Collegio Ingegneri Ferroviari Italiani
Sezione di Torino

RFI RETE FERROVIARIA ITALIANA
GRUPPO FERROVIE DELLO STATO ITALIANE

Il ruolo dell'idrogeno nell'ambito del paradigma della transizione energetica: le applicazioni tecnologiche nell'ambito ferroviario

Prof. Massimo Santarelli
Politecnico di Torino

June 23rd 2021

POLITECNICO DI TORINO

H2 @ POLITO

5
Involved Departments

100+
Research Projects

100+
Researchers

1500 mq
Labs

Focused collaborations:

IIT ISTITUTO ITALIANO DI TECNOLOGIA

ENVIRONMENT PARK Parco Scientifico Tecnologico per l'Ambiente

Current R&D activities on H_2/CO_2

H2 PRODUCTION

- Electrolysis (low T, high T)
- Blu hydrogen
- Biobased processes (thermal, biological)
- Photocatalysis
- Solar-assisted chemical looping
- Aqueous phase reforming

H2 STORAGE AND DISTRIBUTION

- Compression
- Ad/Absorption on solid matrix
- Geological storage
- Injection in NG grids
- LOHC / NH3

H2 FINAL USES

- Hydrogen as a feedstock
- Mobile applications
- Hydrogen/FC to power
- Synthetic chemicals
- Fuel Cell based-CHP
- Grid services

CO2 CAPTURE AND SEPARATION

- Ionic liquids
- Membranes

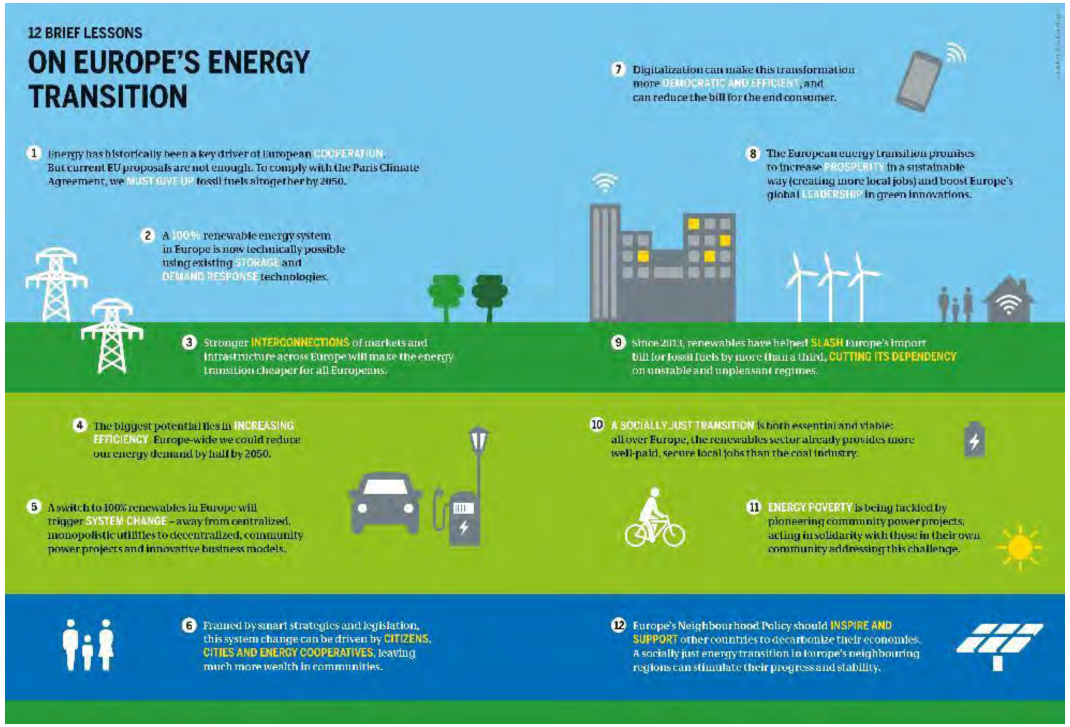
CO2 STORAGE

- Geological storage

CO2 CONVERSION (FUELS AND CHEMICALS)

- Electrocatalysis
- Photocatalysis
- Thermocatalysis
- Biochemical conversion
    - Photosynthetic microorganisms
    - Gas fermentation via acetogenic bacteria
    - Biomethane production

CONTEXT: Energy Transition



The **energy transition** is a dynamic matrix of processes that responds to a need for climate change mitigation, but that generates the opportunities resulting from a paradigm shift.

