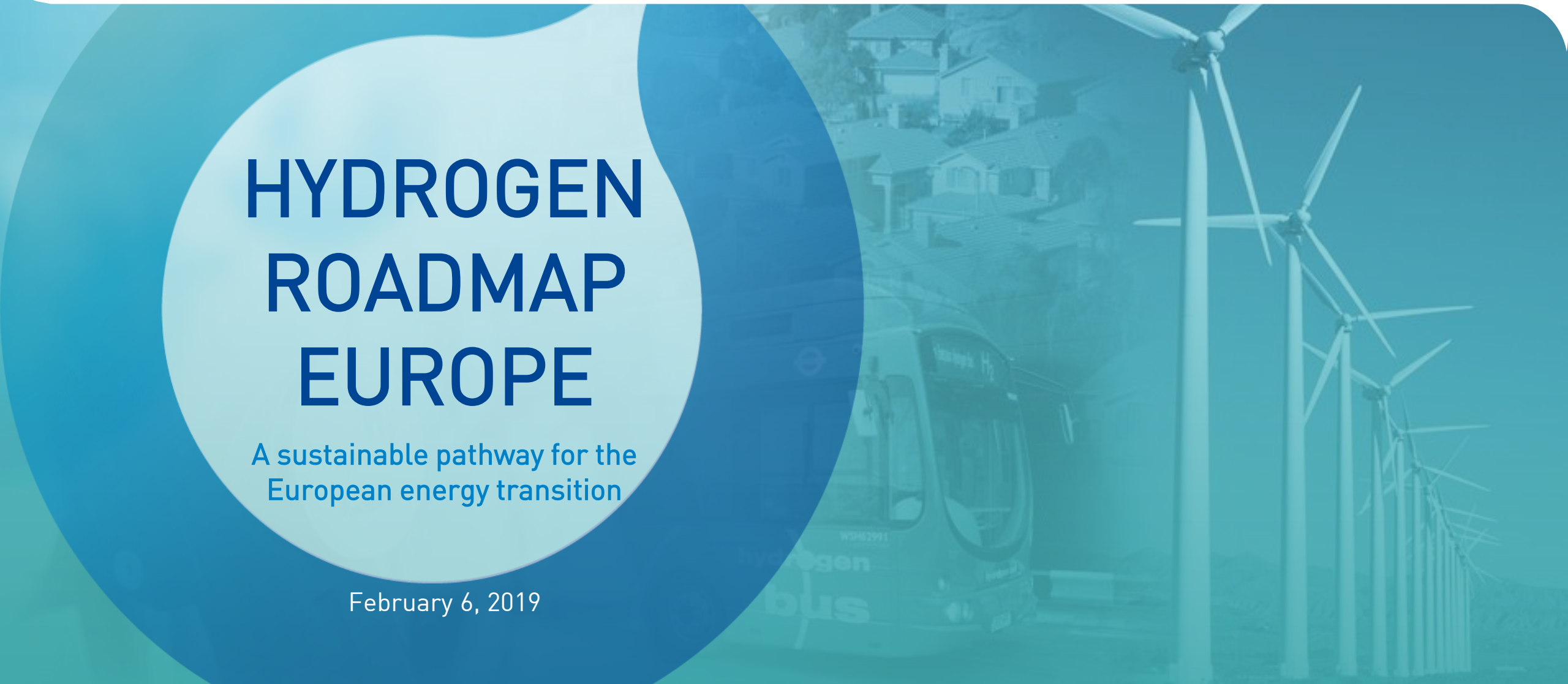
FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

