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IEA Hydrogen and Fuel Cells Technology Roadmap

Paving Clean and Low Carbon Energy and Transport Systems using Hydrogen and Fuel Cells

ADB Transport Forum, September 16, 2016

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Hydrogen and Transport

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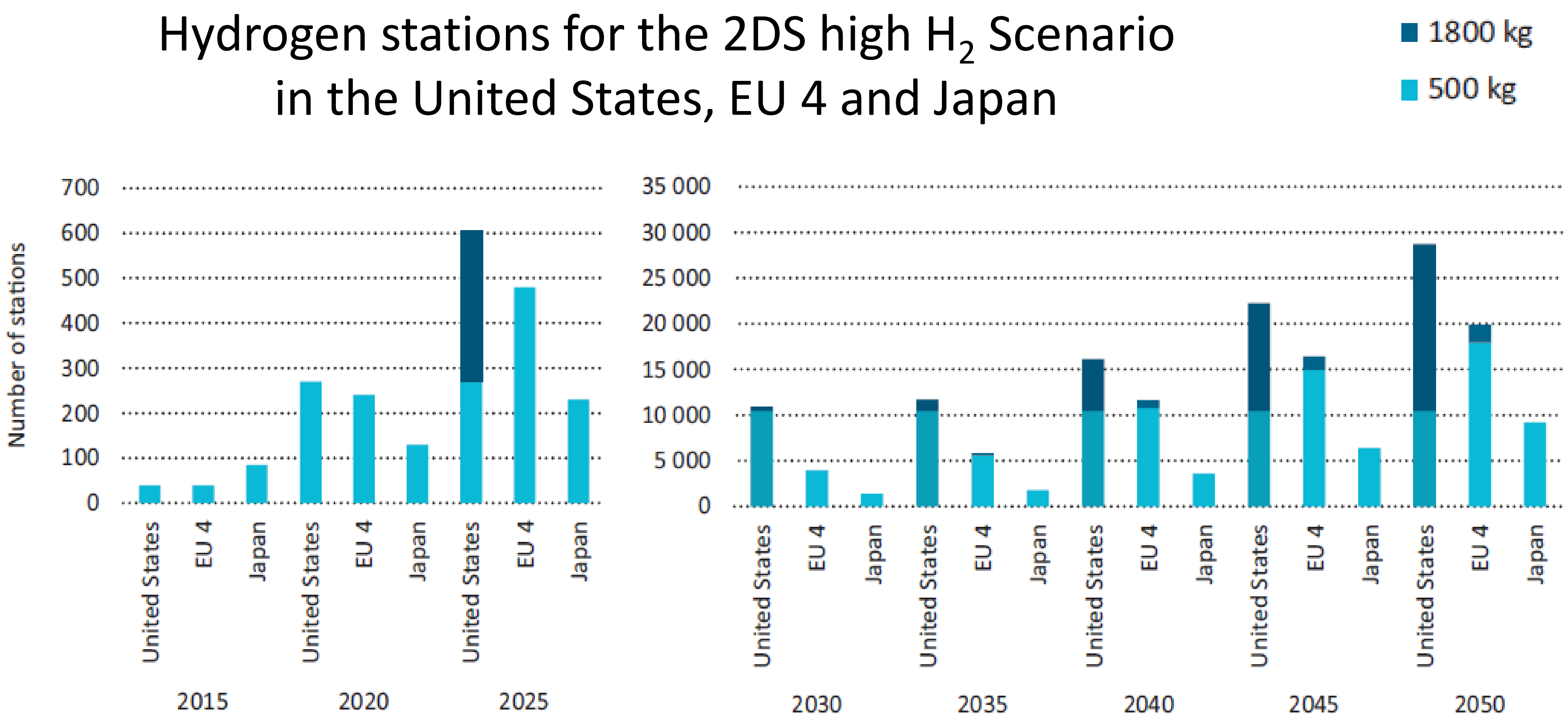
Regional development targets

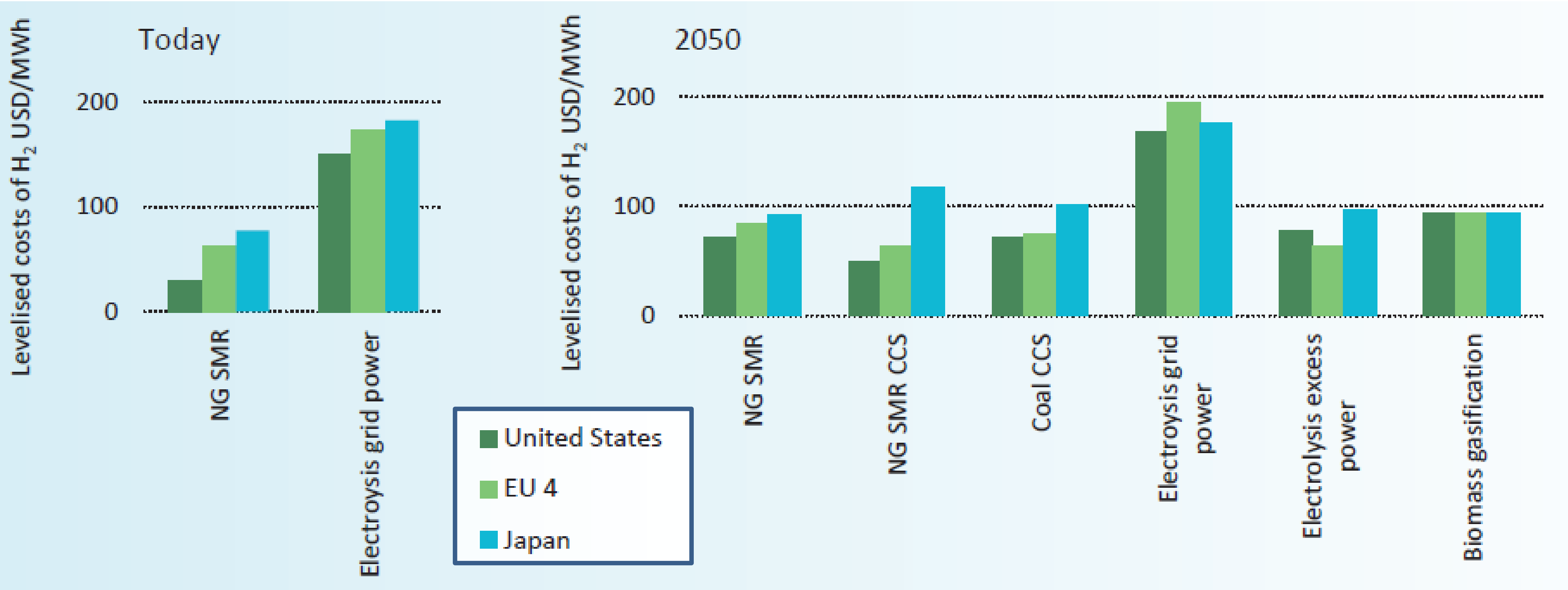


Note: By the end of 2015 already 100 hydrogen stations are planned to be built in Japan.

- **Building out a fueling infrastructure network would require consistent dedicated funding**

Costs of Natural Gas Steam Methane Reformation (NG SMR) are generally favorable

Hydrogen production costs without T&D for the 2DS high H_2 Scenario



- **But excess grid power could potentially become an economically viable generation pathway**
- **carbon taxes can improve the economics**

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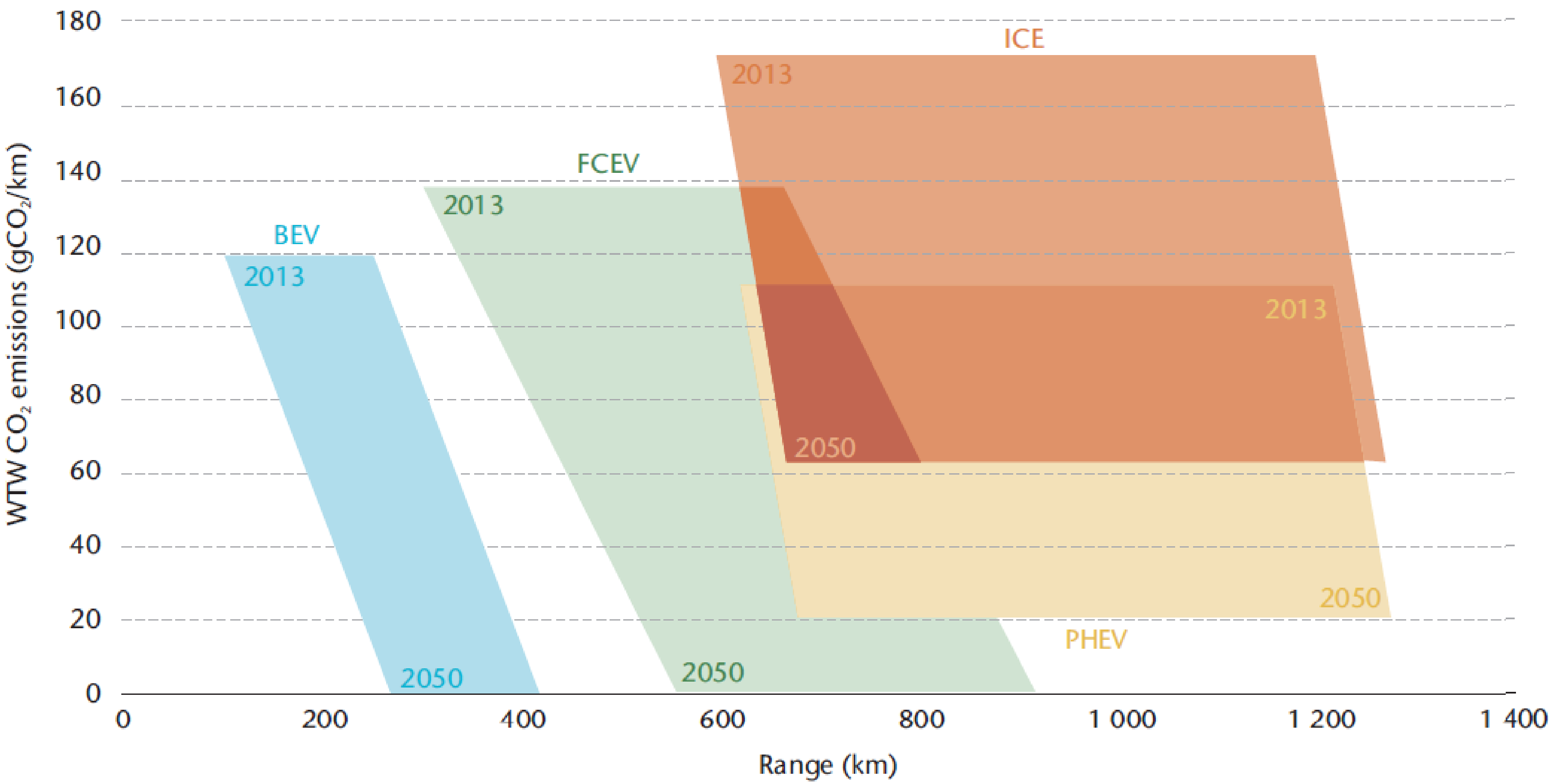
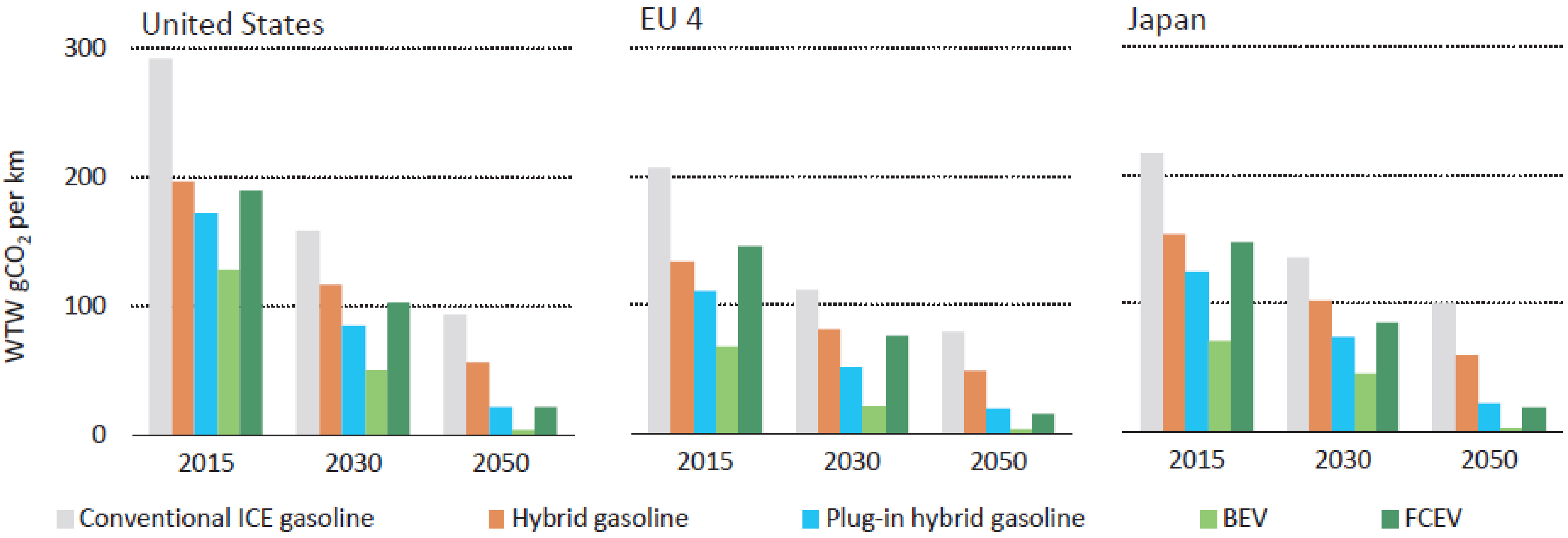
Well-to-wheel emissions vs. vehicle range