The main drivers considered are:

a. increased use of **renewable energy sources** in all sectors of society
b. decarbonisation of industrial processes and end-uses of energy
c. progressive **electrification** of end-uses
d. energy conversion **efficiency**
e. global management of **CO_2**
f. circular economy protocols.

RENEWABLE ENERGY
PRODUCTION and STORAGE

CO_2 MITIGATION and
RE-UTILIZATION SOLUTIONS

CIRCULAR ECONOMY PROTOCOLS

e^- **ELECTRIFICATION** end uses

H_2 **HYDROGEN** value chain

Solar chem **SOLAR** chemicals

EU Policies targets to 2030 - Italian PNRR 2021

EU Clean Hydrogen roadmap

2025-2030

- 40 GW electrolysers
- 10 M ton green hydrogen

2030 - …

- Large green H2 deployment

2020

- 20% CO_2 reduction
- 20% Renewables
- 20% Energy efficiency

2030

- 40% CO_2 reduction

Update European Green Deal (COM/2019/640 final): 55%

- 32% Renewables
- -32,5% primary energy consumption

2050

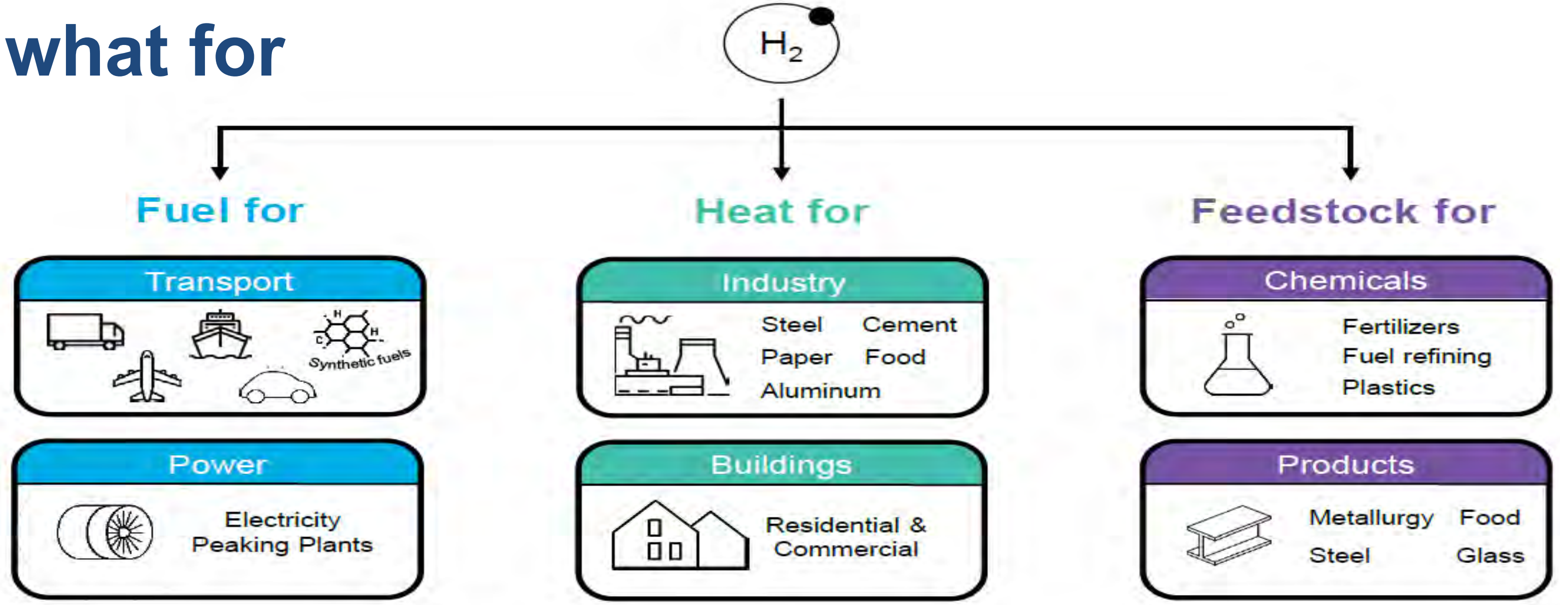
- 80-95% CO_2 reduction

update European Green Deal (COM/2019/640 final): C-neutrality

- 100% final uses electrification (RES)

EU Green Deal roadmap

H_2: what for



Source: BloombergNEF

- Integration of renewables into the power sector.
- Power generation from renewable resources

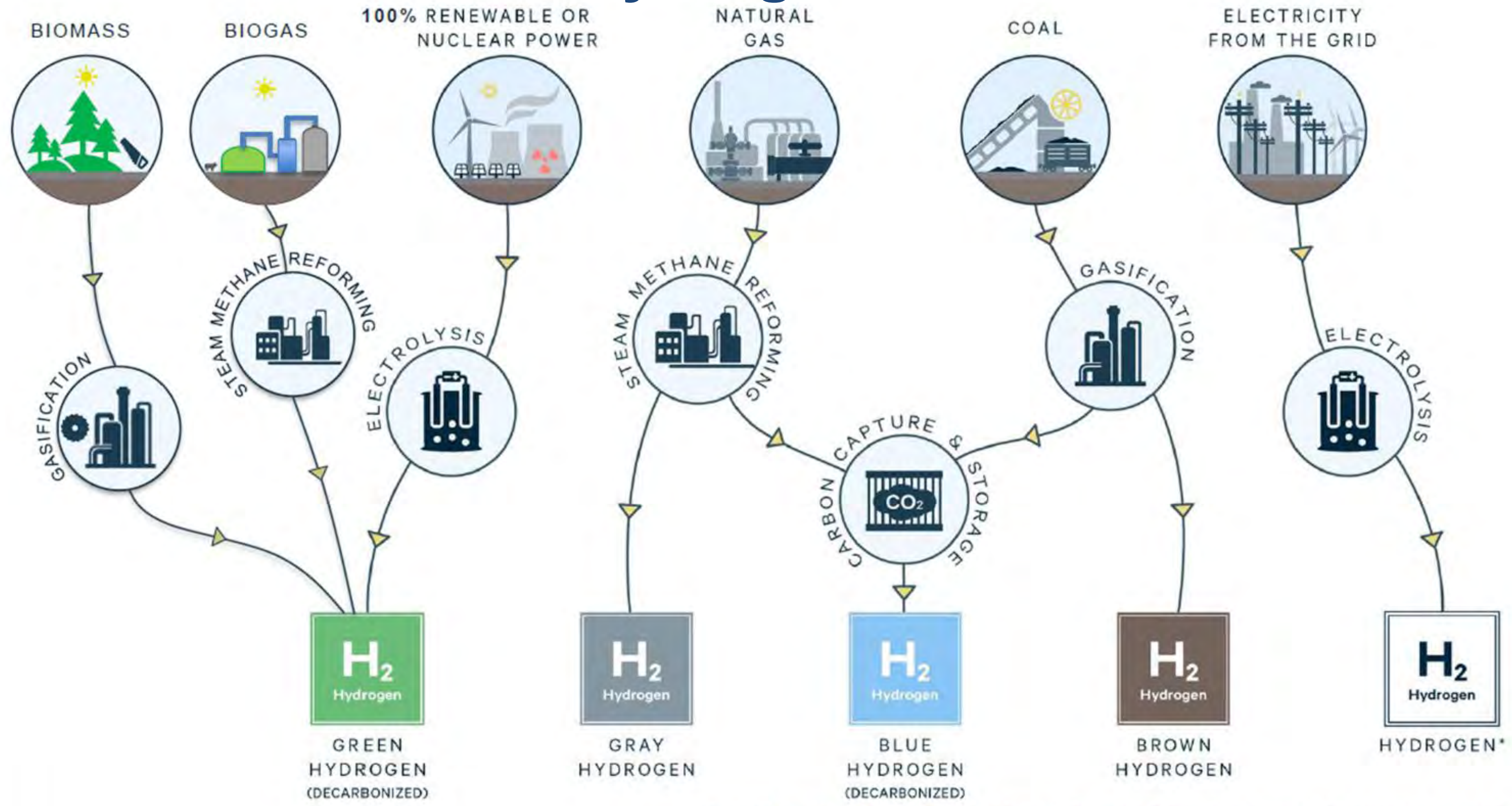
- Replacement of combustion engines with FCEVs, in particular in buses and trucks, taxis and vans as well as larger passenger vehicles
- Decarbonization of aviation fuel through synthetic fuels based on hydrogen
- Replacement of diesel-powered trains and oil-powered ships with hydrogen fuel-cell powered units