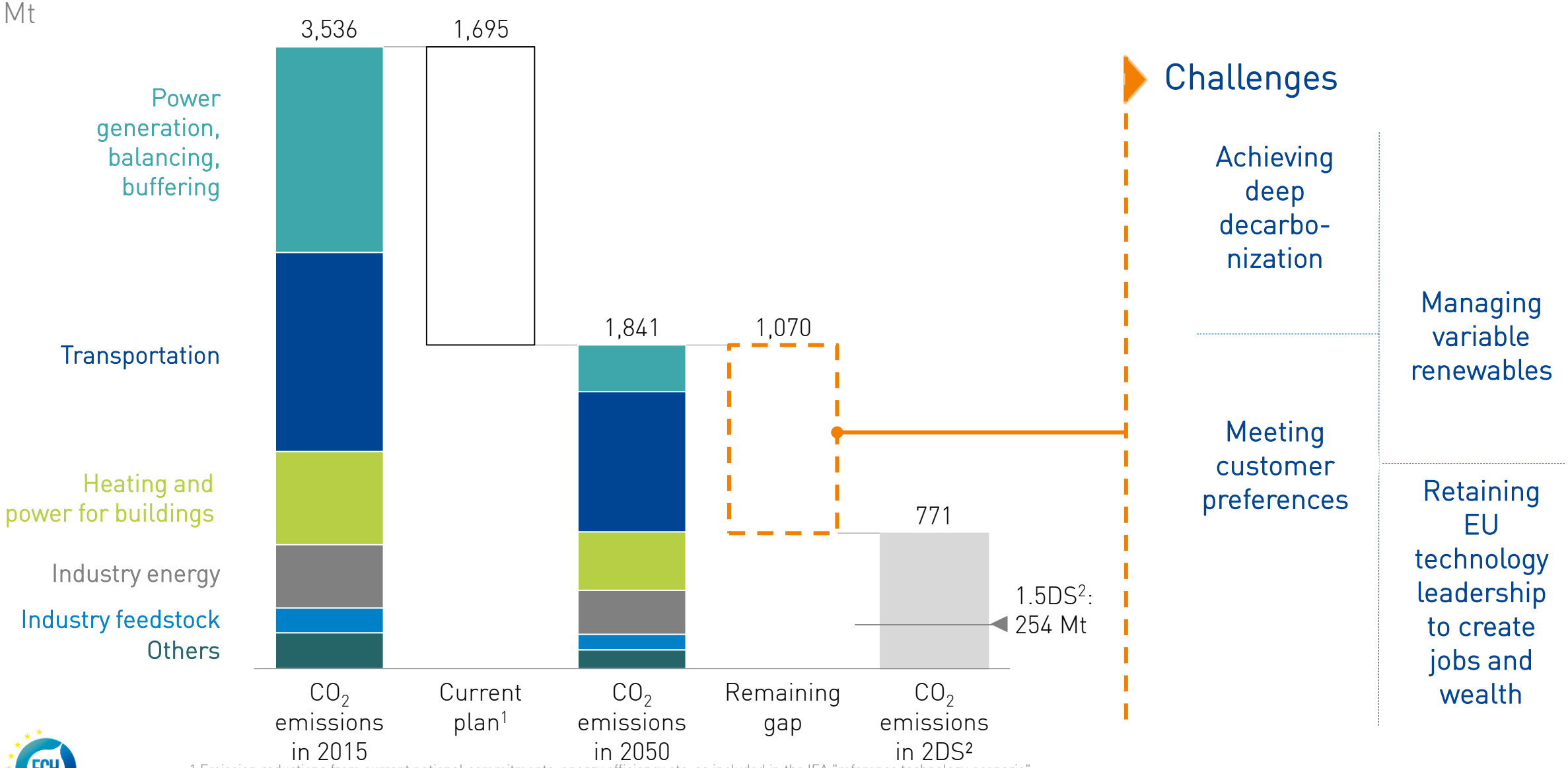
HYDROGEN ROADMAP EUROPE

A sustainable pathway for the European energy transition

February 6, 2019



WHY HYDROGEN: TO REALIZE THE AMBITIOUS TRANSITION OF THE EU'S ENERGY SYSTEM, A NUMBER OF CHALLENGES NEED TO BE RESOLVED



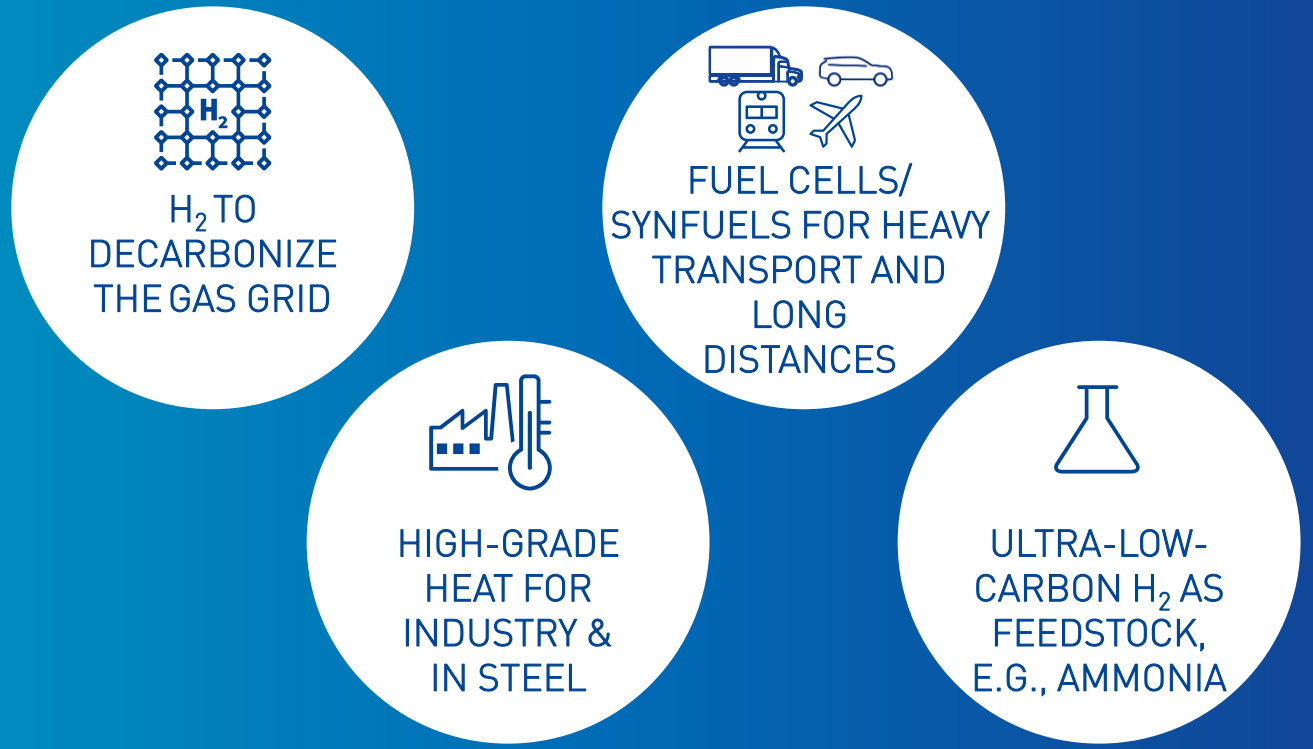
1 Emission reductions from current national commitments, energy efficiency etc. as included in the IEA "reference technology scenario"
2 DS = degree scenario
SOURCE: IEA Energy Technology Perspectives 2017; Hydrogen Roadmap Europe team

ACHIEVING DEEP DECARBONIZATION OF >80% OF CO_2 EMISSIONS REQUIRES HYDROGEN

Challenge

Achieving deep decarboni-zation

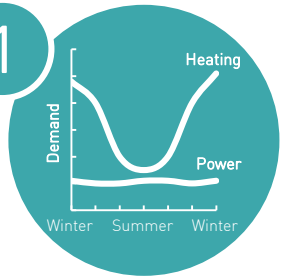
Hydrogen is the best or only choice for at-scale decarbonization of key segments, for example:



USING HYDROGEN IN THE GAS GRID OFFERS THREE MAJOR ADVANTAGES OVER OTHER DECARBONIZATION SOLUTIONS FOR BUILDING HEATING

H_2 TO DECARBONIZE THE GAS GRID

1



Full direct electrification of heating not feasible

Would require significant increase in power generation and grid capacity that is used only in the winter

2

Compatible with existing building stock compared to use of heat pumps

90% of all buildings emissions result from buildings older than 25 years

3

Infrastructure, skills and regulations already available and ready to be leveraged

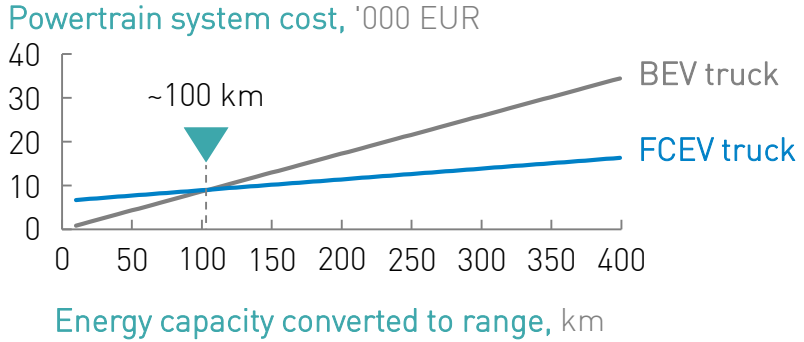
40% of all European households have gas heating as of today making fast and convenient implementation possible

EXAMPLE FOR TRUCKS: HYDROGEN FUEL CELL POWERTRAINS ARE A TECHNICALLY ADVANCED ZERO EMISSION TECHNOLOGY AND COST COMPETITIVE FOR HEAVY TRANSPORT

FUEL CELLS FOR HEAVY TRANSPORT

1

FCEV powertrains for trucks are cost competitive with BEV from 100 km range



2

Hydrogen refueling is 15 times faster than fast charging

After 10 minutes refueling/recharging time

90% FCEV truck vs. 10% BEV truck of ~1000 km range

3

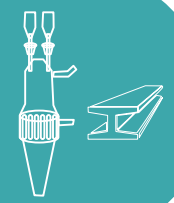
Recharging infrastructure ...

requires 10-15x less space and creates flexible instead of peak load

IN INDUSTRY, HYDROGEN PROVIDES LARGE-SCALE OPPORTUNITIES TO DECARBONIZE HIGH-GRADE HEAT OR REPLACE CARBON-INTENSIVE INPUTS AS A FEEDSTOCK

HIGH-GRADE HEAT FOR INDUSTRY AND AS FEEDSTOCK

1



Only feasible route for decarbonization of steel

Replacement of blast furnace with direct reduction process using hydrogen

2

At-scale decarbonization of high-grade heat industrial processes

Decarbonization route compatible with current processes

3

Conversion of hydrogen production to ultra-low-carbon hydrogen

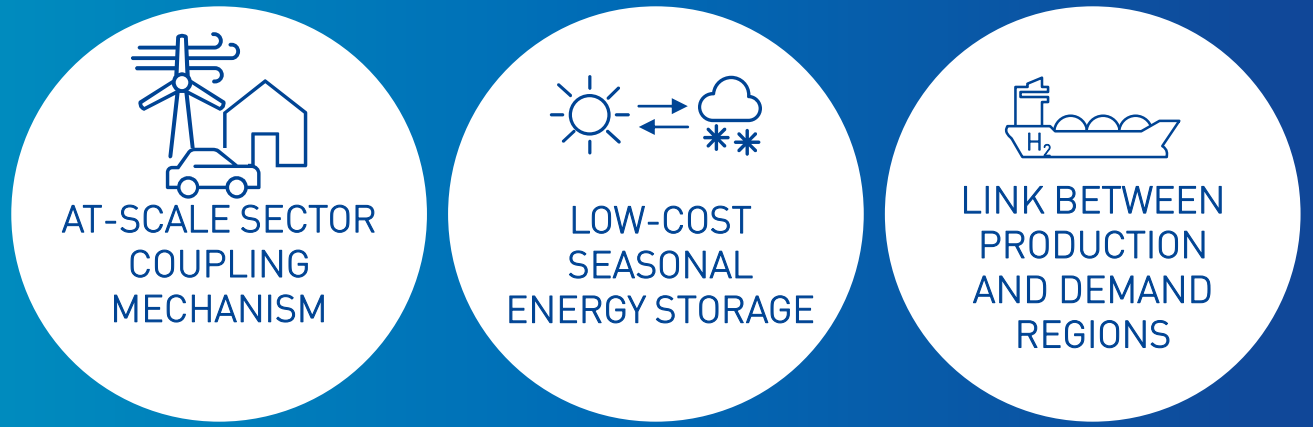
Decarbonization of hydrogen production where currently used – e.g., in ammonia production, refining and petrochemical industries

MANAGING VARIABLE RENEWABLES REQUIRES HYDROGEN

Challenge

Hydrogen is the only option to enable the transition of the energy system – managing quadrupling renewables requires...

Managing variable renewables

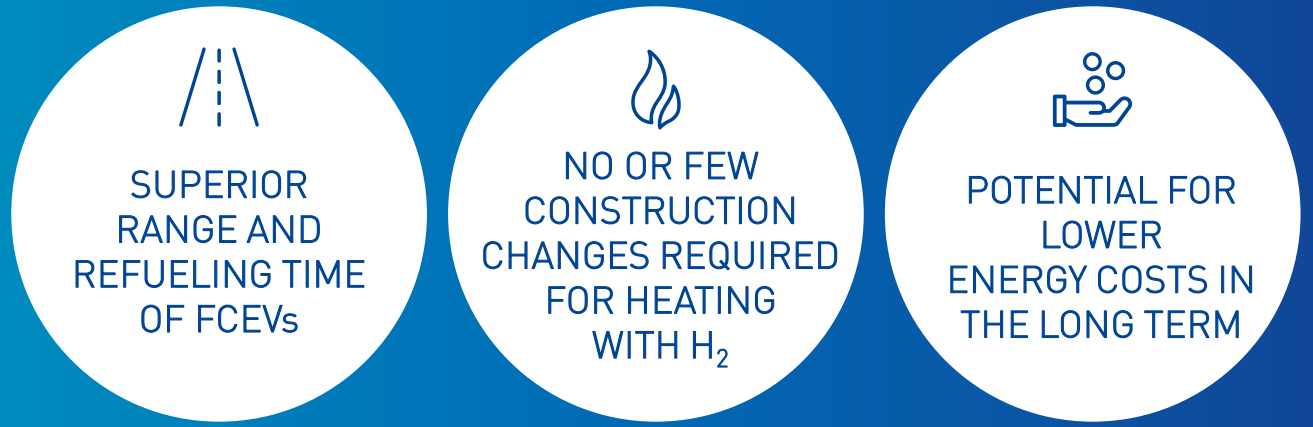


HYDROGEN AND FUEL CELL SOLUTIONS MEET CUSTOMER PREFERENCES AND ARE CONVENIENT

Challenge

Meeting customer preferences

Hydrogen and fuel cells are compatible with current usage patterns and convenience due to...