- ***Fuel Cell Electric Vehicles (FCEVs) can achieve a mobility service compared to today's conventional cars at potentially very low well-to-wheel carbon emissions***

But *low-carbon* hydrogen pathways must be prioritized

Specific PLDV stock on-road WTW emissions by technology for the United States, EU 4 and Japan in the 2DS high H_2 Scenario



- **FCEVs offer comparable carbon benefits to Plug-in Hybrid EVs but with the potential for superior performance**

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Hydrogen in Buildings

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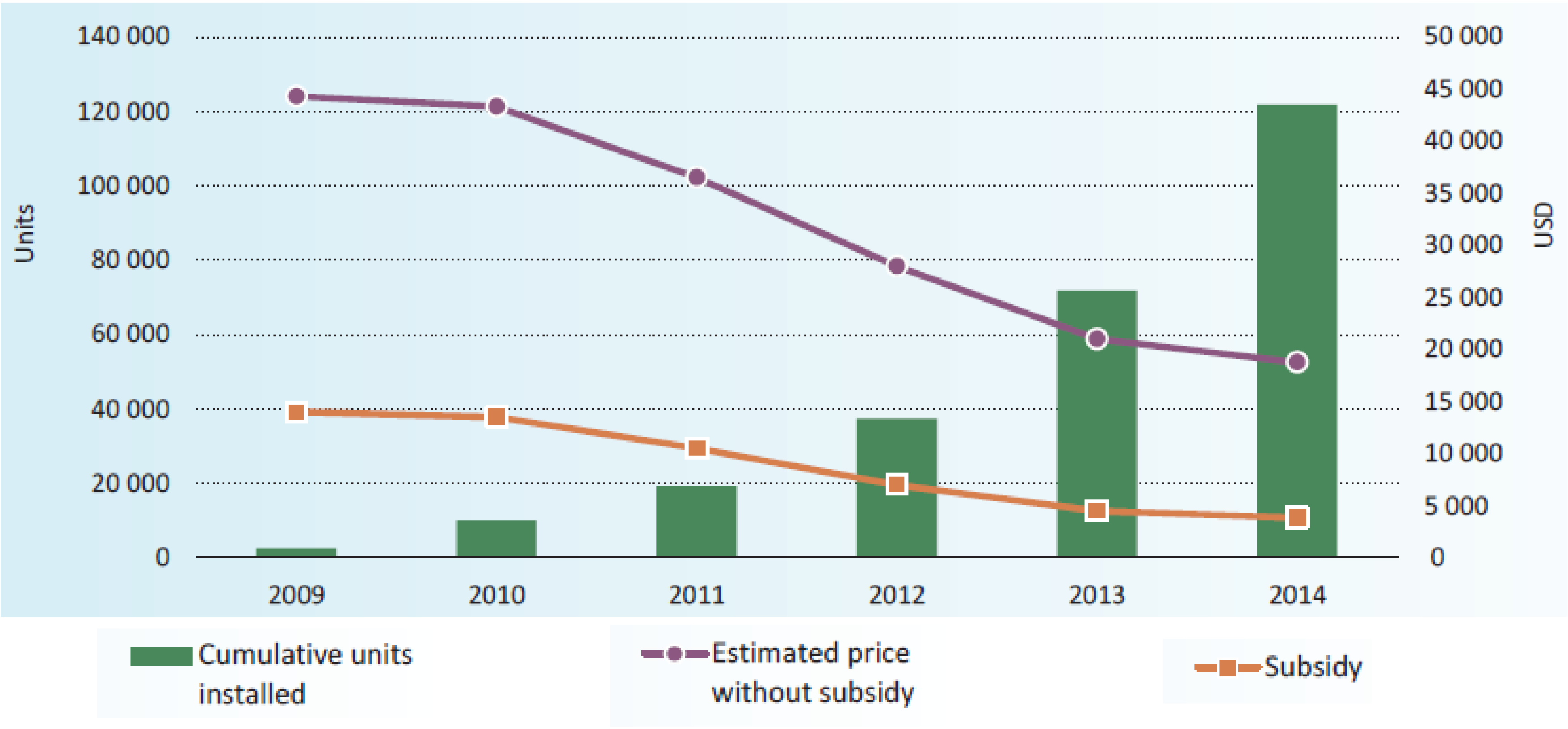
Japan case study: Ene-Farm

Ene-Farm fuel cell micro co-generation cumulative sales, subsidies and estimated prices, 2009-14



- **The price of Ene-Farm fuel cell micro co-generation systems has fallen by more than 50% since 2009.**

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Key findings & key actions

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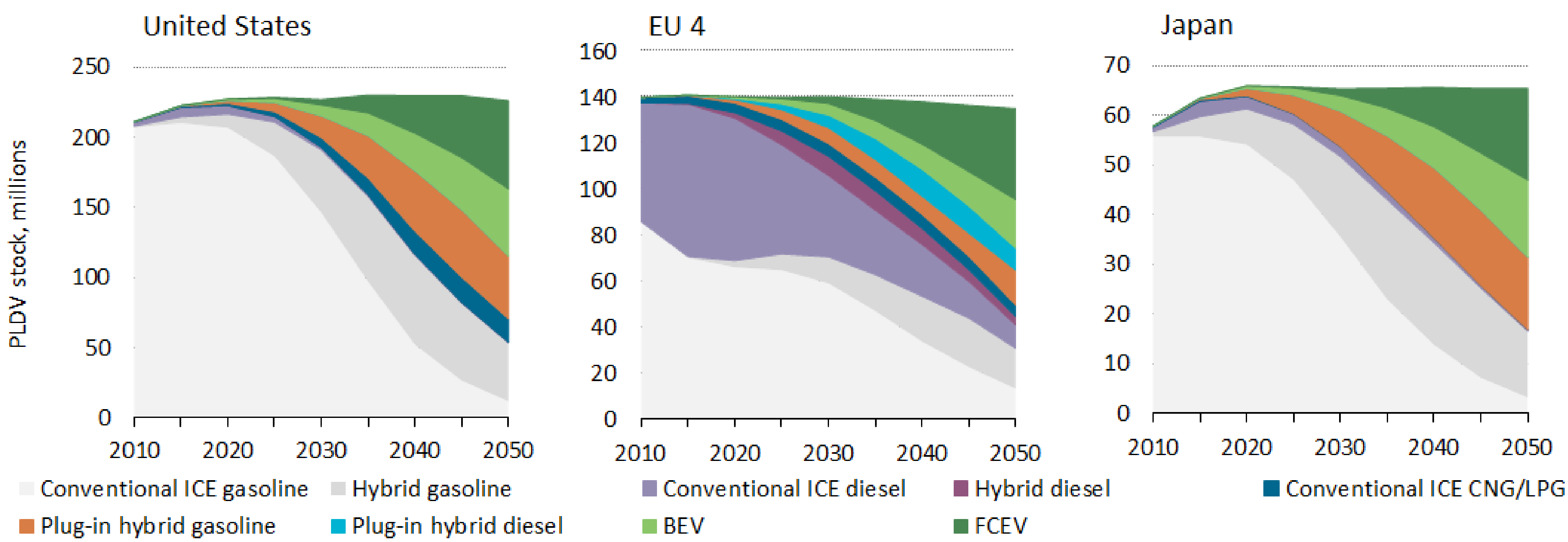
Passenger car stock by technology in the 2DS high H_2 Scenario



- By 2050, the share of FCEVs on total PLDV stock is set to be 25%.
- Based on the assumed large-scale and rapid deployment of hydrogen technologies in transport, the economic barriers linked to the establishment of the hydrogen infrastructure are reduced.

