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Strategic roadmap for Hydrogen in the rail transportation sector

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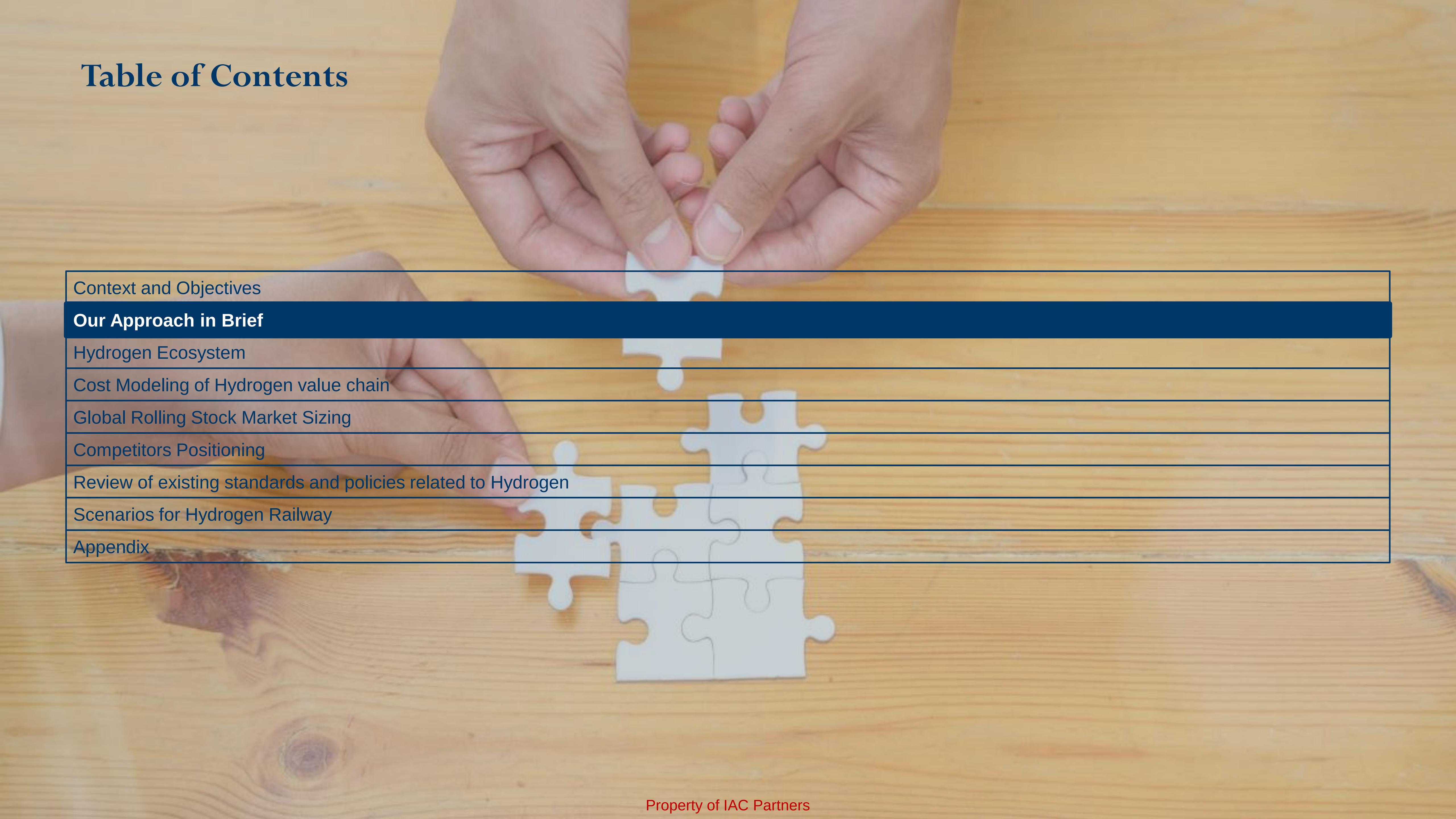
Context & objectives

Context

- Hydrogen is expected to play a critical role in the transportation sector as a source of fuel and as a resource for producing clean electricity
- In the railway sector, hydrogen seems to be a promising option, for example to replace diesel combustion engines
- However, technological, regulation, and infrastructural remaining barriers are still to be crossed to bring the solution to the market on a large scale and at the right cost

Objectives

- Evaluate market trends & competitive structure for Hydrogen in the railway sector: *e.g. business potential and revenue model, competition, strategic drivers, enablers and trends*
- Derive the strategic roadmap: *e.g. macro-planning, required resources, potential organic & external growth levers*



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IAC Partners Approach for Room-to-win

Combine an understanding of use cases scenarios for railway with the hydrogen market to identify application key success factors

1. Room-to-Win

Hydrogen ecosystem
Market & business forecasts

×

H2 for Railway
Scenarios & impacting factors

=

Key Success Factors

Objectives

Understand evolution of hydrogen operating models and costs per application

Understand evolution of hydrogen operating models and costs per application

Maximize synergies and precise trains use cases. Derive key success factors

Activities

1.1 Study hydrogen market (from production to fuel cells)
- Segmentation per application, production/ storage technologies
- Value chains per application x technology
- Ecosystem analysis: players positioning and moves along the value chain
- Regulation and standards: trends, milestones

1.2 Build costs forecasts scenarios Volumes forecasts over time / technology
- Costs models per supply chain scenario: e.g. centralized/ decentralized production, liquid vs gas transportation
- Zoom on fuel cell market trends and volumes and cost forecast per class

2.1 Segment railway + bus derived market
- Railway market segmentation
- Infrastructure analysis: growth, trends, geographical diversity

2.2 Characterize considered technical & operating scenarios
- Technical solutions maturity and feasibility: e.g. fuel cells
- Foreseen infrastructure and operating impact: refueling, maintenance, safety and end of life

2.3 Identify success conditions for ramping up
- Define relevant criteria to evaluate scenarios: CAPEX, OPEX (e.g. €/km), weight, volume, impact on infrastructure
- Evaluate targets to penetrate market segments

3.1 Build value chain and operating model for H2
- Potential value chains: spot synergies with other applications
- Evaluate CAPEX x OPEX x roadmap / scenario. Compare with the target
- Derive key success conditions behind each scenario: supply chain, infrastructure, H2 & operating costs
- Prioritize most relevant scenarios with a total cost approach
- Comparison with other green solutions

3.2 Derive key success factors
- 5 Porter forces analysis
- Opportunities and Threats
- Key success factors: organization, ecosystem, CAPEX, etc.

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Technology roadmap snapshot of 2020 shows diverse maturity of Hydrogen across use cases

Hydrogen Use Cases			**Industry**	**Power**	**Building**	**Mobility**
Technology Readiness Levels:			**Feedstock** for production of ammonia fertilizers & steel	A **gap-filler** between variable production & demand	A progressive **substitute** to fossil fuels used for heating	A **new energy vector** for mobility applications
System Ready	9	Qualified system with **proof of successful use** – product	Petrochemical	(Regenerative) fuel cell Storage	Heating	Buses Cars Forklifts
	8	Qualified system with **proof of functional capability** in area of use – product				Trains Trucks
Prototype in work	7	Prototype in use – **demonstration almost to scale in the operational environment**	Decarbonized steel production			
	6	Prototype in operational environment – **technical feasibility demonstrated** in the area of application				Propeller aircraft
Experimental Tests	5	Experimental setup in operational environment – **key technology elements tested** in a relevant environment	'Green' ammonia fertilizers			
	4	Experimental setup in **lab** environment – **key technology elements tested**				Jet

Especially H2 powered vehicles start to scale-up on a global level with solid business potential – commercial aviation and ships lagging behind

Mobility		Forklifts	Cars	Buses I Trucks	Trams & Railways	Aviation	Ships
Market Readiness		●	●	●	●	◐	○
Commercial Solutions		 Toyota  Linde – FC 35	 Renault - KangooZE  Hyundai - Nexo	 Solaris - Urbino 12  Hyundai - XCIENT	 ALSTOM - iLint  CRRC – H2 Tram	n/a	n/a
Final Stage of Development		Mature technology – key players already commercialized Forklifts (new Players can penetrate the market)	 Toyota - Mirai  BMW – i Hydrogen Next X5	 Daimler – Citaro FC  Nikola – tre hydrogen	 Siemens – Mireo  Stadler – H2 Flirt	 ZeroAvia  Apus - i-2	n/a
Business Potential	2020	31.000	15.000	4.000	100	UAV	Demonstration
In number of products	2030	350.000	8.000.000	100.000	1.100	Biz Jets/ Small Aircrafts	Prototype

● Commercialized ◐ Development ○ Demonstration I Pilots

[1]Chosen examples

[2] Uninhabited Aerial Vehicle

Local governments are investing heavily in a "hydrogenized" world - formulating dedicated hydrogen strategies to address regulatory barriers and stabilize investment climate

	🇺🇸	🇰🇷	🇨🇳	🇩🇪	🇫🇷	🇬🇧	🇪🇺
Time	**July 2020**	**June 2018**	**June 2019**	**June 2020**	**June 2020**	**Sept 2019**	**July 2020**
Budget	**$64 million**	**$22 billion**	**$17 billion**	**€9 billion**	**€1.5 billion**	**£12 billion**	**€145 billion**
Objectives	Support for industry and academia to **scale-up America's hydrogen economy** (US Department of Energy)	Develop private-public **Industry ecosystem for Hydrogen fueled vehicles** by **2022.**	Develop **fuel cell industry** and **H2 mobility supply chain** by **2023**.	Ramp up **Hydrogen production** capacity to **5 GW by 2030** and **10 GW by 2040**	Develop a **carbon-neutral aircraft** by **2035** (Prototype -2028)	Deployment of a **4GW floating wind farm** for **hydrogen production** in the **early 2030s.**	**Scale up** an innovative **new hydrogen manufacturing industry**, to recover economic growth after the Covid-19 crisis.
Main Projects & Initiatives	3M to develop advanced manufacturing equipment for "gigawatt-scale" proton exchange membrane electrolysis technology	South Korea's priorities are leadership in fuel cell cars and large-scale stationary fuel cells for power generation.	China's industrial hub Hebei approved 43 H^2 projects for production, equipment manufacturing, filling stations and fuel cells	German steel giant Thyssenkrupp and the country's largest utility, RWE to forge a long-term green hydrogen alliance	France's ambitions for a zero-carbon plane include a reworking of the popular Airbus A320 product line by 2030 and the move to hydrogen fuel by 2035.	ITM Power uses power from Ørsted's Hornsea One offshore wind farm to generate U.K.'s first green hydrogen using 100 MW of electrolyzers.	Develop renewables-based hydrogen production, scale up hydrogen infrastructure and storage and increase the penetration rate of hydrogen in its applications

3 different hydrogen production paths compete for the best trade-off between economical and ecological KPIs

Thermochemical conversion
- Coal + Grid
- Natural gas + Grid
- Biomass + Grid

Electrolysis
- H20 + Grid
- H20 + Local renewables

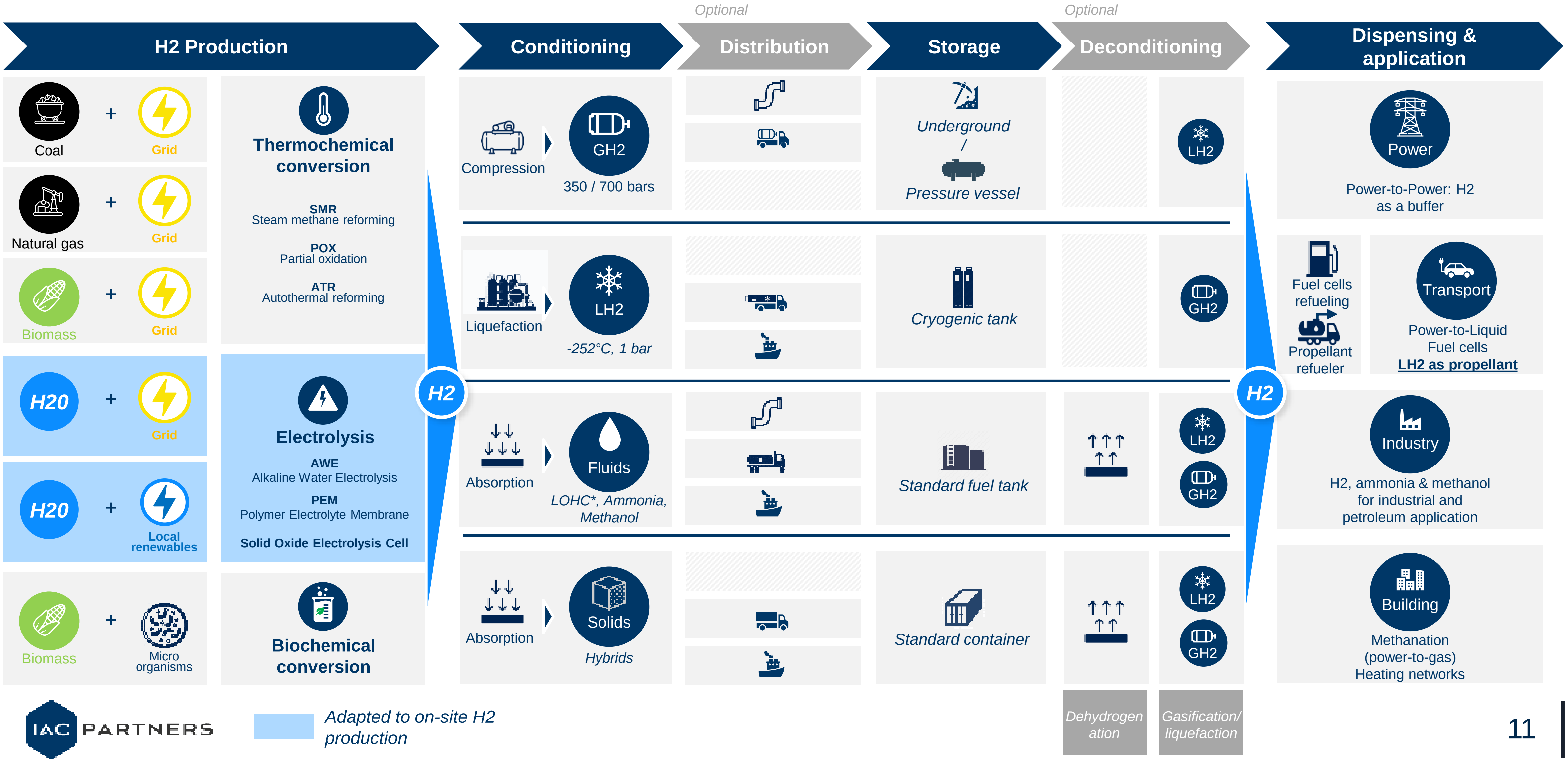
Biochemical conversion
- Biomass + Micro organisms

Different “shades of green”

CO_2 emissions from hydrogen production depends on technology and energy mix

	Grey H2	Blue H2	Green H2
Characteristics	Produced from fossil fuels via carbon intensive processes (96% of all hydrogen today)	Grey hydrogen whose CO2 emitted during production, sequestered via carbon capture and storage	Low or zero-emission hydrogen produced using clean, renewable energy sources
Types	• Gasification – coal / lignite • Steam methane reforming	• Grey with CCS* • Grid electrolysis	• Electrolysis from low-carbon renewables source
CO2-Footprint	🟥🟥🟥	🟨🟨	🟩
Cost	🟩	🟨🟨	🟥🟥🟥

Hydrogen value chain - We identify multiple production and supply patterns, whose selection for a given application will depend on several parameters



Optional

Optional

H2 Production

Conditioning

Distribution

Storage

Deconditioning

Dispensing & application

Coal + Grid

Natural gas + Grid

Biomass + Grid

Thermochemical conversion

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

H20 + Grid

H20 + Local renewables

Electrolysis

AWE
Alkaline Water Electrolysis

PEM
Polymer Electrolyte Membrane

Solid Oxide Electrolysis Cell

Biomass + Micro organisms

Biochemical conversion

H2

Compression – GH2 – 350 / 700 bars

Underground / Pressure vessel

LH2

Liquefaction – LH2 – *-252°C, 1 bar*

Cryogenic tank

GH2

Absorption – Fluids – *LOHC*, Ammonia, Methanol*

Standard fuel tank

LH2

GH2

Absorption – Solids – *Hybrids*

Standard container

LH2

GH2

Dehydrogenation

Gasification/ liquefaction

H2

Power

Power-to-Power: H2 as a buffer

Fuel cells refueling

Propellant refueler

Transport

Power-to-Liquid

Fuel cells

LH2 as propellant

Industry

H2, ammonia & methanol for industrial and petroleum application

Building

Methanation (power-to-gas)

Heating networks

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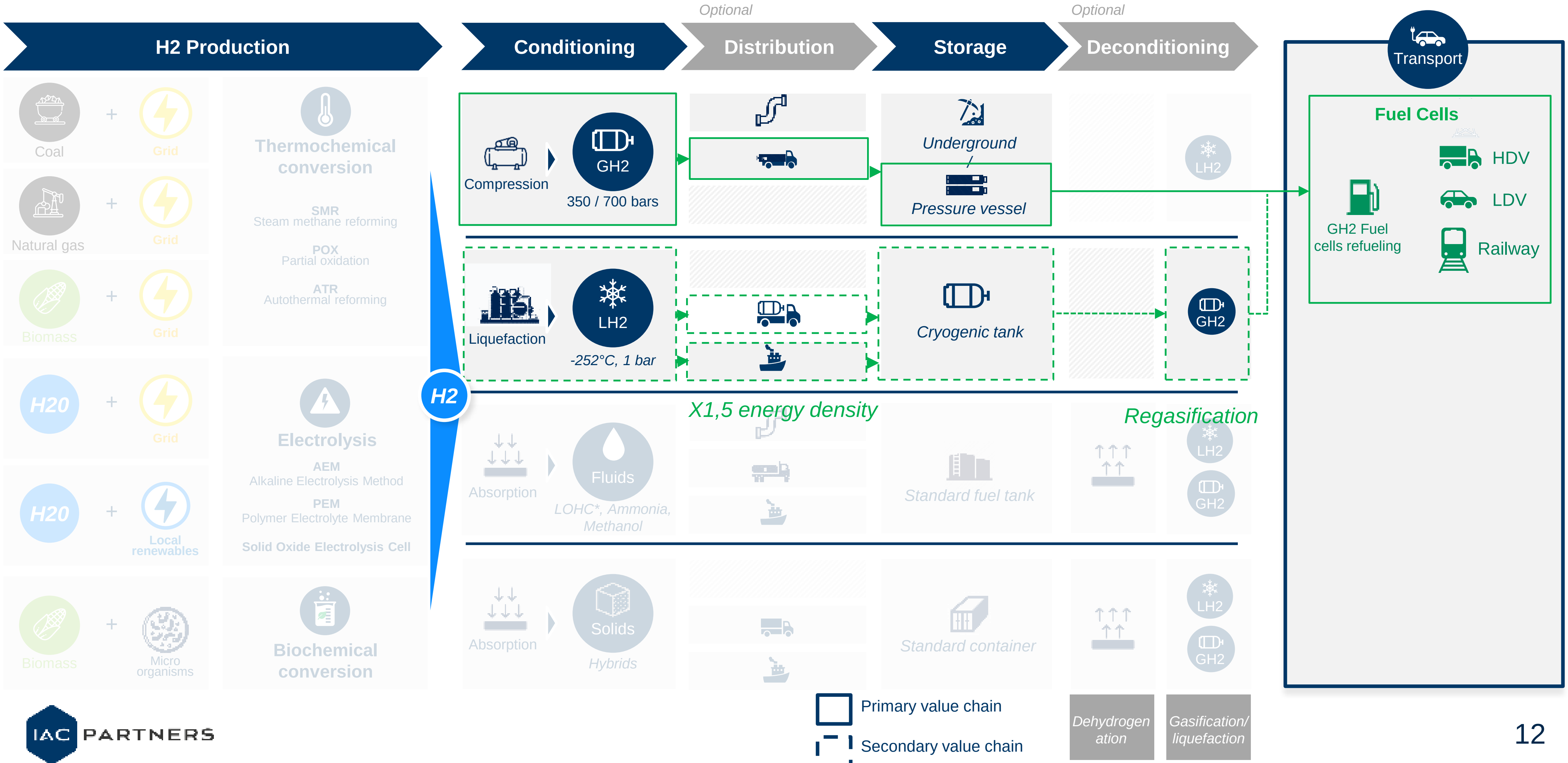
🟦 *Adapted to on-site H2 production*

**Liquid Organic Hydrogen carrier*

Property of IAC Partners

2020 picture - Focus on transport – Identified supply patterns



Optional

Optional

H2 Production

Conditioning

Distribution

Storage

Deconditioning

Transport

Coal + Grid

Natural gas + Grid

Biomass + Grid

H20 + Grid

H20 + Local renewables

Biomass + Micro organisms

Thermochemical conversion

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

Electrolysis

AEM
Alkaline Electrolysis Method

PEM
Polymer Electrolyte Membrane

Solid Oxide Electrolysis Cell

Biochemical conversion

H2

Compression

GH2

350 / 700 bars

Underground
/
Pressure vessel

LH2

Liquefaction

LH2

-252°C, 1 bar

Cryogenic tank

GH2

X1,5 energy density

Regasification

Absorption

Fluids

LOHC, Ammonia, Methanol*

Standard fuel tank

LH2

GH2

Absorption

Solids

Hybrids

Standard container

LH2

GH2

Fuel Cells

GH2 Fuel cells refueling

HDV

LDV

Railway

Primary value chain

Secondary value chain

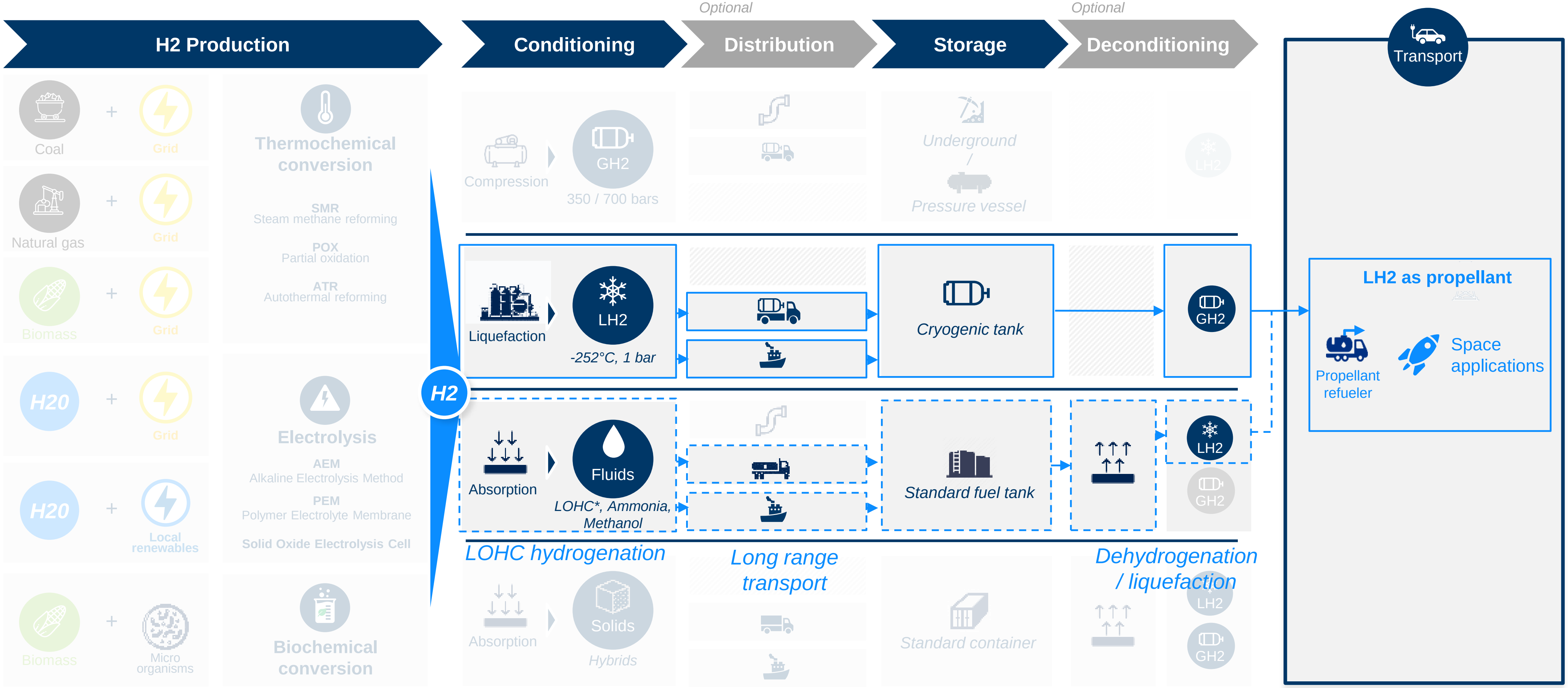
Dehydrogenation

Gasification/ liquefaction

*Liquid Organic Hydrogen carrier

Property of IAC Partners

2020 picture - Focus on transport – Identified supply patterns



Optional
Optional

H2 Production
Conditioning
Distribution
Storage
Deconditioning
Transport

Coal + Grid
Natural gas + Grid
Biomass + Grid
H20 + Grid
H20 + Local renewables
Biomass + Micro organisms

Thermochemical conversion
SMR
Steam methane reforming
POX
Partial oxidation
ATR
Autothermal reforming

Electrolysis
AEM
Alkaline Electrolysis Method
PEM
Polymer Electrolyte Membrane
Solid Oxide Electrolysis Cell

Biochemical conversion

H2

Compression
GH2
350 / 700 bars
Underground
/
Pressure vessel
LH2

Liquefaction
LH2
-252°C, 1 bar
Cryogenic tank
GH2

Absorption
Fluids
LOHC*, Ammonia, Methanol
Standard fuel tank
LH2
GH2

LOHC hydrogenation
Long range transport
Dehydrogenation / liquefaction

Absorption
Solids
Hybrids
Standard container
LH2
GH2

LH2 as propellant
Propellant refueler
Space applications

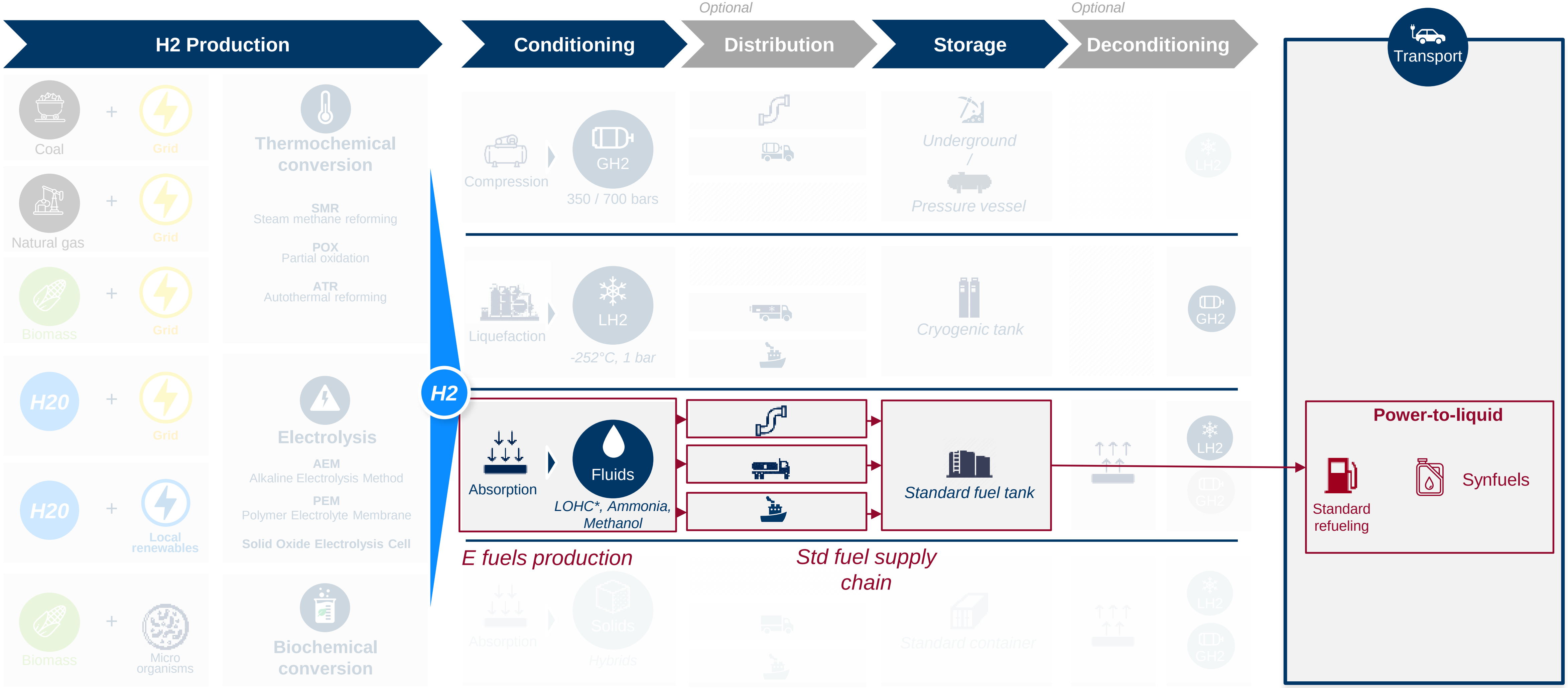
Primary value chain
Secondary value chain