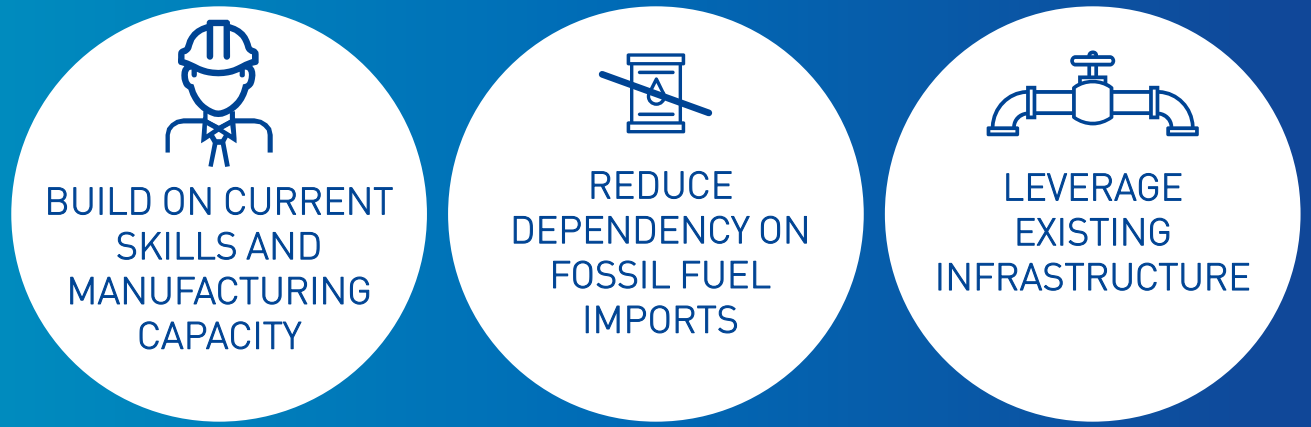


HYDROGEN AND FUEL CELL TECHNOLOGIES ARE AN OPPORTUNITY FOR EUROPE'S INDUSTRY

Challenge

Securing EU technology leadership to create jobs and wealth

Hydrogen and fuel cell technologies are an opportunity for Europe's industry as to...

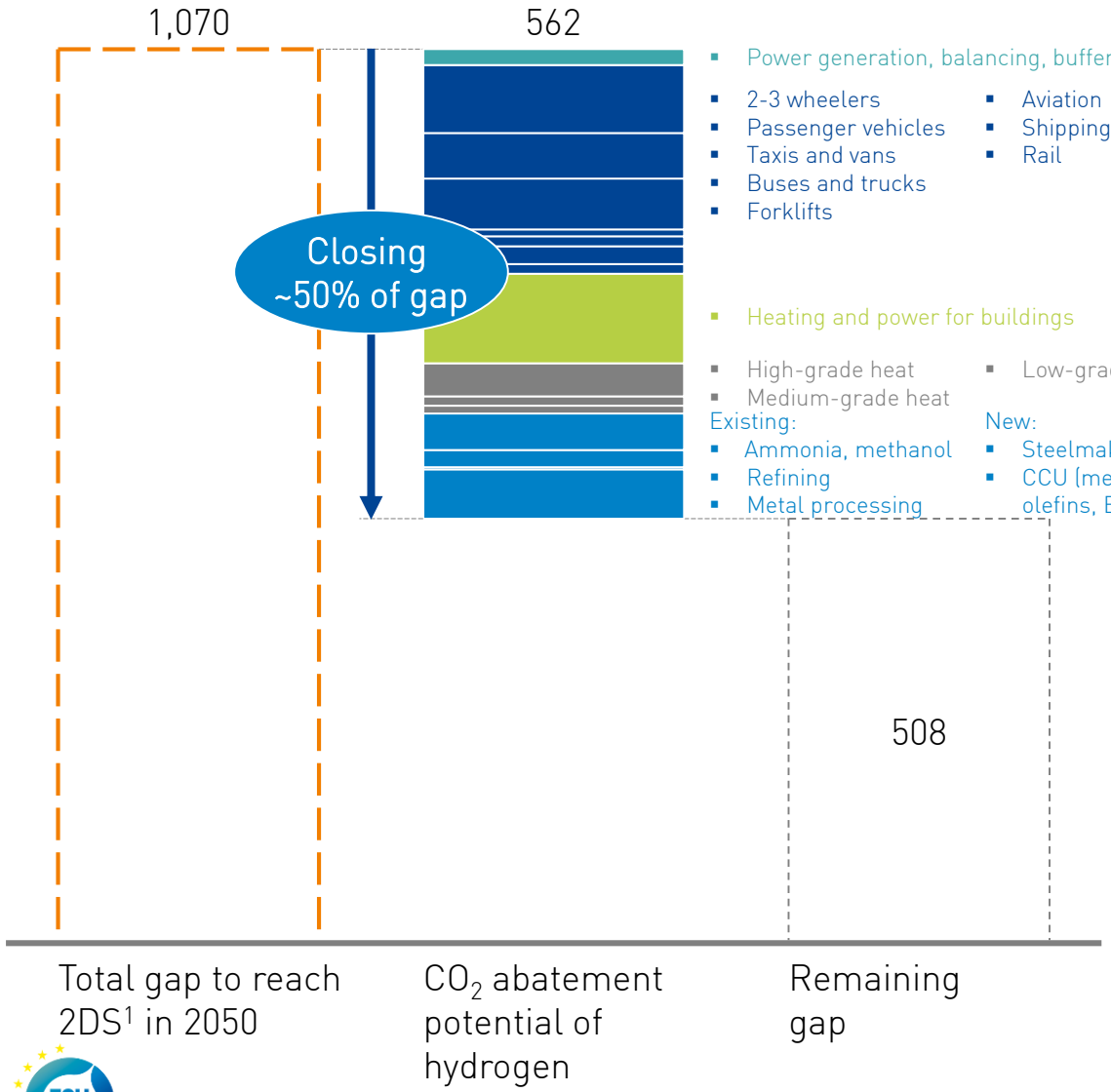


TOGETHER WITH AN INDUSTRY COALITION, A HYDROGEN ROADMAP FOR EUROPE HAS BEEN DEVELOPED

- Study by the FCH JU, supported by Hydrogen Europe and 17 companies and organizations along the whole value chain of hydrogen
- First comprehensive quantified European perspective for deployment of hydrogen and fuel cells in two scenarios
  - Ambitious, yet realistic two-degree scenario and business-as-usual scenario
  - Long-term potential
  - Roadmap with intermediate milestones
  - Recommendations to kickstart

ACROSS APPLICATIONS HYDROGEN CAN CLOSE HALF OF THE GAP TOWARDS THE 2DS

Carbon emissions gap to reach 2DS[1] in 2050, Mt



Segments

- Power generation, balancing, buffering
- 2-3 wheelers
- Passenger vehicles
- Taxis and vans
- Buses and trucks
- Forklifts
- Aviation
- Shipping
- Rail
- Heating and power for buildings
- High-grade heat
- Medium-grade heat
- Low-grade heat

Existing:
- Ammonia, methanol
- Refining
- Metal processing

New:
- Steelmaking (DRI)
- CCU (methanol, olefins, BTX)

Hydrogen decarbonization levers

Power generation	Integration of renewables into the power sector[2] Power generation from renewable resources
Transportation	Replacement of combustion engines with FCEVs, in particular in buses and trucks, taxis and vans as well as larger passenger vehicles Decarbonization of aviation fuel through synthetic fuels based on hydrogen Replacement of diesel-powered trains and oil-powered ships with hydrogen fuel-cell-powered units
Heating and power for buildings	Decarbonization of natural gas grid through blending Upgrade of natural gas to pure hydrogen grid
Industry heat	Replacement of natural gas for process heat
Industry feedstock	Switch from blast furnace to DRI steel Replacement of natural gas as feedstock in combination with CCU

1 2-degree scenario 2 Please see the chapter on renewables and power for information on the role of hydrogen as enabler of a renewable power system. The "enabled" carbon abatement from renewables is not included here and is an additional benefit of hydrogen for decarbonization

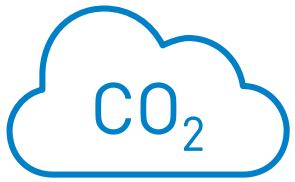
SOURCE: IEA Energy Technology Perspectives 2017; Hydrogen Roadmap Europe team

BESIDES CO_2 ABATEMENT, DEPLOYMENT OF THE HYDROGEN ROADMAP ALSO CUTS LOCAL EMISSIONS, CREATES NEW MARKETS AND SECURES SUSTAINABLE EMPLOYMENT IN EUROPE