- Decarbonization of natural gas grid through blending
- Upgrade of natural gas to pure hydrogen grid

- Replacement of natural gas for process heat

- Switch from blast furnace to DRI (direct reduced iron) steel
- Replacement of natural gas as feedstock in combination with CCU

The “colours” of hydrogen

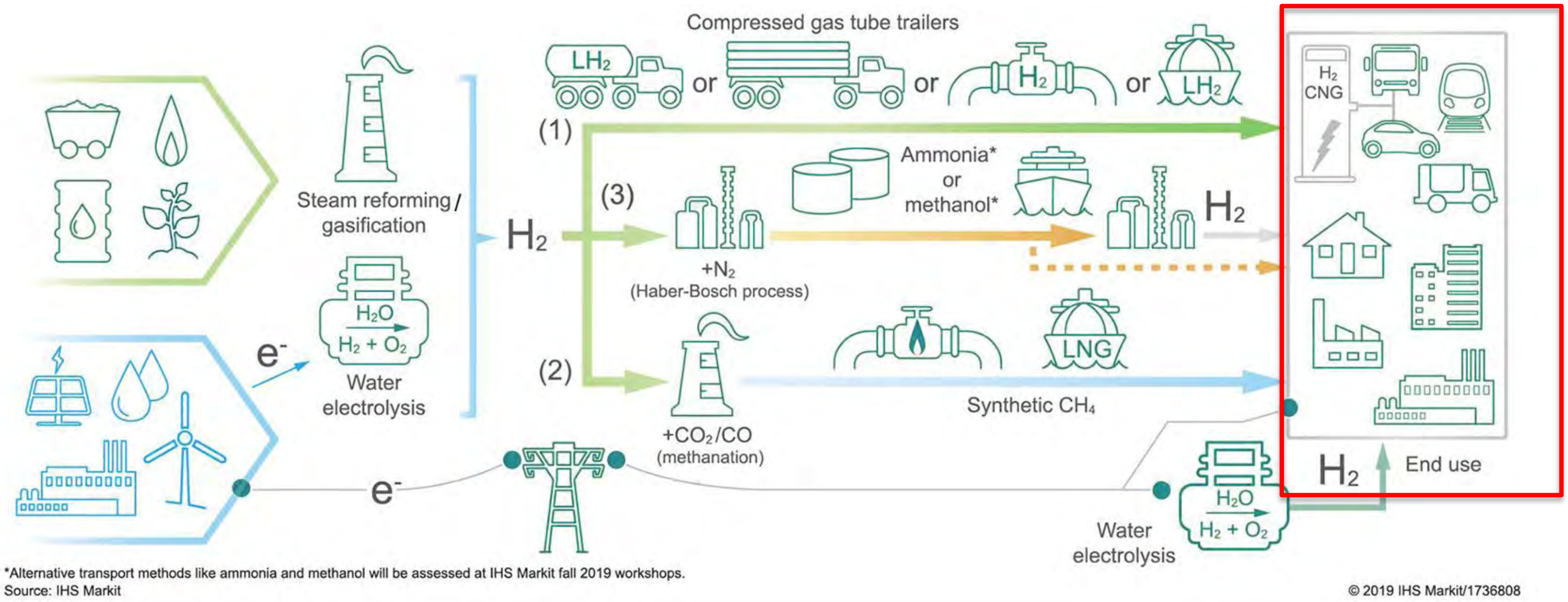


Adapted from: https://www.rff.org/publications/issue-briefs/investment-tax-credits-hydrogen-storage/