Dehydrogenation
Gasification/ liquefaction

*Liquid Organic Hydrogen carrier

Property of IAC Partners

2020 picture - Focus on transport – Identified supply patterns



H2 Production

Coal + Grid

Natural gas + Grid

Biomass + Grid

Thermochemical conversion

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

H20 + Grid

H20 + Local renewables

Electrolysis

AEM
Alkaline Electrolysis Method

PEM
Polymer Electrolyte Membrane

Solid Oxide Electrolysis Cell

Biomass + Micro organisms

Biochemical conversion

H2

Conditioning

Optional

Distribution

Storage

Optional

Deconditioning

Transport

Compression

GH2
350 / 700 bars

Underground / Pressure vessel

LH2

Liquefaction

LH2
-252°C, 1 bar

Cryogenic tank

GH2

Absorption

Fluids
LOHC, Ammonia, Methanol*

Standard fuel tank

LH2

GH2

Power-to-liquid

Standard refueling

Synfuels

E fuels production

Std fuel supply chain

Absorption

Solids
Hybrids

Standard container

LH2

GH2

Primary value chain

Secondary value chain

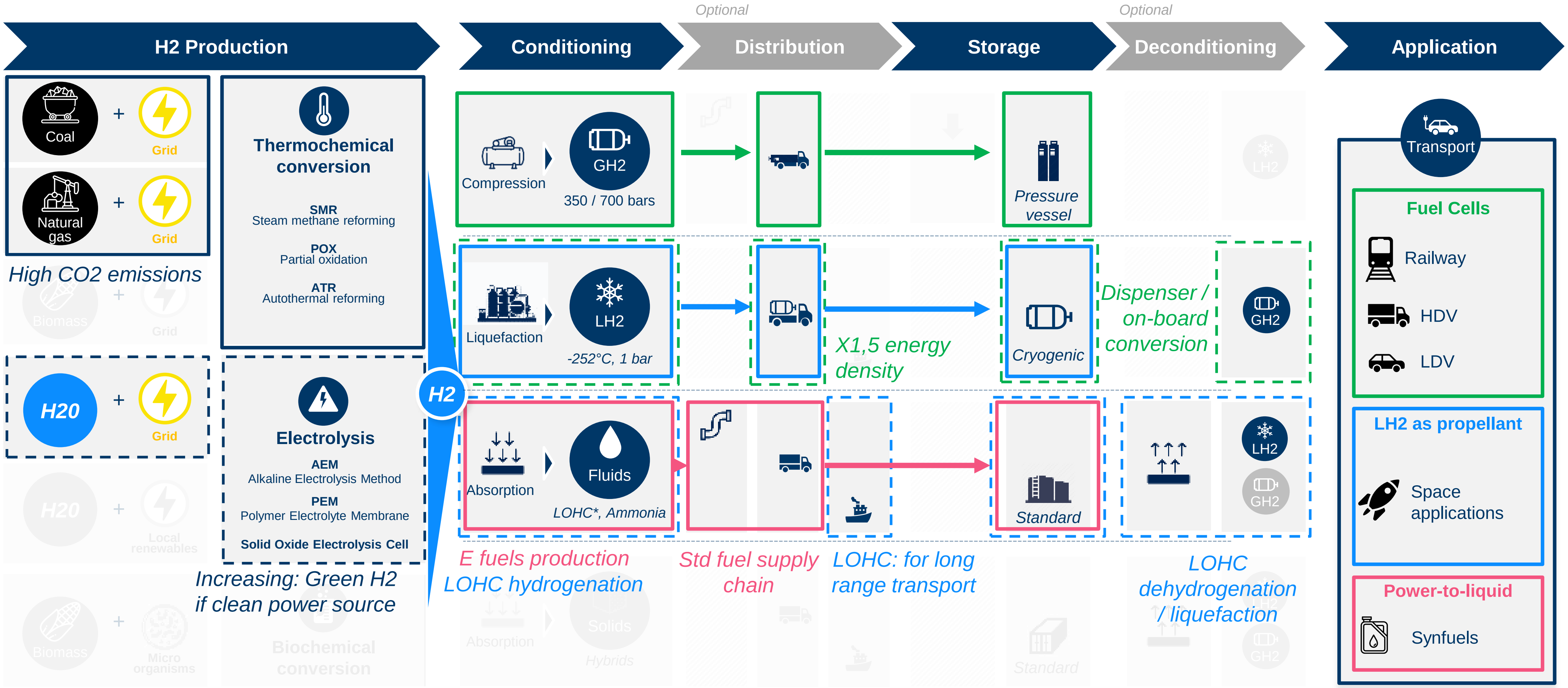
Dehydrogenation

Gasification/ liquefaction

*Liquid Organic Hydrogen carrier

Property of IAC Partners

2020 picture - Focus on transport – Most widespread supply patterns



Optional

Optional

H2 Production

Conditioning

Distribution

Storage

Deconditioning

Application

Coal + Grid

Natural gas + Grid

High CO2 emissions

Biomass + Grid

Thermochemical conversion

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

H20 + Grid

H20 + Local renewables

Electrolysis

AEM
Alkaline Electrolysis Method

PEM
Polymer Electrolyte Membrane

Solid Oxide Electrolysis Cell

Increasing: Green H2 if clean power source

Biomass + Micro organisms

Biochemical conversion

H2

Compression

GH2

350 / 700 bars

Pressure vessel

LH2

Liquefaction

LH2

-252°C, 1 bar

X1,5 energy density

Cryogenic

Dispenser / on-board conversion

GH2

Absorption

Fluids

LOHC, Ammonia*

Standard

LH2

GH2

Absorption

Solids

Hybrids

Standard

GH2

E fuels production
LOHC hydrogenation

Std fuel supply chain

LOHC: for long range transport

LOHC dehydrogenation / liquefaction

Transport

Fuel Cells

Railway

HDV

LDV

LH2 as propellant

Space applications

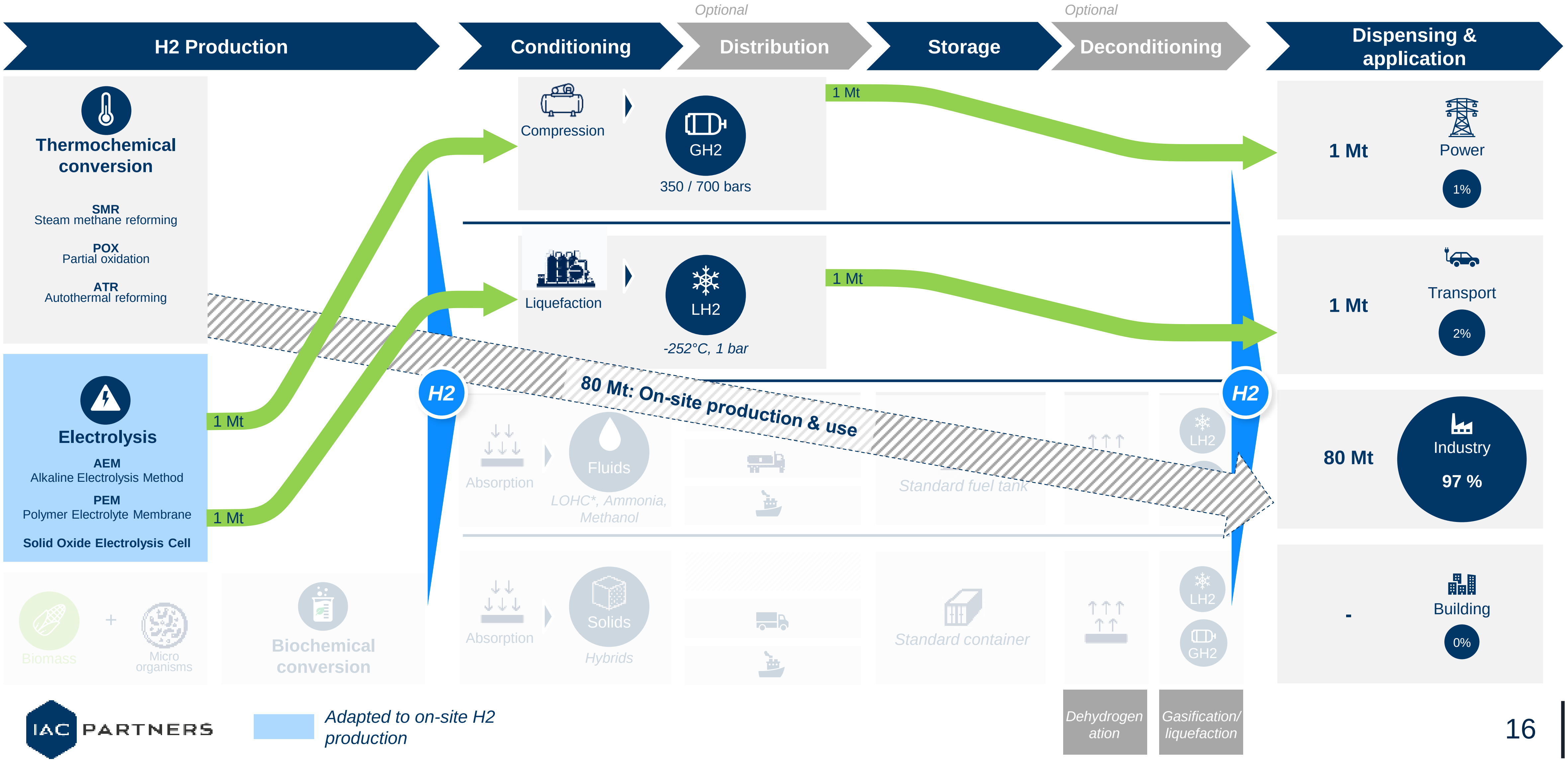
Power-to-liquid

Synfuels

☐ Primary value chain

⬚ Secondary value chain

Hydrogen value chain *in 2020* - We identify multiple production and supply patterns, whose selection for a given application will depend on several parameters



Optional

Optional

H2 Production

Conditioning

Distribution

Storage

Deconditioning

Dispensing & application

Thermochemical conversion

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

Electrolysis

AEM
Alkaline Electrolysis Method

PEM
Polymer Electrolyte Membrane

Solid Oxide Electrolysis Cell

Biomass + Micro organisms

Biochemical conversion

1 Mt

1 Mt

H2

Compression

GH2

350 / 700 bars

Liquefaction

LH2

-252°C, 1 bar

Absorption

Fluids

LOHC, Ammonia, Methanol*

Absorption

Solids

Hybrids

80 Mt: On-site production & use

Standard fuel tank

Standard container

LH2

LH2

GH2

Dehydrogenation

Gasification/ liquefaction

1 Mt

1 Mt

H2

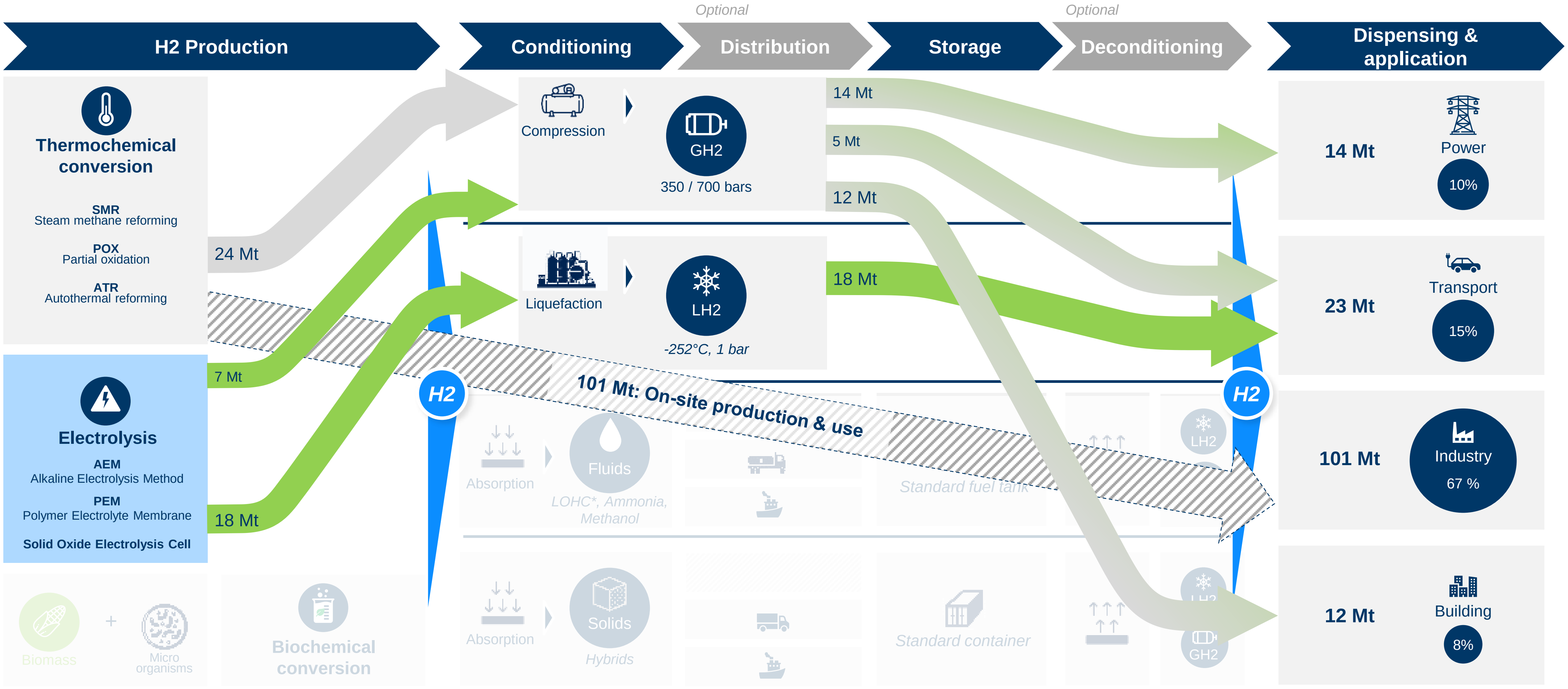
1 Mt	Power	1%
1 Mt	Transport	2%
80 Mt	Industry	**97 %**
-	Building	0%

🟦 *Adapted to on-site H2 production*

*Liquid Organic Hydrogen carrier

Property of IAC Partners

Hydrogen value chain *in 2030* - We identify multiple production and supply patterns, whose selection for a given application will depend on several parameters



Optional *Optional*

H2 Production | **Conditioning** | **Distribution** | **Storage** | **Deconditioning** | **Dispensing & application**

Thermochemical conversion

SMR
Steam methane reforming

POX
Partial oxidation

ATR
Autothermal reforming

24 Mt

Electrolysis

AEM
Alkaline Electrolysis Method

PEM
Polymer Electrolyte Membrane

Solid Oxide Electrolysis Cell

7 Mt

18 Mt

Biomass + Micro organisms

Biochemical conversion

H2

Compression → GH2 350 / 700 bars

Liquefaction → LH2 *-252°C, 1 bar*

Absorption → Fluids *LOHC*, Ammonia, Methanol*

Absorption → Solids *Hybrids*

Standard fuel tank

Standard container

LH2 GH2

101 Mt: On-site production & use

14 Mt

5 Mt

12 Mt

18 Mt

14 Mt	Power	10%
23 Mt	Transport	15%
101 Mt	Industry	67 %
12 Mt	Building	8%

🟦 *Adapted to on-site H2 production*

⬜ *'Grey' (thermochemical) hydrogen*

🟩 *'Green' (low-carbon) hydrogen*

▨ *Mix of low- and high-carbon hydrogen*

Dehydrogenation *Gasification/ liquefaction*

*Liquid Organic Hydrogen carrier

Overview of 4 different kinds of actors and their positioning on the hydrogen market

Core Business	Key player example	Their vision of hydrogen	Competitive advantages	Goals
Fuel producers & suppliers	TOTAL	**TOTAL** sees hydrogen as a green fuel (potential threat to the fossil fuel market)	• Investment capabilities • Production, storage & distribution infrastructures • Influence on public policies	• To reinforce their position as fuel suppliers, along with the shift to a greener economy • Established dispensing network
Gas producers & suppliers	Air Liquide	**AIR LIQUIDE** sees hydrogen as a molecule and wants to remain a world leader in gaseous/liquid molecules production & distribution	• Deep technical expertise and experience • State-of-art technologies • Tank truck fleet for distribution	• Vertical integration of H2 delivery and allied services • Strong end-to-end capabilities
Energy suppliers	ENGIE	**ENGIE** considers hydrogen as a clean source of electricity / a useful buffer for renewable energy production	• One-stop provider for H2 as power and as gas • Established infrastructure and network	• Opportunity for decarbonization • Profitable business
Electrolysis Units Manufacturers	nel	**NEL** sees itself as hydrogen conversion specialist	• Green on-site production capabilities • Turnkey solutions based on requirements	• Dynamic, state-of-art technologies • Strong expertise in electrolysis technologies

New and upcoming Hydrogen Actors*

HYDROGENICS · ITM POWER · hypoint · H2GO Power · Enapter · NPROXX · H-TEC SYSTEMS · HEXAGON · PowiDian · hydrogenious LOHC TECHNOLOGIES

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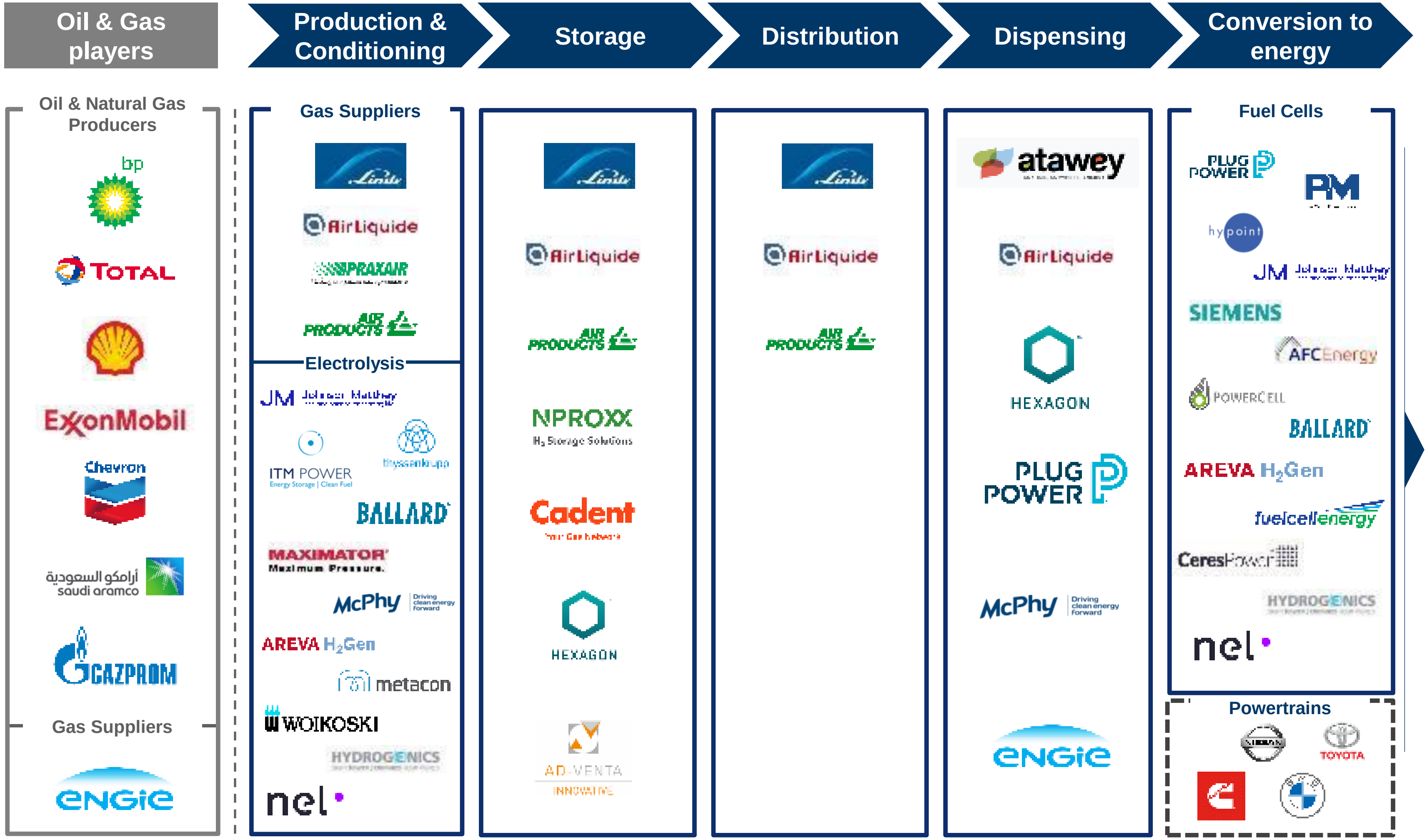
* - Non exhaustive list

Historical gas suppliers have a competitive edge in Hydrogen supply chain, benefiting from deep technical expertise and handling experiences



Key Findings

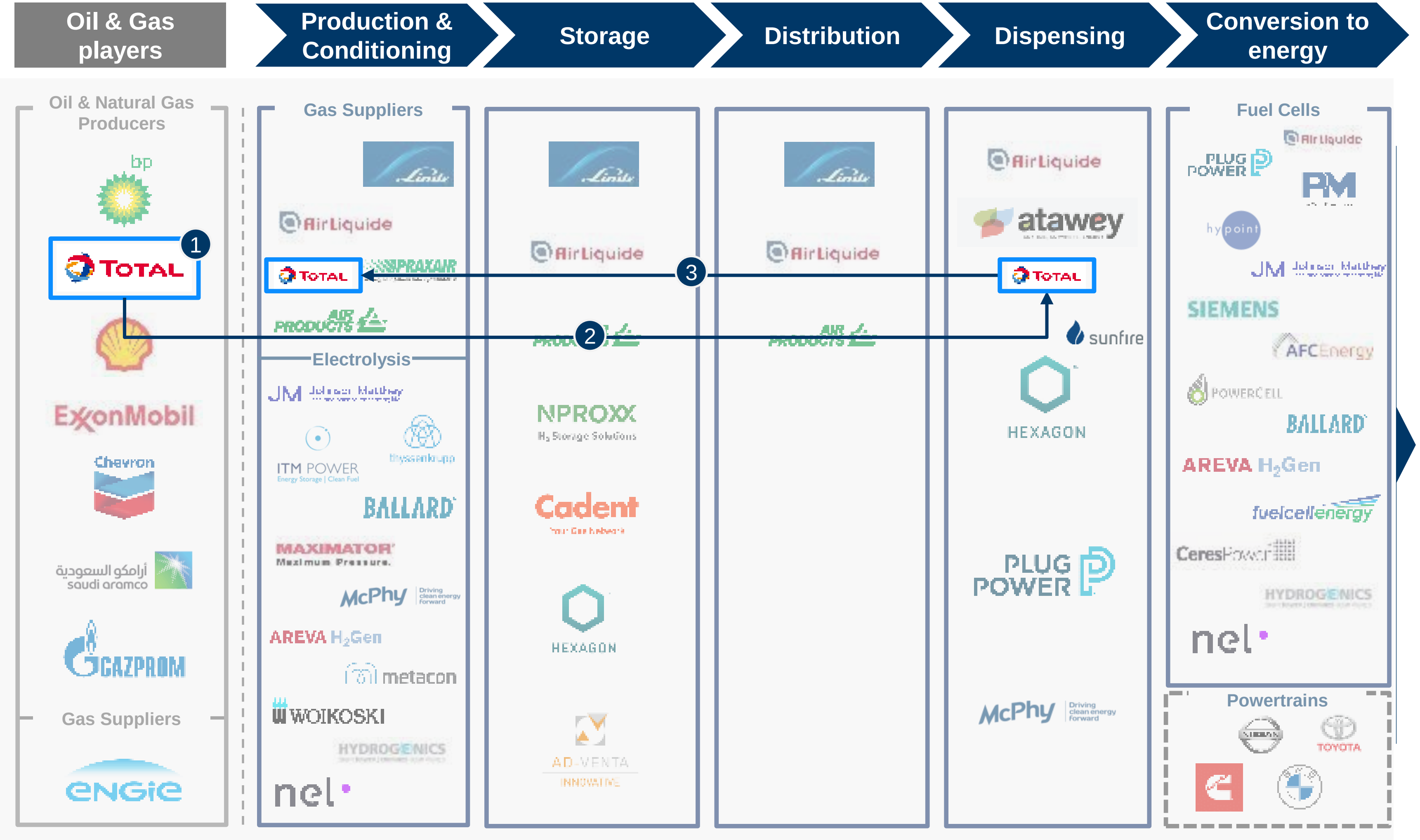
- **Gas suppliers like Air Liquide and Linde** have a **strong position** in hydrogen supply and storage, being the go-to providers for industrial applications.
- **Jet fuel supply chain** is consolidated and **have not changed significantly** over the past 60 years. With the arrival of **hydrogen in aviation**, oil and gas companies are beginning to venture into hydrogen.
- **Electrolysis** manufacturers such as **NEL and Hydrogenics** have the capability to deliver **on-site modular units from renewable electricity** for **decentralized** production and usage, and have developed **end-to-end offerings for fuel cell EVs and trucks.**

Note: Energy Conversion includes power trains, fuel cell manufacturers, vehicle storage and integration

▬ Historical Oil & Gas Players
▬ Hydrogen Value Chain

Sources: Air Liquide, Linde, Air Products, Shell, Total, FCHJU Report on Hydrogen Supply Chain, Hydrogen Europe, Safran Fuel Cells, Aerosociety, E4Tech 2019 Report

Deep Dive: Total aims to focus on on-site dispensing using renewable energy, and on biofuels



Key Findings

① 2002: TOTAL Germany started the move in the development of **hydrogen dispensing infrastructure.** Larger H2 production capacities are planned to draw synergies from LNG liquefaction and transport.

② 2010: With the joint venture **H2 Mobility**, an industry initiative has been established in Germany which aims to build a network of up to **400 hydrogen fueling stations in Germany by 2023**, with the support of the Federal Government.

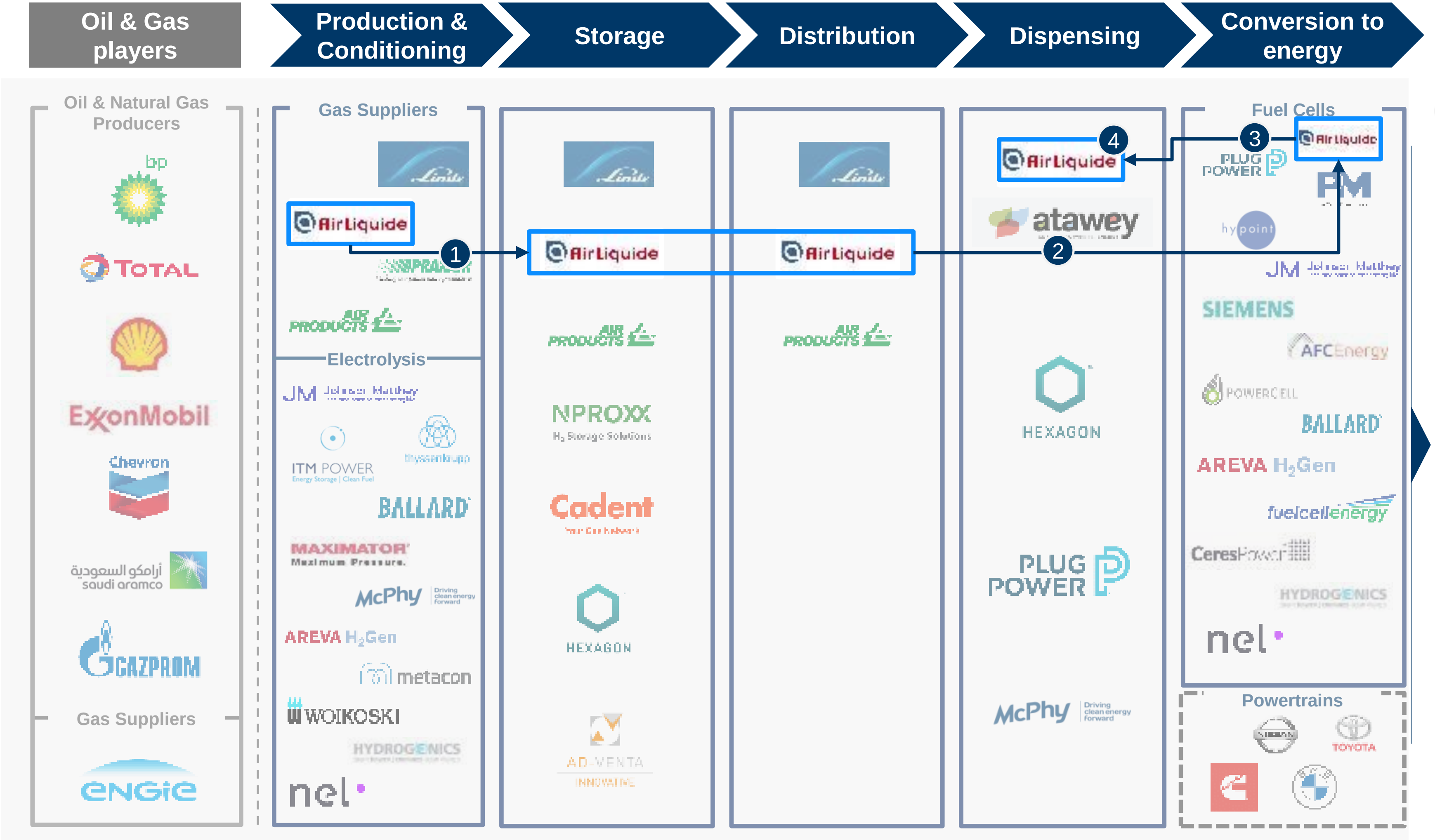
③ 2017: **Total Karlsruhe and Sunfire** is differentiated by producing hydrogen on-site through steam SOEC, using electricity generated by a solar array. (5000hrs).

Total S.A. is part of the research program with Air France Lab for **Amyris and BioTfueL**, to produce Biojet fuel upto 500,000 tons/yr at La Mède Biorefinery.