Low-carbon H_2 generation requires a portfolio of technologies

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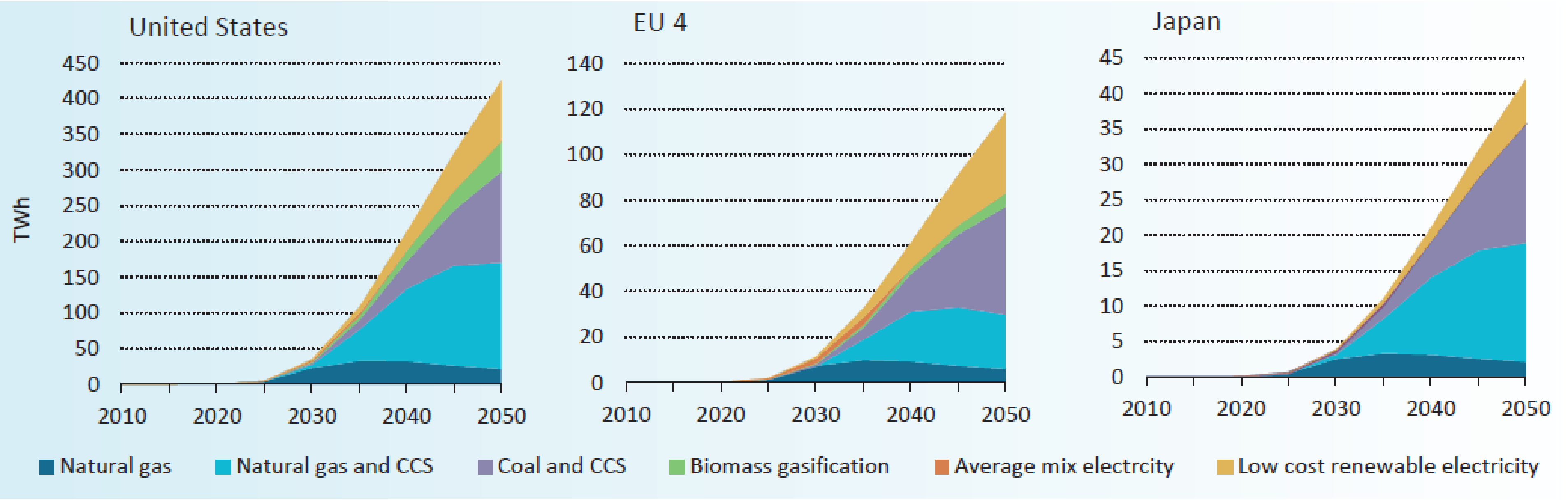
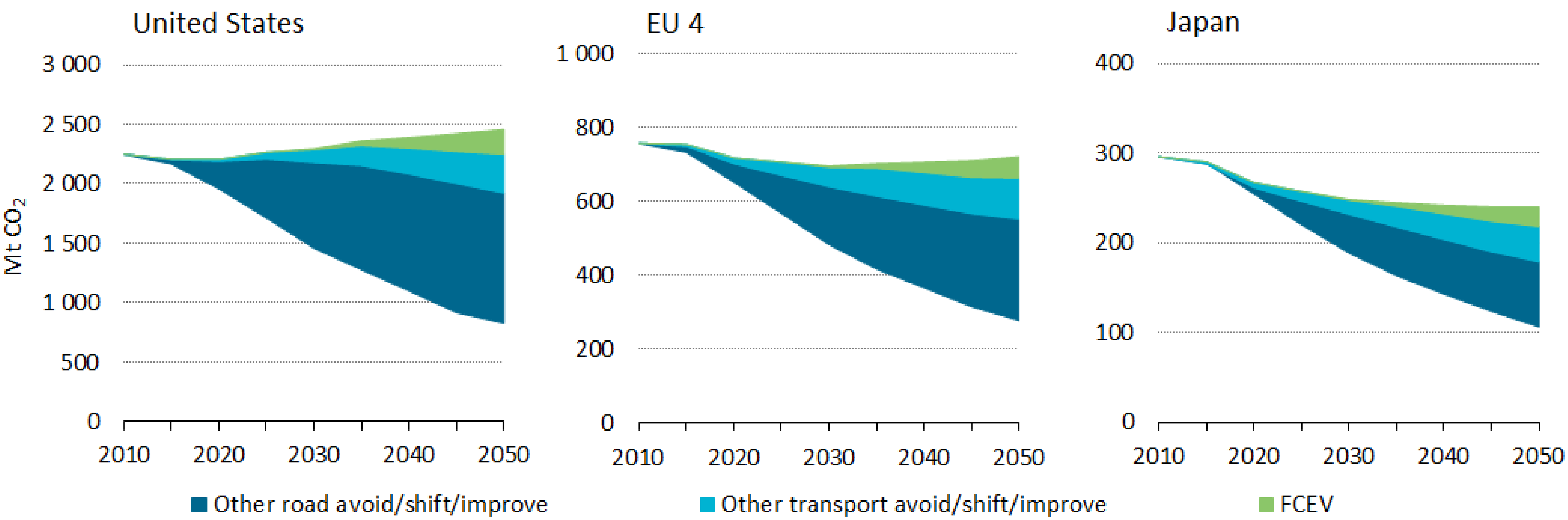
Hydrogen generation by technology for the 2DS high H_2 Scenario in the US, EU 4 and Japan



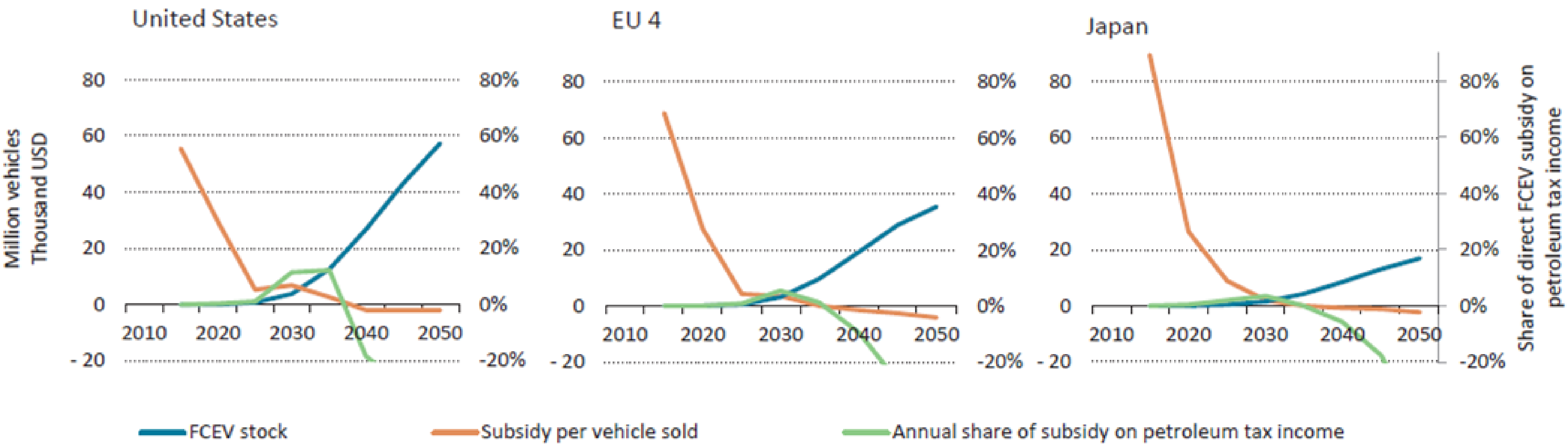
- Steam methane reformation using NG and coal
- Biomass gasification
- Low cost renewable electricity

CO_2 mitigation potential of FCEVs in the 2DS high H_2 Scenario



- The contribution of FCEVs to cumulative total transport CO_2 emission reductions between now and 2050 accounts for between 7% (United States) and 10% (Japan).
- Between now and 2050, almost 3 $GtCO_2$ are saved by FCEVs in these regions.

Direct subsidies for FCEV roll-out in the 2DS high H_2 Scenario



- With rapid market uptake and fuel tax exemption of hydrogen, FCEVs could be entirely cost competitive 15 to 20 years after market introduction
- Until 2035, around USD 90 billion would need to be spent to achieve parity of costs of FCEVs with high efficient gasoline PLDVs, and to bring on the road 30 million FCEVs in the United States, EU 4 and Japan.

Key near-term policy actions

2015 2020 2025

Transport | Stationary

Fuel economy and low emission vehicle policies	Establish and strengthen fuel economy regulation and incentivise efficient vehicles through monetary measures like feebate schemes and CO_2 based vehicle taxation. Support the uptake of FCEVs through zero-emission-vehicle policies
Low carbon/ renewable fuel regulation	Incentivise the uptake of hydrogen as transport fuel through low carbon, sustainable fuel mandates
Vehicle "perks" and consumer information	Introduce the free use of public parking, the use of high occupancy vehicle (HOV) lanes, the use of bus lanes and the exemption from road tolls. Establish labelling schemes
Carbon pricing	Establish national, regional or international carbon pricing schemes.
Grid integration measures and easy grid access	Incentivise VRE operators to adopt grid integration measures. Facilitate entry into energy markets for energy storage technologies including power-to-fuel, power-to-power and power-to-gas
Benefits stacking	Enable benefit-stacking for energy storage systems
Codes and standards: safety, metering, type approval	Strengthen and harmonise international codes and standards necessary for safe and reliable handling and metering of hydrogen in end-use applications and establish a performance-based global technical regulation for FCEV type approval
Natural gas-hydrogen blend shares	Where necessary, establish natural gas-hydrogen blend quality and safety regulation

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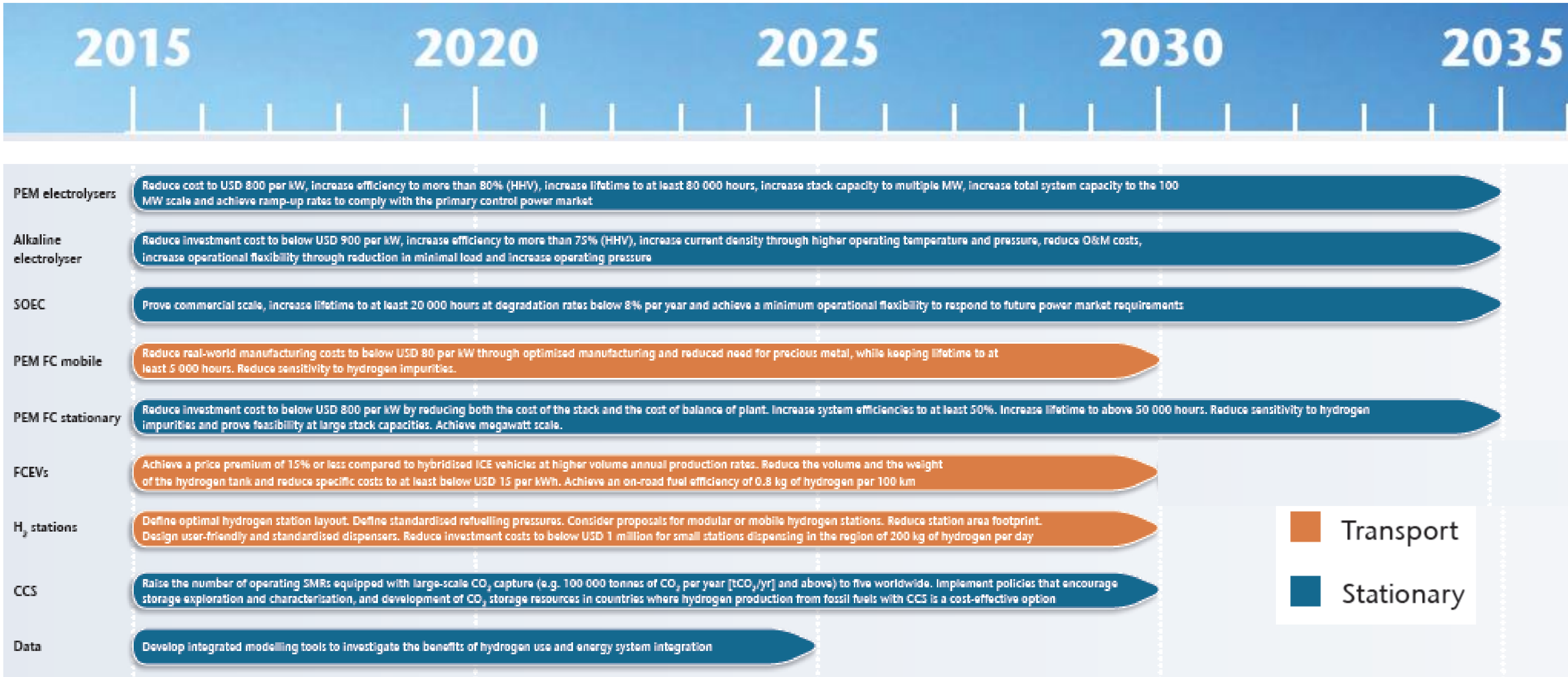
Technology development: longer-term target setting



- Electrolysers & Fuel cells
- T&D infrastructure (including H_2 stations)
- Carbon Capture and Sequestration

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Supplemental Slides

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Hydrogen and fuel cells in transport

