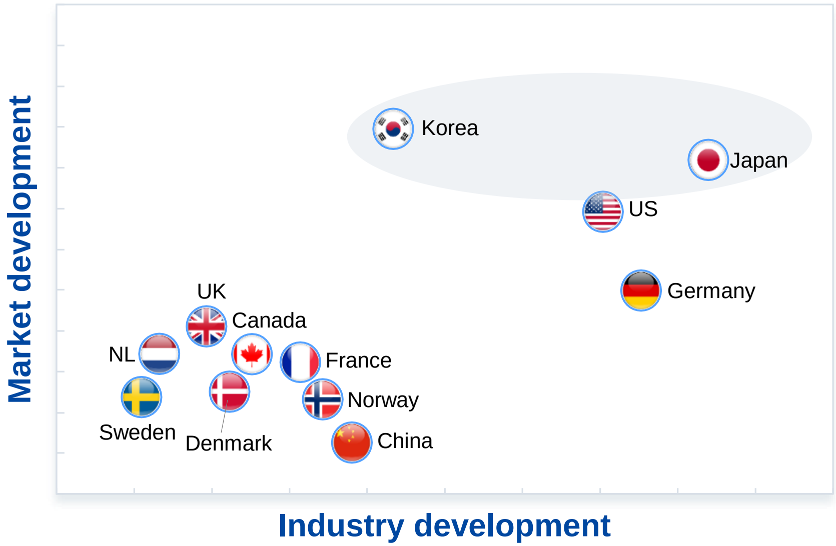
Korea is among most advanced industries in hydrogen mobility applications and has developed its market also for stationary applications

Mobility applications



- Norway and Denmark: most **developed markets**
- Japan: currently **leading supplier of hydrogen mobility**
- **Korea, Germany,** and **US:** in the middle group, with different approaches
- Very **dynamic development** in **China** recently