Total S.A. Annual Revenue : $200 Billion (2019)

Sources: Total Annual Report 2017 and 2018, Green Car Congress,

Deep Dive: Air Liquide has been the leader for H2 production and supply, and is aggressively expanding into dispensing for last-leg delivery infrastructure



Key Findings

1. Innovation in **cryogenic technologies enabled transport and storage of LH2 and GH2** over long distances, rapidly integrated in the space industry.
2. Air Liquide **acquired AXANE, fuel cell manufacturer** working on issues surrounding hydrogen storage and logistics (solid, liquid, or gaseous)
3. Air Liquide opened **its first hydrogen charging station**, in **Düsseldorf, Germany.** Following this, roughly **120 hydrogen charging stations have been designed and built by Air Liquide throughout the world**. Their **market share is around 30%** as per end of mars 2020, 408 Hydrogen refueling stations were operating around the globe.
4. Air Liquide contributed to the construction of **hydrogen charging stations** (United States, Japan, France, Germany, Belgium, Denmark, the Netherlands and Korea) supporting automotive manufacturers.

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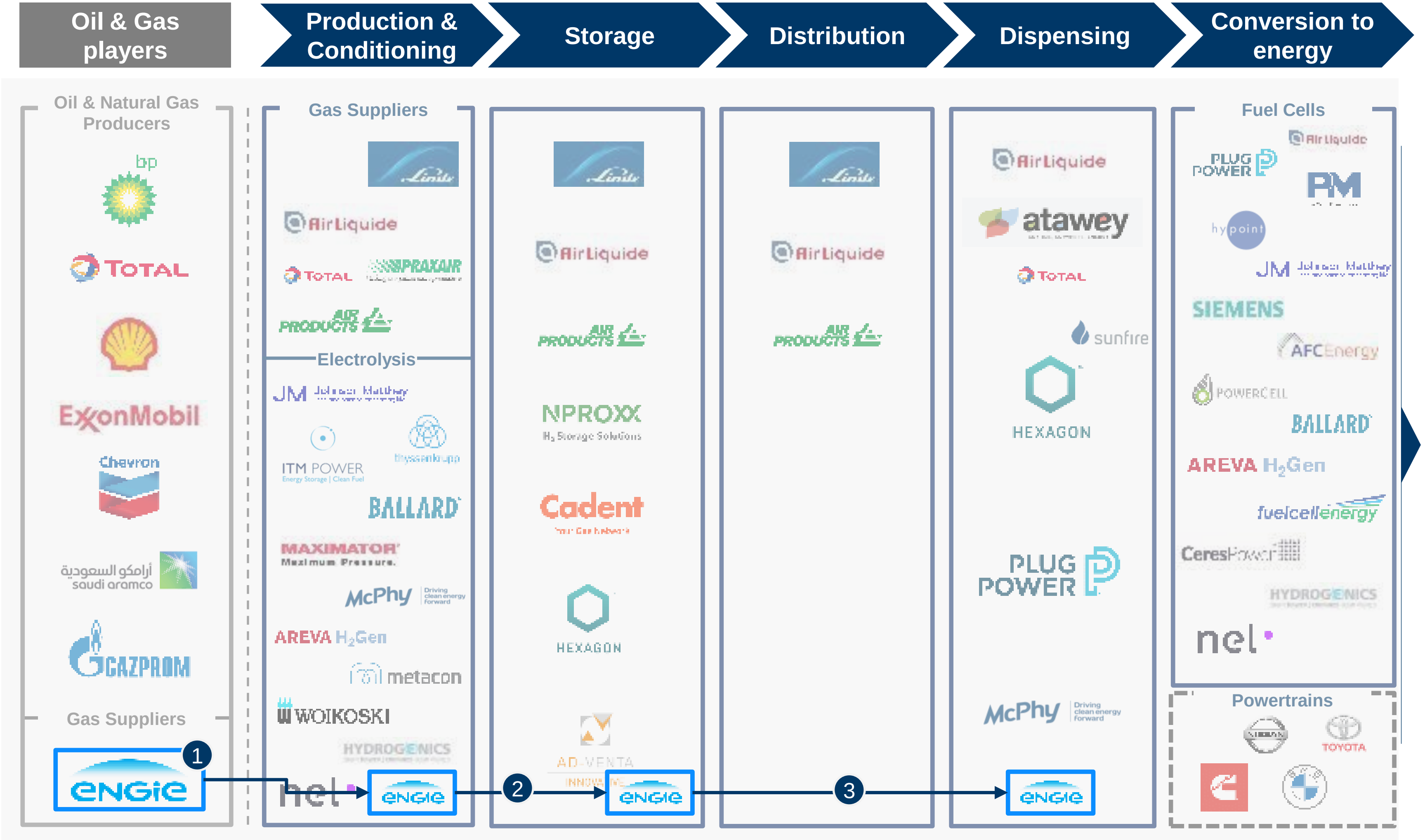
Air Liquide Annual Revenue : $23 Billion (2018)

Sources: Air Liquide Website and Press Kit

Deep Dive: ENGIE sees hydrogen flexibility as an energy vector for power-to-gas and gas-to-power conversions



Oil & Gas players | Production & Conditioning | Storage | Distribution | Dispensing | Conversion to energy

Key Findings

① 2016: ENGIE formalized a **strategic shift** to reduce fossil fuel exploration and invest **massively in renewable energies** and **allied storage services.**

② 2018: **Creation of Hydrogen BU** inside Engie **to produce renewable hydrogen** by **electrolysis of water through various renewable energies and large scale cavern storage.** Large investments in hydrogen as a **storage backup to power grids and transportation.**

③ 2018: ENGIE inaugurated **first hydrogen station at Rungis** that will power a fleet of 50 hydrogen-powered Renault Kangoo Z.E. utility vehicles.

④ 2019: **Hygreen Provence Project** is a synergy between **Engie and Air Liquide** for **green H2 production** for smart mobility, energy and industry sectors.

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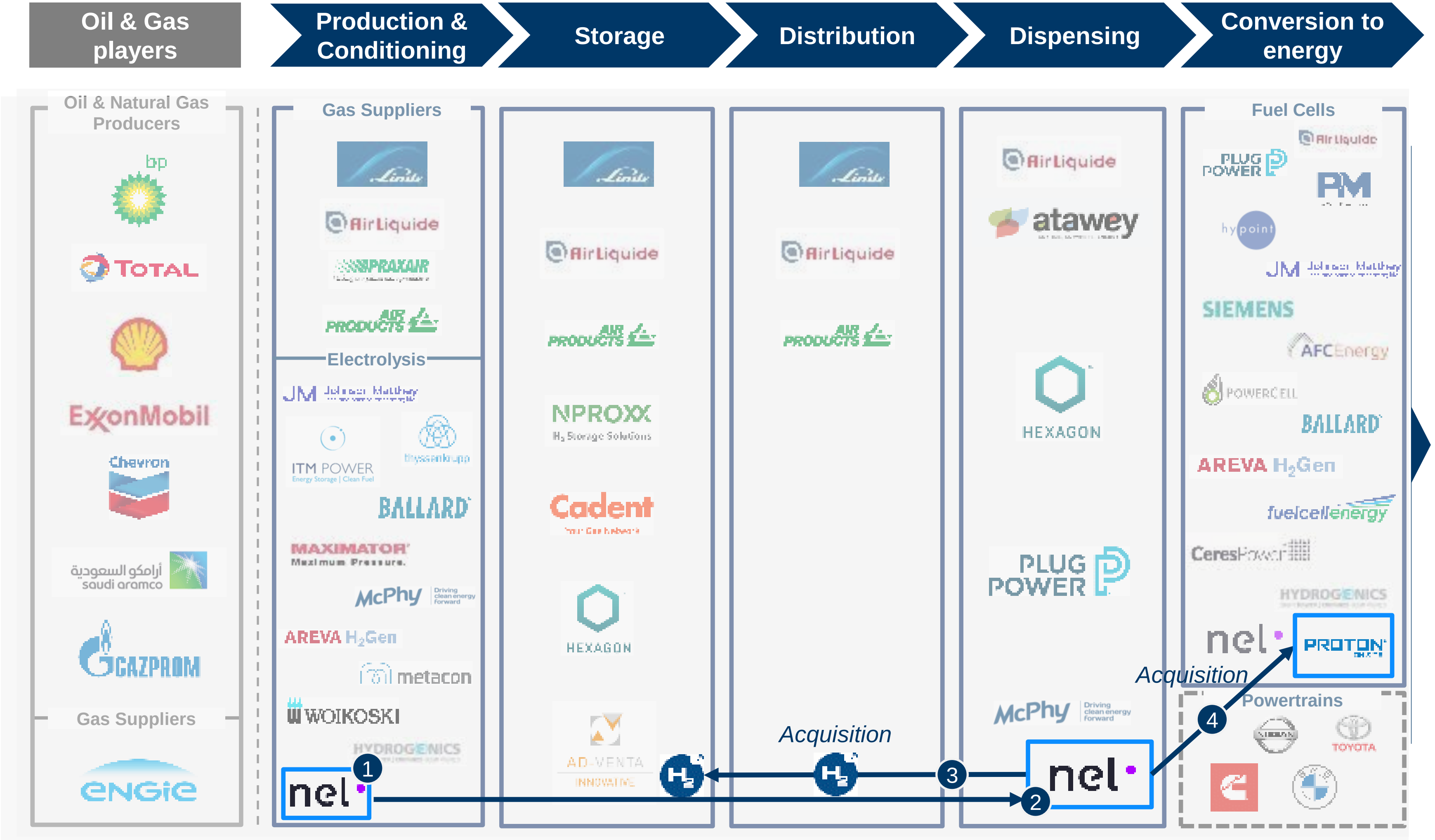
Engie Annual Revenues: €61 Billion (2018)

Sources: Engie Hydrogen, News and Insights

Deep Dive: NEL is a world leader in alkaline electrolysis, and they see themselves as the end-to-end hydrogen specialists



Key Findings

① NEL established its first **alkaline electrolyzer** in Norway for pure hydrogen to **fertilizer production** in 1927. Until 2003, they were completely focused on **delivering hydrogen through electrolysis** for different industry applications.

② In 2003, NEL began their shift down the value chain and opened their **first publicly available Hydrogen fueling station** in Iceland, with growing applications of **fuel cells** in small vehicles. In 2020 **NEL partnered with NIKOLA** to launch the **first 8 ton per day refueling station** for trucks.

③ In 2015, NEL acquired **H2Logic** for world's leading **Hydrogen storage and fueling technology**, and further developed a manufacturing plant to deliver 300 fueling stations per year.

④ In 2017, NEL acquired **Proton On-site**, adding **PEM Electrolysis& Fuel Cells** to product portfolio,& became world's largest electrolysis company.

NEL Annual Revenue : $50 Million (2018) (over 25% growth per year)
Order Backlog of $60 Million (End of 2019)

Sources: NEL Website - History

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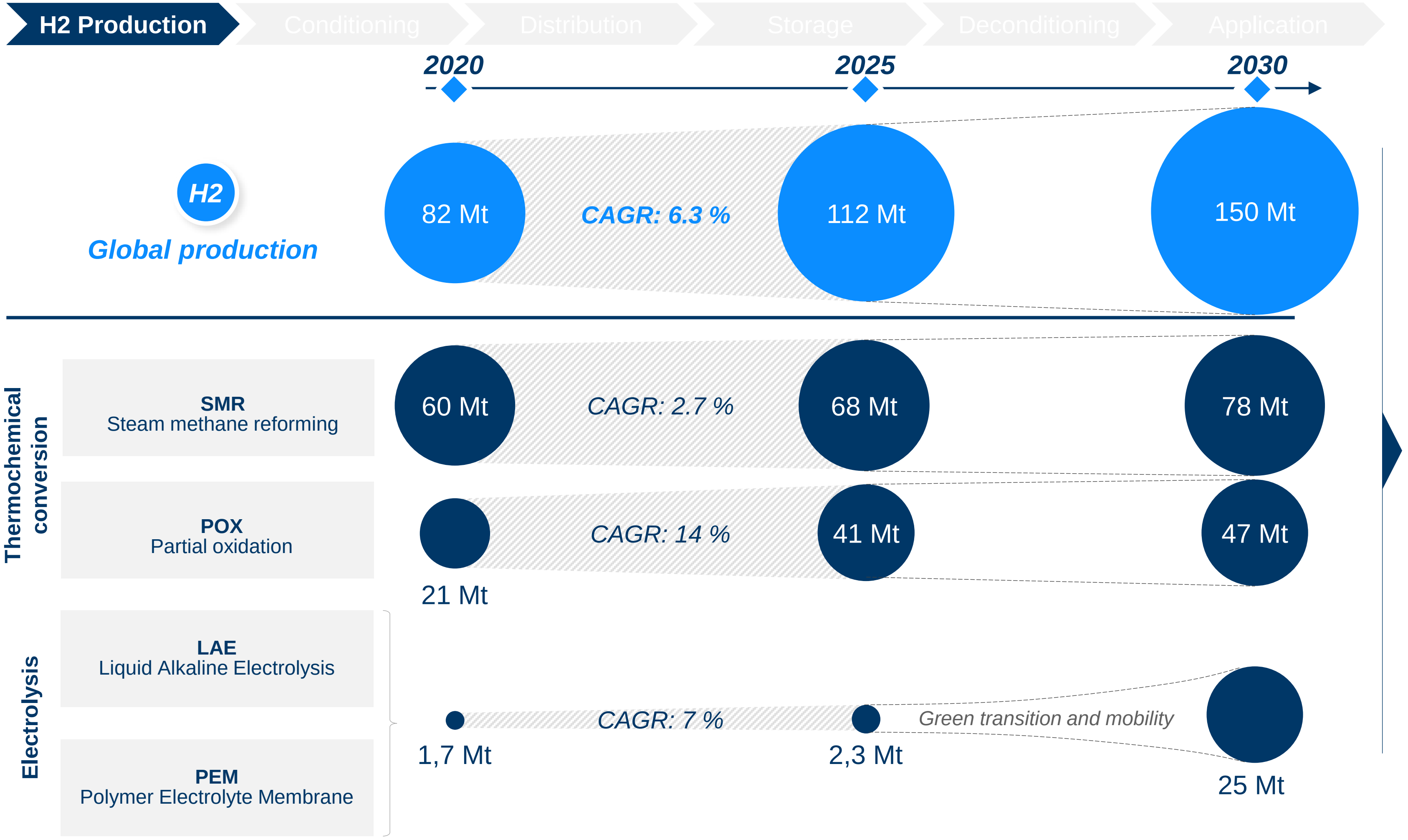
Focus on production – Hydrogen generation is a fast-growing market, highly dominated by fossil conversion technologies



Key Findings

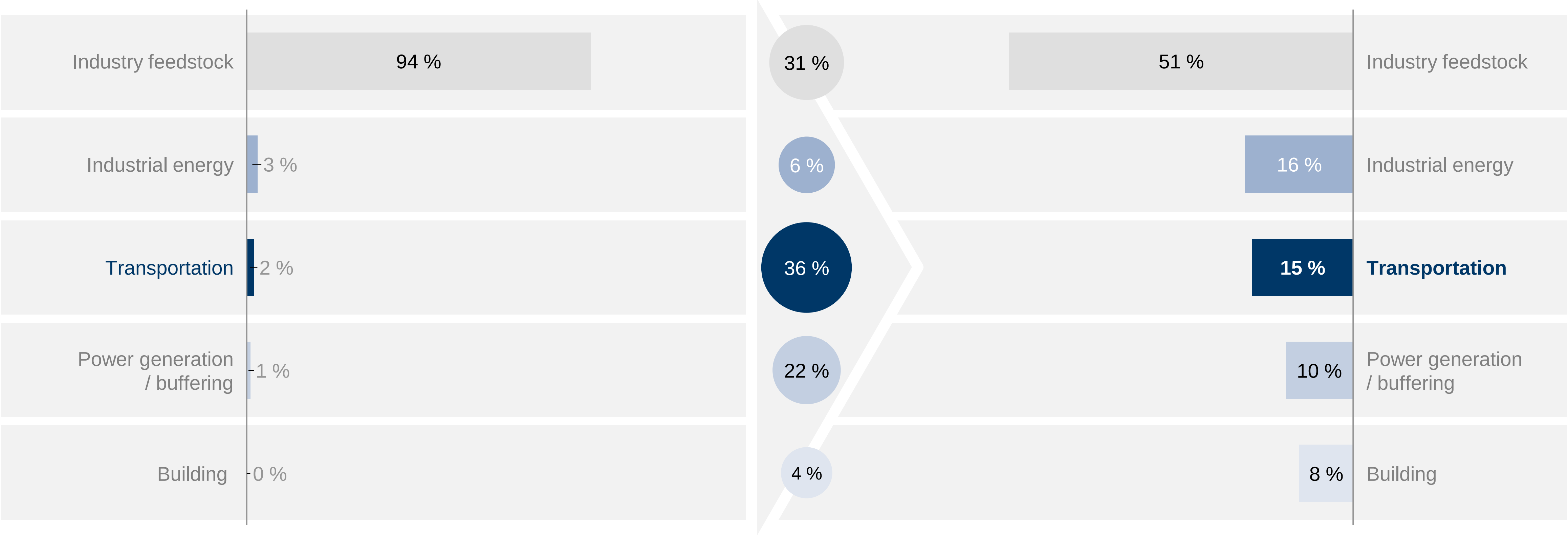
- Despite a high growth rate, **electrolysis and "green hydrogen" production technologies will remain marginal in the next 5 years.** However, electrolysis market is expected to be **boosted thanks to the transition of the transportation sector.**
- Among other electrolysis solutions, **PEM is seen as the most promising technology** and is expected to grow with a **~15% CAGR in the coming years**
- **Coal gasification market growth is driven by Chinese and Indian market.** Partial oxidation is a "grey" production technology, meaning its environmental impact is lower than SMR
- In 2020, **merchant hydrogen** (off-site production), represented **60% of global generation market in terms of business.** However, **captive generation type is the fastest growing segment: ~9% CAGR**

Based on the current public market forecasts for 2030, Transport is the 2nd most promising growth driver for hydrogen-powered system manufacturers

2020 distribution for global hydrogen demand

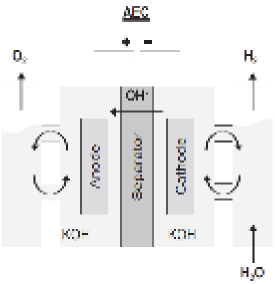
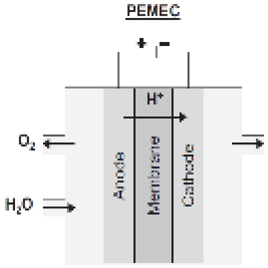
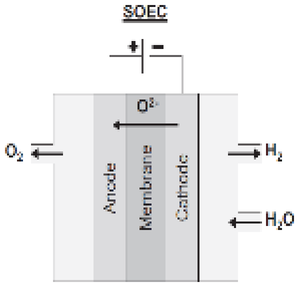
Hydrogen production projects, Capacity starting from 2018 to 2030:

2030 distribution for global hydrogen demand



Sources:
IAC analysis, based on:
(1) Hydrogen Council: « Hydrogen scaling up – A sustainable pathway for the global energy transition », November 2017
(2) Deloitte: « Australian and global hydrogen demand growth scenario analysis », November 2019
(3) ACIL ALLEN: « Opportunities for australia from hydrogen exports », August 2018
(4) SHELL: « Sky scenario – open data table », 2018
(5) IEA: Hydrogen projects database

To match potential on-site production scenarios, current electrolysis technologies should be understood for high production capacities and low OPEX

	Liquid Alkaline Electrolysis	Polymer Electrolyte Membrane	Solid Oxide Electrolysis Cell
Technology			
Maturity	**Mature, Commercial and scalable** Established, cost-effective, long term stability	**Commercial and scalable** High current and voltage densities, compact system	**In Research and Demonstration phase**
Composition	**Anode:** Nickel, Ni-Co Alloys **Cathode:** Nickel, Ni-Mo Alloys **Electrolyte:** Liquid KOH (20-40%wt)	**Anode:** RuO2, IrO2 **Cathode:** Platinum, Pt-Pd Alloy **Electrolyte:** Polymer Membrane (Nafion)	**Anode:** LSM/YSZ **Cathode:** Nickel/YSZ **Electrolyte:** YSZ (Yttria-stabilized Zirconia
Physical properties	Current Density: 0.2-0.4 A/cm2 Cell Voltage: 1.8V-2.4V Temp/Pressure: 60°C-80°C, Up to 30 bar H2 Production Capacity: Up to 8500 Kg/day	Current Density: 0.6-2.0 A/cm2 Cell Voltage: 1.8-2.2V Temp/Pressure: 50°C-80°C, Up to 200bar H2 Production Capacity: Up to 8800 kg/day	Current Density: 0.3-2.0 A/cm2 Cell Voltage: 0.7-1.5V Temp/Pressure: 650°C-1000°C, Up to 25 bar H2 Production Capacity: Up to 100 kg/day
Efficiency	System Efficiency: 62-82% Energy Input: 54 KwH/Kg GH2 (production only)	System Efficiency: 57%-69% Energy Input: 52 KwH/Kg GH2 (production only)	System Efficiency: 85%-90% Energy Input: 40 KwH/Kg GH2
CAPEX & OPEX	***On-going benchmarks & costs models***	***On-going benchmarks & costs models***	CAPEX in 2017 (€/kW): > 2000
Key Players	nel HYDROGENICS McPhy Driving clean energy forward	AREVA H2Gen nel HYDROGENICS McPhy Driving clean energy forward ITM SIEMENS	*Independent Research Labs in Universities (MIT)* elcogen

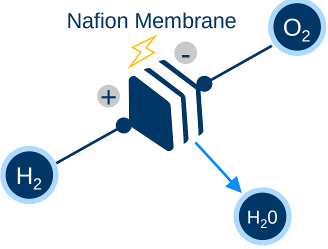
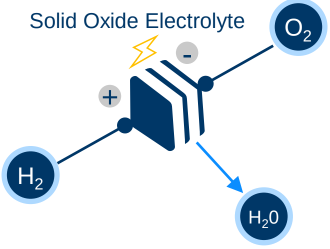
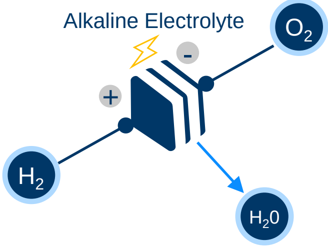
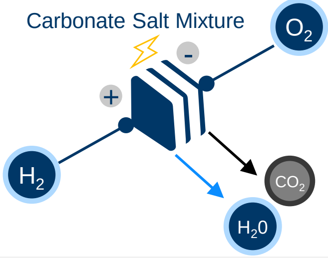
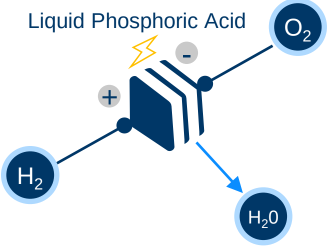
Commercially deployable

Not scalable until 2030

Sources: Elsevier, Hydrogenics, NEL, Hydrogenics, McPhy, DoE, FCHJU, IEA Hydrogen, IRENA, Hydrogen Europe

PEM Fuel Cell is the best suited for rail applications due to low temp operations, high current densities and mature applications in FCEVs and buses

H2 Production › Conditioning › Distribution › Storage › Deconditioning › **Application**

Technology / *Criteria*	**Polymer Electrolyte Membrane**	**Solid Oxide**	**Alkaline**	**Molten Carbonate**	**Phosphoric Acid**
Stack Functioning					
Maturity	**Mature, Scalable**	**Mature, Scalable**	**Mature, Scalable**	**Mature, Large Scale**	**Mature, Large Scale**
Mobility*	**Portable, Stationary, Transportation**	**Stationary, Transportation**	**Stationary**	**Stationary**	**Stationary**
Stack power range	1 – 100 kW	**0.5 kW – 2 MW range**	1 – 100 kW	100 kW – 1 MW range	4 kW – 400 kW range
Peak power density	**0.6 – 1.2 W/cm²**	**0.4 – 2 W/cm²**	0.5 – 0.7 W/cm²	0.8 – 1 W/cm²	**0.5 – 0.7 W/cm²**
Operating temp.	**LT: 40 °C – 90 °C** / HT: 200 °C	**500 °C – 1 000 °C**	**80 °C – 100 °C**	**600 °C – 700 °C**	200 °C – 220 °C
Lifetime	20 000 hours	**20 years**	8 000 – 10 000 hours	**20 years**	40 000 hours
Efficiency	60 % - 70 %	40 % - 80 %	60 % - 70 %	**60 % - 80 %**	**40 % - 50 %**
CAPEX	**50 $/kW**	80 $ / kW	*Work in Progress*	*Work in Progress*	*Work in Progress*
2019 capacity sold	934 MW	78 MW	0.1 MW	10 MW	107 MW
Distinction	**Quick start-up time**	**High operating temperature**	**Low cost components and electrolytes**	**Suitable only for centralized production**	**Liquid electrolyte adds on-board weight in vehicles**

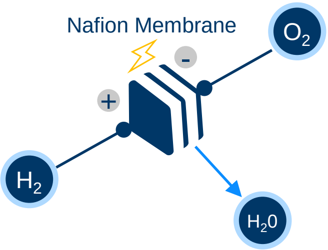
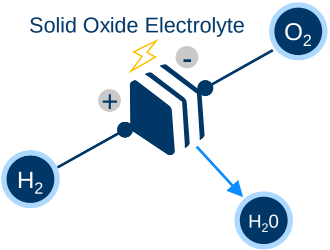
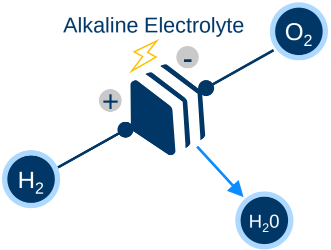
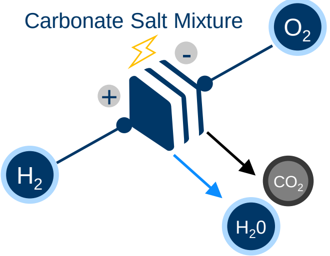
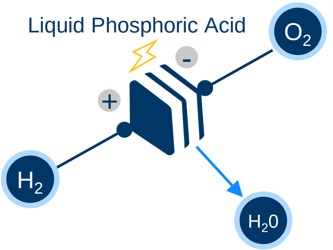
***Mobility:**
Portable: Designed to be moved around, including APUs (0.5-20kW)
Stationary: Provide electricity and not designed to be moved (0.2kW-2MW)
Transportation: Provide propulsion or range extension to a vehicle (1-300kW)

🟩 Advantage for Mobility
🟥 Disadvantage for Mobility

Sources: DoE Fuel Cells Factsheet, NED Stack, E4Tech, Fuel Cells Today, Fuel Cells History and Principles, Research Gate publications on Direct Methanol Fuel Cells, DNVGL Report, Design News – Hydrails are the future of Rail Transportation, 2016 Fuel Cells Technologies Multi Year Research and Development

PEM Fuel Cell is best suited for rail applications due to low temp operations, high current densities and mature applications in FCEVs and buses

H2 Production › Conditioning › Distribution › Storage › Deconditioning › **Application**

Technology / *Criteria*	Polymer Electrolyte Membrane	Solid Oxide	Alkaline	Molten Carbonate	Phosphoric Acid
Stack Functioning					
Maturity	**Mature, Scalable**	**Mature, Scalable**	**Mature, Scalable**	**Mature, Large Scale**	**Mature, Large Scale**
Mobility*	**Portable, Stationary, Transportation**	**Stationary, Transportation**	**Stationary**	**Stationary**	**Stationary**
Applications	• Residential and Grid Backup • Portable power • Distributed power generation • Transportation vehicles	• Large and Small scale power generation for Transportation	• Military and Space Applications for backup powe	• Electrical Utilities • Industrial and Military Applications • Waste water treatment facilities	• Decentralized power generation • Cogeneration for District heating
Key players	Be ALSTOM HYDROGENICS BALLARD PLUG POWER nel	Be Cummins ATREX ENERGY ACUMENTRIX LG NISSAN	AFCEnergy SIEMENS GENCELL	posco ENERGY fuelcellenergy	DOOSAN TOSHIBA Westinghouse FUJITSU

IAC PARTNERS

***Mobility:**
Portable: Designed to be moved around, including APUs (0.5-20kW)
Stationary: Provide electricity and not designed to be moved (0.2kW-2MW)
Transportation: Provide propulsion or range extension to a vehicle (1-300kW)

Sources: DoE Fuel Cells Factsheet, NED Stack, E4Tech, Fuel Cells Today, Fuel Cells History and Principles, Research Gate publications on Direct Methanol Fuel Cells, DNVGL Report, Design News – Hydrails are the future of Rail Transportation, 2016 Fuel Cells Technologies Multi Year Research and Development

Thermochemical conversion historically dominated the H2 production market. Current push towards full decarbonization facilitates on-site electrolysis plants

High-Level Analysis

H2 Production | Conditioning | Distribution | Storage | Deconditioning | Application

in $/kgH2

Thermochemical conversion

Steam Methane Reforming
CAPEX: 0.4 $/kgH2
OPEX: 1.6 $/kgH2
CO2e Emissions: 8-10 Kg/KgH2

Partial Oxidation
CAPEX: 0.3 $/kgH2
OPEX: 1.2 $/kgH2
CO2e Emissions: 4-6 Kg/KgH2

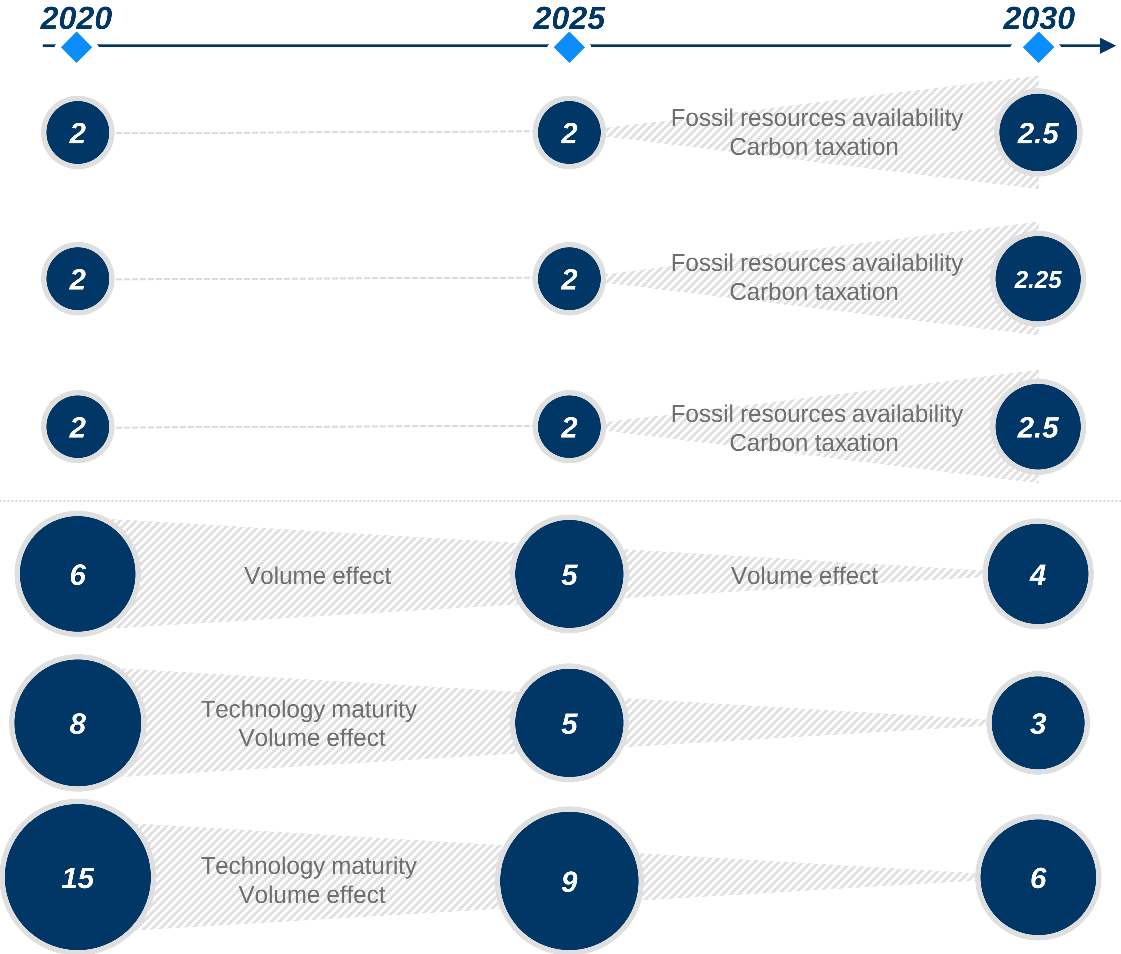
Autothermal Reforming
CAPEX: 0.2 $/kgH2
OPEX: 1.3 $/kgH2
CO2e Emissions: 8-10 Kg/KgH2

Electrolysis

Alkaline Water Electrolysis
CAPEX: 1.8 $/kgH2
OPEX: 4.2 $/kgH2
CO2e Emissions: 1-4 Kg/kgH2

Polymer Electrolyte Membrane
CAPEX: 2.4 $/kgH2
OPEX: 5.6 $/kgH2
CO2e Emissions: 1-4 Kg/kgH2

Solid Oxide EC
CAPEX: 4.5 $/kgH2
OPEX: 11.5 $/kgH2
CO2e Emissions: 2-3 Kg/KgH2



Key Findings

- **SMR without CCS** is **scalable method** for producing H2 in 2020. New technologies **including CCS** can increase **CAPEX but** can **reduce overall emissions by 60%**.
- **Carbon taxes** will play an important role in the **cost competitiveness** of thermochemical conversion methods. If **CCS technology is used**, they can become **cost and emissions competitive** with **electrolysis by 2030**.
- **AWE** is the **widely used** Electrolysis method **(Outdoor and Containerized modules)** because it is **mature and scalable-** Low-cost and stacks are in **MW ranges**, without any noble catalysts.
- **PEM** is expected to be the **future technology** because of its **high current densities**, **voltage efficiencies** and **compact system size**. Many important industrial actors like **NEL, Siemens, Hydrogenics** are in this space.