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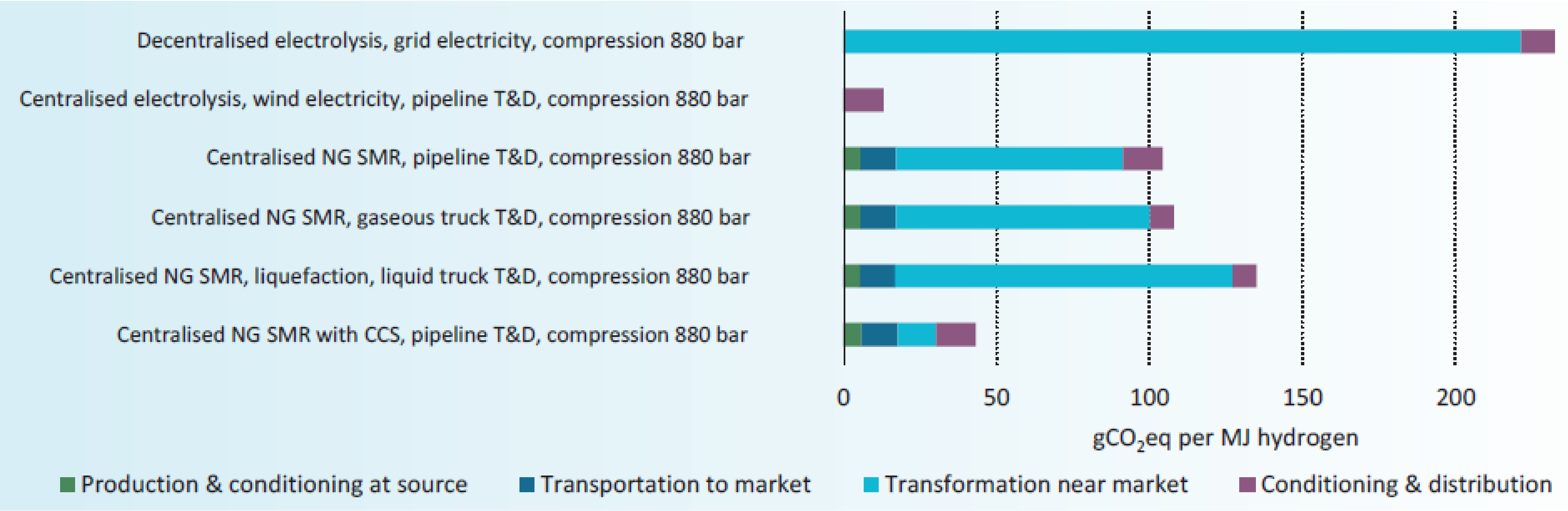
Carbon Intensity – GHG emissions

Today's carbon footprint for various hydrogen pathways and for gasoline and compressed natural gas in the European Union

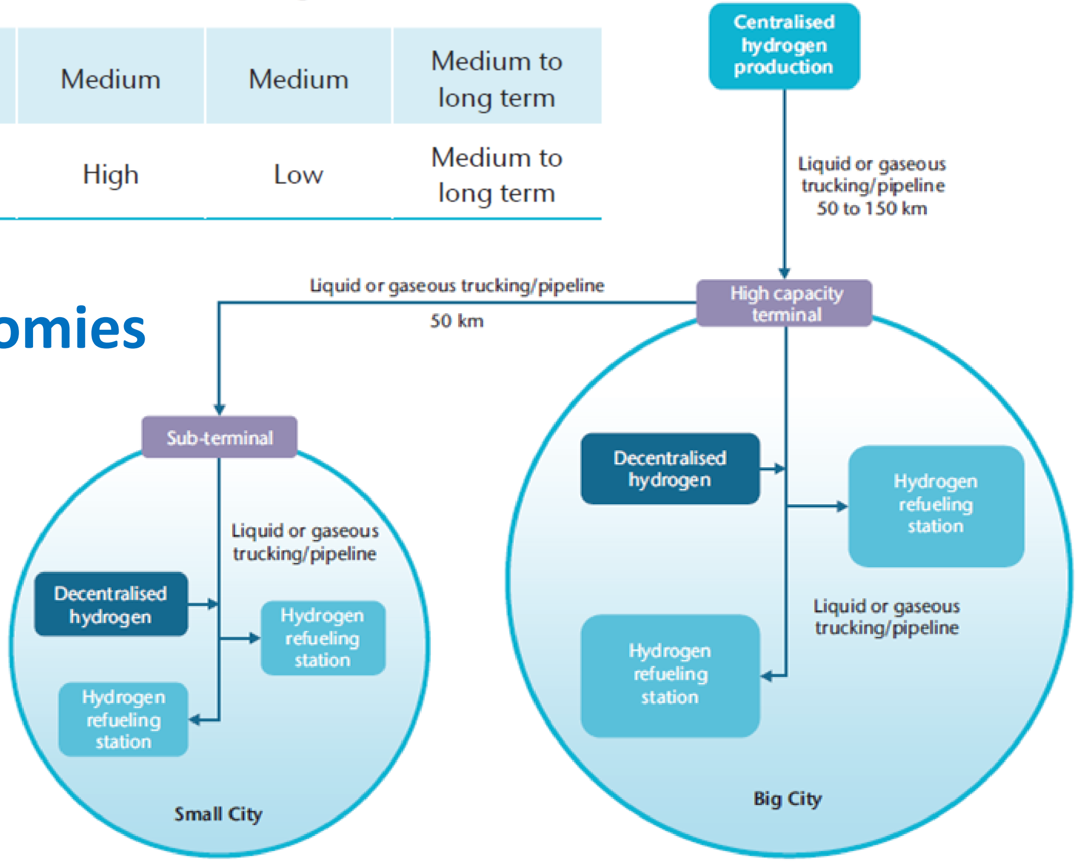


- **Tradeoffs between production, distribution, and storage costs, production capacity, and emissions**

Hydrogen T&D technologies for hydrogen delivery in the transport sector

	Capacity	*Transport distance*	*Energy loss*	*Fixed costs*	*Variable costs*	*Deployment phase*
Gaseous tube trailers	Low	Low	Low	Low	High	Near term
Liquefied truck trailers	Medium	High	High	Medium	Medium	Medium to long term
Hydrogen pipelines	High	High	Low	High	Low	Medium to long term

High cost sensitivity to economies of scale and aggregation



Scheme of hydrogen T&D and retail infrastructure as represented within the model

Distribution and storage technologies, current status

Current performance of hydrogen systems in the transport sector

Application	*Power or energy capacity*	*Energy efficiency**	*Investment cost***	*Lifetime*	*Maturity*
Fuel cell vehicles	80 - 120 kW	Tank-to-wheel efficiency 43-60% (HHV)	USD 60 000-100 000	150 000 km	Early market introduction
Hydrogen retail stations	200 kg/day	~80%, incl. compression to 70 MPa	USD 1.5 million-2.5 million	-	Early market introduction
Tube trailer (gaseous) for hydrogen delivery	Up to 1 000 kg	~100% (without compression)	USD 1 000 000 (USD 1 000 per kg payload)	-	Mature
Liquid tankers for hydrogen delivery	Up to 4 000 kg	Boil-off stream: 0.3% loss per day	USD 750 000	-	Mature

* Unless otherwise stated, efficiencies are based on lower heating values (LHV).

** All power-specific investment costs refer to the energy output.

Notes: HHV = higher heating value; kg = kilogram; kW = kilowatt.

- **Investments needed to reduce costs and improve performance**

Infrastructure – current status

Existing public hydrogen refuelling stations and targets announced by hydrogen initiatives

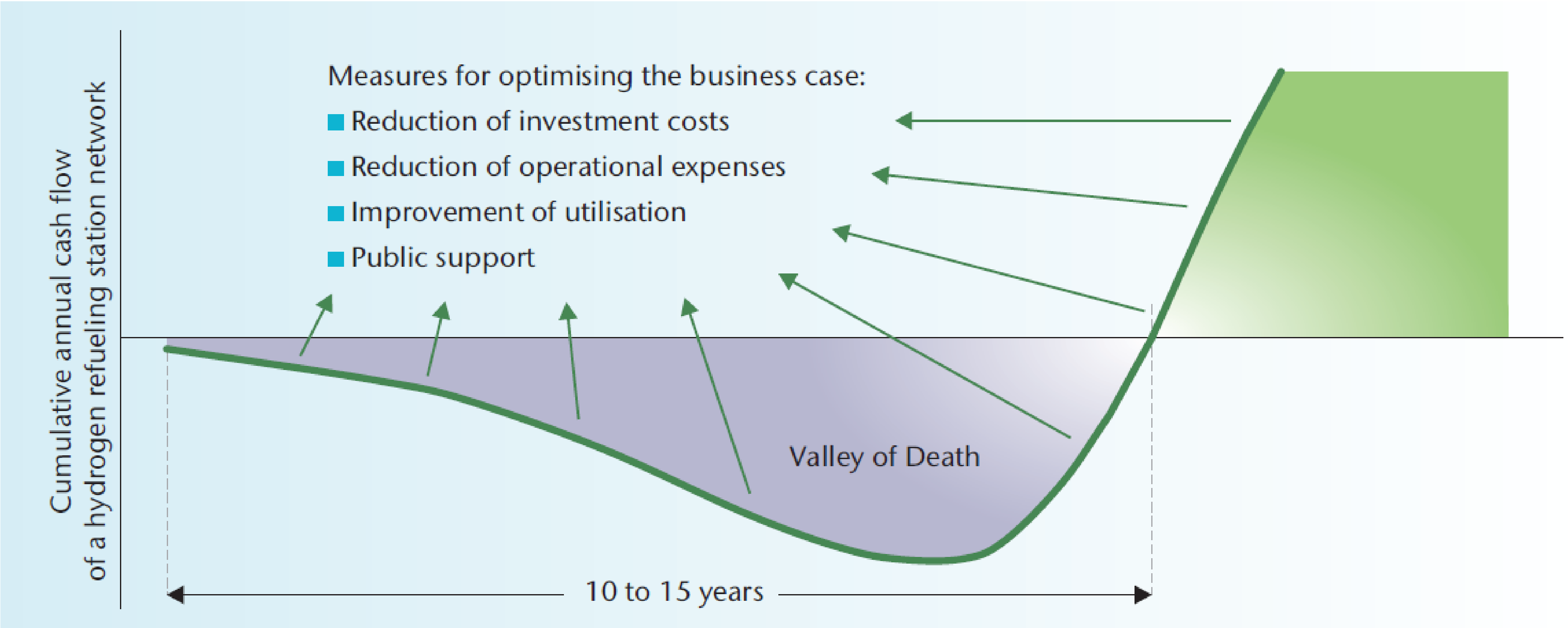
Country or region	Existing hydrogen refuelling stations	Planned stations	
		2015	2020
Europe	36	~80	~430
Japan	21	100	>100
Korea	13	43	200
United States	9	>50	>100

Existing FCEV fleet and targets announced by hydrogen initiatives

Country or region	Running FCEVs	Planned FCEVs on the road	
		2015	2020
Europe	192	5 000	~350 000
Japan	102	1 000	100 000
Korea	100	5 000	50 000
United States	146	~300	~20 000

- **Refueling and vehicle infrastructure are already emerging in key regions**

How much will it cost?
H_2 refueling station – cash flow curve



- **Due to high costs and under-utilisation of the hydrogen refueling infrastructure, the "valley of death" can last for 10 to 15 years.**
- **Small and clustered stations are needed to minimize the time of negative cash flow.**

Supplemental Slides - Summary

- Techno-economic assumptions and parameters
- Hydrogen and fuel cells for variable renewable energy integration
- Hydrogen and fuel cells in industry and buildings

H_2 in industry and buildings

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Current performance of fuel cell systems in the buildings sector

Application	Power or energy capacity	Energy efficiency*	Investment cost**	Life time	Maturity
Fuel cell micro co-generation	0.3-25 kW	Electric: 35-50% (HHV) Co-generation: up to 95%	<20 000 USD/kW (home system, 1 kW_e) <10 000 USD/kW (commercial system, 25 kW_e)	60 000-90 000 hours	Early market introduction

* = Unless otherwise stated efficiencies are based on LHV.

** = All investment costs refer to the energy output.

Notes: 1 kW_e = kilowatt electric output.

- Fuel cell micro co-generation systems are either based on a PEMFC or a solid oxide fuel cell (SOFC), the latter providing much higher temperature heat.
- Although systems with up to 50 kW electrical output exist, most commercially available systems have electrical power outputs of around 1 kW, therefore being insufficient to fully supply the average US or European dwelling.