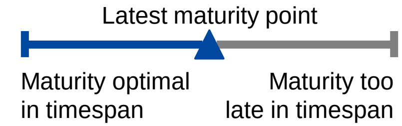
Stationary applications

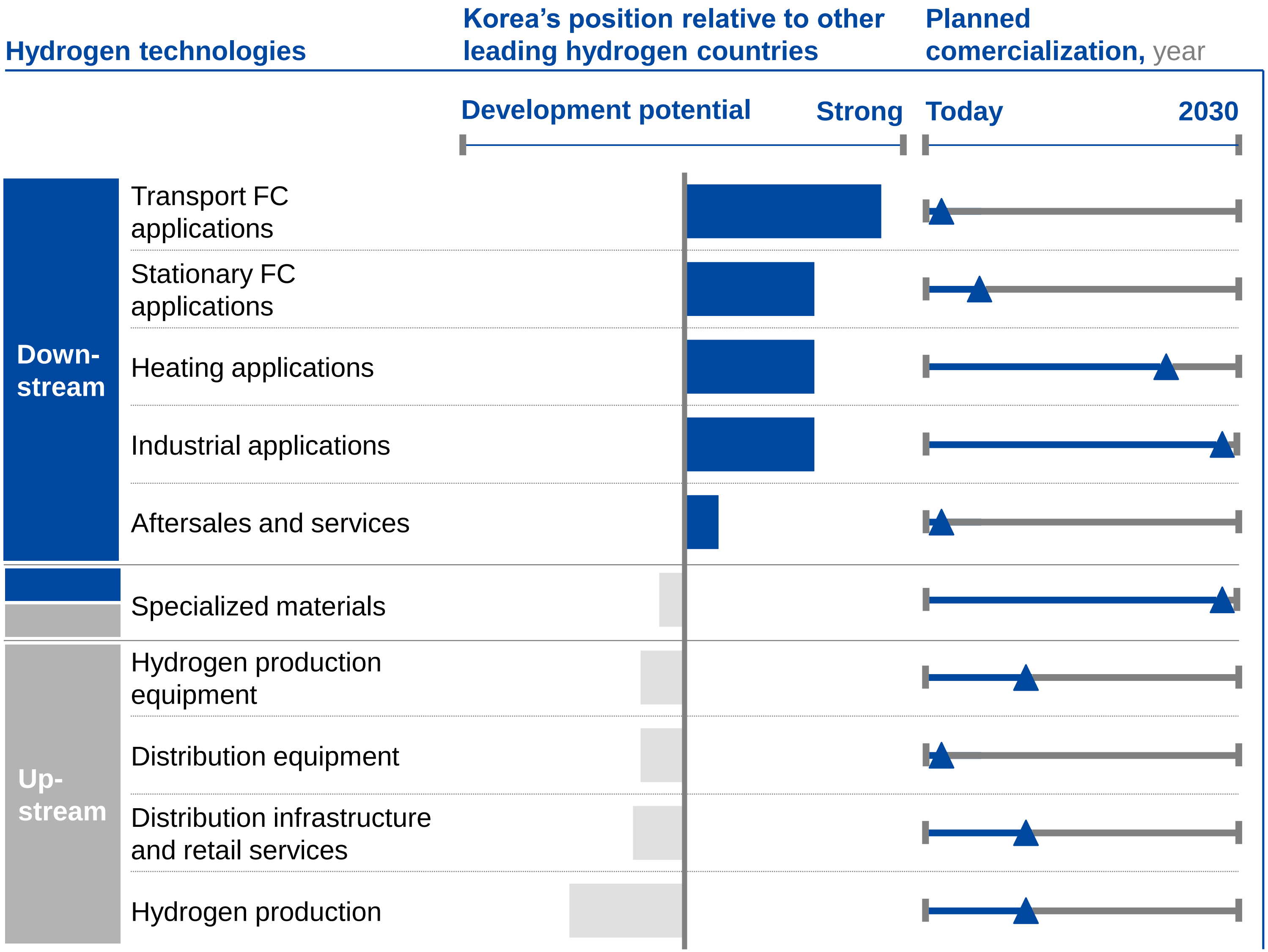


- **Japan** and **Korea** as leading markets for stationary applications: Japan with fuel cell **CHPs** in >250,000 households, Korea with uptake in larger applications
- **US** technologically strong in fuel cell **components**, with focus on **larger applications** for commercial uses
- Strong development for **residential uses** in **Germany**, but market development lags behind Japan and Korea

SOURCE: Index of 38 indicators around current uptake of hydrogen applications, market potential, industry strength, infrastructure (current and planned) and regulatory environment

Korea is strong in downstream technologies yet needs to further develop its industry capabilities in hydrogen upstream