Note: CAPEX costs are estimates for 2020, OPEX includes fuel/electricity costs, Costs for 2030 are based on projections and forecasts.

Sources: IEA "The Future of Hydrogen", Hydrogen Council "Path to H2 competitiveness", DoE, NREL, IEA GHG Report, NETL, DNV-GL Hydrogen Report, NTNU "Concepts of Large Scale H2 Production", Elsevier "Carbon Credentials for H2", MDPI "Well to Tank GHG Emissions"

Thermochemical conversion is a mature process to produce H2 and a cost-breakdown shows that the main cost driver consist of fossil fuels

H2 Production | Conditioning | Distribution | Storage | Deconditioning | Application

in $/kgH2

Thermochemical conversion

① **Steam Methane Reforming**
CO2e Emissions: 8-10 Kg/KgH2

② **Partial Oxidation**
CO2e Emissions: 4-20 Kg/KgH2

③ **Autothermal Reforming**
CO2e Emissions: 8-10 Kg/KgH2

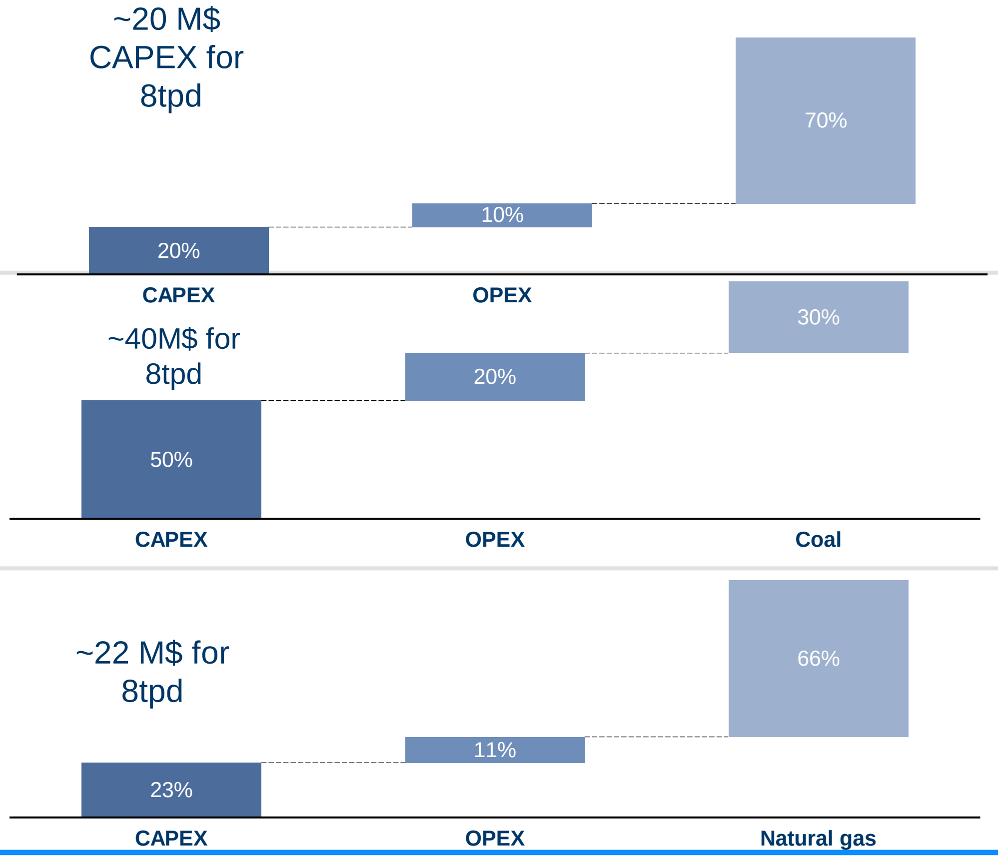
Electrolysis

Alkaline Electrolysis Method
CAPEX: 1,8 $/kgH2
OPEX: 4,2 $/kgH2
CO2e Emissions: 1-4 Kg/kgH2

Polymer Electrolyte Membrane
CAPEX: 2,4 $/kgH2
OPEX: 5,6 $/kgH2
CO2e Emissions: 1-4 Kg/kgH2

Solid Oxide EC
CAPEX: 4,5 $/kgH2
OPEX: 11,5 $/kgH2
CO2e Emissions: Not Available

2020 to 2030



① ~20 M$ CAPEX for 8tpd

② ~40M$ for 8tpd

③ ~22 M$ for 8tpd

Hypothesis + additional information

①
- 80% load
- Price of natural gas: 5 Mbtu
- Mature technology
- Figures with CCS
- No significant changes between 2020 and 2030

②
- 80% load
- Price of coal: 100 $/tonne
- Mature technology
- Figures with CCS
- No significant changes between 2020 and 2030

③
- 80% load
- Price of natural gas: 5 Mbtu
- Mature technology
- Figures with CCS
- No significant changes between 2020 and 2030

Sources: IEA –"The future of hydrogen" / Norwegian University of Science and Technology Department of Energy and Process Engineering "Concepts for Large Scale Hydrogen Production" / IEA GHG Report / MDPI "Well to Tank GHG Emissions" / MDPI "Well to Tank GHG Emissions"

A deeper view into the cost breakdown reveals that the electricity consumption is the biggest cost factor in the production of H2

H2 Production | Conditioning | Distribution | Storage | Deconditioning | Application

in $/kgH2

Thermochemical conversion

Steam Methane Reforming
CAPEX: 0,4 $/kgH2
OPEX: 1,6 $/kgH2
CO2e Emissions: 8-10 Kg/KgH2

Partial Oxidation
CAPEX: 0,3 $/kgH2
OPEX: 1,2 $/kgH2
CO2e Emissions: 4-6 Kg/KgH2

Autothermal Reforming
CAPEX: 0,2 $/kgH2
OPEX: 1,3 $/kgH2
CO2e Emissions: 8-10 Kg/KgH2

Electrolysis

① **Alkaline Water Electrolysis**
CO2e Emissions: 1-4 Kg/kgH2

② **Polymer Electrolyte Membrane**
CO2e Emissions: 1-4 Kg/kgH2

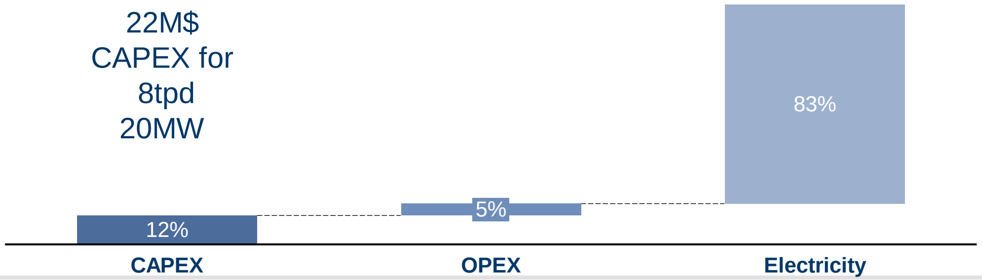
③ **Solid Oxide EC**
CO2e Emissions: *Not Available*

2020 2025 2030

Hypothesis + additional information

①

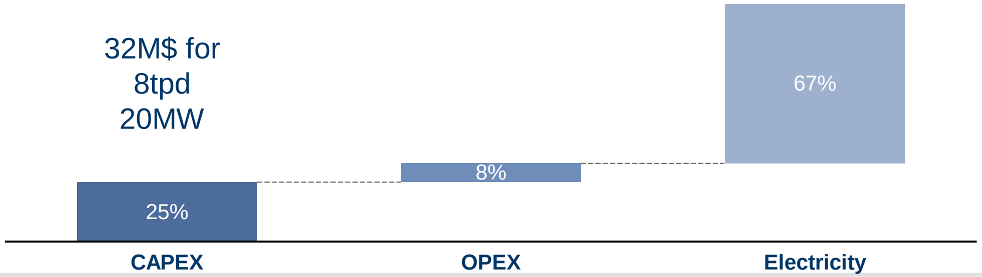
22M$
CAPEX for
8tpd
20MW



- Avg. industry price for electricity: 0,1 $/kWh
- CAPEX & OPEX are based on a 20MW system
- Total cost will decrease from 2020 to 20230 due to efficiency increase of the technology
- OPEX costs increase every 5-7 years due to stack replacement
- Mature technology

②

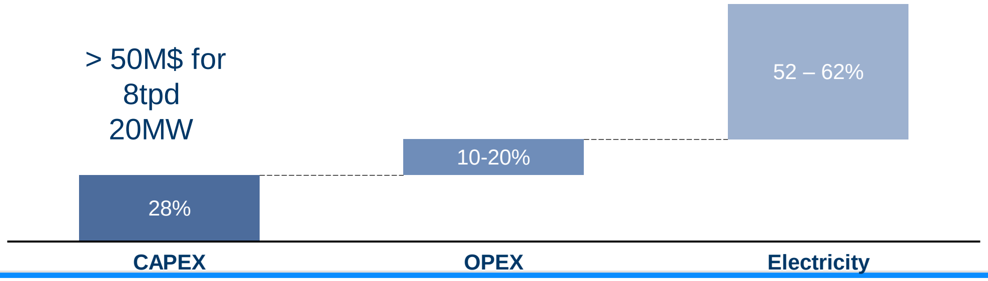
32M$ for
8tpd
20MW



- Avg industry price for electricity: 0,1 $/kWh
- CAPEX & OPEX are based on a 20MW system
- Total cost will decrease due to efficiency increase of the technology
- OPEX costs increase every 5-7 years due to stack replacement
- Mature technology

③

> 50M$ for
8tpd
20MW



- Avg industry price for electricity: 0,1 $/kWh
- Total cost will decrease due to efficiency increase of the technology
- OPEX costs increase every 4-5 years due to stack replacement
- Technology in demonstration phase

Sources: Study IndWEDe „Industrialisation of water electrolysis“ / International Journal of Hydrogen Energy “Techno-economic modelling of water electrolysers in the range of several MW to provide grid services while generating hydrogen for different applications“ / FCH – “Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities“ / IRENA – „Hydrogen from renewable power technology outlook“

After scaling, it becomes clear that the size of the plant accounts for a considerable proportion of the costs

H2 Production | Conditioning | Distribution | Storage | Deconditioning | Application

in $/kgH2

Thermochemical conversion

Steam Methane Reforming
CAPEX: 0,4 $/kgH2
OPEX: 1,6 $/kgH2
CO2e Emissions: 8-10 Kg/KgH2

Partial Oxidation
CAPEX: 0,3 $/kgH2
OPEX: 1,2 $/kgH2
CO2e Emissions: 4-6 Kg/KgH2

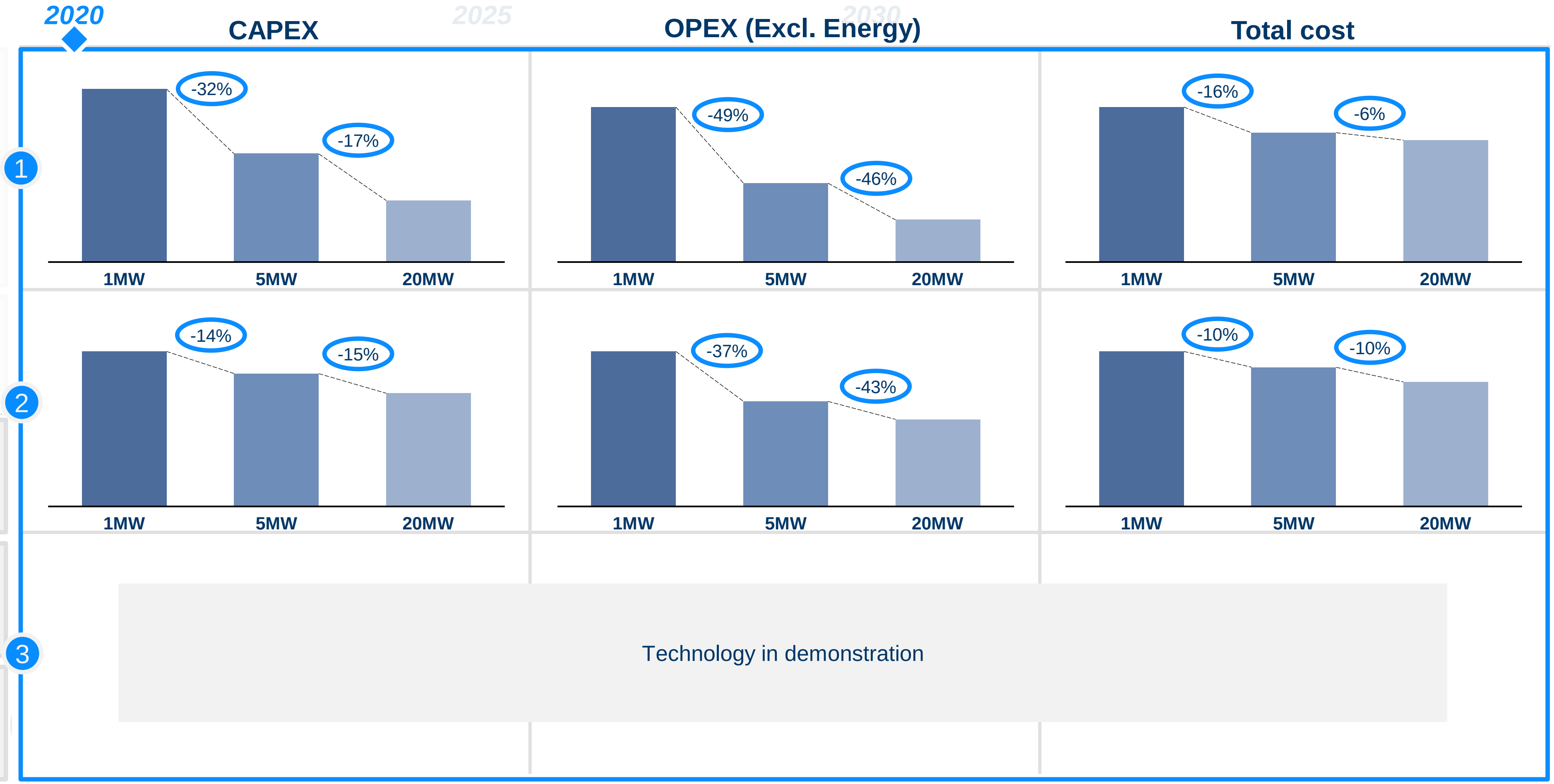
Autothermal Reforming
CAPEX: 0,2 $/kgH2
OPEX: 1,3 $/kgH2
CO2e Emissions: 8-10 Kg/KgH2

Electrolysis

① **Alkaline Water Electrolysis**
CO2e Emissions: 1-4 Kg/kgH2

② **Polymer Electrolyte Membrane**
CO2e Emissions: 1-4 Kg/kgH2

③ **Solid Oxide EC**
CO2e Emissions: *Not Available*



Technology in demonstration

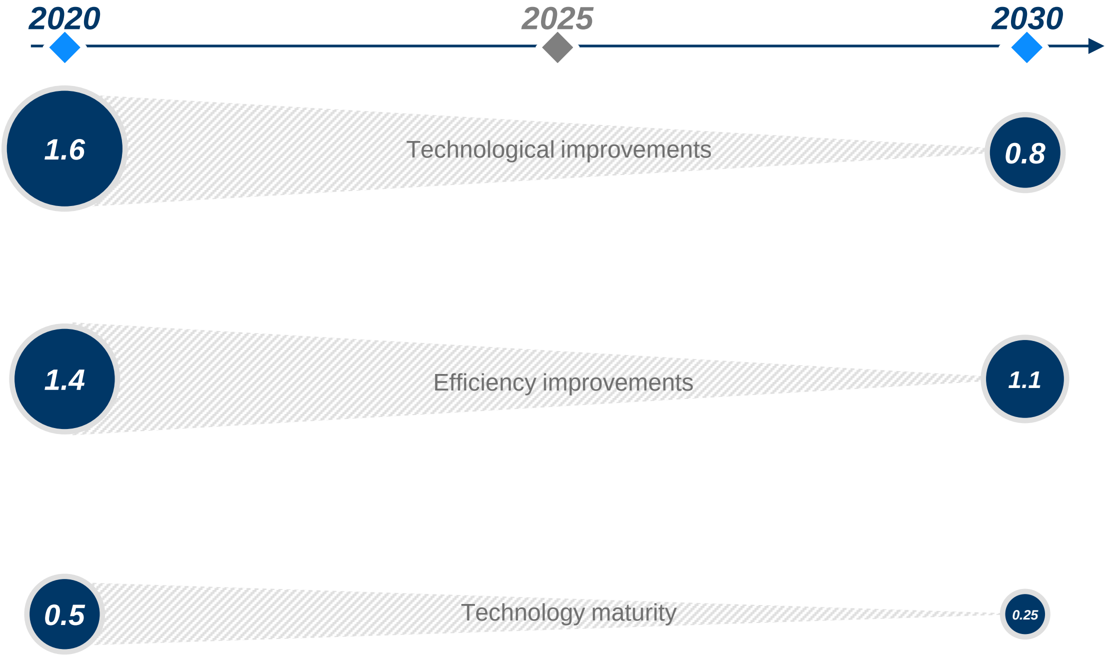
Sources: Study IndWEDe „Industrialisation of water electrolysis“ / International Journal of Hydrogen Energy “Techno-economic modelling of water electrolysers in the range of several MW to provide grid services while generating hydrogen for different applications“ / FCH – “Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities“ / IRENA – „Hydrogen from renewable power technology outlook“

Liquefaction remains the bottleneck in terms of high electricity consumption per kg H2, average production efficiencies, restrictive capacities and boil-off losses

High-Level Analysis

H2 Production | **Conditioning** | Distribution | Storage | Deconditioning | Application

in $/kgH2



Compression (GH2)
CAPEX: 1.2 $/kgH2
OPEX: 0.4 $/kgH2
CO2e Emissions: 2-4 Kg/KgH2

Liquefaction (LH2)
CAPEX: 0.7 $/kgH2
OPEX 0.7 $/kgH2
CO2e Emissions: 4-6 Kg/kgCO2

LOHC Conditioning
CAPEX: 0.3 $/kgH2
OPEX: 0.2 $/kgH2
CO2e Emissions: 0.1-0.3 Kg/KgH2

Solid Absorption

In Research and Demonstration Phase

Key Findings

- **Liquefaction** process is the critical bottleneck in conditioning- **low efficiencies** (40-50%), **CAPEX and OPEX intensive**, restrictions on **production capacities,** high energy consumption and **boiloff losses**.
- **LOHC Hydrogenation (exothermic 8.9KwH/kgH2)** like Ammonia, Lipids, Methanol and Toluene have proven **stability for transportation.** Challenges in **reconversion CAPEX** on-site and limited **H2 production capacities**.

Hypothesis

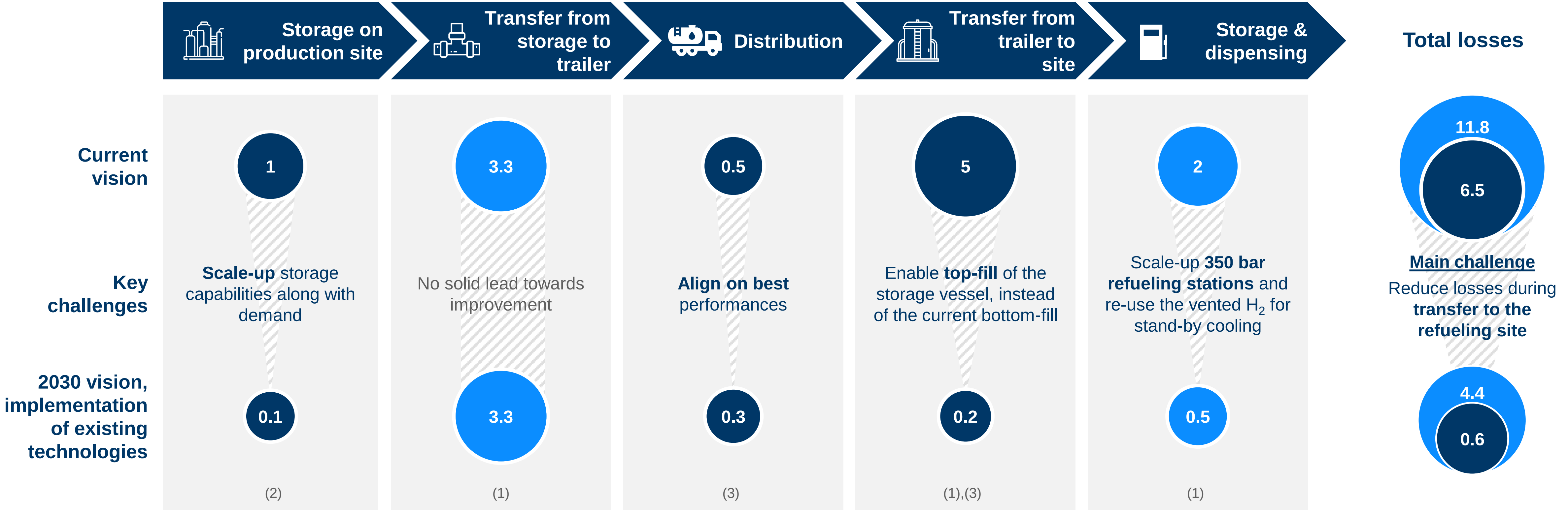
Compression Plant: Off-site, 10000kg/day capacity at 70% efficiency. CAPEX includes reciprocating compressors and HP storage unit, OPEX includes O&M (25%) and Electricity (75%)

Liquefaction Plant: Off-site, 10000Kg/day at 50% efficiency, CAPEX includes Brayton cycle with heat exchanger units. OPEX includes electricity (85%) and O&M (15%).

Note: CAPEX costs are estimates for 2020, OPEX includes fuel/electricity costs, Liquefaction for 6 KwH/kgH2 DoE Target for 2020

Sources: Air Resources Board, DoE HFC Program, HAL University Lorraine, AFHYPAC, IOPScience, Linde Engineering, Air Liquide Engineering, Elsevier Publications, Arxiv, GINER, Shell Hydrogen Roadmap, IEA "The Future of Hydrogen", Hydrogenious Technologies, SPGlobal

Most of the boil-off / venting losses will be reusable in 2030, with only 0,6 % of initial liquid H_2 kg permanently lost



	Storage on production site	Transfer from storage to trailer	Distribution	Transfer from trailer to site	Storage & dispensing	Total losses
Current vision	● 1	🔵 3.3	● 0.5	● 5	🔵 2	🔵 11.8 ● 6.5
Key challenges	**Scale-up** storage capabilities along with demand	No solid lead towards improvement	**Align on best** performances	Enable **top-fill** of the storage vessel, instead of the current bottom-fill	Scale-up **350 bar refueling stations** and re-use the vented H_2 for stand-by cooling	**Main challenge** Reduce losses during **transfer to the refueling site**
2030 vision, implementation of existing technologies	● 0.1	🔵 3.3	● 0.3	● 0.2	🔵 0.5	🔵 4.4 ● 0.6
	(2)	(1)	(3)	(1),(3)	(1)	

In % of initial H_2 kg:

- 🔵 Boil-off / venting losses that can be recycled in the liquefaction process or re-used
- ● Boil-off / venting losses with no yet known re-use mean

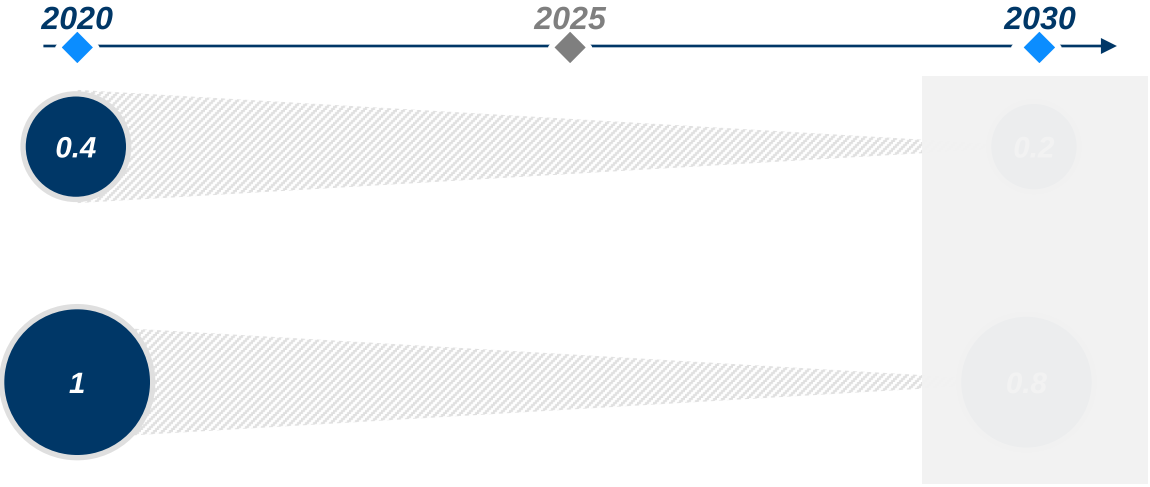
Sources: « Liquid Hydrogen Distribution Technology », Linde, HPER Closing Seminar, 2019
« Boil-off losses along LH2 pathway », G. Petitpas, Lawrence Livermore National Laboratory, 2018
« Norwegian future value chains for liquid hydrogen », Norwegian Centre of Expertises – Maritime CleanTech, 2016

LH2 Trailers are economically preferred method for a long transportation range, because of their high volumetric capacities and mature infrastructure

High-Level Analysis

H2 Production | Conditioning | *Optional* **Distribution** | Storage | Deconditioning | Application

In $/kgH2 per 100kms



LH2 Trailer
Trailer Cost: 650K-1M USD
OPEX: Negligible
CO2e Emissions: 0.1 KgCO2/km

GH2 Truck
Trailer Cost: 150K-200K USD
OPEX: Negligible
CO2e Emissions: 0.1 KgCO2/km

Pipelines

CAPEX intensive: 1M USD per km of pipelines, OPEX negligible
High capacities of transport (Up to 900 tons per day).
Insight: Rotterdam is expected to become a Hydrogen Hub in Europe, with a planned pipeline infrastructure of 40Kms to the largest GW scale Electrolysis plant.