Hydrogen production today is estimated at 70 Mt/yr (million tons):

- 76% is based on the use of natural gas in steam methane reforming plants.
- The use of electrolyzers accounts today 2% of stock.

H_2 value chain

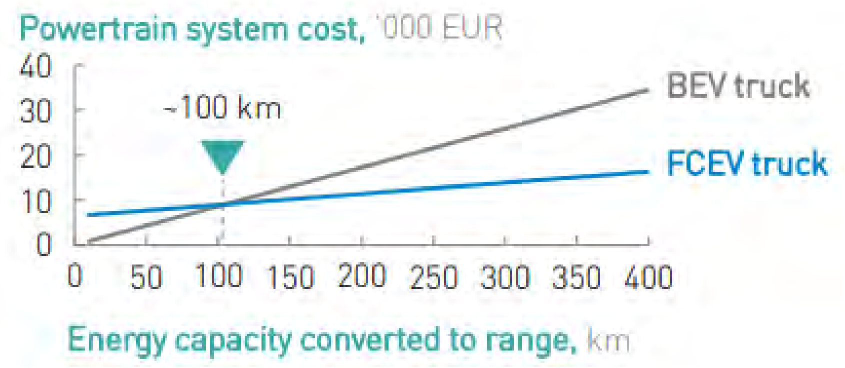


H_2 sector coupling

Priorities: Decarbonize heavy transports

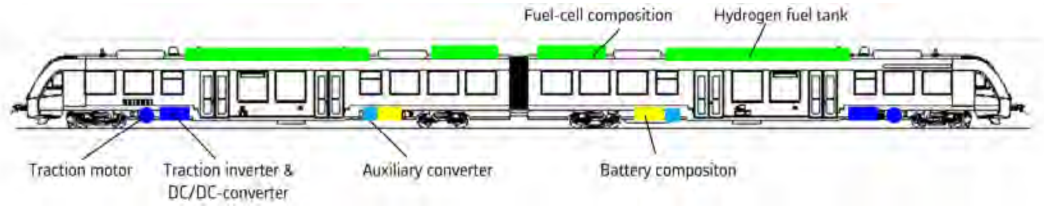
In transport, hydrogen is the most promising decarbonization option for trucks, buses, ships, trains, large cars, and commercial vehicles

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



- Hydrogen refueling is 15 times faster than fast charging

Fuel cell trains



	Characteristics	Value
Dynamics & capacity	> Maximum speed > Passenger capacity	> 140 km/h > 300/150[1] seats
Consumption & range	> Fuel consumption > Average range per tank	> 0.25 kg/km > 1,000[2] km
On board hydrogen system	> Storage pressure > Storage capacity > Fuel cell system > Fuel cell power	> 350 bar > 260 kg (1 tank[2] of ~130 kg per car) > Hydrogenics HyPM™ Power Modules > 400 kW (200 kW module per car)
Powertrain	> Traction motors > Hybridization system > Energy storage capacity	> Alstom-power-management-system > Li-Ion batteries > 110 kWh
Costs	> Rolling stock costs > Infrastructure costs > Hydrogen fuel	> tbc > Included in hydrogen fuel cost > EUR 4-7 per kg

1) Seated seats 2) Latest modification of Coradia iLint – Each tank contains several pressurized bottles

STUDY ON THE USE OF FUEL CELLS & HYDROGEN IN THE RAILWAY ENVIRONMENT –State of the art & business case and market potential - © Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking, 201910

Coradia iLint is the World's first passenger train powered by a hydrogen fuel cell.