2050 hydrogen vision

~24%

of final energy demand[1]



~560 Mt

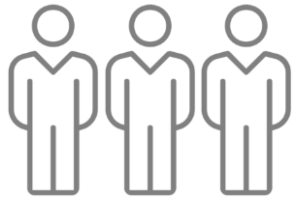
annual CO_2 abatement[2]

~EUR 820bn

annual revenue (hydrogen and equipment)

~15%

reduction of local emissions (NO_x) relative to road transport



~5.4m

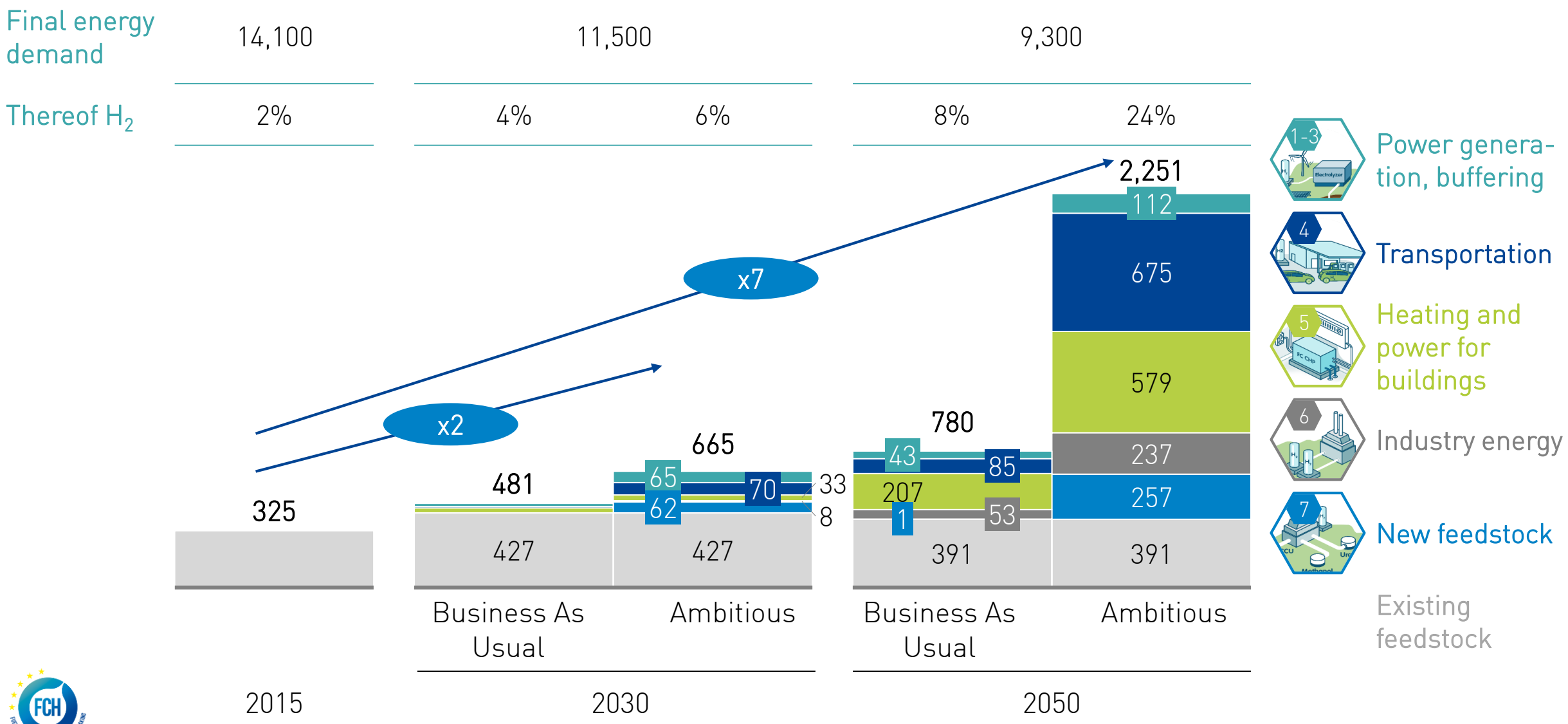
jobs (hydrogen, equipment, supplier industries)[3]

1 Including feedstock 2 Compared to the reference technology scenario 3 Excluding indirect effects

SOURCE: Hydrogen Roadmap Europe team

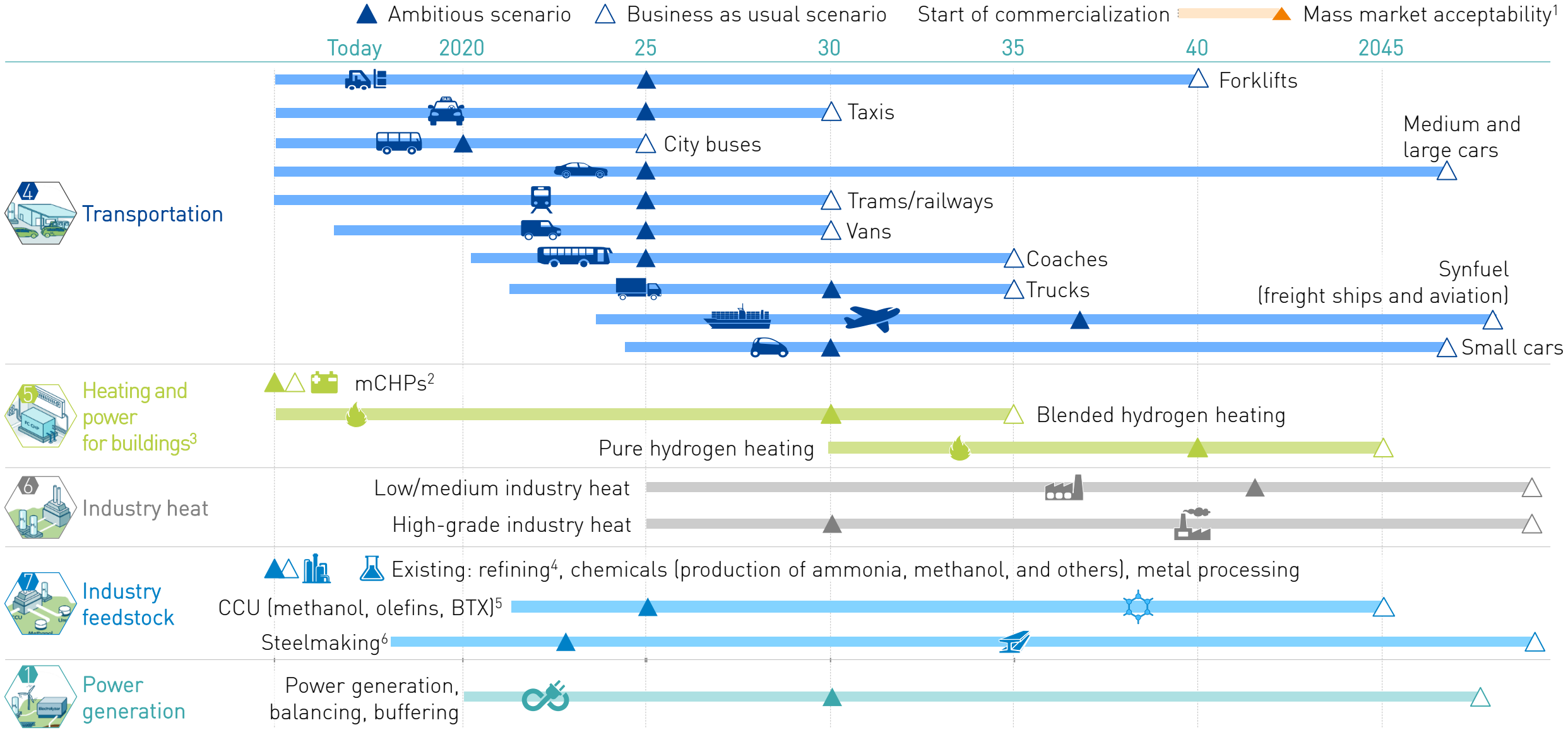
HYDROGEN COULD PROVIDE UP TO 24% OF TOTAL ENERGY DEMAND, OR UP TO ~2,250 TWH OF ENERGY IN THE EU BY 2050

TWh



SOURCE: Hydrogen Roadmap Europe team

HYDROGEN TECHNOLOGY EXISTS AND IS READY TO BE DEPLOYED



1 Defined as sales >1% within segment; 2 mCHPs sales in EU independent of fuel type (NG or H_2); 3 Pure and blended H_2 refer to shares in total heating demand; 4 Refining includes hydro-cracking, hydro-treating, bio-refinery; 5 Market share refers to the amount of production that uses hydrogen and captured carbon to replace feedstock; 6 CDA process and DRI with green H_2, iron reduction in blast furnaces, and other low-carbon steel making processes using H_2