Ships/Rails

CAPEX Intensive, OPEX negligible
Feasible only if destination is close to a seaport or connected by cargo railway

Key Findings

- **LH2 Trailer** is the **economical method** to transport- can **hold up to 50,000L** for the same distance compared to gas trailers. Transportation range of **up to 4000kms.**
- **GH2 Truck cannot store compressed gas as compactly as LH2 Trailer**, with available tank volume for hydrogen per tanker is lower. **Single-tube trailers** carry approximately **500kg of hydrogen**, depending on the pressure and container material- limited due to country-specific **road safety regulations** on **trailer weight and dimensions** for gases.
- **Natural gas pipelines can carry GH2 (15%-20% blend)** to utilize existing infrastructure. Using the pressures and pipe diameter of **existing pipe storages** of natural gas, approximately **12 tons of hydrogen** could be stored per km of pipeline, but **hydrogen embrittlement can occur in the pipes.**

Note: CAPEX costs are estimates for 2020, OPEX includes fuel/electricity costs, Costs for 2030 are based on projections and forecasts.

Sources: DoE-Hydrogen Transportation Methods, Hydroville, Hydrogen Europe, NREL-Hydrogen Pathways, DNV-GL “Hydrogen in Electricity value chain”, IEA “The Future of Hydrogen” , Hydrogen Europe “Enabling a Zero Emission Europe”, FCH Roland Berger Study

Cryogenic vessels have been historically utilized in space programs for large capacities, with new technologies to reduce boil-off losses through re-condensation

High-Level Analysis

H2 Production | Conditioning | Distribution | **Storage** | Deconditioning | Application

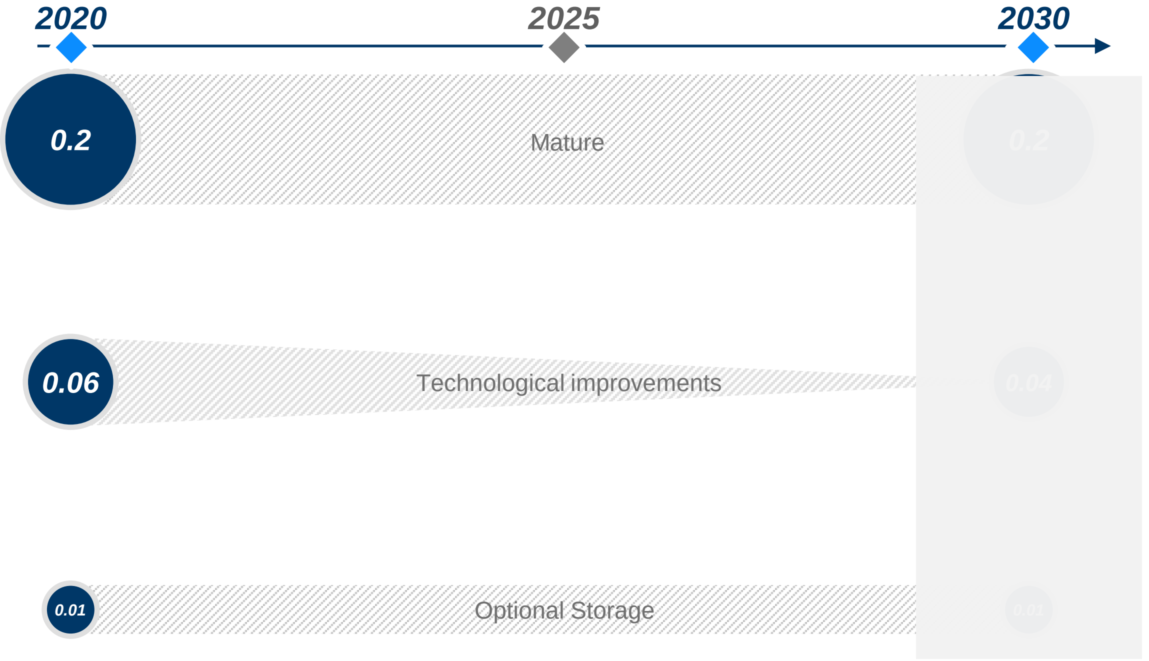
in $/kgH2 per day

Above the Ground

Pressure Vessel (GH2)
CAPEX: 0.2 $/kgH2
OPEX: Negligible
CO2e Emissions: 0.5-1 Kg/kgH2

Cryogenic Vessel (LH2)
CAPEX: 0.04 $/kgH2
OPEX: 0.02 $/kgH2
CO2e Emissions: 0.5-1 kg/kgH2

LOHC Storage
CAPEX: 0.01 $/kgH2 (Methanol)
OPEX: Negligible
CO2e Emissions: < 1kg/kgH2



Under the Ground

Caverns, Aquifers
CO2e Emissions: < 1kg/kgH2

Not suitable for airport storage and utilization

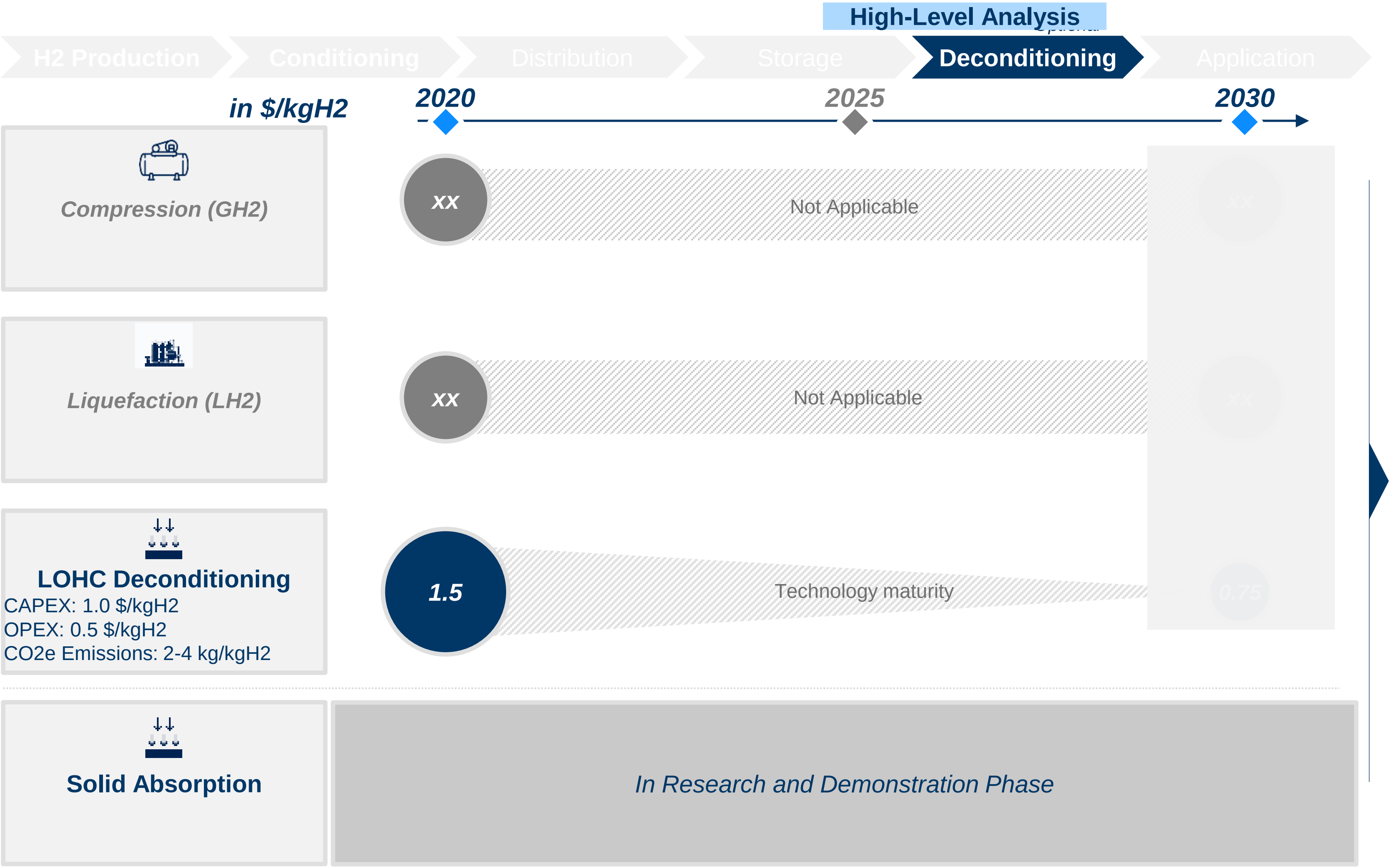
Key Findings

- **Cryogenic tank (cylindrical and spherical)** OPEX includes continuous refrigeration with heavy thermal insulation **to prevent boil-off losses**. Large scale cryogenic tanks **recirculate boiloff GH2** to condense back to LH2. Typical **Storage CAPEX** costs: **$220/kg for 10tpd** capacity.
- **GH2 Pressure vessels** hold a maximum pressure of 1000bar (commonly used are 350bar and 700bar) made of **stainless steel and aluminum**, commonly used in space applications. **New low-cost materials using composites** are in research that can hold up to **2000bar pressures**.
- Not all regions have underground storage capabilities, although they have **high storage capacities, low construction costs**, low leakage rates, fast withdrawal and injection rates and minimal risks of hydrogen contamination.

Note: CAPEX costs are estimates for 2020, OPEX includes fuel/electricity costs for cryogenic vessel, Costs for 2030 are based on projections and forecasts.

Sources: TU Delft "Feasibility study into Blue Hydrogen", NREL "Hydrogen Pathways", Air Liquide "Hylial", FCH "Commercialization of Energy Storage in Europe", Hydrogen Europe, FCH-HYSTOC Study, MDPI "Well to Tank GHG Emissions"

LOHC Deconditioning is energy-intensive (~3x more than hydrogenation) with makes it cost-effective only over long-distance transport (greater than 4000kms)



High-Level Analysis

H2 Production | Conditioning | Distribution | Storage | **Deconditioning** | Application

in $/kgH2

2020 | *2025* | *2030*

Compression (GH2): xx — Not Applicable — xx

Liquefaction (LH2): xx — Not Applicable — xx

LOHC Deconditioning
CAPEX: 1.0 $/kgH2
OPEX: 0.5 $/kgH2
CO2e Emissions: 2-4 kg/kgH2

1.5 — Technology maturity — 0.75

Solid Absorption

In Research and Demonstration Phase

Key Findings

- Dehydrogenation is **endothermic** and is realized typically close to atmospheric pressure at **elevated temperatures normally between 200°C-450°C.**
- Dehydrogenation **conversion efficiencies are between 90% to 100%.** However, another major drawback of LOHC is the **low pressure of dehydrogenation** step, leading to **additional compressor CAPEX**.
- About **70% of the overall cost** goes into **dehydrogenation CAPEX**, use of solvents and **post-purification of LOHC** gases from GH2.
- Considering the heat transfer losses, around 25–30% of the released hydrogen would have to be burned should the heat be provided by hydrogen. **If the heat released from hydrogenation is utilized, the dehydrogenation process is partially compensated.**

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Note: LOHC chosen is Methanol (energy density of 3.3 KwH/L), CAPEX includes compressors and post-purification infrastructure during dehydrogenation.

Sources: HySTOC LOHC Market Study, Hydrogen Council-Path to Hydrogen competitiveness, Energy and Environmental Science “Techno-Economic Analysis of LOHC Carriers”, VTT “Liquid Organic Hydrogen Carriers”, IJHE Studies on LOHC

Current HRS market is focused on 350bar for buses and 700bar for FCEVs of GH2 refueling; LH2 dispensing is restricted to space applications

High-Level Analysis

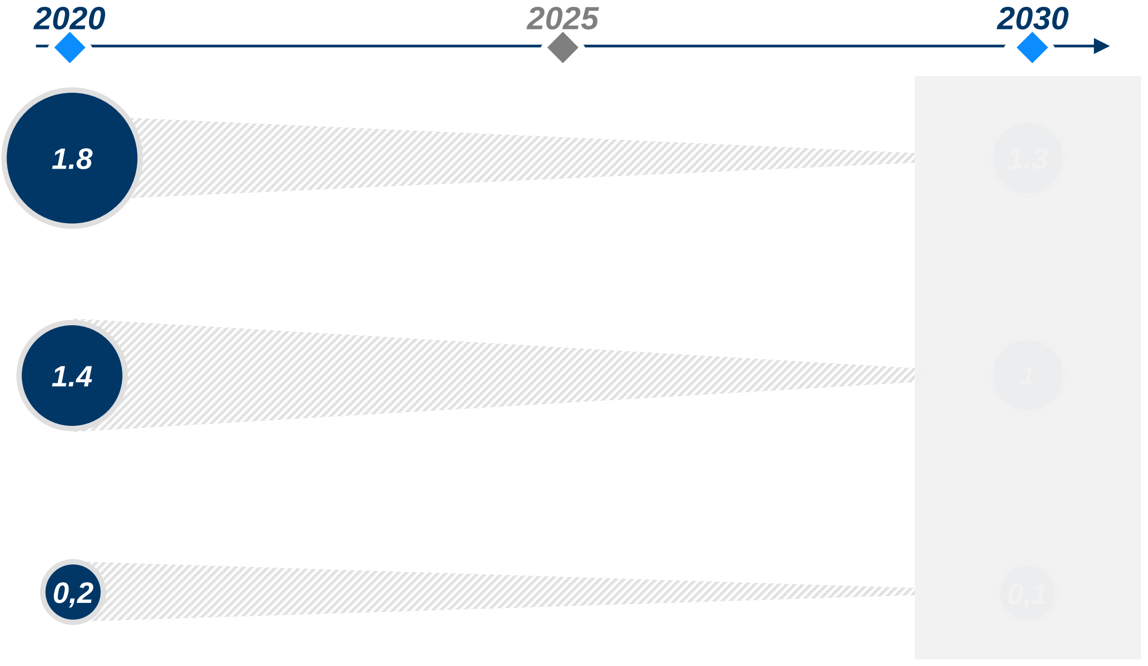
H2 Production → Conditioning → Distribution → Storage → Deconditioning → **Dispensing**

in $/kgH2/day

GH2 Dispensing*
(From GH2 supply)
CAPEX: 1.0 $/kgH2
OPEX: 0.8 $/kgH2
CO2e Emissions: 2-3kg/kgH2

GH2 Dispensing*
(From LH2 supply)
CAPEX: 1.1 $/kgH2
OPEX: 0.3 $/kgH2
CO2e Emissions: 1-1.5kg/kgH2

LH2 Dispensing
CAPEX: 0.15 $/kgH2
OPEX: 0.05 $/kgH2
CO2e Emissions: 1-1.5 kg/kgH2



Cryo-Compressed GH2	First prototype tests done by BMW and Linde (can fill up to 100-120 kg/hr)
LOHC Supplied GH2	In Research and Demonstration Phase

Key Findings

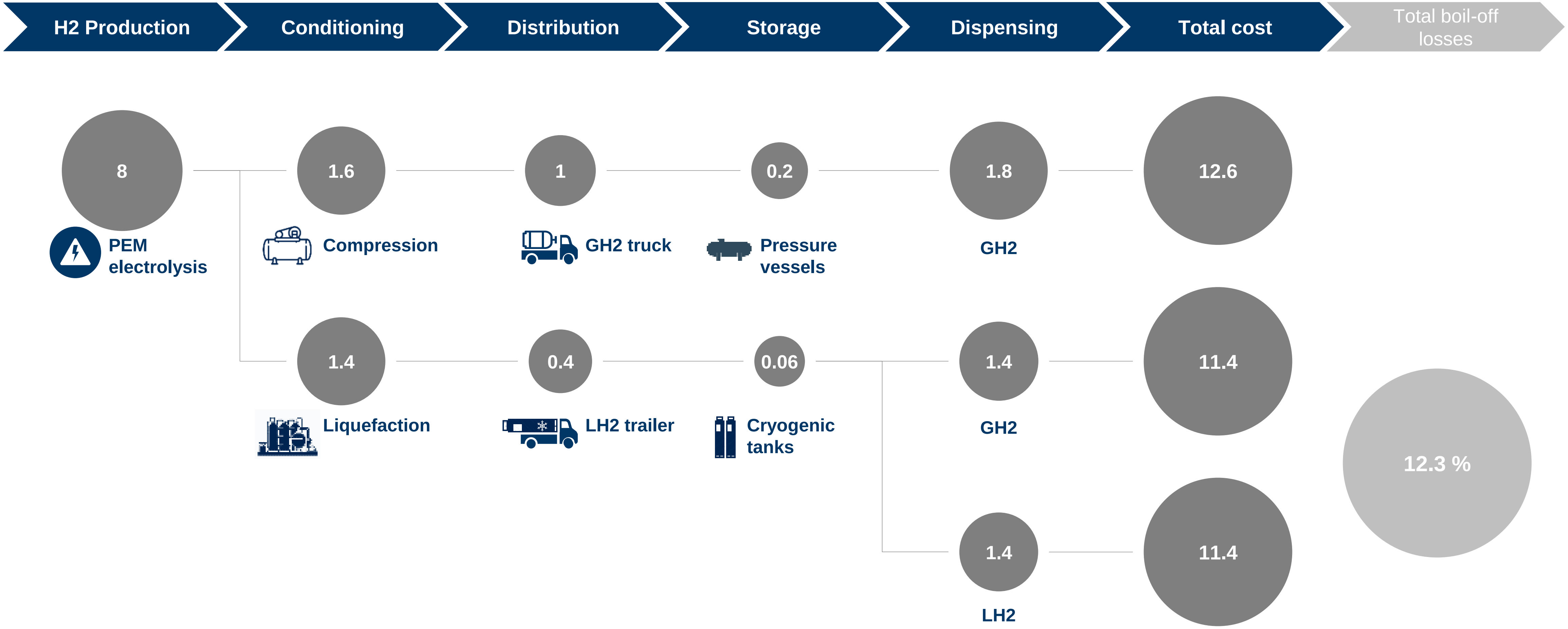
- **GH2 dispensing** is **a mature technology** used in FCEVs and buses today at pressures of **350bar and 700bar respectively.** Wide infrastructure coverage that can dispense up to 2Kg/min. **Demand management** is necessary to optimize **GH2 availability based on fueling tendencies** and number of **available dispensers.**
- Liquid Hydrogen dispensing station costs about **0.5 €M for one point of filling**. Current fueling technologies can refuel up to **300kgs in 15mins.**
- **Cryo-compressed dispensing** (GH2 at 350bar) stored in a **cryogenic insulated tank** is being researched by BMW that can achieve **under 5mins for refueling for 500kms range.**

*- For 400Kg/day HRS station with compressor, 2 dispensers, refrigeration, evaporators and electrical components. OPEX includes electricity prices, O&M costs and boil-off losses in LH2 station.

Sources: DoE "Hydrogen Delivery Options and Issues", BMW Cryo-compressed H2 Storage and Dispensing, NREL "Hydrogen Station Costs", Linde Hydrogen Transport and Stations, NASA LH2 dispensing, IEA Hydrogen Pathways and Dispensing, FCHJU-NewBusFuel, CryoH2

Hydrogen costs: current vision

Current vision
Scale-up
Technical evolutions



H2 Production
Conditioning
Distribution
Storage
Dispensing
Total cost
Total boil-off losses

8
PEM electrolysis

1.6
Compression

1
GH2 truck

0.2
Pressure vessels

1.8
GH2

12.6

1.4
Liquefaction

0.4
LH2 trailer

0.06
Cryogenic tanks

1.4
GH2

11.4

1.4
LH2

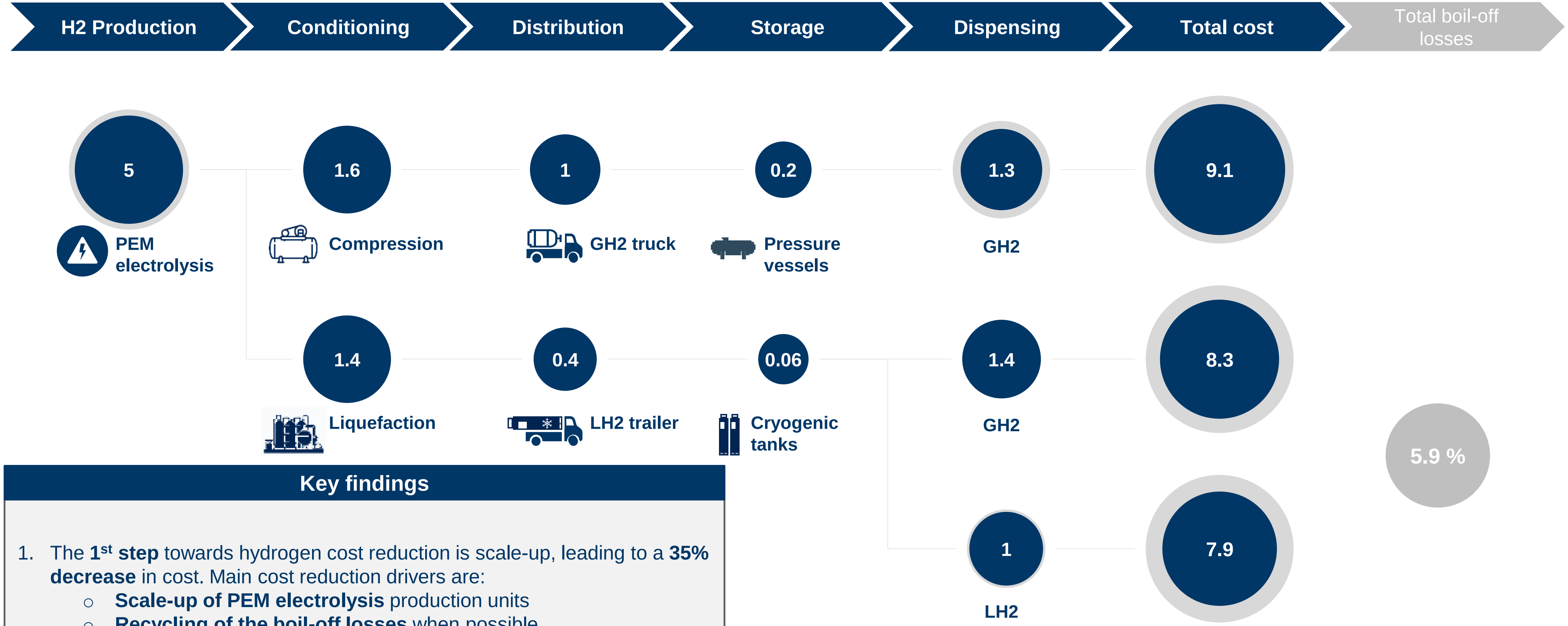
11.4

12.3 %

Values indicated in $ / kgH2

Hydrogen costs: a vision based on a scale-up of 2020 technologies

Current vision | Scale-up | Technical evolutions



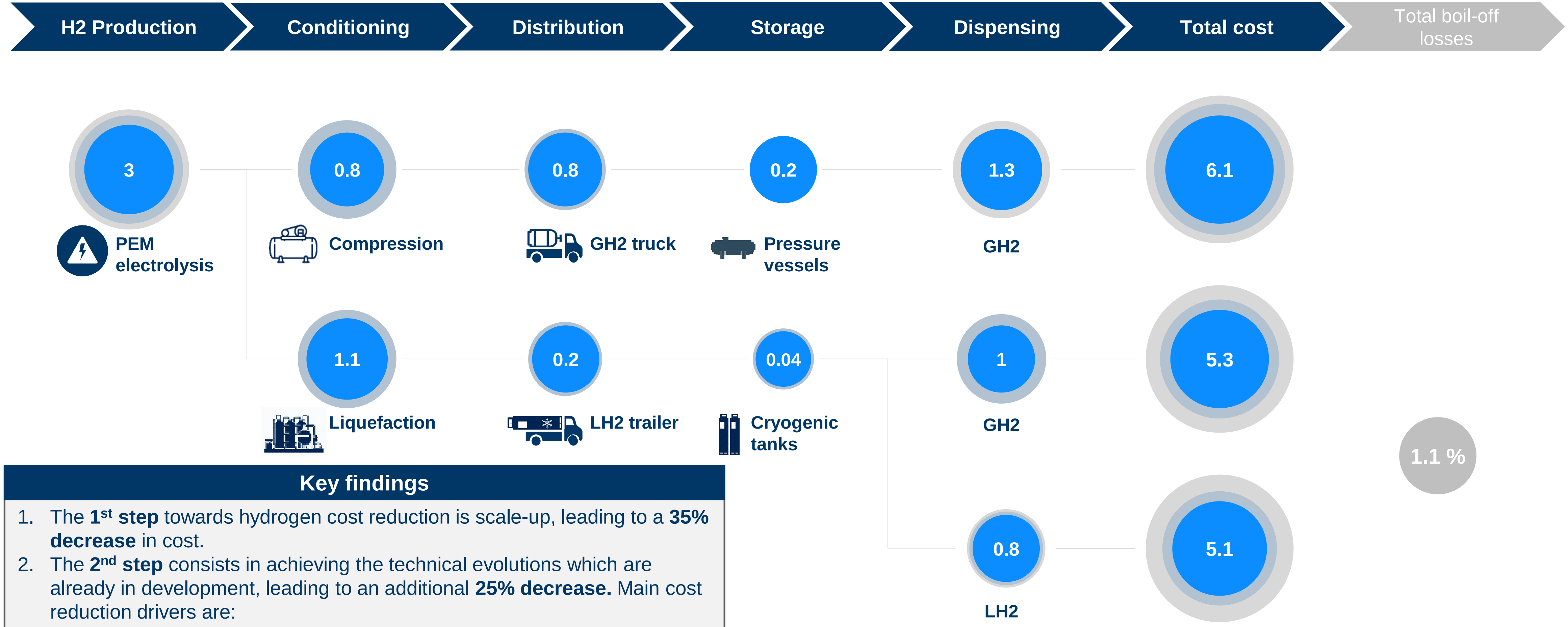
Key findings

1. The **1st step** towards hydrogen cost reduction is scale-up, leading to a **35% decrease** in cost. Main cost reduction drivers are:
    - **Scale-up of PEM electrolysis** production units
    - **Recycling of the boil-off losses** when possible

Values indicated in \$ / kgH2

Hydrogen costs: a 2030 vision, after scale-up & technical evolutions

Current vision → Scale-up → **Technical evolutions**

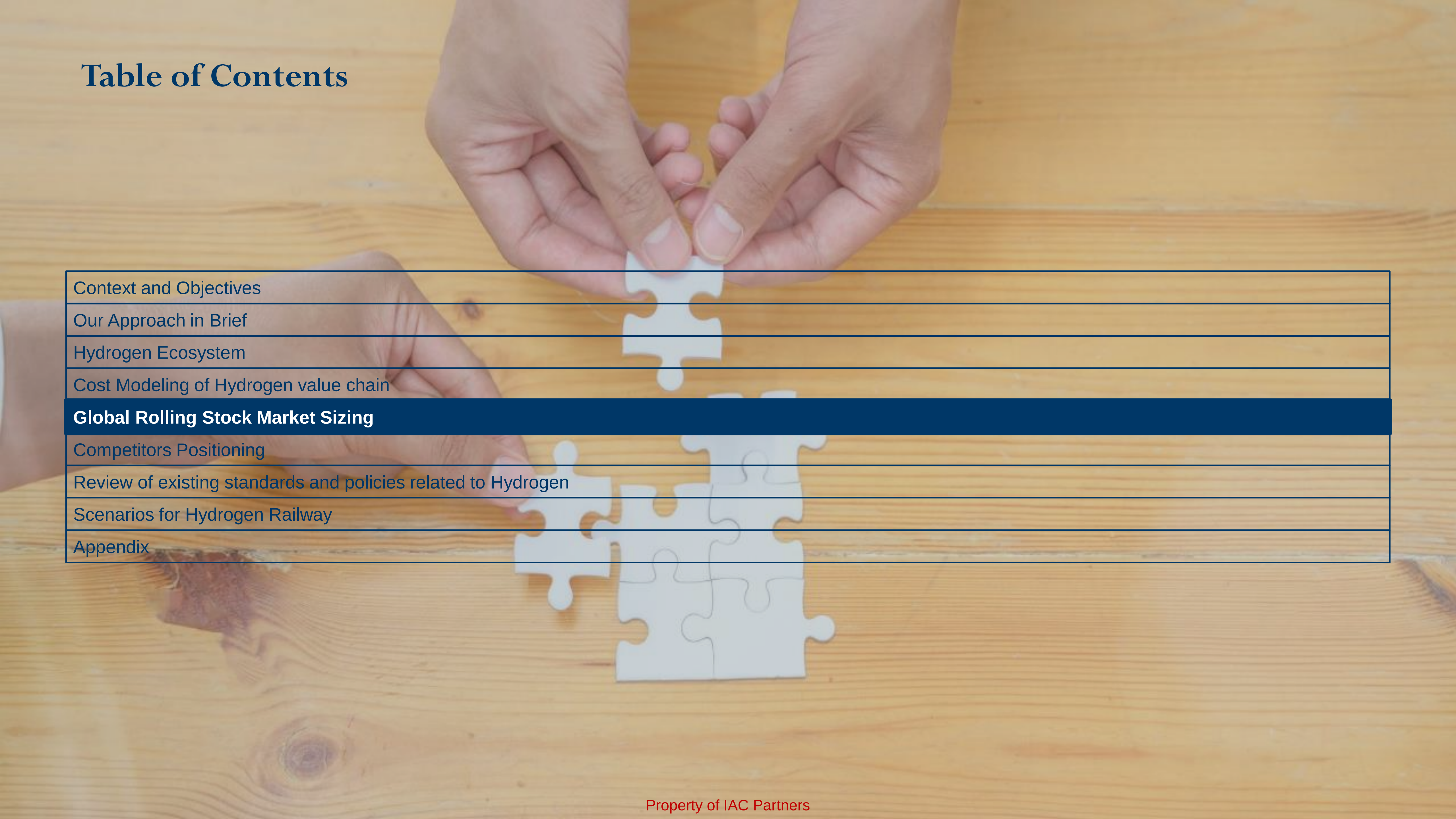


H2 Production	Conditioning	Distribution	Storage	Dispensing	Total cost	Total boil-off losses
3 PEM electrolysis	0.8 Compression	0.8 GH2 truck	0.2 Pressure vessels	1.3 GH2	6.1	
	1.1 Liquefaction	0.2 LH2 trailer	0.04 Cryogenic tanks	1 GH2	5.3	1.1 %
				0.8 LH2	5.1	