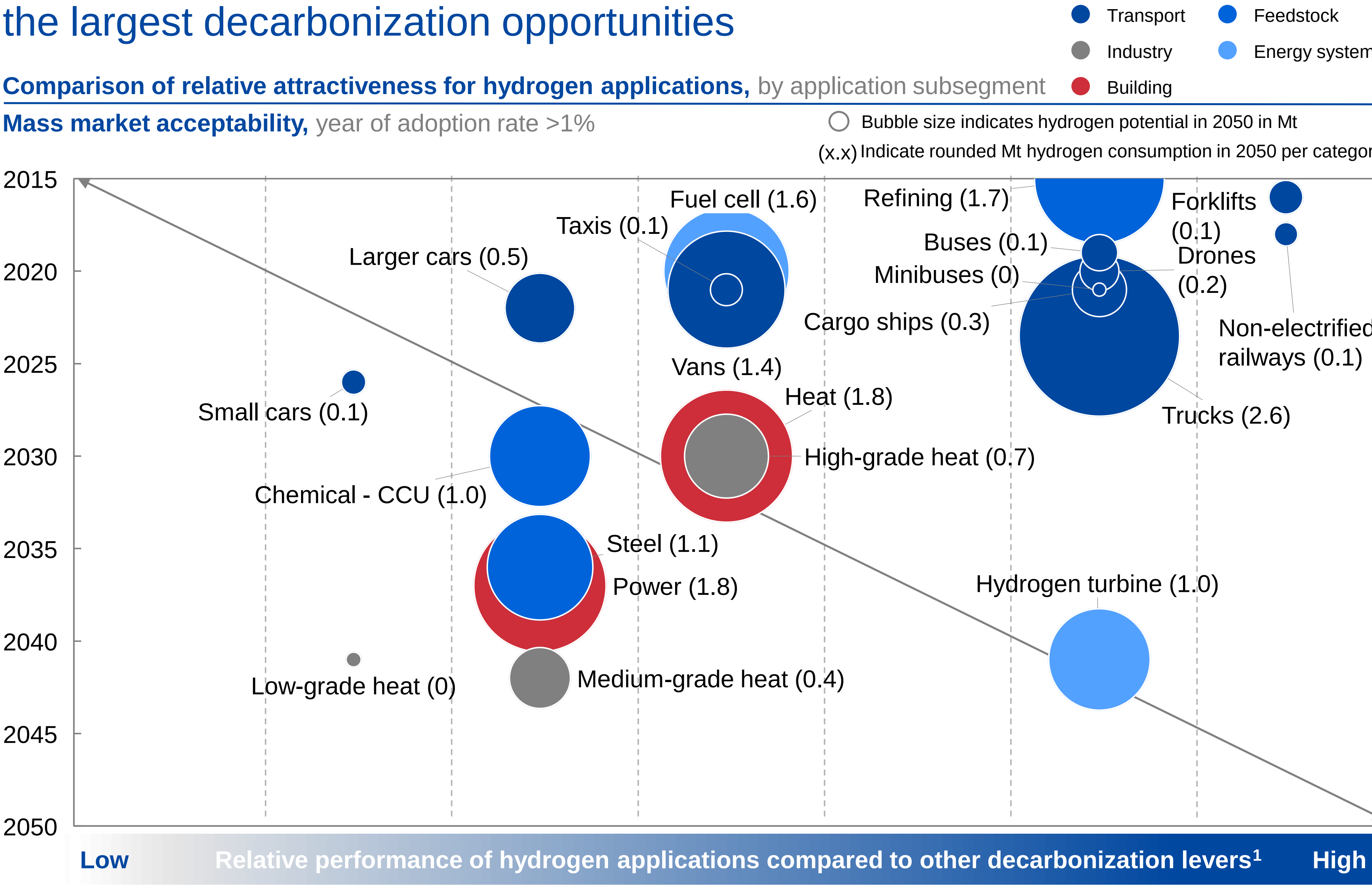
- Korea's upstream capabilities **must be developed now to reach technical maturity by 2022**[1]
- Transport fuel cell applications along with its aftersales and services, and distribution equipment **requires tech. maturity already today**[2]

1 In order to reach 2022 milestones for hydrogen production through electrolysis and FCEV infrastructure | 2 Based on mass market acceptability for hydrogen applications

SOURCE: Coalition members' feedback, 38 indicators from benchmarking, Expert interviews

Transport across different vehicle types, power generation and buildings are the largest decarbonization opportunities

Comparison of relative attractiveness for hydrogen applications, by application subsegment



1 Advantages of hydrogen compared to other decarbonization levers is assessed using three metrics for the given application: Cost performance; Timing of availability; Performance. Cumulative score used for ranking ranges from 0 to 6

SOURCE: Hydrogen Korea Study team

A holistic policy framework and support mechanisms are key to a successful introduction of hydrogen technologies in Korea

Recommendations

1. **Set concrete deployment milestones for key applications**, short-term for 2022, long term for 2030

   Korea should establish short-term deployment milestones through 2022 to spark the initial deployment of prioritized applications, and develop mid-term milestones for 2030.

2. **Support deployment milestones via public-private partnerships**

   Public sector and key players in the industries should jointly commit to a hydrogen partnership, roadmap and milestones.

3. **Develop Korea's transport system into the leading global hydrogen and fuel cell mobility market**

   Given the strong market position of domestic manufacturers and their lead in hydrogen and fuel cell technology, the country could readily become a leading hydrogen mobility market.

4. **Strengthen Korea's hydrogen and fuel cell industry**

   To strengthen Korea's industry across the hydrogen value chain, including upstream technologies, Korea should acquire and/or partner with competitive players and form industry alliances.

5. **Build a long-term pathway for the decarbonization of Korea's gas network**

   Korea should benefit from its experience with an extensive natural gas infrastructure and leading manufacturers of industrial equipment, to develop the hydrogen infrastructure.

6. **Build a sustainable and competitive hydrogen supply industry**

   To make domestic electrolysis and imports of 'green' hydrogen economically viable, Korea should develop electrolysis technology at a utility scale and develop a hydrogen import supply chain.

7. **Adhere to set roadmap goals and policy frameworks and provide stable investment conditions**

Full study report