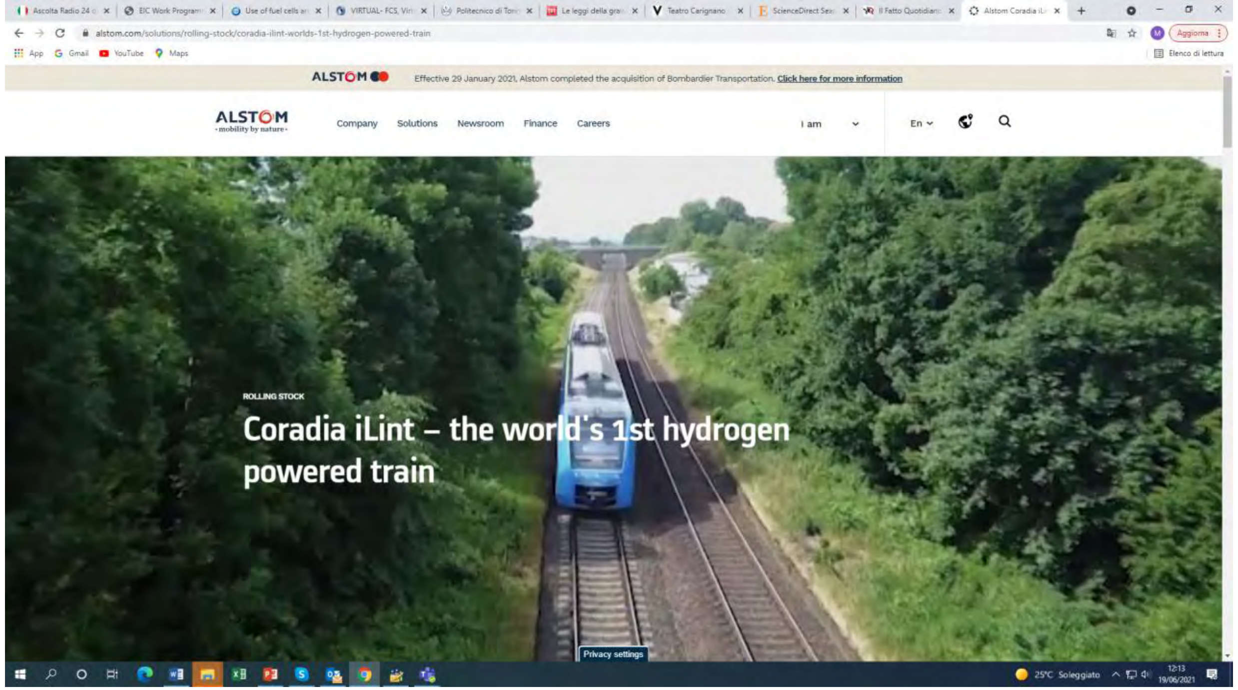
Specifically designed for operation on non-electrified lines, it enables clean, sustainable train operation while ensuring high levels of performance.

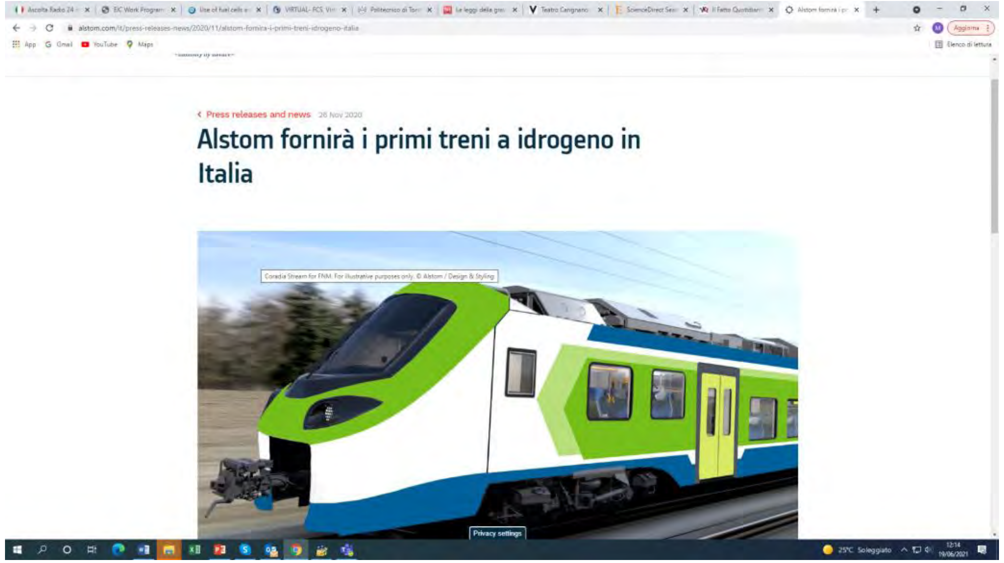
ALSTOM Savigliano is now producing FCH trains for Trenord