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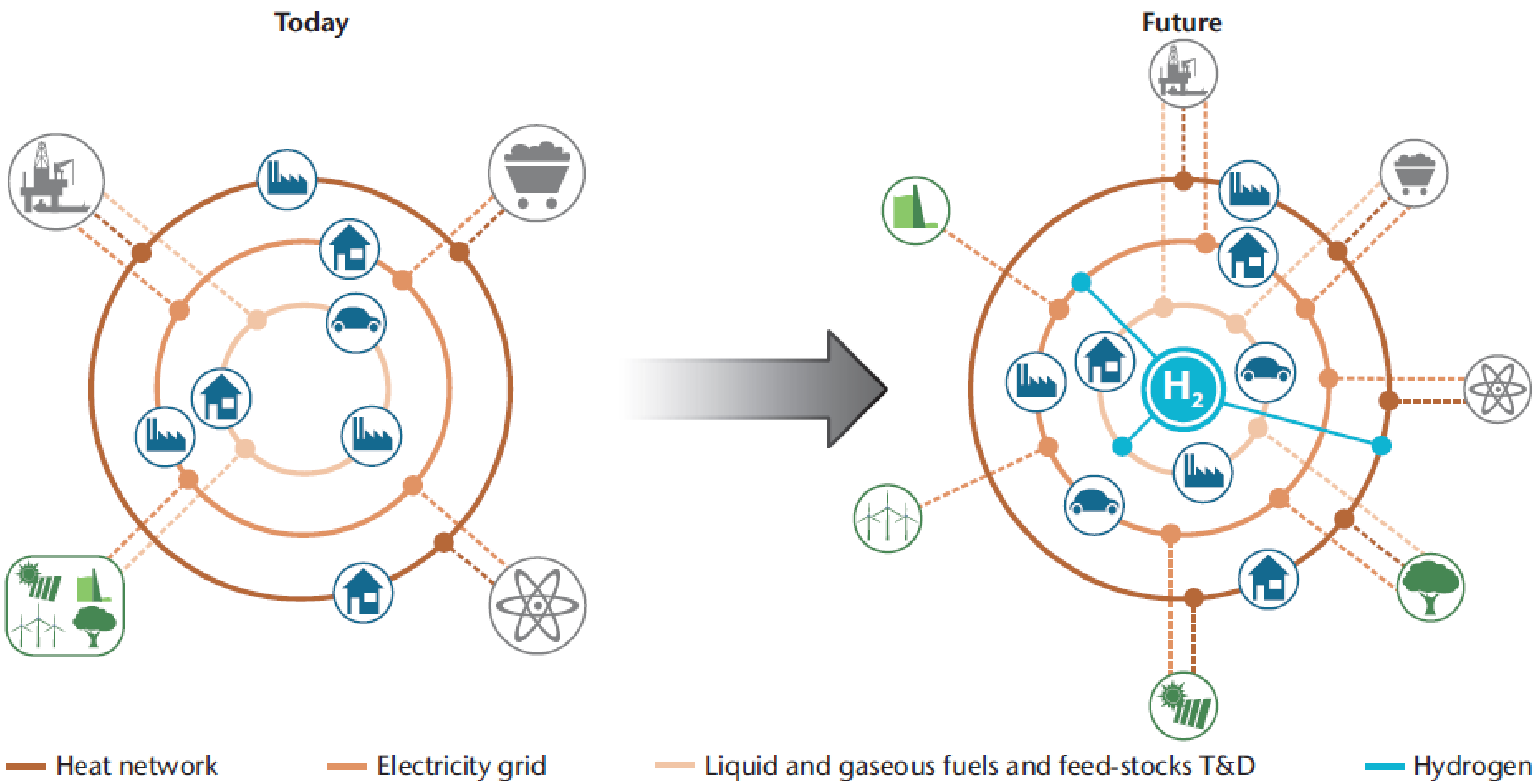
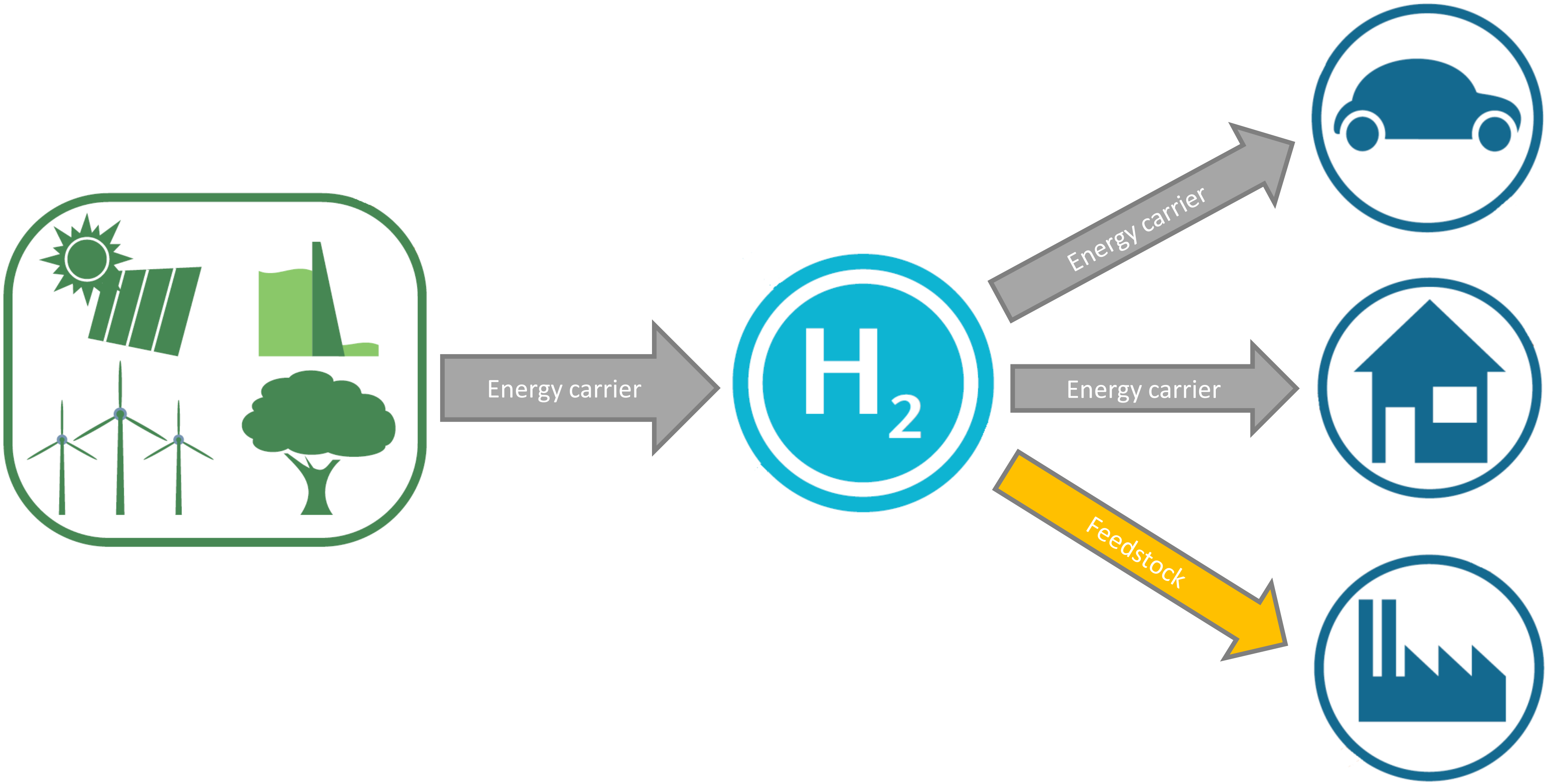
Why Hydrogen?



- Hydrogen is a flexible energy carrier that can be produced from any regionally prevalent primary energy source
- Hydrogen can be effectively transformed into any form of energy for diverse end-use applications

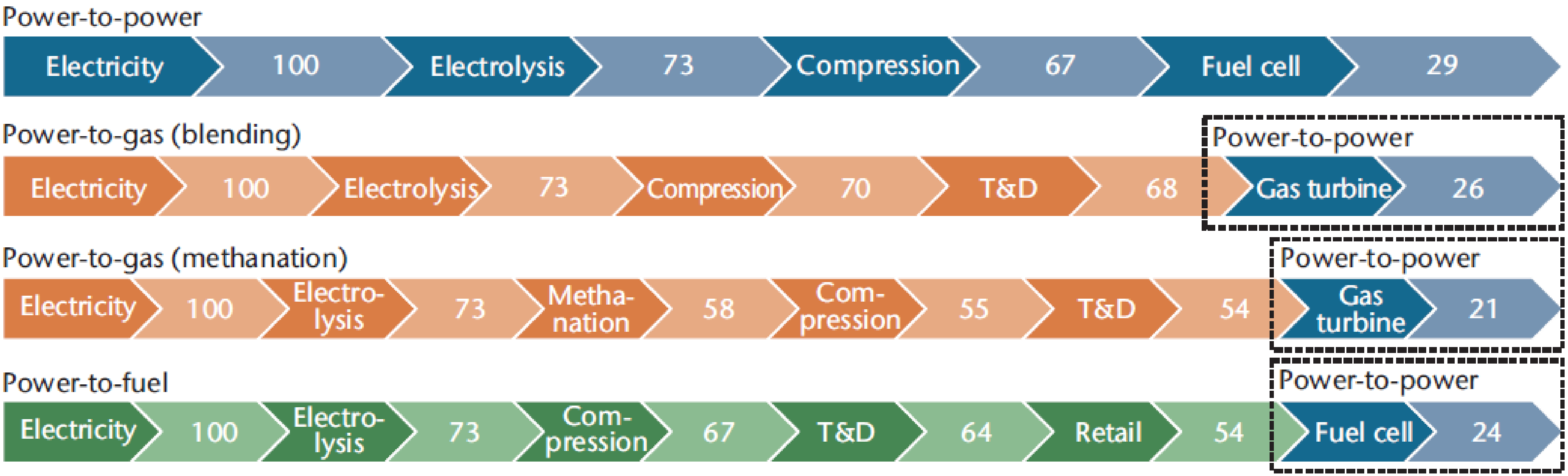
Hydrogen is a *low carbon footprint* energy carrier that can be stored



Surplus, low-value renewable electricity is used to split water into H2 and O2 with ***electrolysers***

Used as energy carrier, hydrogen can be efficiently transformed to electricity using ***fuel cells***

H_2 based "power-to-x" trajectories



- **Hydrogen based electricity storage applications can include power-to-power, power-to-gas and power-to-fuel trajectories.**
- **Round trip efficiencies are low – the availability of low value, surplus renewable electricity is a prerequisite for H_2 based electricity storage**

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Techno-economic assumptions & parameters

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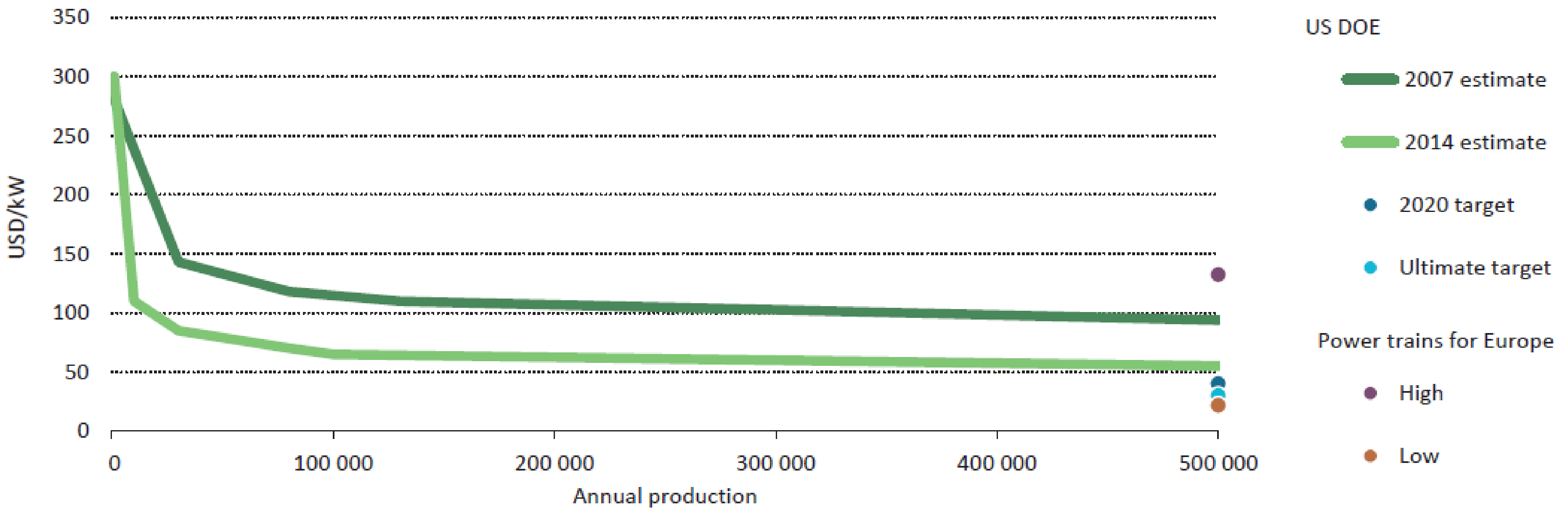
How much will it cost? Learning curves and cost targets