SOURCE: Hydrogen Roadmap Europe team

HYDROGEN PLAYS AN IMPORTANT, COMPLEMENTARY ROLE IN THE 2050 ENERGY SYSTEM

Segments	Key subsegments	Relative importance by 2050[1]	Complementary decarbonization solutions
4 Transportation	■ Large cars (fleets) and taxis ■ Trucks and buses ■ Light commercial vehicles ■ Trains	39% 22% 30% 9%	■ Battery-electric vehicles ■ Plug-in hybrid electric vehicles ■ Electrified trains
5 Heating and power for buildings	■ Hydrogen blending for heating ■ Pure hydrogen grids for heating	2% 16%	■ Electrification of heating via heat pumps ■ Energy efficiency measures ■ Biogas/biomass
6 Industry energy	■ High-grade heat	23%	■ Demand side and energy efficiency measures ■ Electrification ■ Biogas/biomass ■ Carbon capture
7 Industry feedstock	■ Ultra-low-carbon hydrogen as feedstock for — Ammonia, methanol — Refining ■ Feedstock in steelmaking (DRI) ■ Combined with CCU in production of olefins and BTX	100% 80% 20% 30%	*For steel:* ■ Coke from biomass ■ CCS on blast furnace *For CCU:* ■ Carbon storage
1 Power generation	■ Power generation from hydrogen ■ Flexible power generation from hydrogen	2% 55%	■ Biogas ■ Post-combustion CCS ■ Batteries

1 In transportation: percent of total fleet; in heating and power for buildings: percent of total heating demand; in industry energy: percent of final energy demand; in industry feedstock: percent of total feedstock for production; in power generation: percent of total power generation and percent of power generated from natural gas

SOURCE: Hydrogen Roadmap Europe team

TO REACH THE AMBITIOUS 2050 VISION, WE PROPOSE SHORT- AND MEDIUM-TERM MILESTONES ACROSS ALL SEGMENTS

	2030		2040		
One in...	12		5		...light commercial vehicles sold are FCEVs...
...and one in...	22		7		...passenger vehicles sold are FCEVs.
There are...	45	'000	450	'000	...trucks and buses on the road...
...and...	570		2,000		...diesel trains replaced with hydrogen.
A total of...	7	%	32	%	...of natural gas (by volume) is replaced by hydrogen
...equivalent to...	30	TWh	120	TWh	
...meaning...	2	m	11	m	...households are heated.
The deployment of...	250	'000	2,560	'000	...fuel cell CHPs increases energy efficiency.
There is...	33	%	63	%	...carbon-free hydrogen production in all applications.

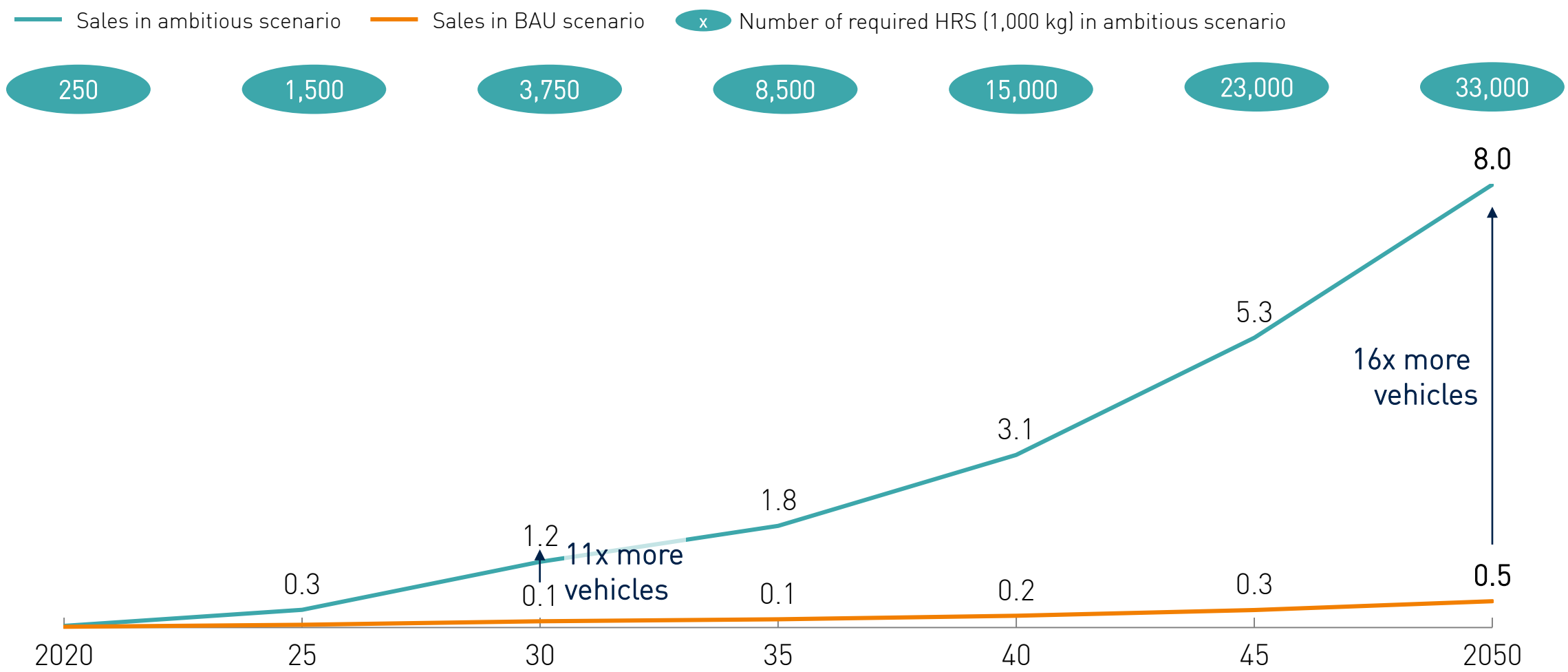
1 At 25% utilization; additional hydrogen is produced through SMR and as byproduct
2 Values calculated for "mixed scenario" (hydrogen production via water electrolysis and SMR/ATR with CCS)

SOURCE: Hydrogen Roadmap Europe team

HOWEVER, THIS AMBITIOUS SCENARIO REQUIRES A JOINT ROLLOUT OF SOLUTIONS, OTHERWISE DEPLOYMENT WILL REMAIN AT MUCH LOWER LEVELS

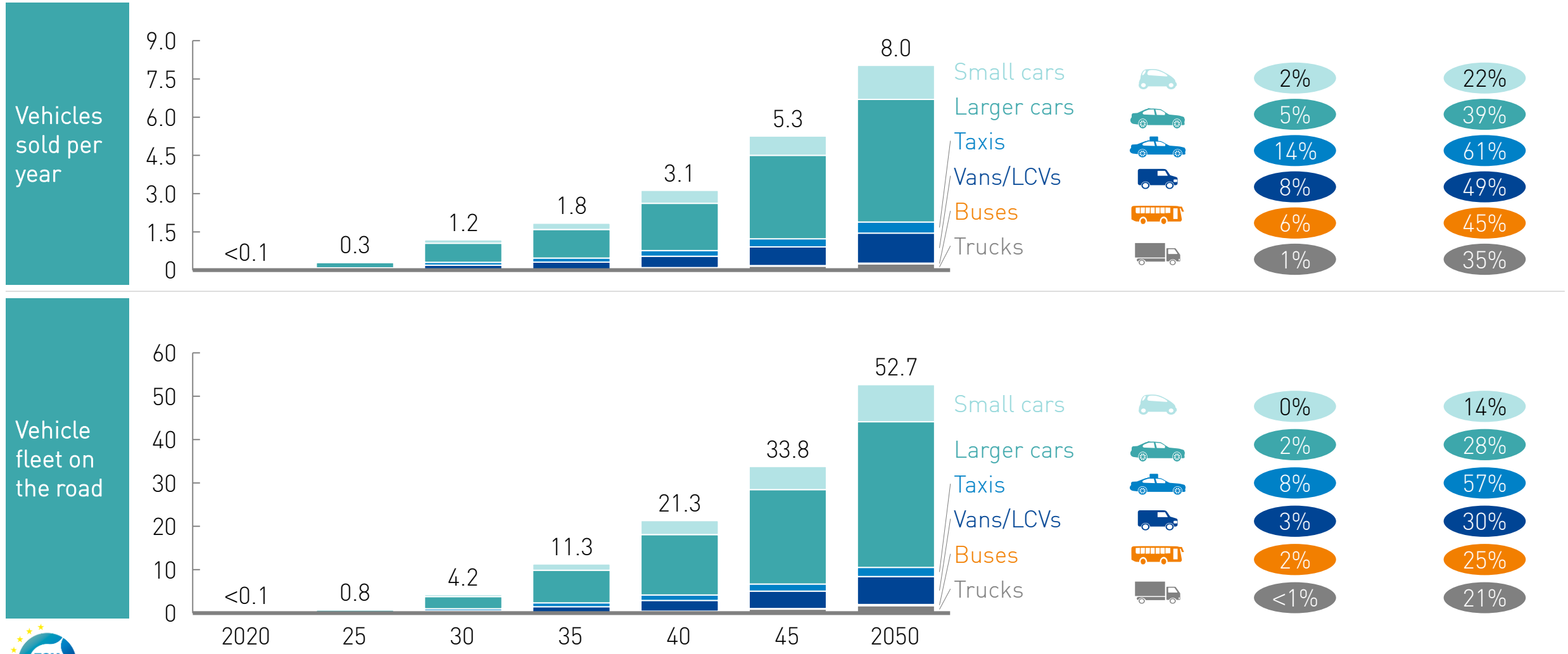
Sales number of vehicles in road transport (2050)