Key findings

1. The 1st **step** towards hydrogen cost reduction is scale-up, leading to a **35% decrease** in cost.
2. The **2nd step** consists in achieving the technical evolutions which are already in development, leading to an additional **25% decrease.** Main cost reduction drivers are:
   - **Technology maturation** of PEM electrolysis plants
   - **Efficiency improvement** of the conditioning step

Values indicated in \$ / kgH2



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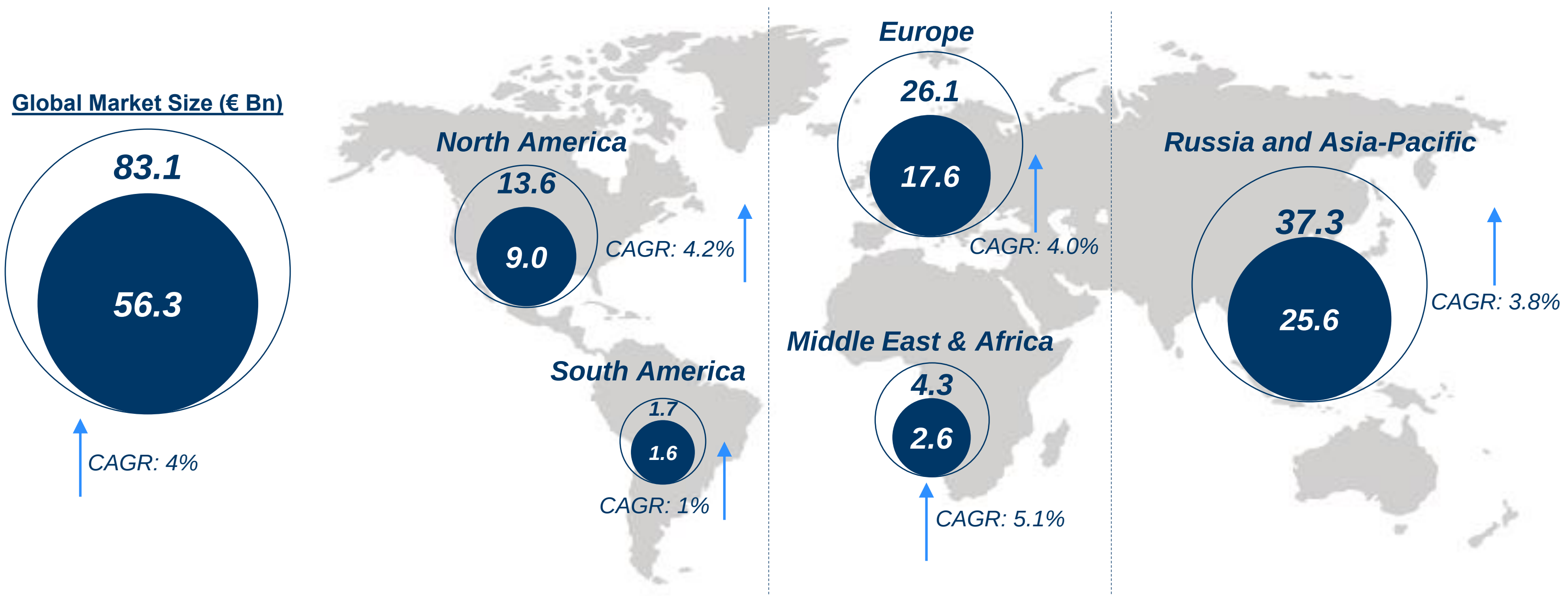
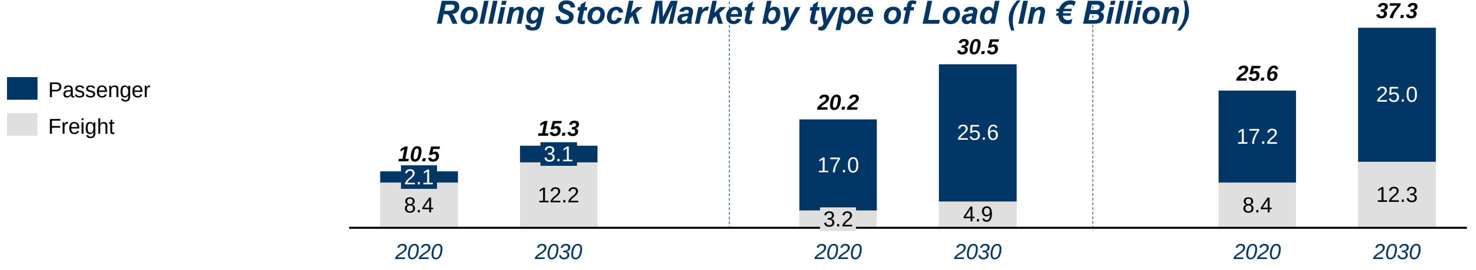
Global Rolling stock market is dominated by Asia, with EMEA market expected to grow strongly by 2030

Global Rolling Stock Market Sizes by Geographical Regions (In € Billion)



Rolling Stock Market by type of Load (In € Billion)



● 2020 ○ 2030

Key Findings

- Asia is the **largest rolling stock market, led by China, Japan and India**, and with large scale development of passenger rail, with these three countries also topping the list of passenger-kilometer per year
- Europe is expected to be the **primary focus of railway rolling stock actors**, with strong growth driven by new environmental policies and the renewing of existing rolling stock units. **Freight market should grow** as EU commission has set a target of moving 30% of the 300 + km range freight to other transport modes (**rail** or water) by 2030.
- North American rolling stock market is **driven by rail freight market**. In contrary to EU, funds will come from private organizations who own US railroads and are responsible for their own maintenance and improvement projects.

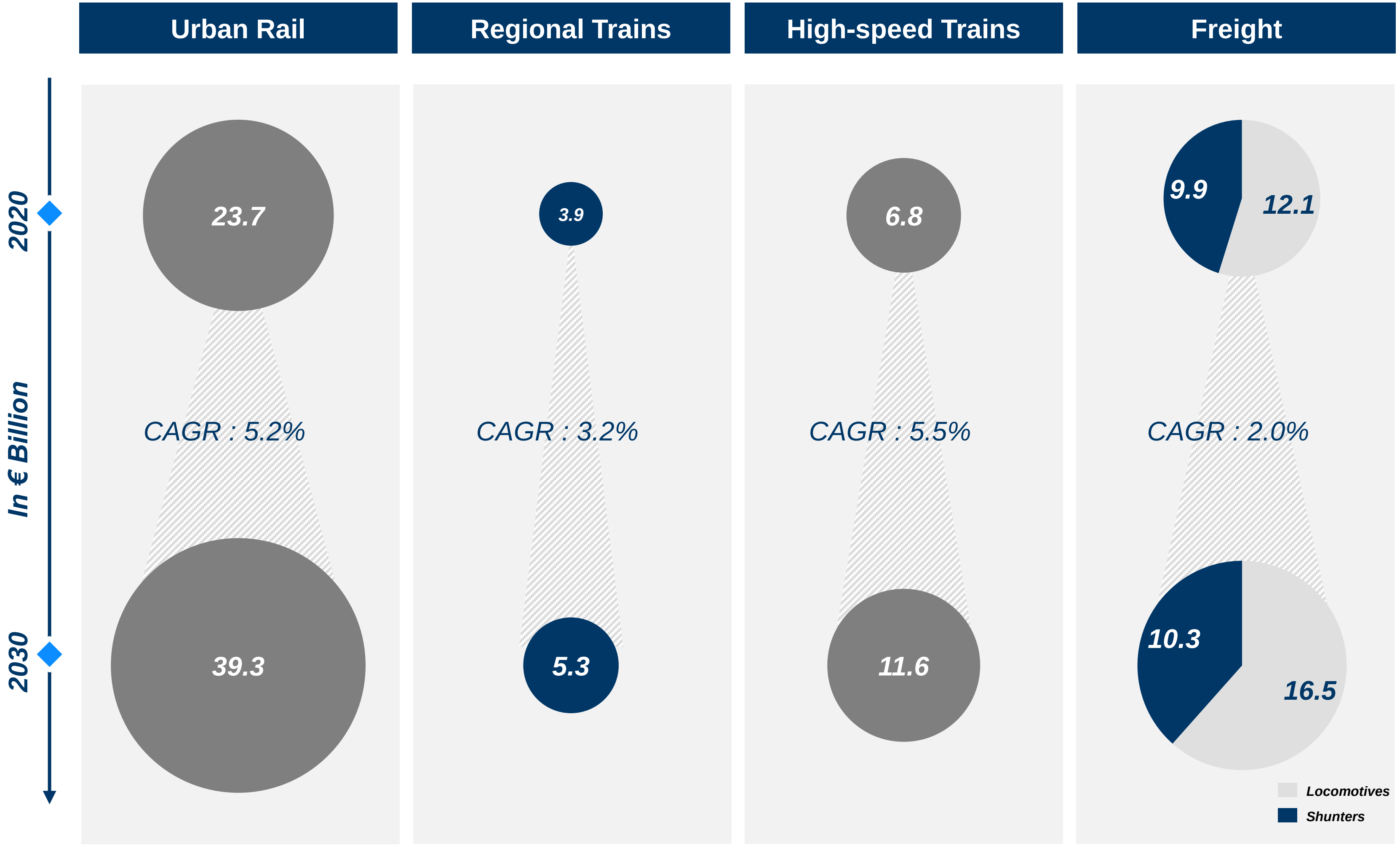
Sources: Markets and Markets, Mordor Intelligence, Grandview research, imarc Group, Financial buzz, Unife, Sci.de Flyer MC Worldwide 2018

Railway rolling stock market segmentation by type of trains is done as follows:

Types of Trains *Segmentation Parameters*	Urban Rail	Regional Trains	High-speed Trains	Freight
Trains in Scope	Trams Metro Rail	Suburban Intercity	Bullet Trains, TGVs, Maglevs	Cargo & Goods Commercial
Load Type	Passengers	Passengers	Passengers	Freight
Operating Range per trip	Less than 20 kms radius	Up to 200 kms	Up to 1000 kms	Up to 13000 kms
Average Speed	Up to 70 km/hr	Up to 200 Km/hr	Up to 300 Km/hr	Up to 100 Km/hr
Traction Power Supply	600V to 3000V	15000V	25000V	Up to 55000V
Power Mode	Electric	Diesel, Electric, Hybrid	Electric	Diesel, Electric, Hybrid

Sources: Shift2Rail Project, ARUP group “How has the market for rail passenger demand been segmented?”, IEA “The Future of Rail”, FCH Roland Berger Report, IEA “The Future of Rail”

Global Rolling stock segmentation by type: regional and freight trains are the non-electrified lines that can be addressed by Hydrogen

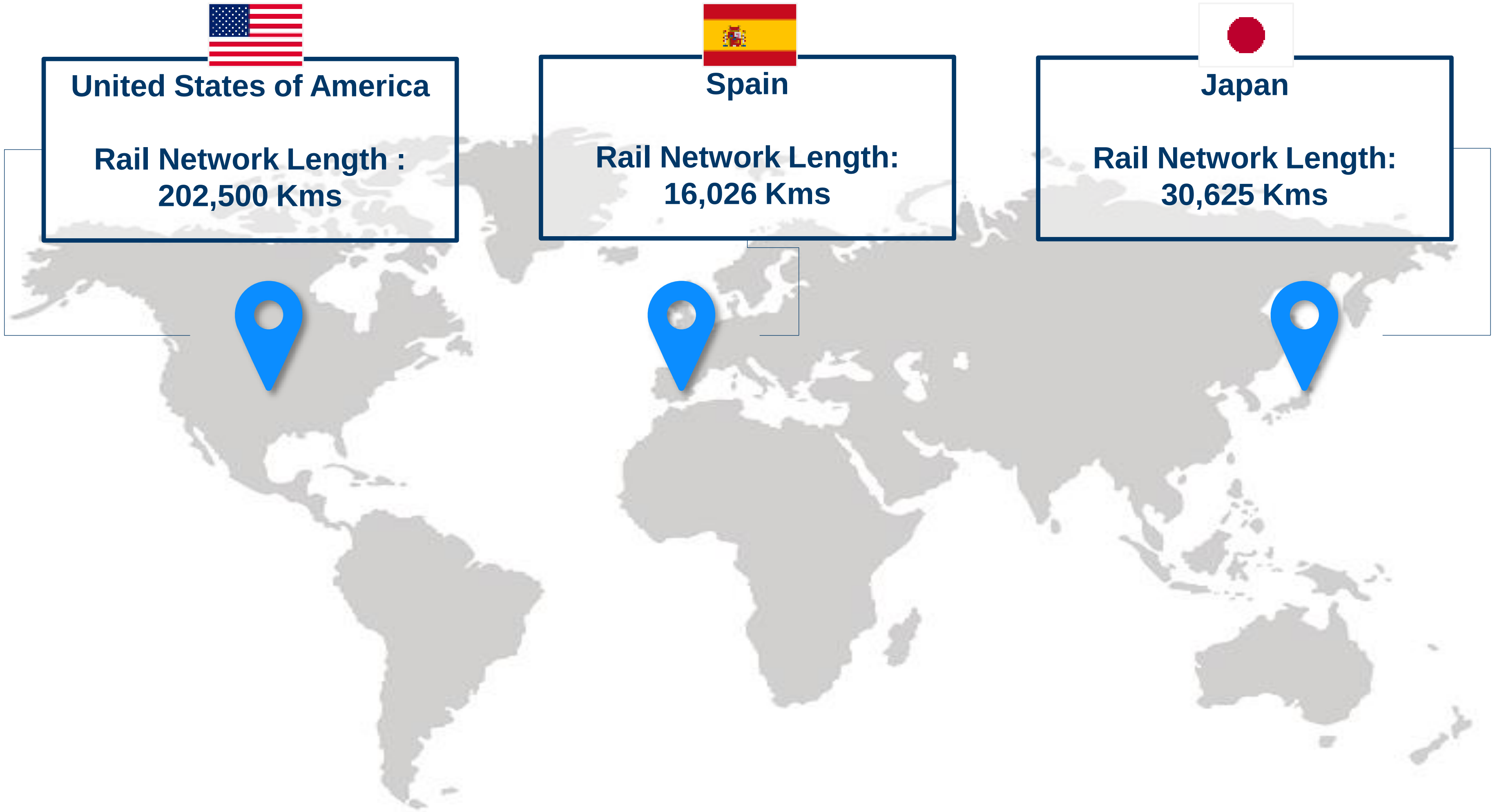


Key Findings

- **Urban rail (metros and trams)** is largest market segment in rolling stock. However, **almost 100% of them are electrified.** So, Hydrogen application is ruled out in this segment. If Hydrogen train is expected to replace electric trains, then this is a promising segment.
- **Urban rail and High-speed trains** market is driven by **China's massive expansion** in these segments. However, it is expected to be electrified 100%. **This market cannot be addressed by Hydrogen.**
- Hybrid trains **(electro-diesel, battery operated, Hydrogen, etc.)** occupy less than 1% of the total rolling stock market today, which will continue to rise until 2030.

Sources: GlobenewsWire, IEA "The Future of Rail", ALSTOM Investor Presentation 2019, Markets and Markets, Mordor Intelligence, Market Data Forecast, Research and Market Forecasts, Mass Transit Magazine

Different country profiles were chosen for an in-depth analysis of hydrogen trains' go-to market attractiveness



United States of America

Rail Network Length : 202,500 Kms

Spain

Rail Network Length: 16,026 Kms

Japan

Rail Network Length: 30,625 Kms

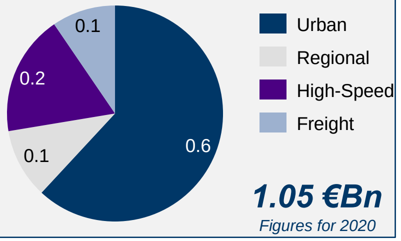
Note: Railway Network length as of 2019

Sources: Statistia 2019, Rail transport in North America, Spain and Japan

Deep Dive: Spain has favorable conditions for H2 trains thanks to political will, topography and low percentage of network electrification

Regional Overview

Market Overview (€ Bn)



1.05 €Bn

Figures for 2020

Advantages

- Favorable H2 policies and infrastructure in rail transport
- Significant network of non-electrified lines

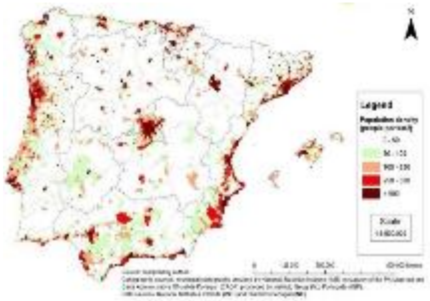
Challenges

- Large urban rail market which is 100% electrified
- State-operated system responsible for planning of H2 train introductions

Land Topography

Mountain Regions: 15% of Spain's landmass

Average Elevation: 2100 feet



Railway Characteristics

Length of Railway : 16,026 kms

Track Gauge: Standard Gauge (4 ft 8 1⁄2 in / 1,435 mm), Iberian Gauge 1,668 mm (5 ft 5 21⁄32 in)

Railway Electrification : 63% of network

Percentage of Passenger Load: 84%

Average Grid Electricity Emissions: 174 gCO2/kWh

Cost of H2 to Diesel ($/kWh) : 0.40 : 0.09

Policies and Enablers for H2

- Spain has a **hydrogen roadmap** which proposes the rollout of at **least 4 GW of electrolysis capacity by 2030**, along with a **25% share for green hydrogen** in industrial processes.
- For the mobility sector, the ministry proposes a fleet of **150 buses, 5,000 light and heavy vehicles, and two commercial trainlines run from renewable hydrogen for 2030**, all with an associated hydrogen refueling network.

Key H2 Projects in Railway

- **RENFE** presented an innovative prototype of **a tram powered by hydrogen fuel cells**. in operation in the region in 2012.

Primary Actors

RENFE
EUSKOTREN
FGC

RENFE
ACCIONA
COMSA
CONTINENTAL RAIL

Regional trains is the most addressable market, connecting big cities with smaller towns. The railway network is not much electrified, hence there is a big addressable market for Hydrogen. Geographical topography with low % of mountains is also favorable.

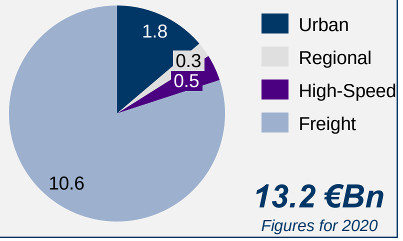
Passenger Freight

Sources: SPGlobal Market intelligence, Indexmundi, Rail Transport in Spain, Renfe Operadora website, Global Railway Review

Deep Dive: USA has the largest freight railway network in the world primarily running on diesel

Regional Overview

Market Overview (€ Bn)



13.2 €Bn

Figures for 2020

Advantages

- Largest market for freight rolling stock
- Heavily reliant on diesel fuel, Low level of electrification
- Low competition intensity

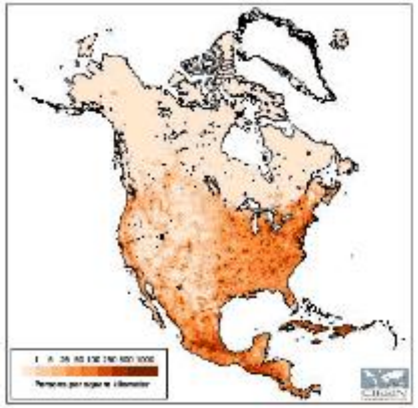
Challenges

- State-specific policies for hydrogen development
- Competitive threat from LNG in train locomotives

Land Topography

Mountain Regions: 24% of US landmass

Average Elevation: 2500 feet



Railway Characteristics

Length of Railway : 202,500 kms

Track Gauge: Standard Gauge (4 ft 8 1⁄2 in / 1,435 mm).

Railway Electrification : 1% of network

Percentage of Passenger Load: 20%

Average Grid Electricity Emissions: 424 gCO2/kWh

Cost of H2 to Diesel ($/kWh) : 0.42 : 0.06

Policies and Enablers for H2

- California has proposed a **railway emissions adoption plan** to be adopted at a federal level for **locomotives** to be manufactured after 2025. (CA Air Resources Board 2017)
- USA allows for the **rail shipment of LNG**, and companies like **CNGMotive** are delivering low-cost, “clean” and safe natural gas to heavy duty freight locomotives. (2019)

Key H2 Projects in Railway

- California's **San Bernardino County** announced a deal with Swiss train manufacturer **Stadler Rail** to install the first U.S. hydrogen train by 2024. (November 2019)
- **BNSF tested a H2 locomotive** with 250 kW fuel cells and 1250 kW battery in 2009.

Primary Actors

AMTRAK

BNSF Railway
CSX Transportation
Kansas City Southern Railway
Norfolk Southern Railway
Union Pacific Railroad

Freight rolling stock is the biggest addressable market in USA. There is a large potential for hydrogen shunters to replace diesel ones. The remaining question is to identify if there is a political and infrastructural will to develop a profitable hydrogen ecosystem. This will highly depend from the State: California, as shown here, is promising market for hydrogen businesses.

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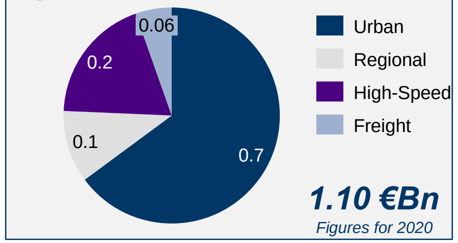
Passenger Freight

Sources: US DoE H2@Rail Workshop, Popular Mechanics, Rail transport in North America

Deep Dive: Japan has high grid emissions and favorable hydrogen policies for addressing the non-electrified rail lines

Regional Overview

Market Overview (€ Bn)



1.10 €Bn

Figures for 2020

Advantages

- Significant network of non-electrified lines
- Competitive prices of Hydrogen vs diesel and favorable Hydrogen policies

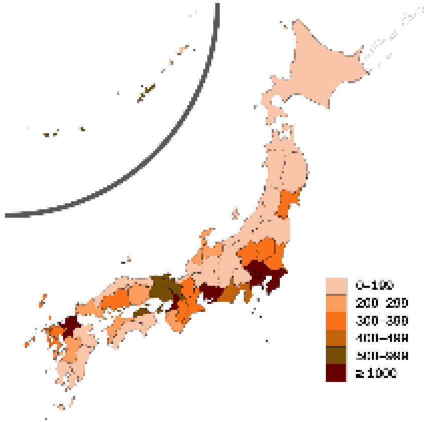
Challenges

- High grid CO2 emissions
- High % of electric passenger rail
- Topographical challenges because of mountains
- Strong competition

Land Topography

Mountain Regions: 73% of Japan's landmass

Average Elevation: 1437 feet



Railway Characteristics

Length of Railway : 30,625 kms

Track Gauge: Standard Gauge (4 ft 8 1⁄2 in / 1,435 mm), Narrow Gauge 1,067 mm (3 ft 6 in)

Railway Electrification : 71% of network

Percentage of Passenger Load: 95%

Average Grid Electricity Emissions: 490 gCO2/kWh

Cost of H2 to Diesel ($/kWh) : 0.30 : 0.10

Policies and Enablers for H2

- Japan was the first country to adopt a **"Basic Hydrogen Strategy"** as early as 2017. which aims to achieve **cost parity with competing fuels** such as gasoline & LNG in transportation sector.
- **Kawasaki Heavy Industries** also announced the $350M construction of **hydrogen export infrastructure to Japan** in the Australian state of Victoria. (2019)

Key H2 Projects in Railway

- **East Japan Railway Co.:** Testing new hydrogen-powered trains beginning in the year 2021. The company plans to spend $37 million on the development of a two-car setup and test runs, aiming to commercialize the design by the year 2024.

Primary Actors

HOKKAIDO
EAST JAPAN
CENTRAL JAPAN
WEST JAPAN
SHIKOKU
KYUSHU

Japan Freight Railway company (JR GROUP)

Japan's grid electricity has high CO2 emissions per kWh, which makes electric trains less attractive for decarbonization. However, there are multiple addressable segments, as the ecosystem is hydrogen-ready.

IAC PARTNERS

Passenger Freight

Sources: Geography of Japan – SPICE, Carbon Footprint emissions, Rail Transport in Japan, Japan Railways Group

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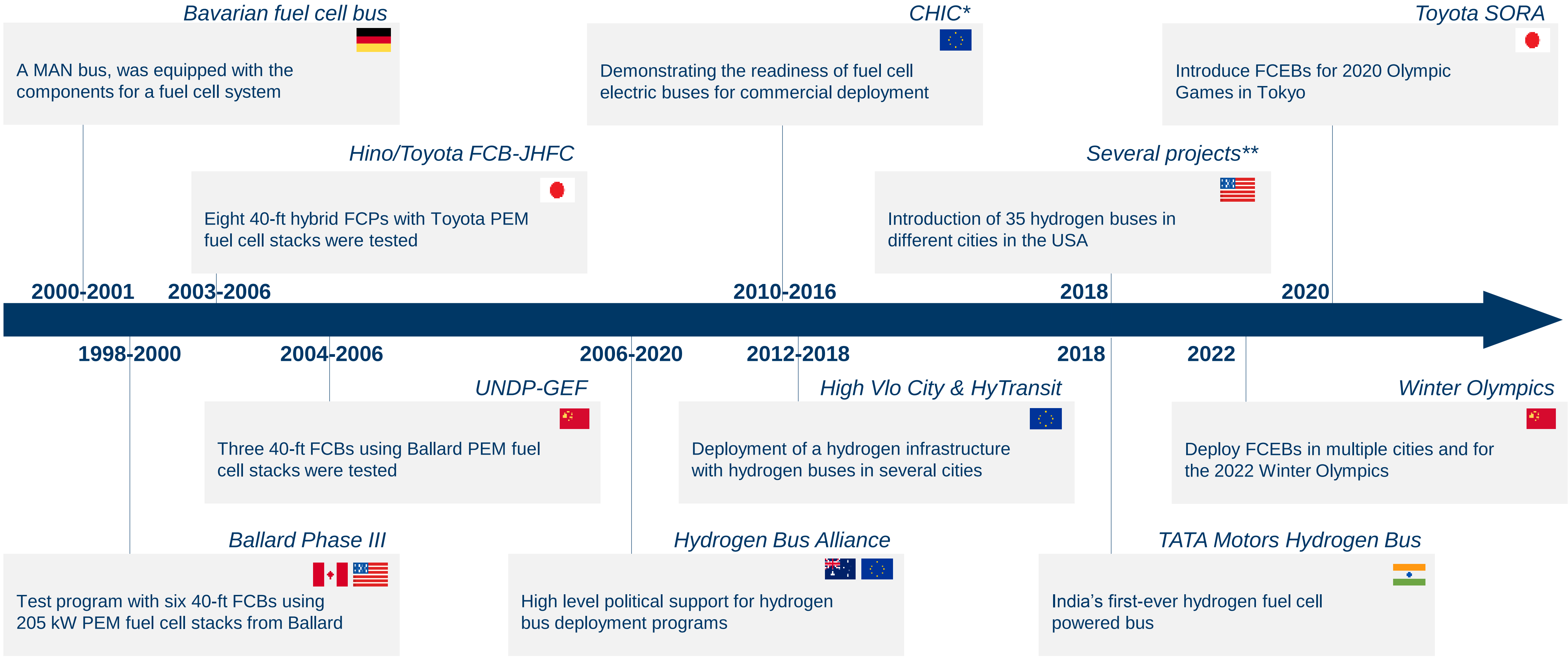
The history of hydrogen buses shows that this sector has been pushing the hydrogen topic for a long time, leading to mature technologies



1998-2000

Ballard Phase III

Test program with six 40-ft FCBs using 205 kW PEM fuel cell stacks from Ballard

2000-2001

Bavarian fuel cell bus

A MAN bus, was equipped with the components for a fuel cell system

2003-2006

Hino/Toyota FCB-JHFC

Eight 40-ft hybrid FCPs with Toyota PEM fuel cell stacks were tested

2004-2006

UNDP-GEF

Three 40-ft FCBs using Ballard PEM fuel cell stacks were tested

2006-2020

Hydrogen Bus Alliance

High level political support for hydrogen bus deployment programs

2010-2016

*CHIC**

Demonstrating the readiness of fuel cell electric buses for commercial deployment

2012-2018

High Vlo City & HyTransit

Deployment of a hydrogen infrastructure with hydrogen buses in several cities

2018

*Several projects***

Introduction of 35 hydrogen buses in different cities in the USA

2018

TATA Motors Hydrogen Bus

India’s first-ever hydrogen fuel cell powered bus

2020

Toyota SORA

Introduce FCEBs for 2020 Olympic Games in Tokyo

2022

Winter Olympics

Deploy FCEBs in multiple cities and for the 2022 Winter Olympics

**CHIC: Clean Hydrogen in European Cities*
***Several projects: NFBCP, CEC, Low-No, CARB*

A large number of companies have already commercialized hydrogen-powered buses and are further pushing the topic with mature knowledge and technology

Major fuel cell electric bus OEM's	YUTONG	中通客车	FOTON	NEW FLYER	TOYOTA	WRIGHTBUS	VANHOOL	SOLARIS
Revenue	4 bn. €	6.72 bn. €	5.2 bn. €	2.4 bn. €	-	230 mio. €	560 mio. €	585 mio. €
City Buses	✓	✓	✓	✓	✓	✓	✓	✓
Intercity Buses	✓	✓	✓			✓	✓	✓
School Buses	✓							
Electric Buses	✓	✓	✓	✓	✓	✓	✓	✓
Minibus			✓		✓			
Special Vehicles	✓	✓						✓
Partnerships/ Consortium	• Partnership with **SinoHytec**, a state-level tech enterprise focusing on **R&D** and industrialization of **FC engines**	• Joined the **Shangdong Heavy Industries Group** to strengthen its efforts in **developing** and **marketing fuel cell buses** • Close partnership with **Weichai Power** to build **multiple fuel cell bus** demonstration lines in Shandong	• **Foton, Toyota** and **SinoHytec** to jointly **launch fuel Cell Buses** • Co-operative agreement with **SinoHytec** and **SPIC** to promote fuel cell vehicles in China by producing **1000** fuel cell buses till **2022**	• New Flyer and **OCTA** are partners in the Fuel Cell Electric Bus Commercialization Consortium project • **Ballard** in **consortium** with New Flyer to deploy **20 zero-emission fuel cell electric buses** in CA	• **Toyota, Foton** and **Bejing Yuhuatong Technology** have cooperated in the field of **hydrogen fuel cell buses** • Toyota is **developing a hydrogen bus** by partnering with **Hino motors**	• **Everfuel**, **Wrightbus, Ballard**, **Hexagon Composites, Nel Hydrogen** and **Ryse Hydrogen** are joining forces to form the **H2Bus Consortium**. The members are committed to deploy **1,000** hydrogen fuel cell electric buses in Europe by **2023**	• The consortium comprising bus-maker **Van Hool**, **ITM Power, SMTU-PPP** and **Engie** deployed the **first hydrogen bus route** in France, in Pau	• **Ballard** partners with Solaris Bus & Coach on **hydrogen fuel cell buses** by providing the fuel cell technology • Agreement with **Hexagon** on delivering **CNG fuel system** to Solaris' low-emission bus fleet
Fuel Cell manufacturer	亿华通 SinoHytec	BALLARD	亿华通 SinoHytec TOYOTA	BALLARD	TOYOTA	BALLARD	BALLARD	BALLARD

Note: The revenue section displays the annual bus revenue

A large number of companies have already commercialized hydrogen-powered buses and are further pushing the topic with mature knowledge and technology

1 **Green bus actors are hedging their bets, showing that no one really knows which technology (hydrogen / electric) to choose.**
City buses are great opportunities to conduct projects and gain knowledge on hydrogen, as market demand is guaranteed and infrastructure is not a major concern.