Production costs decline with annual production



- **Although current PEMFC systems for FCEVs cost around USD 300 to USD 500 per kW, cost can be reduced dramatically with economies of scale.**

Current and future costs based on learning curves

Cost of PLDVs by technology as computed in the model for the United States

	Today	2030	2050	Unit
Conventional ICE gasoline	28 600	30 900	32 300	USD
Conventional ICE diesel	29 300	31 700	33 100	USD
Hybrid gasoline	30 000	31 800	33 200	USD
Plug-in hybrid gasoline	32 400	33 200	34 400	USD
BEV (150 km)	35 400	32 800	34 000	USD
FCEV	60 000	33 600	33 400	USD

Techno-economic parameters of FCEVs as computed in the model for the United States

	Today	2030	2050	Unit
FCEV costs	60 000	33 600	33 400	USD
Thereof				
Glider*	23 100	24 100	25 600	USD
Fuel cell system**	30 200	4 300	3 200	USD
H_2 tank**	4 300	3 100	2 800	USD
Battery**	600	460	260	USD
Electric motor and power control**	1 800	1 600	1 400	USD
Specific costs				
Fuel cell system (80 kW)	380	54	40	USD/kW
H_2 tank (6.5 kg H_2)	20	14	13	USD/kWh
Battery (1.3 kWh)	460	350	200	USD/kW
Other parameters				
Tested fuel economy	1.0	0.8	0.6	Kg H_2/100 km
Life time	12	12	12	Years

* future cost increase is due to light-weighting, improved aerodynamics, low resistance tyres and high efficient auxiliary devices.

** future costs are based on learning curves with learning rates of 10% (H_2 tank), 15% (electric motor, power control, battery) and 20% (fuel cell system) per doubling of cumulative deployment.

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Hydrogen and fuel cells for variable renewable energy integration

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Current performance of H_2 generation technologies

Application	Power or capacity	Fflciency*	Initial investment cost	Life time	Maturity
Steam methane reformer, large scale	150-300 MW	70-85%	400-600 USD/kW	30 years	Mature
Steam methane reformer, small scale	0.15-15 MW	~51%	3 000-5 000 USD/kW	15 years	Demon-stration
Alkaline electrolyser	Up to 150 MW	65-82% (HHV)	850-1 500 USD/kW	60 000-90 000 hours	Mature
PEM electrolyser	Up to 150 kW (stacks) Up to 1 MW (systems)	65-78% (HHV)	1 500-3 800 USD/kW	20 000-60 000 hours	Early market
SO electrolyser	Lab scale	85-90% (HHV)	-	~1 000 h	R&D

* = Unless otherwise stated efficiencies are based on LHV.

** = All investment costs refer to the energy output.

Notes: PEM = proton exchange membrane; SO = solid oxide.

- **Around 48% of hydrogen is currently produced from natural gas using the SMR process**

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Deployment potential of different electrolyser technologies

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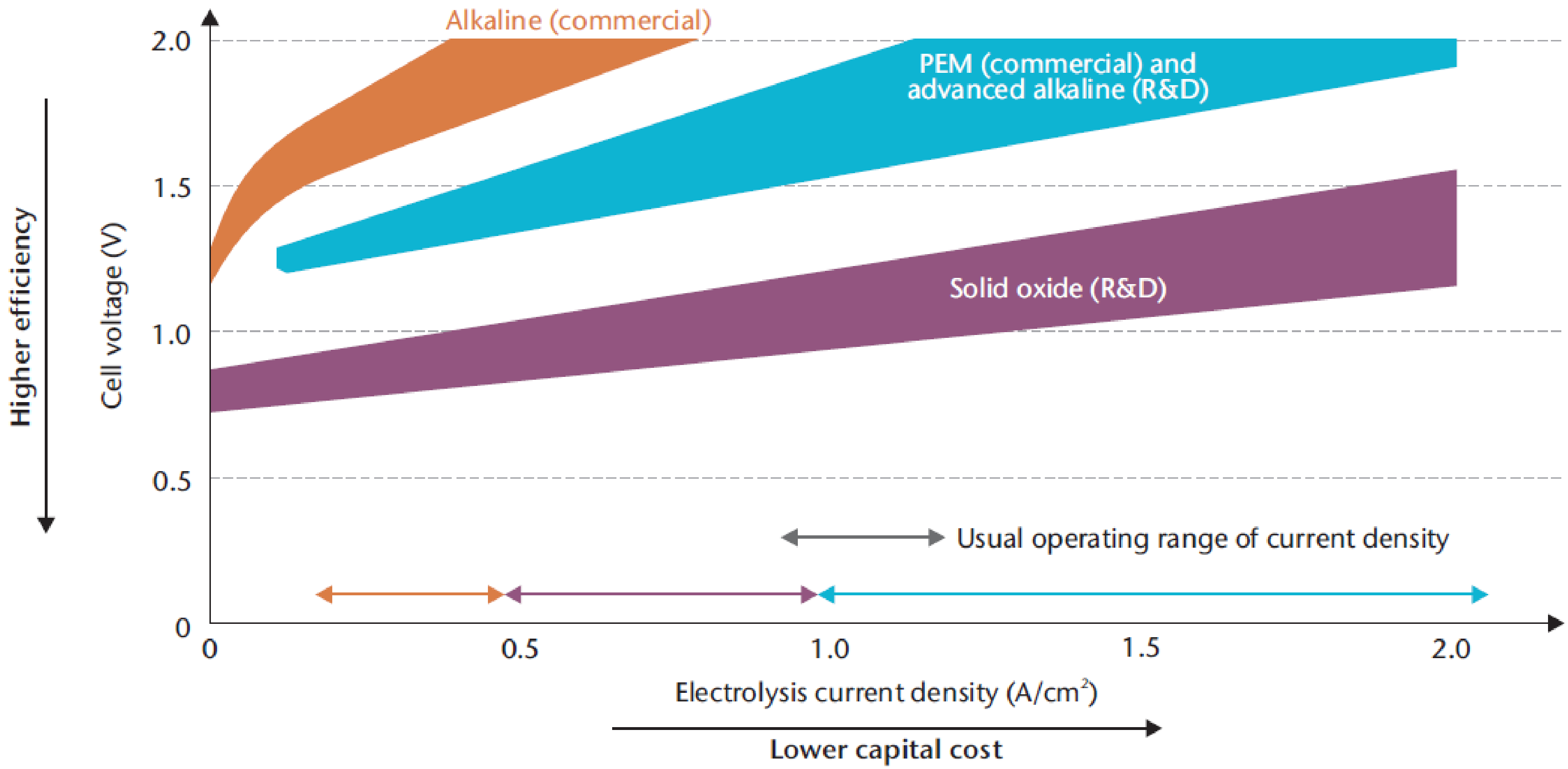
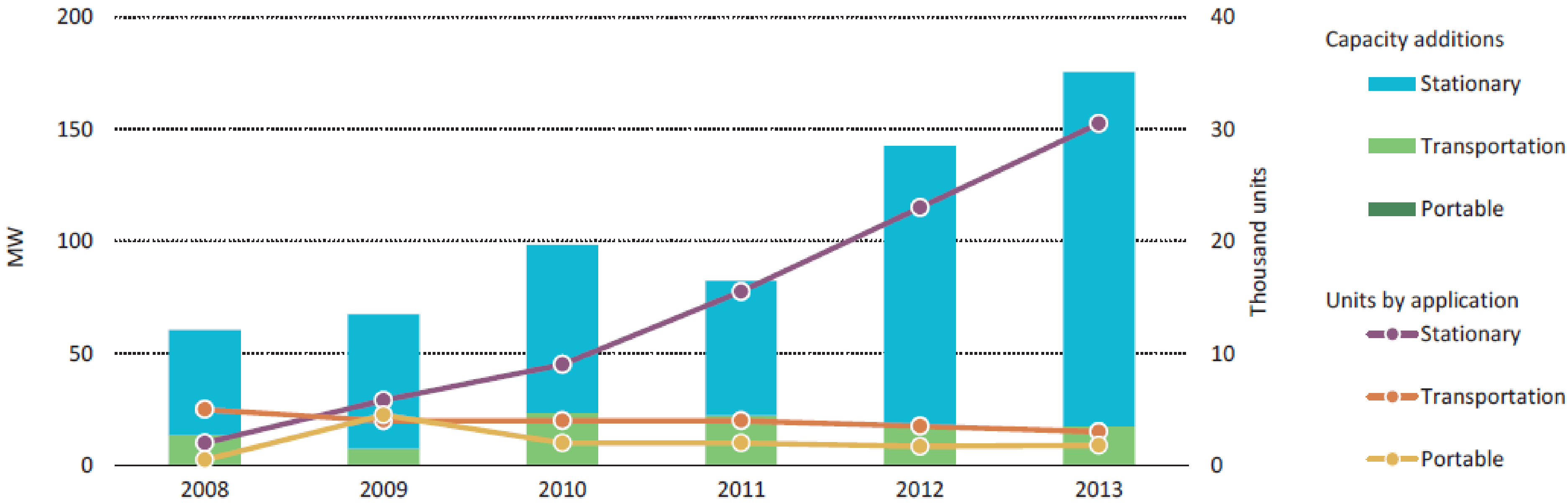


Note: A/cm² = ampere per square centimetre.