m vehicles



SOURCE: Hydrogen Roadmap Europe team

CARS ARE MANUFACTURED IN THE GREATEST QUANTITIES AND ACHIEVE SIGNIFICANT PENETRATIONS IN COMMERCIAL FLEET CATEGORIES



1 Including fuel cell hybrid vehicles

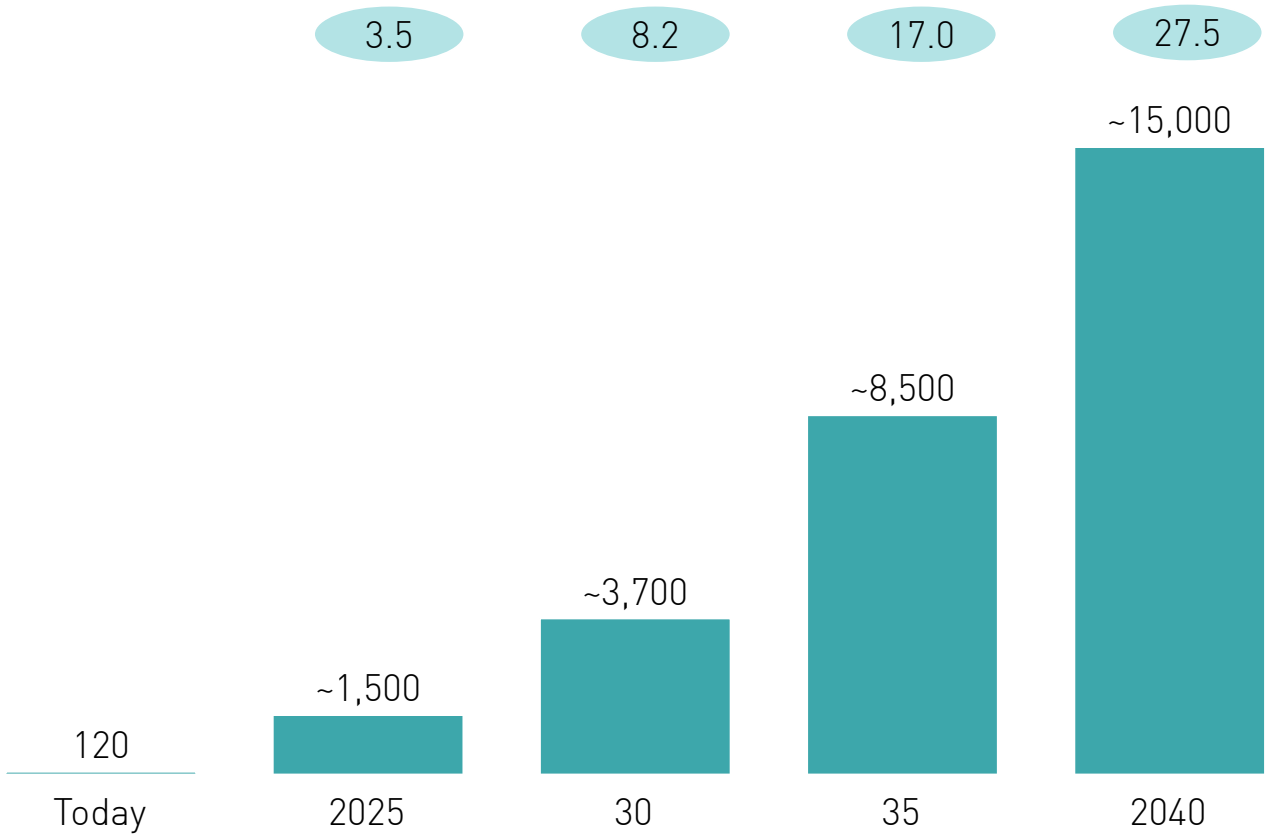
SOURCE: Hydrogen Roadmap Europe team

THE EQUIVALENT OF ~3,740 REFUELING STATIONS WOULD BE REQUIRED BY 2030, IMPLYING INVESTMENT NEEDS OF EUR ~8.2 BN

Required large HRS[1], number

xx Cumulative investment need, EUR billions

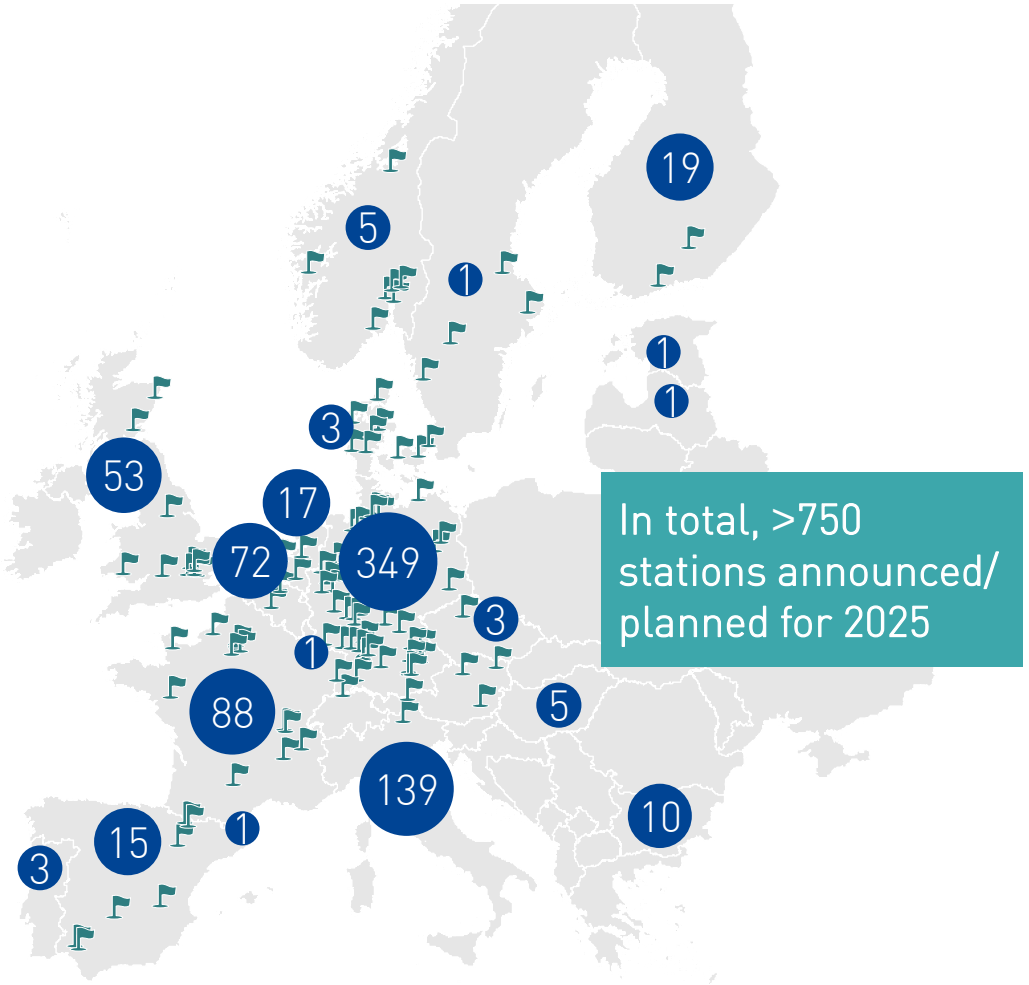
AMBITIOUS SCENARIO



Current and planned HRS in Europe

HRS in operation[2]

Number of HRS announced and/or planned until 2025



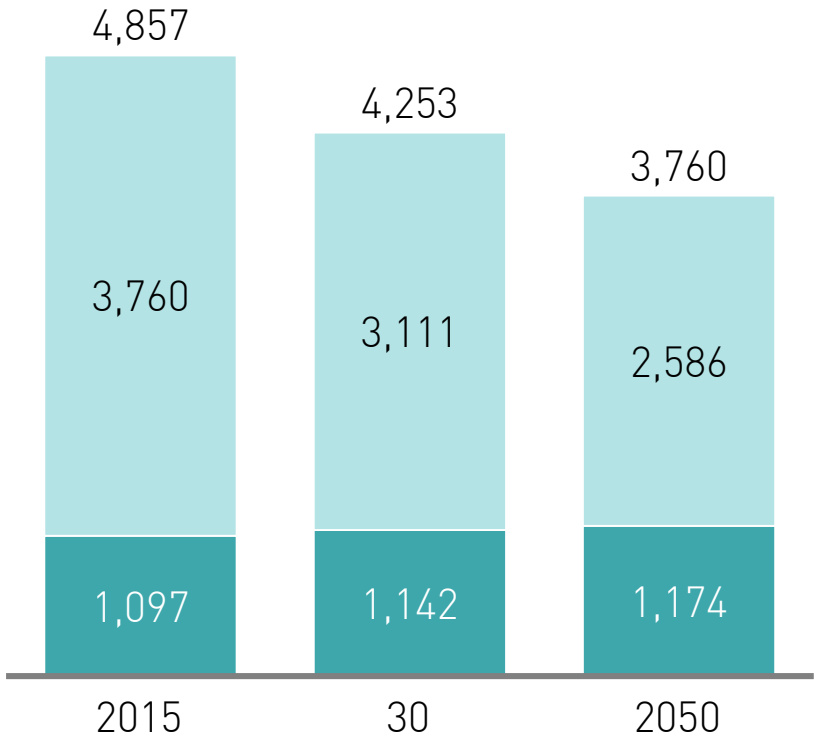
In total, >750 stations announced/ planned for 2025