Major fuel cell electric bus OEM's	YUTONG	中通客车	FOTON	NEW FLYER	TOYOTA	WRIGHTBUS	VANHOOL	SOLARIS
Revenue	4 bn. €	6.72 bn. €	5.2 bn. €	2.4 bn. €	-	230 mio. €	560 mio. €	585 mio. €
City Buses								
Intercity Buse								
School Buse								
Electric Buses								
Minibus			✓		✓			
Special Vehicles	✓	✓						✓
Partnerships/ Consortium	- Partnership with **SinoHytec**, a state-level tech enterprise focusing on **R&D** and industrialization of **FC engines**	- Joined the **Shangdong Heavy Industries Group** to strengthen its efforts in **developing** and **marketing fuel cell buses**	- **Foton, Toyota** and **SinoHytec** to jointly **launch fuel Cell Buses** - Co-operative agreement with **SinoHytec** and **SPIC** to promote fuel cell vehicles in	- New Flyer and **OCTA** are partners in the Fuel Cell Electric Bus Commercialization Consortium project - **Ballard** in **consortium** with New Flyer to	- **Toyota, Foton** and **Bejing Yuhuatong Technology** have cooperated in the field of **hydrogen fuel cell buses** - Toyota is **developing a hydrogen bus** by	- **Everfuel**, **Wrightbus, Ballard**, **Hexagon Composites, Nel Hydrogen** and **Ryse Hydrogen** are joining forces to form the **H2Bus Consortium**. The	- The consortium comprising bus-maker **Van Hool**, **ITM Power, SMTU-PPP** and **Engie** deployed the **first hydrogen bus route** in France, in Pau	- **Ballard** partners with Solaris Bus & Coach on **hydrogen fuel cell buses** by providing the fuel cell technology - Agreement **gon** ng **CNG** m to v- us fleet
Fuel Cell manufacturer	亿华通 SinoHytec	BALLARD	亿华通 SinoHytec TOYOTA	BALLARD	TOYOTA	BALLARD	BALLARD	BALLARD

2 **Although they don't sell fully integrated fuel cells systems, Ballard is presumably the Fuel Cell supplier with the highest volumes for buses.**

Note: The revenue section displays the annual bus revenue

The biggest bus manufacturers are investing in various technologies, from electro buses to hydrogen buses - but they are not the forerunners in hydrogen technology

	YUTONG	TRATON[1]	TATA MOTORS	DAIMLER	HINO	NFI GROUP[2]
Revenue	4 bn. €	6.6 bn. €	1.7 bn. €	4.7 bn. €	2 bn. €	2.8 bn. €
City Buses	✓	✓	✓	✓	✓	✓
Intercity Buses	✓	✓	✓	✓	✓	✓
School Buses	✓		✓	✓		
Electric Buses	✓	✓	✓	✓	✓	✓
Minibus		✓		✓		✓
Special Vehicles	✓		✓	✓		✓
Partnerships/ Consortium	• Partnership with **SinoHytec**, a state-level tech enterprise focusing on **R&D** and industrialization of **FC engines**	• Scania fuel cell 'refuse truck' development with **PowerCell, Renova** • In cooperation with **Asko** to develop **fuel cell technology**	• Published the **first hydrogen fuel cell powered bus in India** in collaboration with the **Indian Oil Corporation** • The hydrogen powered bus has been developed in a **partnership** with **ISRO** (Indian Space Research Organization)	• Joint venture with **Linde, Royal Dutch Shell and Total** to develop a **network of hydrogen fueling stations** • Joint venture with **VOLVO** to develop **fuel cell trucks and buses** • **SWEG** and Daimler sign letter of intent for fully electric Mercedes-Benz **eCitaro with fuel cell**	• Toyota is developing a **hydrogen bus** and Hino motors is a partner of the project, responsible for the design of the bus **body** and both **interior** and **exterior design** • **Volkswagen Truck & Bus** and Hino Motors agree to enter into a **strategic partnership**	• New Flyer of America, in partnership **with Ballard developed FCEB** with a range approaching 300 miles
Fuel Cell manufacturer	亿华通 SinoHytec	POWERCELL HYDROGENICS	TATA MOTORS	DAIMLER	TOYOTA	BALLARD

Note: The revenue section displays the annual bus revenue

---

[1] MAN, Scania and Volkswagen Caminhoes e Onibus

[2] Alexander Dennis, ARBOC Specialty Vehicles, Carfair Composites Motor Coach Industries, New Flyer, Plaxton

The biggest bus manufacturers are investing in various technologies, from electro buses to hydrogen buses - but they are not the forerunners in hydrogen technology

	YUTONG 🇨🇳	TRATON[1] 🇩🇪	TATA MOTORS 🇮🇳	DAIMLER 🇩🇪	HINO 🇯🇵	NFI GROUP[2] 🇨🇦
Revenue	4 l €	6.6 bn. €	1.7 . €	4.7 €	2 l €	2.8 €
City Buses	✓	✓				✓
Intercity Buses	✓	✓				✓
School Buses	✓					
Electric Buses						
Minibus						
Special Vehicles						
Partnerships/ Consortium	• Partnersh ith **Sir**	• Scania fuel cell refuse	• Publishe **first** bus has b developed in a **partn hip** with **ISRO** (In Space Research ganization)	• Joint vent with **Linde,** **VOLVO** t velop **fuel cell truck nd buses** • **SWEG** ar aimler sign letter of in for fully electric M edes-Benz **eCitaro w fuel cell**	• Toyota is eloping a and exte design • **Volkswa Truck & Bus** and) Motors agree to e r into a **strategic tnership**	• New Flye America, in d a
Fuel Cell manufacturer	亿华通 SinoHytec	POWERCELL HYDROGENICS	TATA MOTORS	DAIMLER	TOYOTA	BALLARD

① **Biggest historical bus manufacturers are preferring local fuel cell suppliers, or a ‘Make’ strategy.**

② **The fact that some of them already began to manufacture their own fuel cells shows that they see a real future for the fuel cells market.**

Note: The revenue section displays the annual bus revenue

---

[1] MAN, Scania and Volkswagen Caminhoes e Onibus

[2] Alexander Dennis, ARBOC Specialty Vehicles, Carfair Composites Motor Coach Industries, New Flyer, Plaxton

Main train manufacturers are carrying out several hydrogen projects and gaining crucial technological knowledge to produce and commercialize rail applications

	中国中车 CRRC 🇨🇳	SIEMENS Ingenuity for life 🇩🇪	ALSTOM 🇫🇷	BOMBARDIER TRANSPORTATION 🇨🇦	STADLER 🇨🇭	BNSF 🇺🇸
Total revenue	28.8 bn. €	8.8 bn. €	8.2 bn. €	8.3 bn. €	3 bn. €	23.5 bn. €
Hydrogen/Battery Application	🚊 H2 ⚡	🚆 H2	🚆 H2	🚆 ⚡	🚆 H2	🚂 H2 ⚡
Train Specifications	**-**  **In Operation** ▪ Range: 40 km ▪ Refueling Time: 12kg in 15 minutes ▪ 100 kg/day capacity ▪ Top speed: 70 km/h ▪ Capacity: 366 passengers (66 seated)	***Mireo***  **Under development** ▪ Powered by 200 kW fuel cell from Ballard ▪ Top speed: 160 km/h	***Coradia iLint***  **In Operation** ▪ Range: 1 000 km ▪ Top speed: 140 km/h ▪ 27 trains order in Germany	***Talent 3***  **Trial Runs in Progress** ▪ 90% recyclable ▪ Range 40-100kms ▪ Top Speed: 140km/hr ▪ 3 car unit has 169 seats ▪ Battery recharging time: 7-10mins ▪ 18gCO2e/km/seat	***Flirt H2***  **Under Development** ▪ 108 Passengers ▪ 130km/hr ▪ Planned for US passenger service in 2024	**-**  **Under Development** ▪ Ballard and BNSF tested a 250kW fuel cell power module in a hybrid hydrogen shunting locomotive.
Fuel Cell manufacturer	BALLARD	BALLARD	HYDROGENICS	-	?	BALLARD

🚊 Tramways 🚆 Trains 🚂 Locomotives

*State Power Investment Corporation

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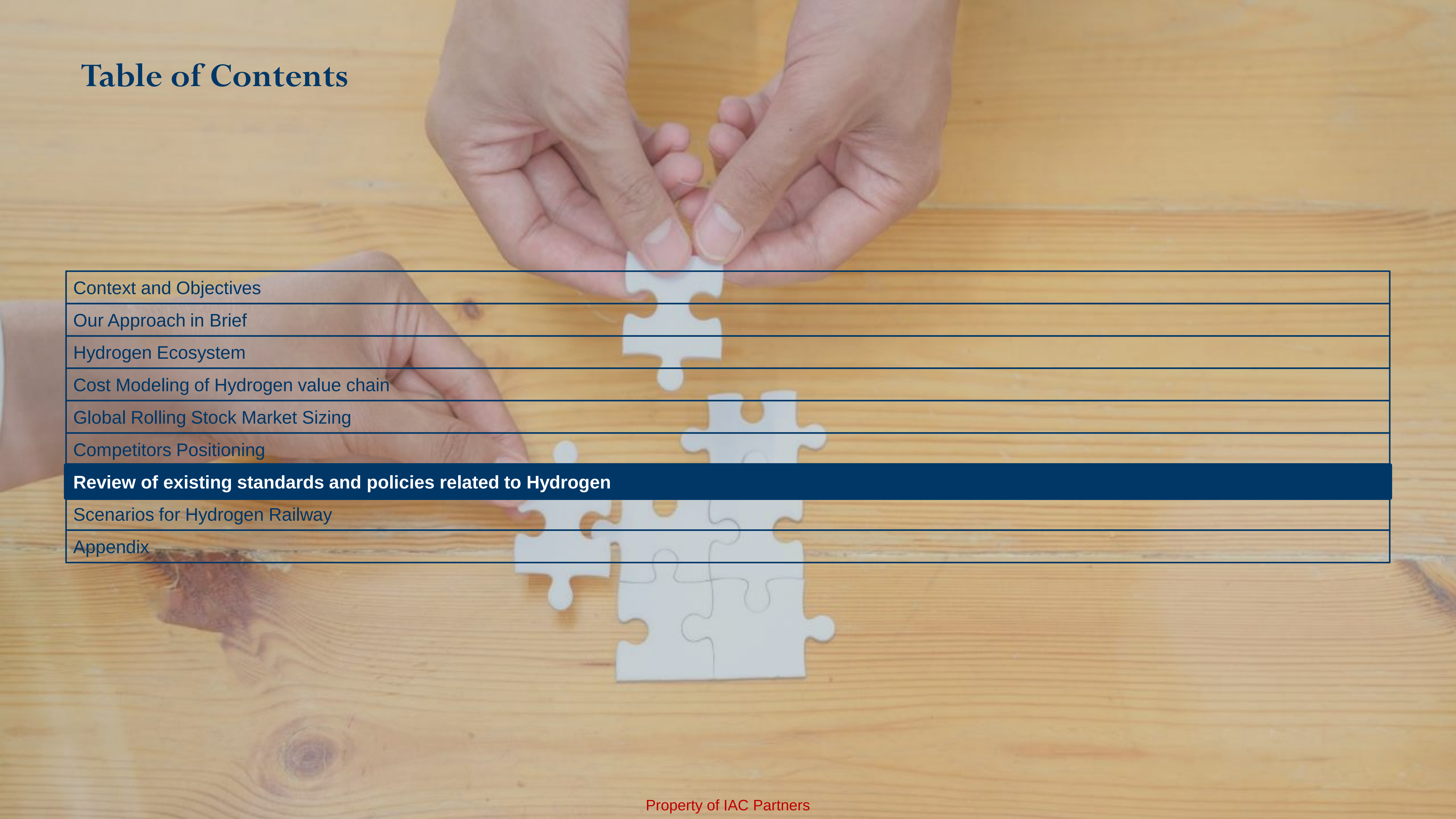


Gaseous hydrogen regulation has been developed over the past two decades. Liquid hydrogen regulation is shaping up

Non-exhaustive List of Standards

Value Chain *Standards*	Production	Conditioning	Storage and Transport	Dispensing	Operations* *excluding Fuel Cells*
Safety Standards related to safety of use, best practices and lessons learnt 🚗 🚌	🌐 ISO 22734 (2008) ISO 16110 (2010) IFC 5003 (2009) 🇺🇸 CGA H-10 (2018) CGA G-5.5 (2018) OSHA 1910.103 NFPA 55	New standards are expected to emerge in the forthcoming years specific to Hydrogen vehicle applications	🌐 **ISO/TC-197 (1990)** 🇺🇸 CGA P-12 (2017) CGA P-28 (2019) NFPA 2 NFPA 55 CGA P-H5 CGA P-41	🌐 ISO/TS 19880 (2020) 🇺🇸 Hydrogen Fueling Station Codes & Standards 🇪🇺 HYapproval Project	🌐 ISO 23273 (2013) ISO/TR 15916 (2015) **ISO/TR 15916 (2015)** 🇪🇺 **FCHJU Safety Planning Committee****
Testing & Performance Standards related to testing, verification procedures, measurement parameters and devices 🚗 🚌	🌐 ISO 16110 (2010) ISO 26142 (2010) 🇺🇸 ASTM D7941/7941M	🇨🇳 GB/T 33291 (2016)	🌐 ISO 11114 (2017) ISO 15330 (1999) ISO 16573 (2015) ISO 17081 (2014) IGC Doc 59/98/E 🇨🇳 GB/T 26466 (2011) GB/T 33292 (2016) GB/T 35544 (2017)	🇺🇸 CGA G-5.3 (2017) 🇨🇳 GB/T 23606 (2009) GB/T 24185 (2009) GB/T 26107 (2010) GB/T 34542.2 (2018) GB/T 34542.3 (2018) GB/T 35178 (2017) GB/T 37154 (2018)	🌐 ISO 14687 (2019) ISO 2626 (1973) ISO 7539 (2013) ISO 15859 (2004) ISO/TR 11954 (2008) ISO 15859 (2004) ISO 23828 (2013) **ISO 20421 (2019)**
System Design Technical and infrastructural requirements, design parameters, guidelines for integration on vehicles 🚗 🚌	🌐 ISO 22734 (2008) UL Subject 2264 A 🇨🇳 GB/T 19774 (2005) GB/T 29411 (2012) GB/T 29412 (2012) GB/T 37562 (2019) GB/T 34540 (2017)	🌐 ISO 16111 (2018)	🌐 ISO 19881 (2015) ISO 19882 (2018) **ISO 13984 (2015)** **ISO 13985 (2015)** 🇺🇸 SAE J2578 (2014) 🇨🇳 GB/T 34542 (2017) **CG1 H-3 (2019)**	🌐 ISO 17268 (2012) ISO/TS 19880 (2015) **ISO 13984 (1999)** 🇨🇳 GB/T 30718 (2014) GB/T 34425 (2017) **OIML R81 (1999)** 🇰🇷 **KS-B ISO 13984**	🌐 ISO 12619 (2014) ISO 11114 (2012) **ISO 21011 (2008)** **ISO 21013 (2016)** **ISO 24490 (2016)**

Key Findings

- **Codes and standards** are developing rapidly in cars and buses value chains, with **no established standards** in **trains and flights**. **Liquid Hydrogen testing and performance remains under-developed for vehicles.**
- **Standards for H2 production** are well established in **Production and Liquefaction,** following historic **safety and technical codes**, while new standards are developing **downstream (dispensing).**
- **GH2 standards** are being extensively developed for **testing and performance characteristics** at a **dispensing level**, while **system design** is mainly focused on tank **design and integration modules for FCEVs.**
- Consortiums like **FCHEA (USA) and FCHJU (EU)** are **standardizing fuel cells and H2 codes**, consolidating **best practices from different countries** to deliver consistent **technology and infrastructural policies** in each region.
- New **safety and system design** regulations are emerging in **with LOHC carriers** like Methanol, Ammonia and Hydrides, once the technology is **economically feasible.**

IAC PARTNERS

Note:
*Operations include H2 functioning, power density, working conditions, hydrogen fuel purity & contamination standards.
****Codes marked in bold are specific to Liquid Hydrogen.**

🌐 International Standard

Sources: FCHEA "Global Hydrogen and Fuel Cells Codes and Standards", FCHJU "Hydrogen Safety Reference Database", European Hydrogen Safety Planning Committee, Review of Hydrogen Standards in China (2019), FCHJU-PRESLHY

Fuel cell standards are mature for Buses and Cars and only beginning for Aviation and Railway

Non-exhaustive List of Standards

Applications	**Operations for Fuel Cells***			
Standards	*FCEVs*	*Buses*	*Trains*	*Airplane (only APUs)*
Safety Standards related to safety of use, best practices and lessons learnt	🌐 Working Party 29 - Global Technical Regulations (GTR) GTR-13: Hydrogen and Fuel Cell Vehicle Safety 🇨🇳 IEC 62282-4-101 IEC 62282 (2012-2019) 🇪🇺 GB/T 31037.1 (2014) Plan No. 20130689-T-604 (2017) 🇯🇵 JIS C 62282	🌐 Working Party 29 - Global Technical Regulations (GTR) GTR-13: Hydrogen and Fuel Cell Vehicle Safety 🇨🇳 IEC 62282-4-101 IEC 62282 (2012-2019) 🇪🇺 GB/T 31037.1 (2014) Plan No. 20130689-T-604 (2017) 🇯🇵 JIS C 62282	• Overwork existing regulatory and permitting structures for H2, fuel cells and related infrastructure • Permitting/regulation related to the vehicle technology itself • Permitting/regulation related to the individual project development • Craft hydrogen regulations and standards and initiate steps to harmonize and develop a common set of standards • Set international zero-emission standards and safety requirements • Development of risk assessment approaches for rail • Facilitate the coordination and collaboration of R&D and codes and standards activities • Focus on the entire ecosystem around implementing a local FCH railway project	🇪🇺 SAE AIR 6464 (2013) DO-160 (Explosion and Fire resistance)
Testing & Performance Standards related to testing, verification procedures, measurement parameters and devices	🌐 IEC 62282 (2015-2017) PTC 50 (2002) 🇨🇳 GB/T 20042 (2008) GB/T 25319 (2010) GB/T 31035 (2014) GB/T 23645 (2009) GB/T 26991 (2011) GB/T 34544 (2017) GB/T 37154 (2018)	🌐 IEC 62282 (2015-2017) PTC 50 (2002) 🇨🇳 GB/T 20042 (2008) GB/T 25319 (2010) GB/T 28183 (2011) GB/T 31035 (2014) GB/T 23645 (2009) GB/T 26991 (2011) GB/T 34544 (2017) GB/T 37154 (2018)		New standards are expected once design is finalized
System Design Technical and infrastructural requirements, design parameters, guidelines for integration on vehicles	🌐 ISO 23273 (2013) IEC TC105 🇺🇸 SAE AS 6858 (2017) SAE J2579 SAE J2719 🇯🇵 JIS C 8800 (2008) JIS C 8826 (2020) JIS C 8851 (2013)	🌐 ISO 23273 (2013) **CEN/TC 268** IEC TC105 🇺🇸 SAE AS 6858 (2017) SAE J2579 SAE J2719 🇯🇵 JIS C 8800 (2008) JIS C 8826 (2020) JIS C 8851 (2013)		🇪🇺 SAE AS 6858 (2017)

🌐 International Standard

Key Findings

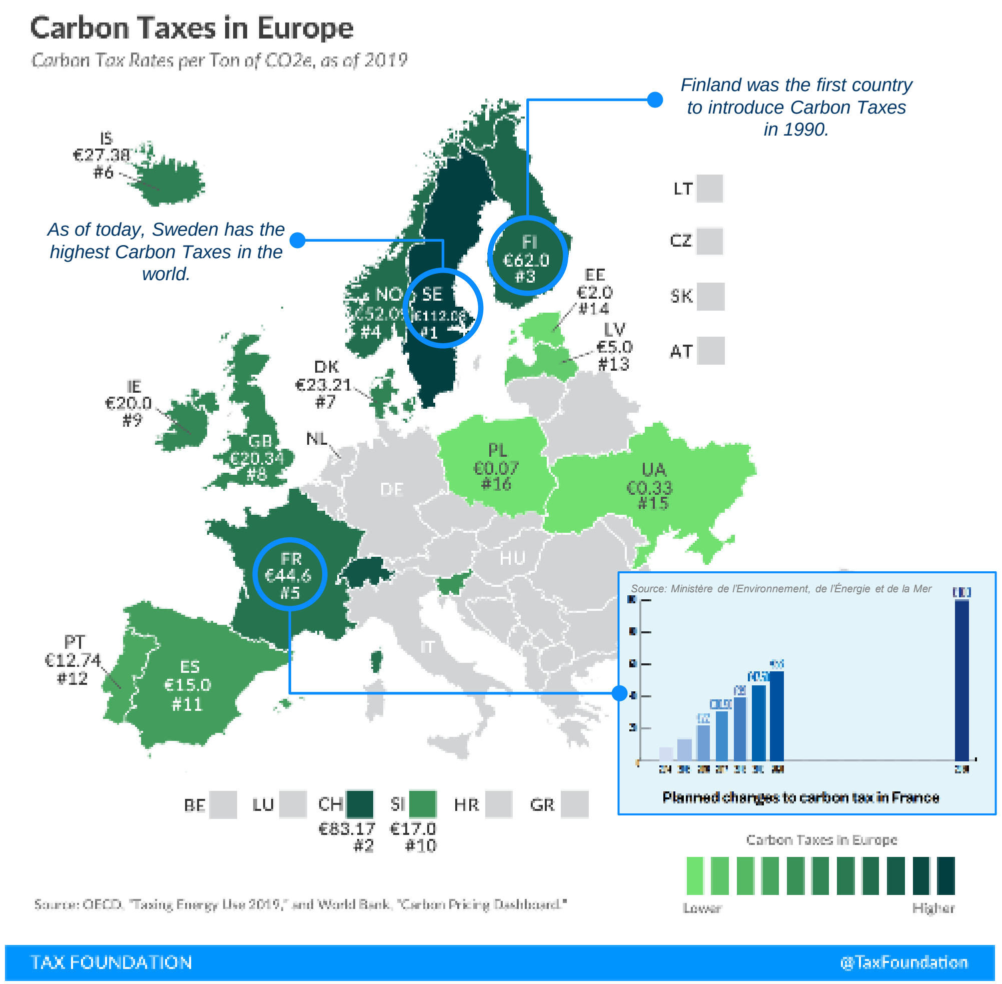
- **Preliminary standards** were created by **SAE Germany in 2013** for installation of **Fuel Cell Systems in Large Civil Aircraft, & technical guidelines for the safe integration of PEM Fuel Cell,** (considered to be LH2 and CGH2 types only), fuel storage, fuel distribution and appropriate **electrical systems** into the aircraft.
- **Safety codes and standards** have yet to be developed specifically for **hydrogen fuel and power systems** for **rail applications. Harmonizing international standards** might expedite the **use of H2 fuel and fuel cell systems** in **rail applications. Infrastructure and safety** under **crash scenarios** is also **underdeveloped.**
- **China** has a larger number of **hydrogen national standards** than ISO and IEC, focused on **terminology, fuel quality, safety, construction, production and purification, storage, transportation and fueling, applications, and testing**. ISO standards are mainly specialized in hydrogen **fuel quality, safety and testing.**

Note:
*Operations include Fuel Cell functioning, power density, working conditions, hydrogen fuel purity & contamination standards.
Codes marked in bold are specific to Liquid Hydrogen.

Sources: FCHEA “Global Hydrogen and Fuel Cells Codes and Standards”, FCHJU “Hydrogen Safety Reference Database”, European Hydrogen Safety Planning Committee, Review of Hydrogen Standards in China (2019), SANDIA National Laboratories (H2 Workshop 2019)

Carbon Tax is one of the market-based economic instruments to put a price on carbon emissions, urging businesses to shift towards efficient non-carbon fuels

1	***What is Carbon Tax?***	▪ **Carbon tax is a fee imposed on CO2** and other GHG emissions, encouraging people, businesses, and governments to **emit less** and **reduce impacts of climate change.** ▪ The revenue generated will be used to invest in **clean energy, green technologies and infrastructure and climate adaptation measures.**
2	***What does it include?***	▪ Different types of GHG emissions specific to country: **Oxides of Carbon, Methane, Oxides of Nitrogen and Sulphur and Fluorine gases.** ▪ **Carbon dioxide equivalent** (CO2e) is a metric measure used to compare the emissions from various greenhouse gases on the basis of their **global-warming potential.**
3	***Who implements Carbon Taxes?***	▪ **French government** sets prices that emitters must pay for each ton of GHG emissions. ▪ **Carbon Pricing Leadership Coalition (CPLC)** is a voluntary initiative of governments and private partners that catalyzes action towards the successful implementation of **carbon pricing** around the world, monitored by World Bank.
4	***Who does it affect?***	▪ Investors in carbon-intensive energy industries like Coal and petroleum ▪ High emissions transportation sector actors: Aviation, ships, trains ▪ Regions that depend heavily on carbon-intensive fuels, particularly coal and petroleum. ▪ Low-income consumers paying resource consumption taxes
5	***Evolution across the world?***	▪ **USA: 2019-** $15 / tCO2e; **2030-** $50 / tCO2e (DoE) ▪ **Singapore: 2019-** $5 / tCO2e; **2030-** $15 / tCO2e

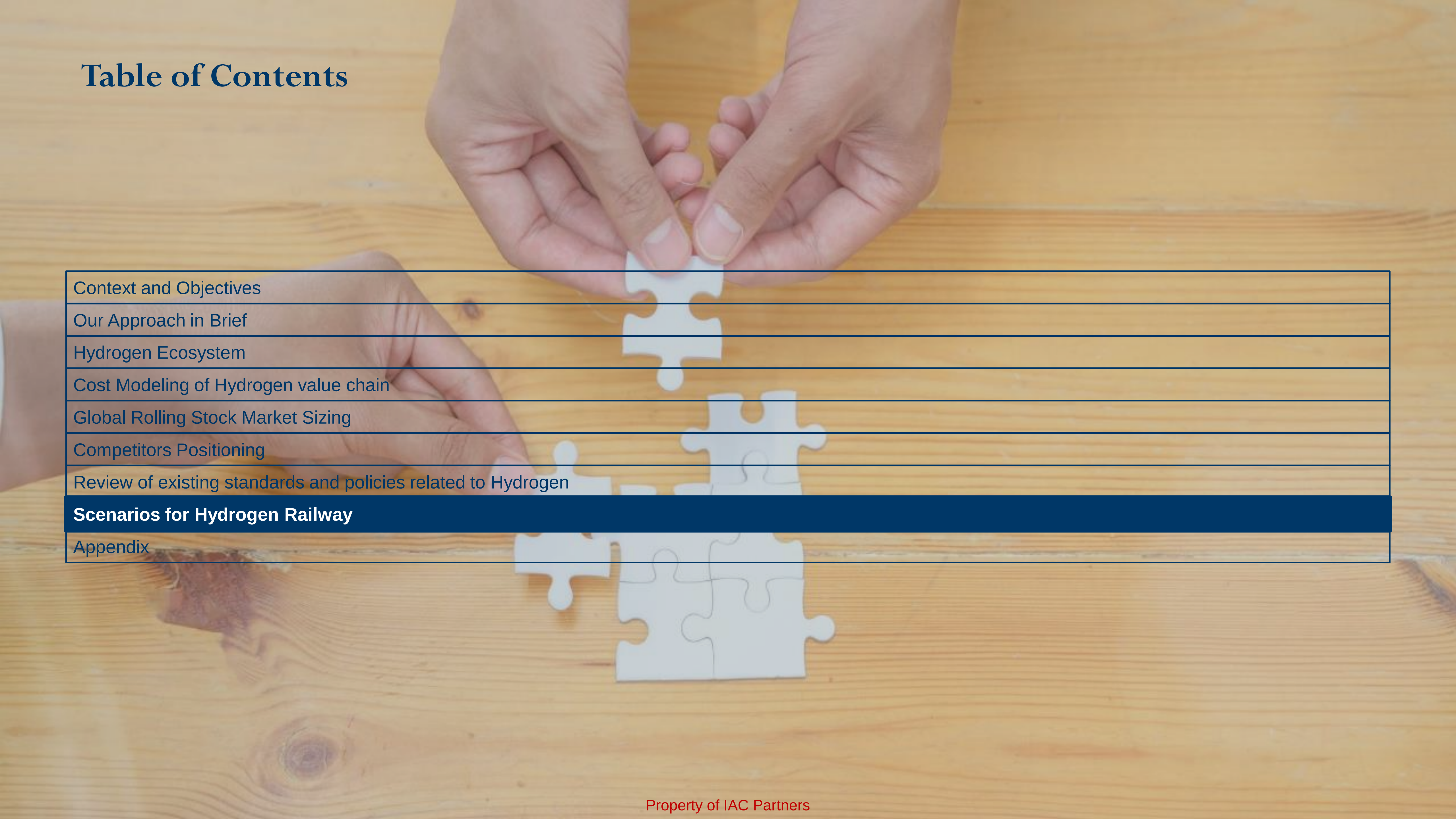


Finland was the first country to introduce Carbon Taxes in 1990.