- **Although alkaline electrolysers are a mature and affordable technology, PEM and SO electrolysers show a greater potential to reduce capital costs and to increase efficiency.**

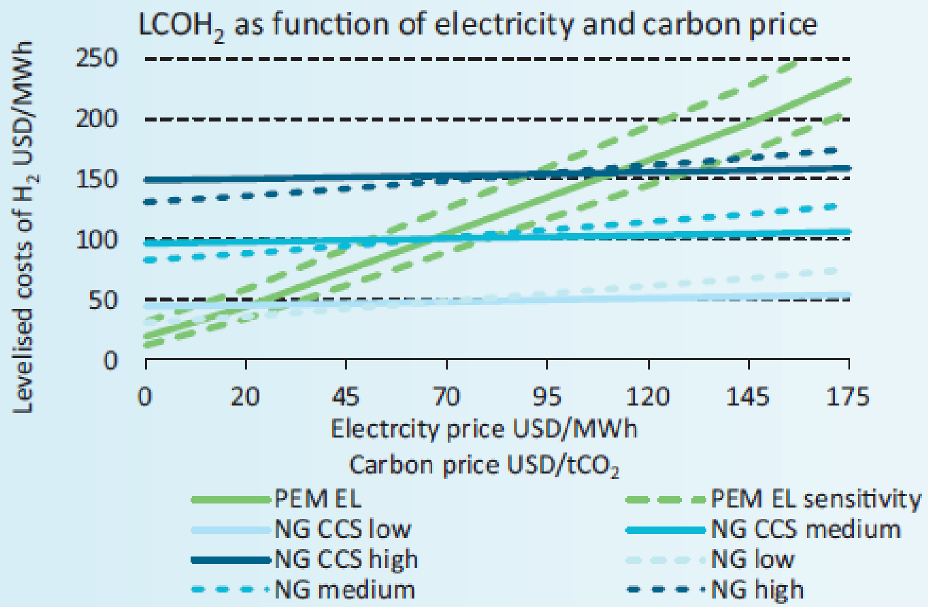
H_2 conversion – fuel cells

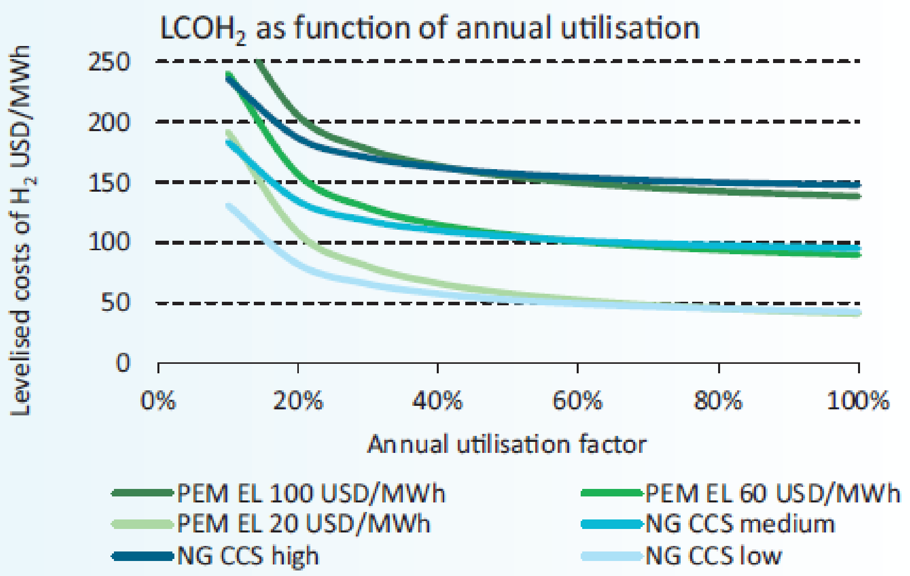
Production volumes of fuel cells according to application



- **Currently, more than 80% of all fuel cells sold are used in stationary applications.**

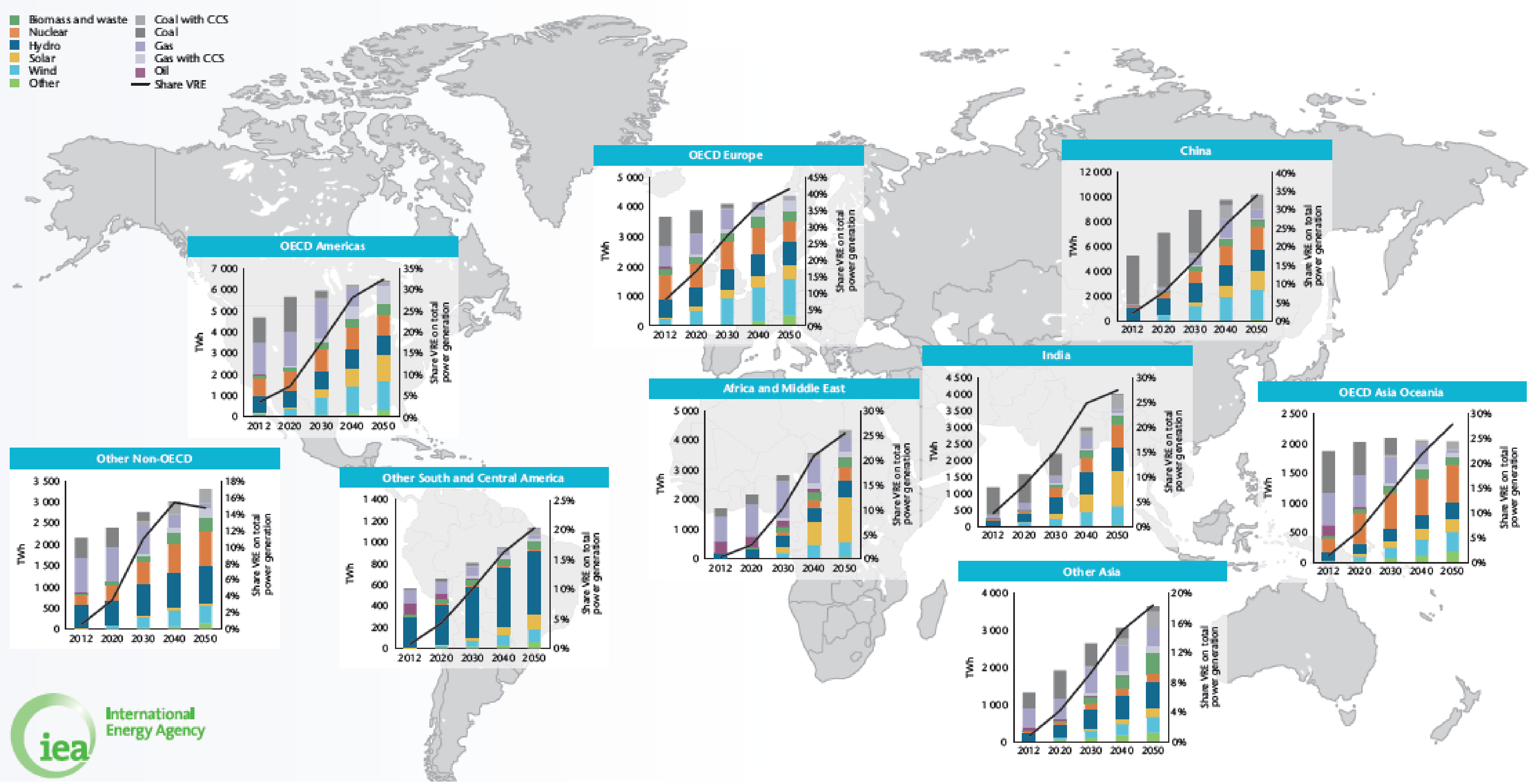
The economics of renewable hydrogen



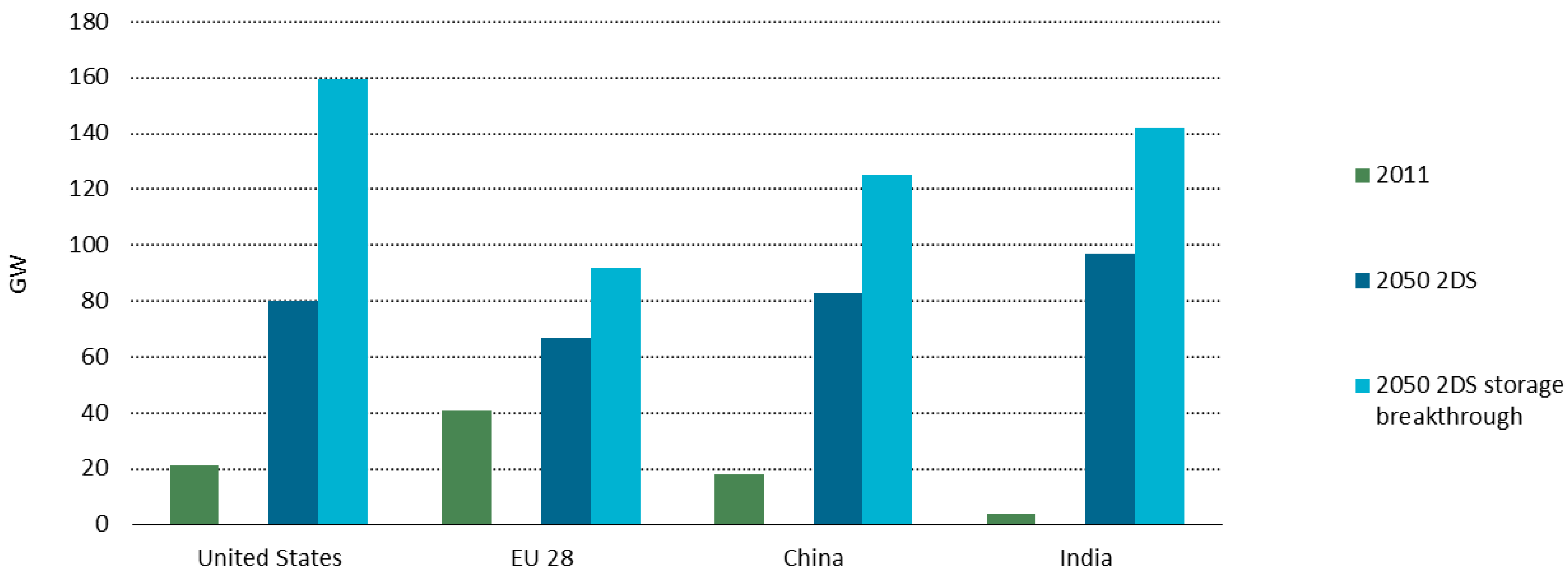


- **Low-carbon electrolytic hydrogen requires low-cost renewable electricity and a combination of higher natural gas and carbon prices to be cost competitive.**

Variable renewable power in the 2DS

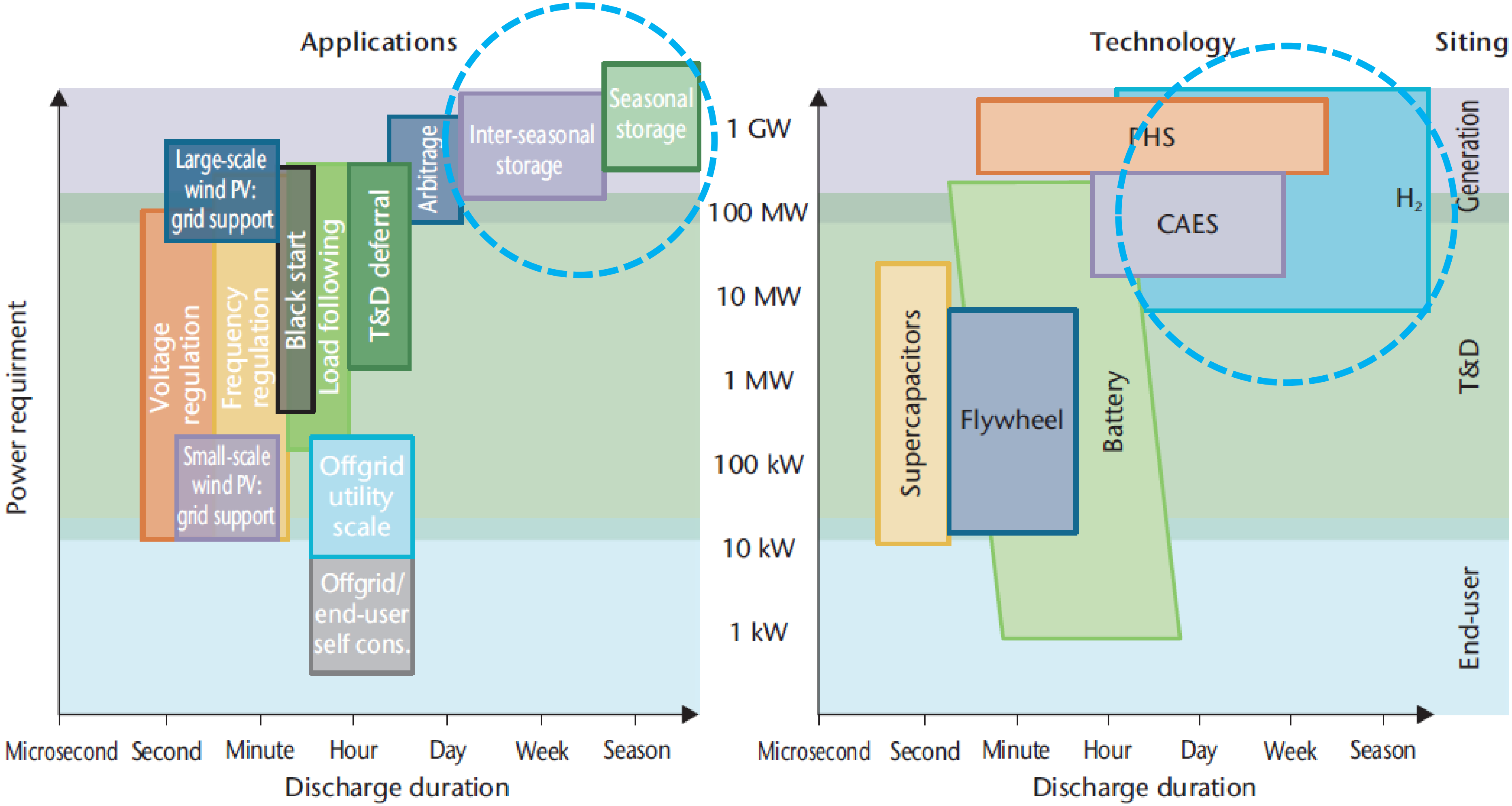


Electricity storage potential in the 2DS



- Under the 2DS, electricity storage accounts for up to 8% of total installed power capacity.
- Annual electricity output from energy storage reaches shares of between 3% and 9% of total VRE power generation.