1 Equivalents of medium HRS (1,000kg daily capacity); utilization relative to steady-state 2 Indicative position

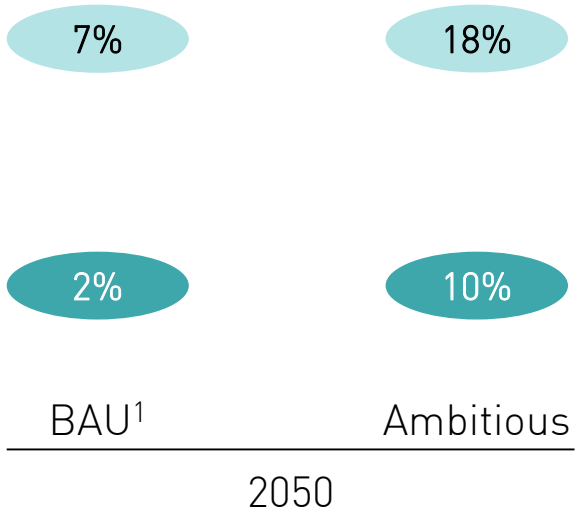
SOURCE: European Commission (2017); H2stations.org; press research; Hydrogen Roadmap Europe team

IN THE EU OVERALL, A 10-18% SHARE OF BUILDING HEAT AND POWER COULD BE REPLACED BY HYDROGEN IN 2050

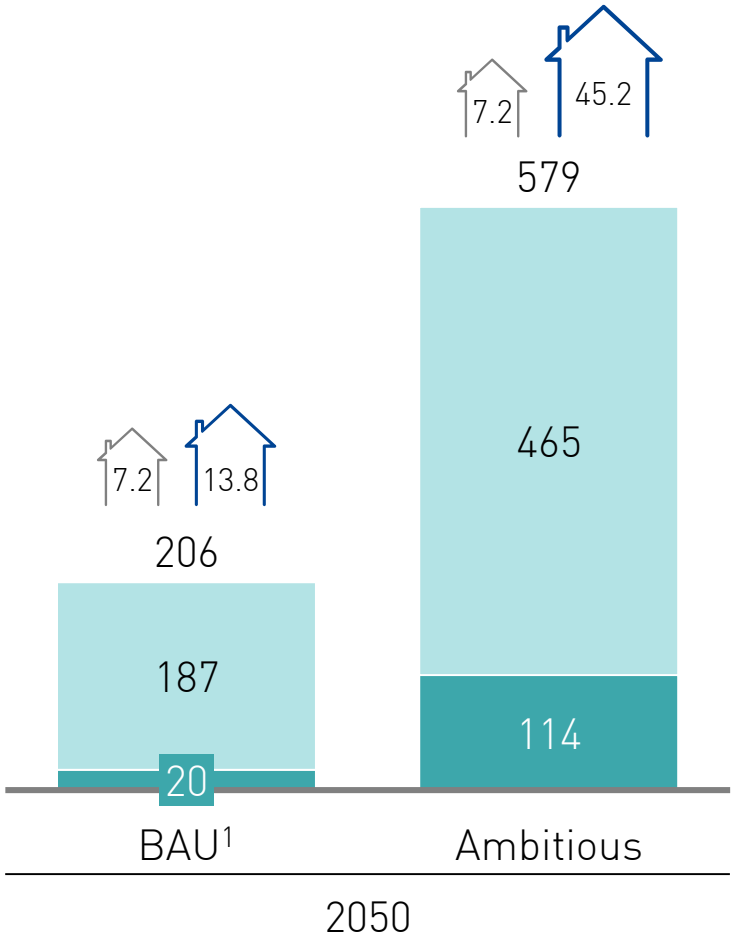
Total building energy demand, TWh



Adoption rates percent



Total building energy supplied by H_2, TWh; Heating rate, m household equivalents



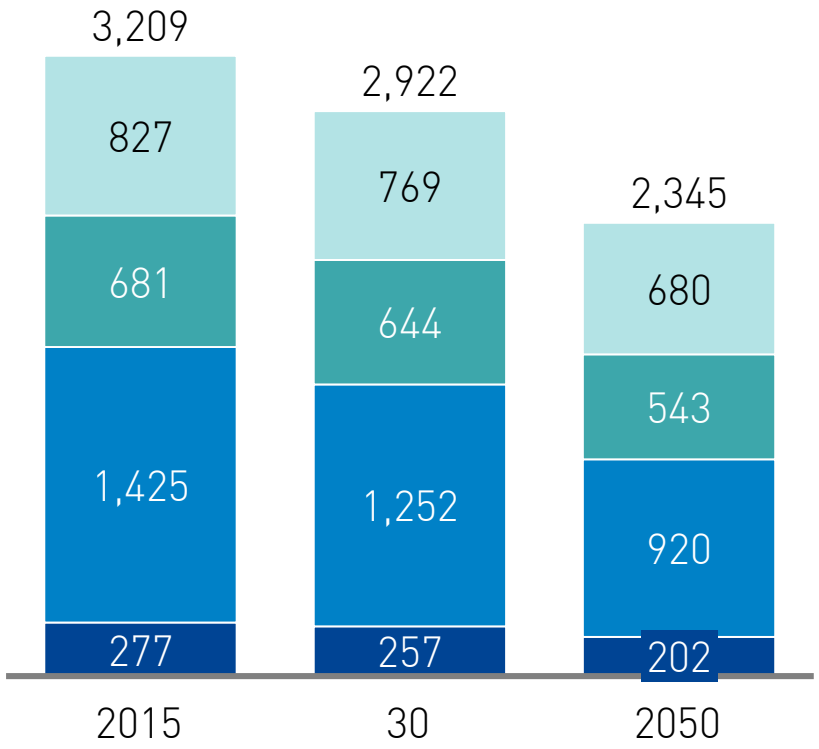
1 Business as usual scenario

SOURCE: heatroadmap.eu; Hydrogen Roadmap Europe team

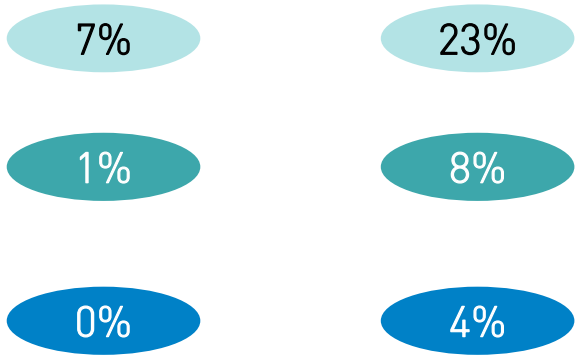
6 FOR INDUSTRY, HYDROGEN HAS THE POTENTIAL TO GENERATE A SHARE OF UP TO 23% OF HIGH-GRADE HEAT FOR INDUSTRY IN 2050