As of today, Sweden has the highest Carbon Taxes in the world.

Source: OECD, "Taxing Energy Use 2019," and World Bank, "Carbon Pricing Dashboard."

Abbreviations:
GHG: Greenhouse Gases
tCO2e: tons CO2 equivalent



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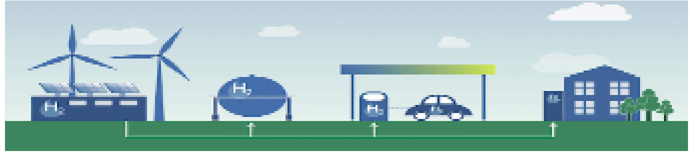
Scenarios for the Model and Key KPIs have been visualized…

Hydrogen Train Characteristics

1. **Profiles of Trains**
   - Hydrogen train - iLint
   - Diesel Trains:
     - Lint 54
   - Locomotives = shunters
   - Buses
     - APTIS platform, then more specialized vehicles (firemen, garbage truck…)
2. **Type of Fuel Cell to be used**
   - PEM Fuel Cell
   - Direct Methanol / Ammonia based
3. **Trip Characteristics**
   - Max. distance between 2 refueling points
   - Fuel Requirement per trip
   - Refueling Time and Frequency
   - Electrified portion on the line: *assumption = 0 for now*
   - Number of refueling points
   - Elevation gain: *assumption = 0 for now*
4. **Train's design & procedures**
   - Safety under extreme conditions
   - New installation vs Retrofit
   - On-board storage: LH2 / 700 bars GH2 / 350 bars GH2

+

Hydrogen Supply Infrastructure



1. **Supply scenario**
   - On-site LH2 Electrolysis
   - On-site GH2 Electrolysis
   - On-Demand LH2 Supply
   - On-Demand GH2 Supply

2. **Type of feedstock for H2 Production**
   - Grid
   - Renewable
   - Mixed

=

Scenario KPIs for incorporating Hydrogen in Railway

- **1st step: technical simulations**
- Maximum autonomy
- Safety comparison between different solutions
- Volume & Weight change for a Train
- CO2 emissions per trip / per train mass

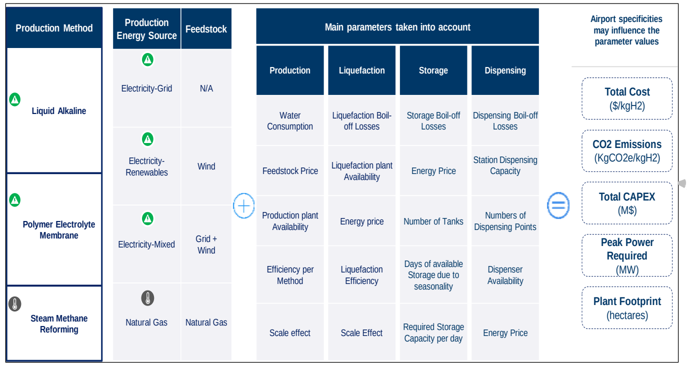
- **2nd step: economics**
- Cost of 1 km (OPEX only, based on energy consumption)
- Business potential on market segment
- Operating costs
- Investments required
- Infrastructure investments

Our H2 scenarios and business cases modeling simulates costs, revenue and investments for an objective RoI* decision basis

H2 Business Case Model for Analysis and Simulation

Strategic Recommendations

1 H2 Supply Chain Scenarios (End-to-end)



Production Method	Production Energy Source	Feedstock
Liquid Alkaline	Electricity-Grid	N/A
Polymer Electrolyte Membrane	Electricity-Renewables	Wind
	Electricity-Mixed	Grid + Wind
Steam Methane Reforming	Natural Gas	Natural Gas

+

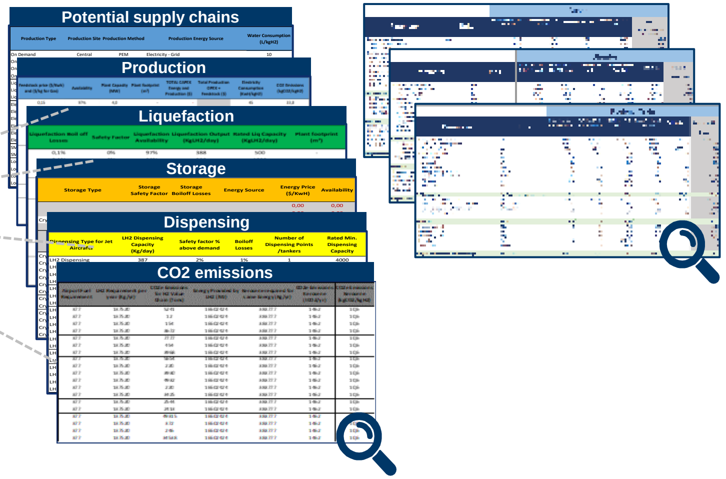
Main parameters taken into account			
Production	**Liquefaction**	**Storage**	**Dispensing**
Water Consumption	Liquefaction Boil-off Losses	Storage Boil-off Losses	Dispensing Boil-off Losses
Feedstock Price	Liquefaction plant Availability	Energy Price	Station Dispensing Capacity
Production plant Availability	Energy price	Number of Tanks	Numbers of Dispensing Points
Efficiency per Method	Liquefaction Efficiency	Days of available Storage due to seasonality	Dispenser Availability
Scale effect	Scale Effect	Required Storage Capacity per day	Energy Price

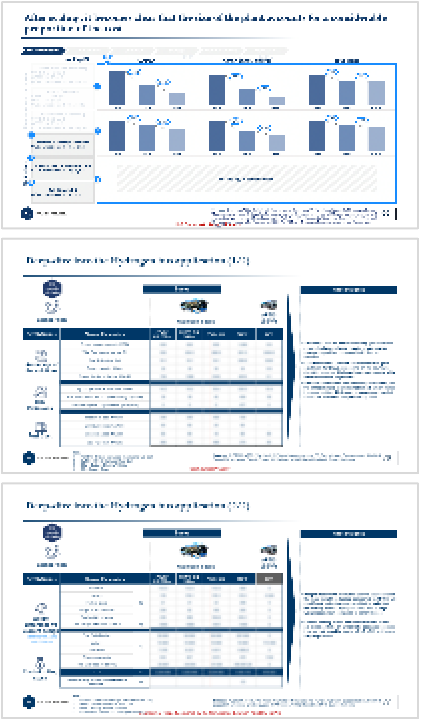
=

Airport specificities may influence the parameter values

- **Total Cost** ($/kgH2)
- **CO2 Emissions** (KgCO2e/kgH2)
- **Total CAPEX** (M$)
- **Peak Power Required** (MW)
- **Plant Footprint** (hectares)

2 Detailed Cost and CO2 emissions models for Trains, Shunters and Buses





Property of IAC Partners

IAC is creating a model which shows a detailed comparison of the selected solutions and conventional applications

IAC Scenario calculation

Comparison

Buses

Hydrogen Bus

APTIS (BEV[1])

Regional Trains

Hydrogen Train (iLint)

Diesel Train (Lint 54)

Shunters

Hydrogen Shunter

Diesel Shunter (Prima H4)

Key Outcomes

Autonomy of the solutions	**Based on the vehicle characteristics (e.g. Power/Battery Capacity/Efficiency/Energy Storage Capacity etc.) calculations are based on the autonomy of the current solution**
CO2 Emissions	**End-to-end CO2 emissions, from fuel production to the actual fuel consumption**
Fuel Cost	**Fuel cost calculation based on the production, distribution and dispensing methods**
Weight difference vs current design	**Sizing of all relevant vehicle components (e.g. fuel cell, battery, fuel tank, accessories etc.) and estimation of their weights**
Cost of rolling stock	**Sizing of all relevant vehicle components (e.g. fuel cell, battery, fuel tank, accessories etc.) and estimation of their costs**

Note:

1. BEV (Battery electric vehicle)

Set of global assumptions used throughout all scenarios calculations in the model

IAC Scenario calculation

Comparison

Buses

Hydrogen Bus

APTIS (BEV[1])

Regional Trains

Hydrogen Train (iLint)

Diesel Train (Lint 54)

Shunters

Hydrogen Shunter

Diesel Shunter (Prima H4)

Main Assumptions

Fuel specifications

Energy Density		
GH2 @ 350bar	33	kWh/kg
GH2 @ 700bar	33	
LH2	33	
Methanol	12.7	
Diesel	6.1	
GH2 @ 350bar	23	kg/m^3
GH2 @ 700bar	42	
LH2	71	
Methanol	790	
Diesel	860	

CO2 Emissions

Supply Chain Emissions		
GH2 from Electrolysis	650	gCO2/kgH2
LH2 from Electrolysis	750	
Methanol from Reforming	700	gCO$_2$/kgMethanol

Fuel Cell specifications

Supply Chain Emissions		
PEMFC[2] efficiency	50%	
DMFC[3] efficiency	25%	
FC system power density	1.6	kW/kg
Methanol power density	0.4	

Battery specifications

Supply Chain Emissions		
Battery cost	135	€/kWh
Battery cooling system	3.50	
Battery autonomy	10	Minutes

IAC PARTNERS

Note:
1. BEV (Battery electric vehicle)
2. PEMFC (Proton-exchange membrane fuel cell)
3. DMFC (Direct-methanol fuel cell)

Sources: Research Gate, MDPI Report, KEARNEY Hydrogen Applications and business models, Air Liquide, Southern Chemical, Forsee Power, Oorja, Quantum Fuel Cell Systems

Deep-dive into the Hydrogen bus application (1/2)

IAC Scenario calculation

Comparison

Buses

Hydrogen Buses

APTIS (BEV[3])

Key Outcomes	Chosen Parameters	PEMFC[1] GH2 350bar	PEMFC GH2 700bar	PEMFC LH2	DMFC[2]	BEV
Autonomy of the solutions	Energy storage capacity (kWh)	630	630	630	1.260	315
	Total Fuel Volume per car (L)	830	454.5	268.9	261.5	2404.6
	Total fuel weight (kg)	19.1	19.1	19.1	206.6	2520
	Battery capacity (kWh)	30	30	30	30	315
	Energy density of the fuel (kWh/L)	759	1386	2343	4819	0.1
CO2 Emissions	KgCO2 per hour at Maximum Power	14.2	14.2	16.4	330.5	10.4
	Fuel production & SC[4] CO_2 emission (gCO_2/kWh)	39	39	45	459	58
	Fuel consumption CO_2 emission (gCO_2/kWh)	0	0	0	477	0
Fuel Cost	Production cost (€/MWh)	240	240	450	150	-
	Distribution cost (€/MWh)	60	60	20	60	-
	Dispensing cost (€/MWh)	60	60	10	60	80
	Total Fuel Cost (€/MWh)	360	360	480	270	80

First Insights

- **Autonomy:** For the **same autonomy** (hours at max power), **battery systems require lower energy storage capacities** compared to H2 fuel and methanol**.**
- **CO2 Emissions: Green H2 is cleaner than grid electricity for BEVs**, depending on the country's electricity sources. **Methanol does not comply with decarbonization objectives.**
- **Fuel Cost: Methanol and electricity** are **cheap,** and the **infrastructure is well-established**, which makes them competitive. **Hydrogen is expensive now** but should become **cost competitive** by 2030.

Note:
1. PEMFC - Proton-exchange membrane fuel cell)
2. DMFC – Direct Methanol Fuel Cell
3. BEV – Battery Electric Vehicle
4. SC – Supply Chain

Sources: ALSTOM APTIS, Van Hool, IME Actia battery systems, FCHEA Hydrogen Buses strategy, Fuel Cell Buses EU, Mrcagney Electric Buses, IOP Science, CDN2 Ballard Fuel Cell Buses, Dechema

Deep-dive into the Hydrogen bus application (2/2)

IAC Scenario calculation

Comparison

Buses

Hydrogen Buses

APTIS (BEV[3])

Key Outcomes	Chosen Parameters		PEMFC[1] GH2 350bar	PEMFC GH2 700bar	PEMFC LH2	DMFC[2]	BEV
Weight difference vs current design *First order calculations – Cross-effect of weight on power is not considered in this model.*	Fuel Cell	kg	112.5	112.5	112.5	450	0
	Battery		176	176.1	176.1	176.1	2.520
	Fuel on board		21	21	22	206	0
	Weight of one fuel tank		239	92	185	205	0
	Total weight of tanks		239	368	184,6	205,1	0
	Total Weight difference vs BEV	kg	-1945	-1809	-1917	-1440	0
Cost of rolling stock	Fuel Cell / Engine	€	59.500	59.500	59.500	297.000	0
	Battery		10.800	10.800	10.800	10.800	113.400
	Fuel tanks		7.376	9.221	4.811	1.800,0	0
	Other components		919	927	2372	470	1102
	Total Over cost vs BEV (€)		-35.907	-34.054	-37.020	195.567,29	0
	TCO[3]	€	3.204.096	3.205.948	4.224.983	1.445.110	678.563
	Distance / day to reach TCO balance with BEV	km				-53	

First Insights

- **Weight Reduction:** Methanol fuel cell seems to offer **the least weight reduction compared to APTIS**, yet **significant reduction** compared to the **weight of the battery buses**. Hydrogen could offer a **large weight reduction** compared to battery buses.
- **Cost of Rolling stock: Methanol fuel cell buses** are expected to be an **unrealistic scenario** because they are **not scalable (order of 1-5 kWs)** and hence, **very expensive.**

Note:

1. PEMFC - Proton-exchange membrane fuel cell)
2. DMFC – Direct Methanol Fuel Cell
3. BEV – Battery Electric Vehicle
4. Considered lifetime: 30 years (100 km/day)

Sources: ALSTOM APTIS, Van Hool, IME Actia battery systems, FCHEA Hydrogen Buses strategy, Fuel Cell Buses EU, Mrcagney Electric Buses, IOP Science, CDN2 Ballard Fuel Cell Buses, Dechema

Deep-dive into the Hydrogen regional train application (1/2)

IAC Scenario calculation

Comparison

Regional Trains

Hydrogen Trains (iLint)

Diesel Train (Lint 54)

Key Outcomes	Chosen Parameters	PEMFC[1] GH2 350bar	PEMFC GH2 700bar	PEMFC LH2	DMFC[2]	Diesel
Autonomy of the solutions	Energy storage capacity (kWh)	3140	3140	3140	6280	6500
	Total Fuel Volume per car (L)	4137	2265.5	1340.1	1303.1	800
	Total fuel weight (kg)	95.2	95.2	95.2	1029.5	690
	Battery capacity (kWh)	110	110	110	110	0
	Energy density of the fuel (kWh/L)	759	1386	2343	4819	10.922
CO2 Emissions	KgCO2 per hour at Maximum Power	-	-	-	576.5	921.3
	Fuel production & SC[4] CO_2 emission (gCO_2/kWh)	39	39	45	459	709
	Fuel consumption CO_2 emission (gCO_2/kWh)	0	0	0	477	2700
Fuel Cost	Production cost (€/MWh)	60	60	20	60	30
	Distribution cost (€/MWh)	60	60	10	60	20
	Dispensing cost (€/MWh)	360	360	480	270	190
	Total Fuel Cost (€/MWh)	240	240	450	150	140

First Insights

- **Autonomy: Diesel trains** requires **higher energy storage capacity** compared to DMFC trains, for 5 hours at maximum power. **Methanol on-board** to be an **unrealistic scenario** due to its **high fuel weight on-board.**
- **CO2 Emissions: Diesel is the most polluting fuel** for trains, and **Methanol offers significant reduction** in emissions**, but not CO2-free**. For deep decarbonization, **H2 could be the best case.**
- **Fuel Cost: Methanol and Diesel are cheap**, and the **infrastructure is well-established**, which makes them competitive. **Hydrogen is expensive** now but should become **cost competitive by 2030.**

Note:

1. PEMFC - Proton-exchange membrane fuel cell)
2. DMFC – Direct Methanol Fuel Cell
3. SC – Supply Chain

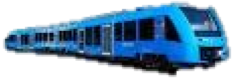
Sources: ALSTOM Lint and iLint Product catalogs, AKASOL, Selectron, FCHJU Roland Berger Hydrogen in Transportation, iMeche, Now GmbH, Railvolution, Volker, Ecoscore, Methanol.org, EIA Fuel Prices Outlook, OSTI, Statistia, Ballard Fuel Cell Systems

Deep-dive into the Hydrogen regional train application (2/2)

IAC Scenario calculation

Comparison

Regional Trains



Hydrogen Trains (iLint)

Diesel Train (Lint 54)

Key Outcomes	Chosen Parameters		PEMFC[1] GH2 350bar	PEMFC GH2 700bar	PEMFC LH2	DMFC[2]	Diesel
Weight difference vs current design	Fuel Cell	tons	0.19	0.19	0.19	4.5	0
	Battery		0.42	0.42	0.42	0.42	0
	Fuel on board		0.10	0.10	0.10	1.02	0.68
	Weight of one fuel tank		0.12	0.72	0.54	1.02	0.62
	Total weight of tanks		2.0	0.72	0.54	1.02	0.62
	Total Weight difference vs Diesel	tons	+1.5	+0.17	+0.03	+2.02	-
Cost of rolling stock	Fuel Cell / Engine	€	59.500	59.500	59.500	518.100	48.100
	Battery		39.600	39.600	39.600	39.600	0
	Fuel tanks		36.765	45.956	23.978	13.032	8.000
	Other components		2518	4356	4794	1441	0
	Total Over cost vs Diesel (€)		23.881	34.911	13.370	457.671	0
	TCO[3]	€	30.857.883,6	30.868.913,1	41.067.372,4	46.426.864	26.660.105,5
	Distance / day to reach TCO balance with diesel	km				32	

First Insights

- **Weight Reduction: DMFC train** does **not offer significant weight reduction** compared to a diesel train, because of the **fuel weight increase**. **Maximum weight reduction** seems achievable with **GH2** compared to standard Lint diesel train.
- **Cost of rolling stock: DMFC trains** are expected to **cost more than Diesel trains** because of their **fuel cell costs** and prove to be an **unrealistic scenario** compared to diesel trains. **Hydrogen trains** could **cost more** than diesel trains but are **realistic.**

Note:
1. PEMFC - Proton-exchange membrane fuel cell)
2. DMFC – Direct Methanol Fuel Cell
3. Considered lifetime: 30 years (500 km/day)

Sources: ALSTOM Lint and iLint Product catalogs, AKASOL, Selectron, FCHJU Roland Berger Hydrogen in Transportation, iMeche, Now GmbH, Railvolution, Volker, Ecoscore, Methanol.org, EIA Fuel Prices Outlook, OSTI, Statistia, Ballard Fuel Cell Systems

Deep-dive into the Hydrogen shunters application (1/2)

IAC
Scenario
calculation

Comparison

Shunters

Hydrogen Shunter

Shunter (Prima H4)

Key Outcomes	Chosen Parameters	PEMFC[1] GH2 350bar	PEMFC GH2 700bar	PEMFC LH2	DMFC[2]	Diesel
Autonomy of the solutions	Energy storage capacity (MWh)	18000	18000	18000	36	30
	Total Fuel Volume per car (m3)	23715	12987	7682	0.7	0.4
	Total fuel weight (tons)	545	545	545	5.9	3.5
	Battery capacity (MWh)	300	300	300	0.3	0
	Energy density of the fuel (MWh/L)	759	1386	2343	4.8	10.9
CO2 Emissions	KgCO2 per hour at Maximum Power	141.8	141.8	163.6	3305	4252
	Fuel production & SC[3] CO_2 emission (gCO_2/kWh)	39	39	45	459	709
	Fuel consumption CO_2 emission (gCO_2/kWh)	0	0	0	477	2700
Fuel Cost	Production cost (€/MWh)	240	240	450	150	140
	Distribution cost (€/MWh)	60	60	20	60	30
	Dispensing cost (€/MWh)	60	60	10	60	20
	Total Fuel Cost (€/MWh)	360	360	480	270	190

First Insights

- **Autonomy: DMFC shunter require higher energy storage capacity** compared to Diesel shunters, for 5 hours at maximum power. It is found to be an **unrealistic scenario** due to its **high fuel weight on-board.**
- **CO2 Emissions: Diesel is the most polluting fuel** for trains, and **Methanol offers small reduction** in emissions**, but not completely CO2-free**. For deep decarbonization, **H2 could be the best case.**
- **Fuel Cost: Methanol and Diesel are cheap**, and the **infrastructure is well-established**, which makes them competitive. **Hydrogen is expensive** now but should become **cost competitive by 2030.**

Note:
1. PEMFC - Proton-exchange membrane fuel cell)
2. DMFC – Direct Methanol Fuel Cell
3. SC – Supply Chain

Sources: ALSTOM Prima H4 Catalog, AKASOL, Selectron, FCHJU Roland Berger Hydrogen in Transportation, iMeche, Now GmbH, Railvolution, Volker, Ecoscore, Methanol.org, EIA Fuel Prices Outlook, OSTI, Statisia, Ballard Fuel Cell Systems

Deep-dive into the Hydrogen shunters application (2/2)

IAC
Scenario
calculation

Comparison

Shunters

Hydrogen Shunter

Shunter (Prima H4)

Key Outcomes	Chosen Parameters		PEMFC[1] GH2 350bar	PEMFC GH2 700bar	PEMFC LH2	DMFC[2]	Diesel
Weight difference vs current design	Fuel Cell	tons	1125	1125	1125	4.5	0
	Battery		1761.3	1761.3	1761.3	1.7	0
	Fuel on board		600	600	627.3	5.9	3.4
	Weight of one fuel tank		125,5	4181.8	1722	5.8	3.1
	Total weight of tanks		9038	4181.8	1722	5.8	3.1
	Total Weight difference vs Diesel	tons	+6.3	+1.2	-1.0	+18.6	-
Cost of rolling stock	Fuel Cell / Engine	€	341,083	341,083	341,083	2,970,000	222,000
	Battery		108,000	108,000	108,000	108,000	0
	Fuel tanks		210,754	263,443	158,073	74,704	40,000
	Other components		662.1	827.6	496.6	7961,5	125,7
	Total Over cost vs Diesel (€)		423,617	484,831	398,609	2,898,540	0
	TCO[3]	€	16.345.485	16.406.700	21.430.477	28,798,961	13,762,078
	Distance / day to reach TCO balance with diesel	km				301	-

First Insights

- **Weight Reduction: DMFC train** does **not offer significant weight reduction** compared to a diesel train, because of the **fuel weight increase**. **Maximum weight reduction** seems achievable with **LH2** compared to standard Prime H4 Shunter.
- **Cost of rolling stock: DMFC trains** are expected to **cost at least €3 Million more than Diesel trains** and prove to be an **unrealistic scenario** compared to diesel trains. **Hydrogen trains** could **cost more** than diesel trains but are a more **realistic option for decarbonization.**

Note:
1. PEMFC - Proton-exchange membrane fuel cell)
2. DMFC – Direct Methanol Fuel Cell
3. Considered lifetime: 30 years (500 km/day)

Sources: ALSTOM Prima H4 Catalog, AKASOL, Selectron, FCHJU Roland Berger Hydrogen in Transportation, iMeche, Now GmbH, Railvolution, Volker, Ecoscore, Methanol.org, EIA Fuel Prices Outlook, OSTI, Statistia, Ballard Fuel Cell Systems

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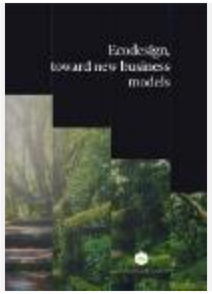

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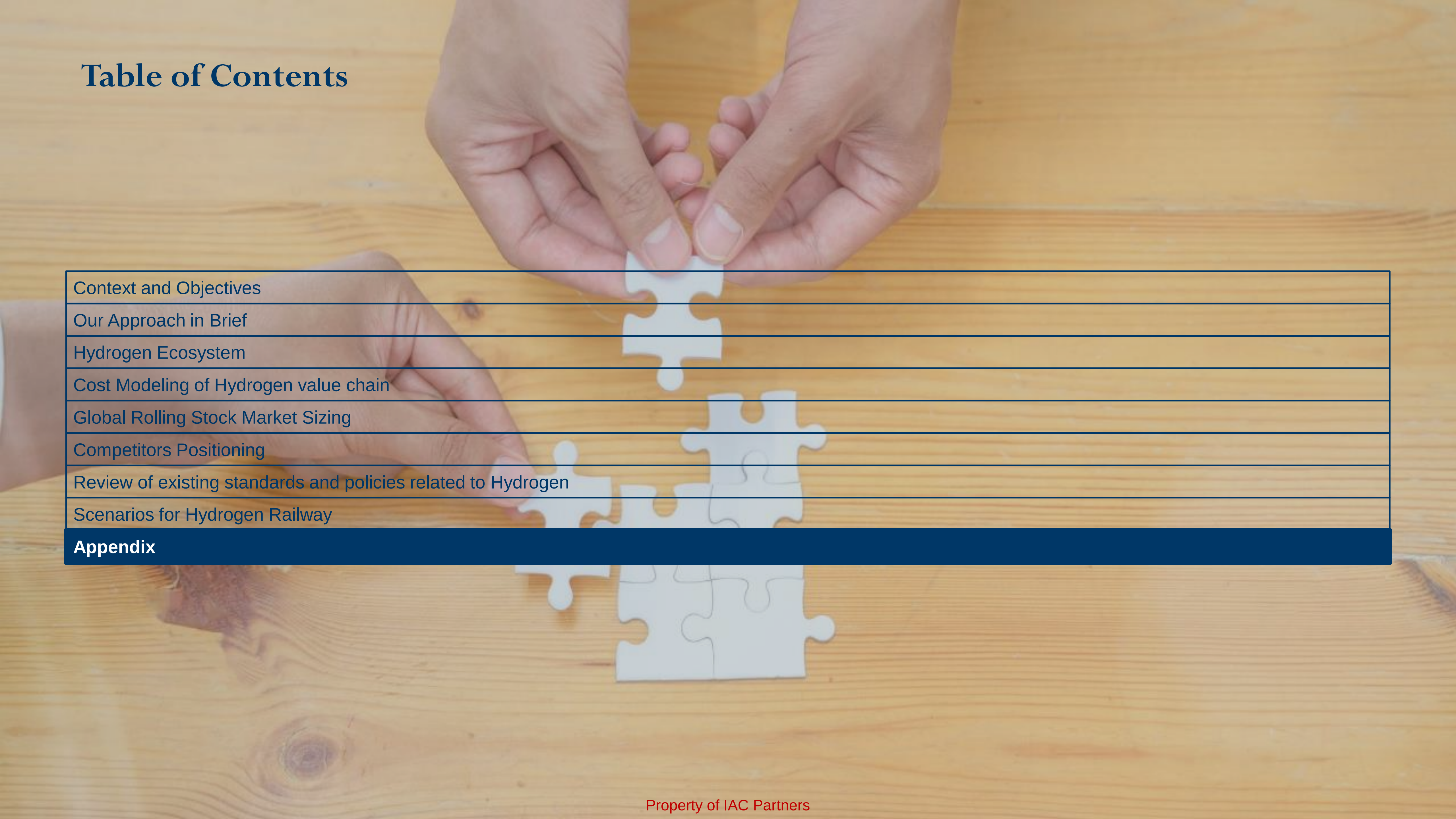

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