Hydrogen-based electricity storage



Note: CAES = compressed air energy storage; PHS = pumped hydro energy storage.

- Hydrogen-based electricity storage covers large-scale and long-term storage applications.

Hydrogen-based large-scale energy storage

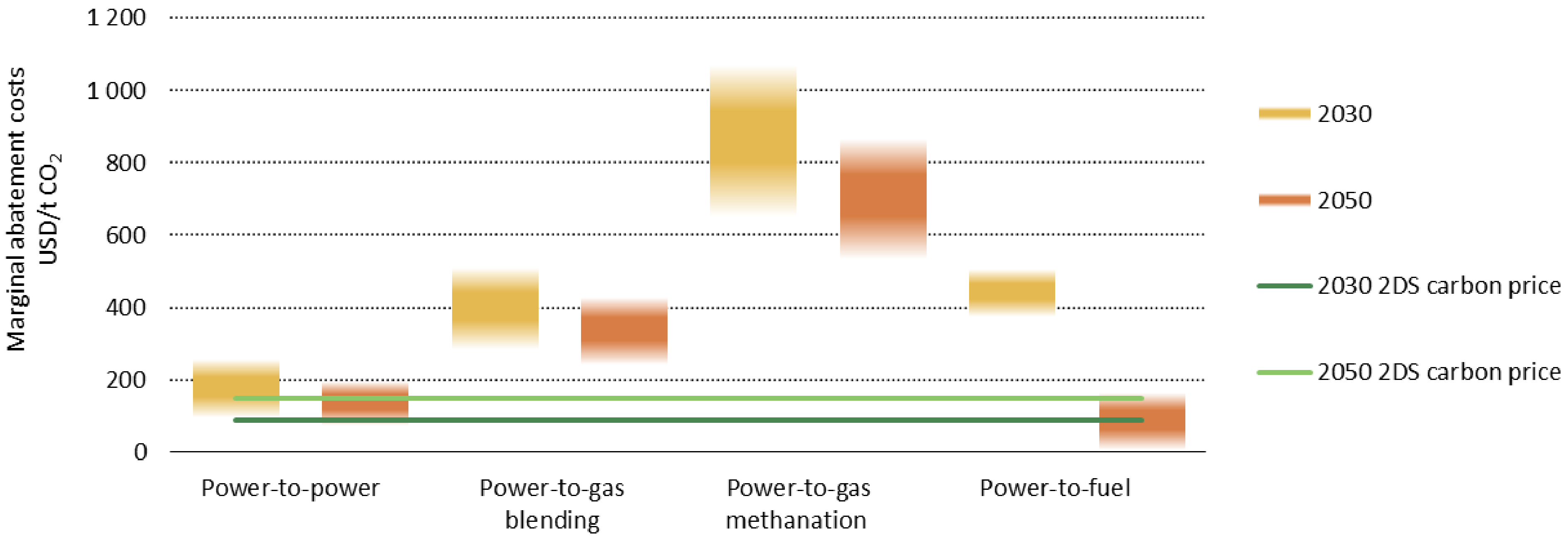
Application	Power or energy capacity	Energy efficiency*	Investment cost**	Lifetime	Maturity
Power-to-power (including underground storage)	GWh to TWh	29% (HHV, with alkaline EL) - 33% (HHV, with PEM EL)	1 900 (with alkaline EL) - 6 300 USD/kW (with PEM EL) plus ~8 USD/kWh for storage	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration
Underground storage	GWh to TWh	90-95%, incl. com-pression	~8 USD/kWh	30 years	Demonstration
Power-to-gas (hydrogen-enriched natural gas, HENG)	GWh to TWh	~73% excl. gas turbine (HHV) ~26% incl. gas turbine (PtP)	1 500 (with alkaline EL) - 3 000 USD/kW (with PEM EL), excl. gas turbine 2 400 (with alkaline EL) - 4 000 USD/kW (with PEM EL), incl. gas turbine (PtP)	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration
Power-to-gas (methanation)	GWh to TWh	~58% excl. gas turbine (HHV) ~21% incl. gas turbine (PtP)	2 600 (with alkaline EL) - 4 100 USD/kW (with PEM EL), excl. gas turbine 3 500 (with alkaline EL) - 5 000 USD/kW (with PEM EL), incl. gas turbine (PtP)	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration

* = Unless otherwise stated, efficiencies are based on LHV.

** = All investment costs refer to the energy output.

Notes: excl. = excluding; incl. = including; PtP = power-to-power; GWh = gigawatt hour; TWh = terawatt hour.

Abatement costs of hydrogen based variable renewable energy integration



- ***In the long term, power-to-fuel applications offer the lowest marginal abatement costs to integrate otherwise curtailed renewable power in the energy system.***

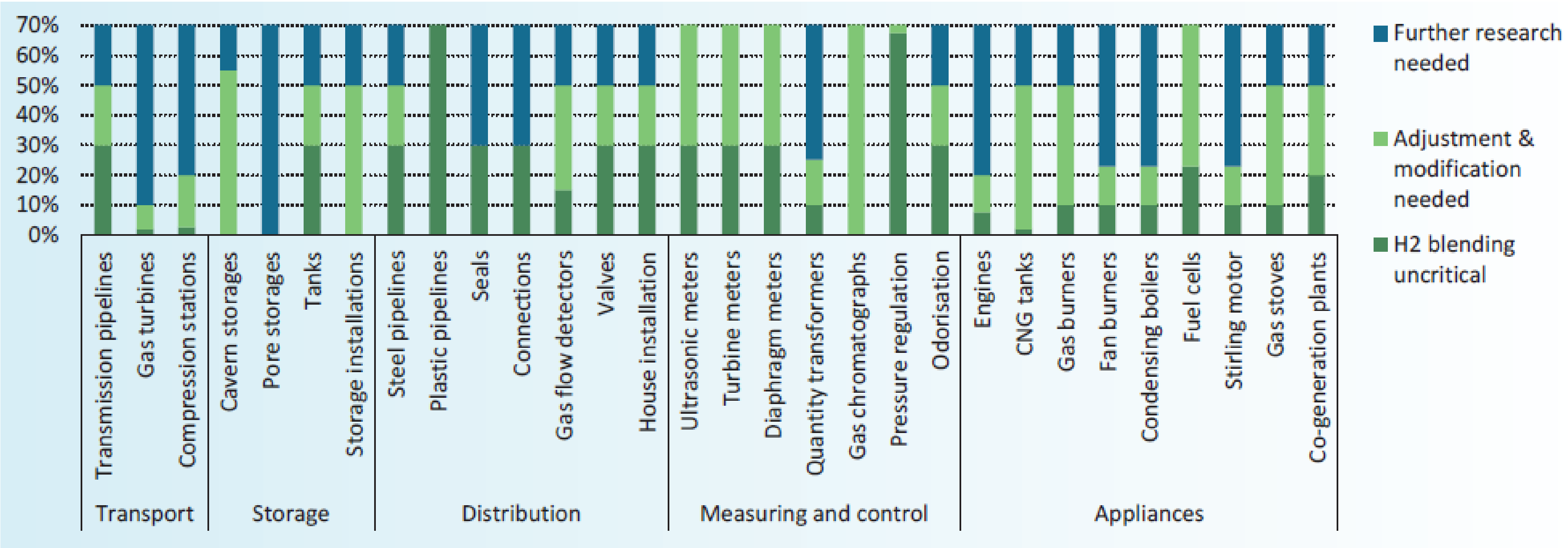
Characteristics of geological formations suitable for hydrogen storage

	Salt caverns	Depleted oil fields	Depleted gas fields	Aquifers	Lined rock caverns	Unlined rock caverns
Safety	++	+	-	-	-	-
Technical feasibility	+	++	++	++	o	-
Investment costs	++	o	o	o	+	+
Operation costs	++	-	o	+	++	+

Source: adapted from HyUnder (2013), *Assessment of the Potential, the Actors and Relevant Business Cases for Large Scale and Seasonal Storage of Renewable Electricity by Hydrogen Underground Storage in Europe - Benchmarking of Selected Storage Options*.

- **A geological formation can be suitable for hydrogen storage if:**
  - tightness is assured,
  - the pollution of the hydrogen gas through bacteria or organic and non-organic compounds is minimal, and
  - the development of storage and the borehole is possible at acceptable costs.
  - Actual availability of suitable geological formations is another limiting factor.

Limitations on the blend share of hydrogen by application



- **Blending hydrogen into the natural gas grid faces several limitations:**
  - H_2 can embrittle steel materials (pipelines & pipeline armatures), which necessitates upper blending limits of around 20% to 30%, depending on the pipeline pressure and regional specification of steel quality.
  - The much lower volumetric energy density of hydrogen compared to natural gas significantly reduces both the energy capacity and efficiency of the natural gas T&D system at higher blend shares.

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Techno-economic parameters

- The Roadmap is a rich source of techno-economic parameters from leading hydrogen researchers around the world

Application	Power or capacity	Efficiency *	Initial investment cost	Life time	Maturity
Alkaline FC	Up to 250 kW	~50% (HHV)	USD 200-700/kW	5 000-8 000 hours	Early market
PEMFC stationary	0.5-400 kW	32%-49% (HHV)	USD 3 000-4 000/kW	~60 000 hours	Early market
PEMFC mobile	80-100 kW	Up to 60% (HHV)	USD ~500/kW	<5 000 hours	Early market
SOFC	Up to 200 kW	50%-70% (HHV)	USD 3 000-4 000/kW	Up to 90 000 hours	Demon-stration
PAFC	Up to 11 MW	30%-40% (HHV)	USD 4 000-5 000/kW	30 000-60 000 hours	Mature
MCFC	KW to several MW	More than 60% (HHV)	USD 4 000-6 000/kW	20 000-30 000 hours	Early market
Compressor, 18 MPa	-	88%-95%	USD ~70 /kWH_2	20 years	Mature
Compressor, 70 MPa	-	80%-91%	USD 200-400/kWH_2	20 years	Early market
Liquefier	15-80 MW	~70%	USD 900-2 000/kW	30 years	Mature
FCEV on-board storage tank, 70 MPa	5 to 6 kg H_2	Almost 100% (without compression)	USD 33-17/kWh (10 000 and 500 000 units produced per year)	15 years	Early market
Pressurised tank	0.1-10 MWh	Almost 100% (without compression)	USD 6 000-10 000/MWh	20 years	Mature
Liquid storage	0.1-100 GWh	Boil-off stream: 0.3% loss per day	USD 800-10 000/MWh	20 years	Mature
Pipeline	-	95%, incl. compression	Rural: USD 300 000-1.2 million/km Urban: USD 700 000-1.5 million /km (dependent on diameter)	40 years	Mature

* = Unless otherwise stated efficiencies are based on LHV.

** = All investment costs refer to the energy output.

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