High-grade heat | Medium-grade heat | Low-grade heat | Power

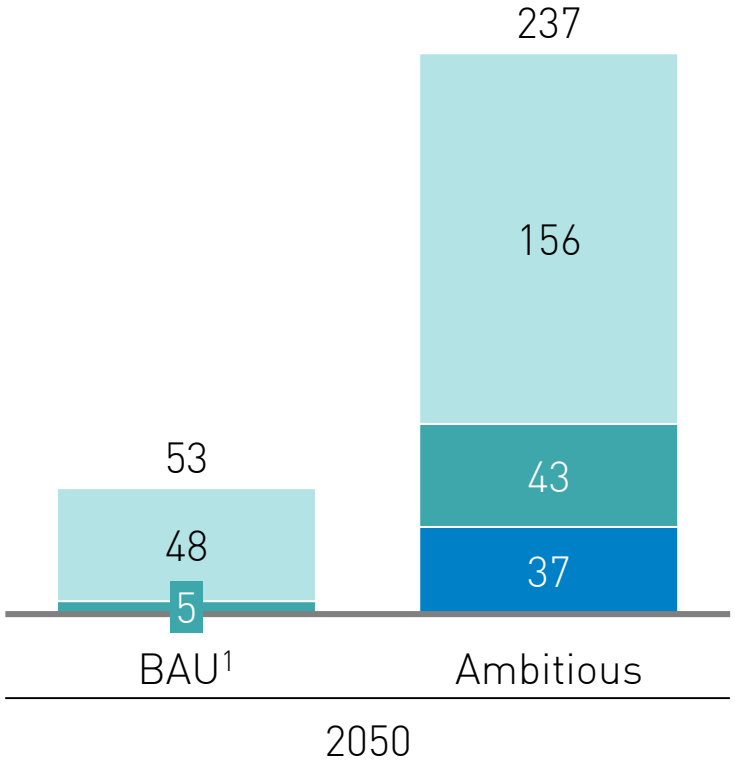
Total industry energy demand, TWh



Adoption rates percent



Total industry heat supplied by H_2, TWh

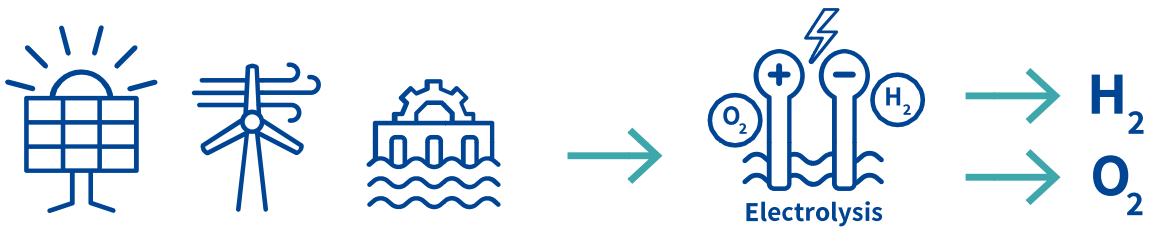


1 Business as usual scenario

SOURCE: IEA ETP (2017), expert interviews, Hydrogen Roadmap Europe team

HYDROGEN PRODUCTION WILL BE A MIX OF MOSTLY ELECTROLYSIS AND SMR/ATR WITH CCS IN EUROPE

Water electrolysis



Carbon-free production method for hydrogen if fueled by renewables

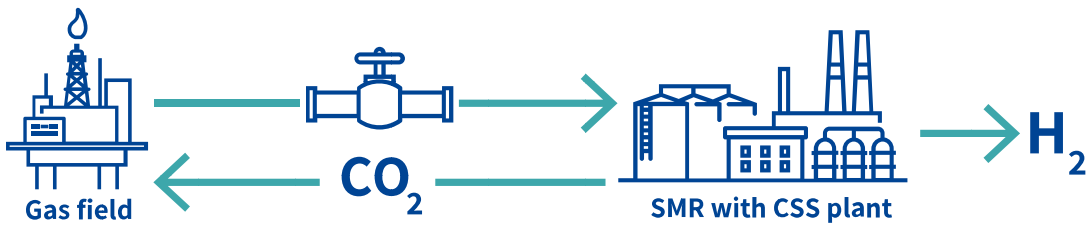
Long-term potential to **match or even beat SMR costs** in case of low-cost solar and/or electrolyzer capex decrease

Provision of **sector-coupling** mechanism required for integration of renewables

No issues with political/ societal acceptance compared to CCS

Decentral production taking load off the grid and providing power at remote locations or points of sale (e.g., at refueling stations)

SMR/ATR with CCS



In combination with carbon capture (CCS), **carbon emissions are reduced significantly by** up to 90%

SMR is established and mature technology

Hydrogen production method **for large scale** as required for the industry

Reliable constant production possible

Higher infrastructure costs for natural gas and CO_2 handling

SMR is currently **lowest-cost hydrogen production**

THE HYDROGEN ECONOMY REQUIRES EUR 65 BN CUMULATIVE INVESTMENTS AND OPENS A MARKET OF UP TO EUR 55 BN ANNUAL SALES IN EUROPE BY 2030

EUR bn

	Cumulative investments in manufacturing equipment (2018-2030)[1]		Annual revenues in end-uses (2030)[1]	
	Supplier	OEM	Equipment	Hydrogen
Power generation	0.1	0.2	1.5	2.9
Transportation	5.8	9.7	16.7	7.7
Buildings heat and power	0.1	0.1	0.1	2.9
Industry energy	<0.1	<0.1	<0.1	0.6
New feedstock	n/a	n/a	n/a	22.4

Cumulative investments in hydrogen production, storage, and distribution (2018-2030)[1]

1.2	0.6	1.9	R&D and manu-facturing
Hydrogen distribution and retail	Hydrogen storage and buffering	Hydrogen produc-tion	
10.6	8.4	26.5	Infra-structure

1 Including investments/revenues in aftermarket services and new business models (assumption: 8% of investment/revenue)

SOURCE: Hydrogen Roadmap Europe team

IN TOTAL, A MARKET OF EUR ~150 BN AND ~1 M JOBS COULD BE UNLOCKED BY 2030

2030 hydrogen vision

Estimation of industry size

EU and global market potential taken from hydrogen vision

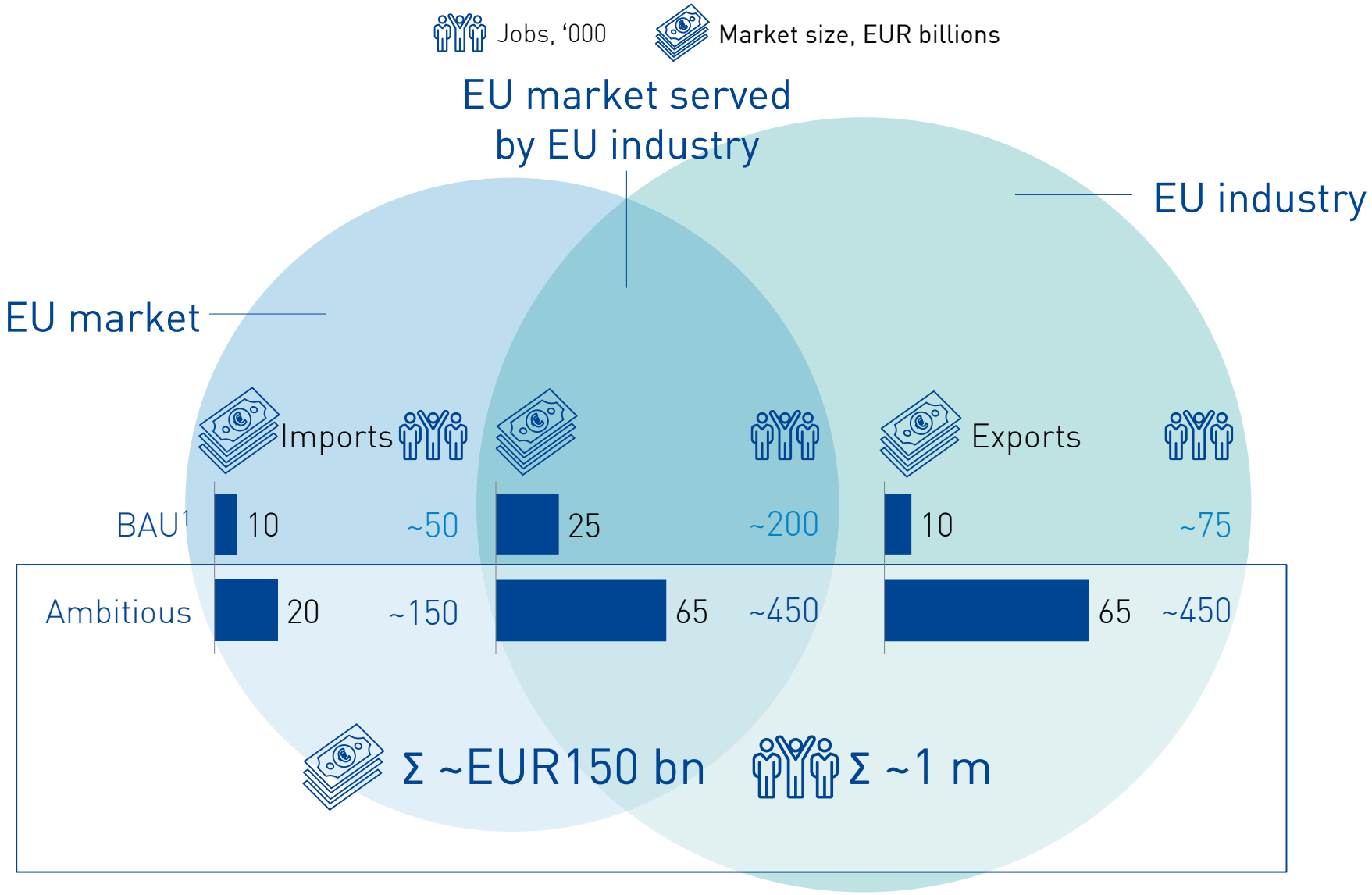
"Fair share" of EU industry on domestic and worldwide market derived from industry statistics and industry interviews

Revenue and jobs multipliers estimated from EU input-output models

Ambitious scenario

Fair domestic market share for EU players (between 60% and 90% depending on the step in the value chain)

Fair market share for EU players in RoW (between 10% and 25% depending on the step in the value chain)



1 Business as usual scenario

SOURCE: Hydrogen Roadmap Europe team

INDUSTRY, REGULATORY AND INVESTORS NEED TO ACT TOGETHER