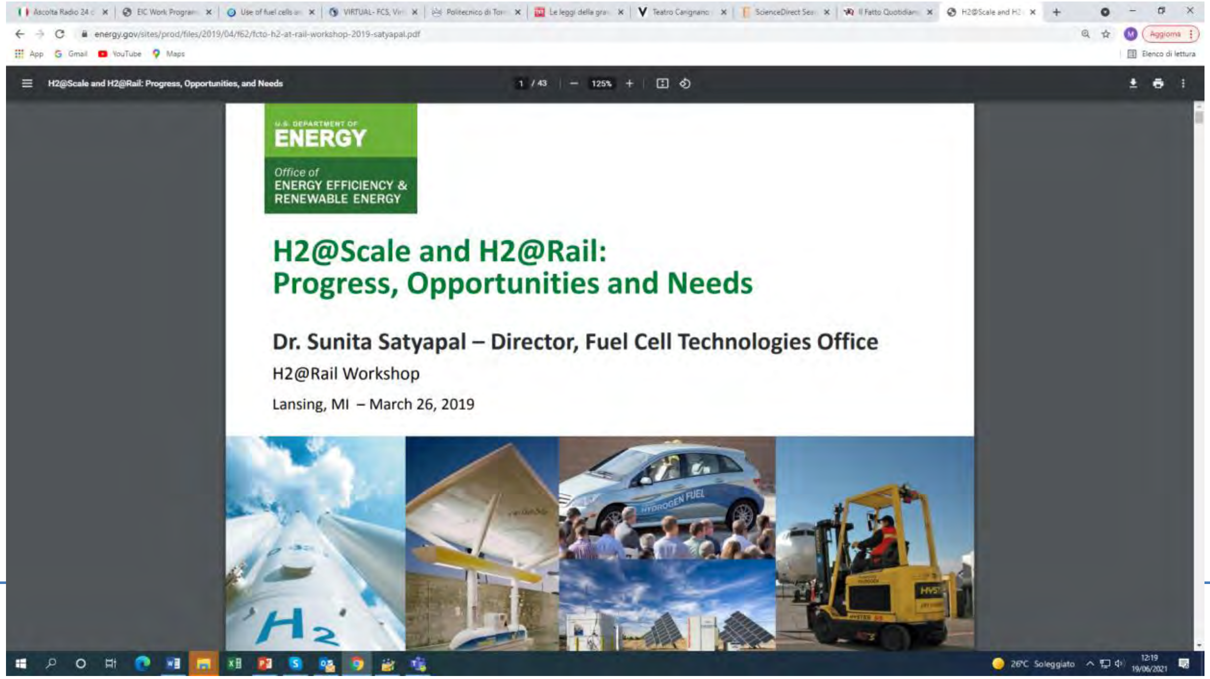
H2 storage@350 bar

Fuel cells

Fuel cell trains







Fuel cell trains – Short history

Alstom iLint Coradia

German, 2017

CRRC Fuel Cell Tram

China, 2015

BNSF Fuel Cell Shunter

California, 2008

FC Tram Locomotive

Spain, 2011

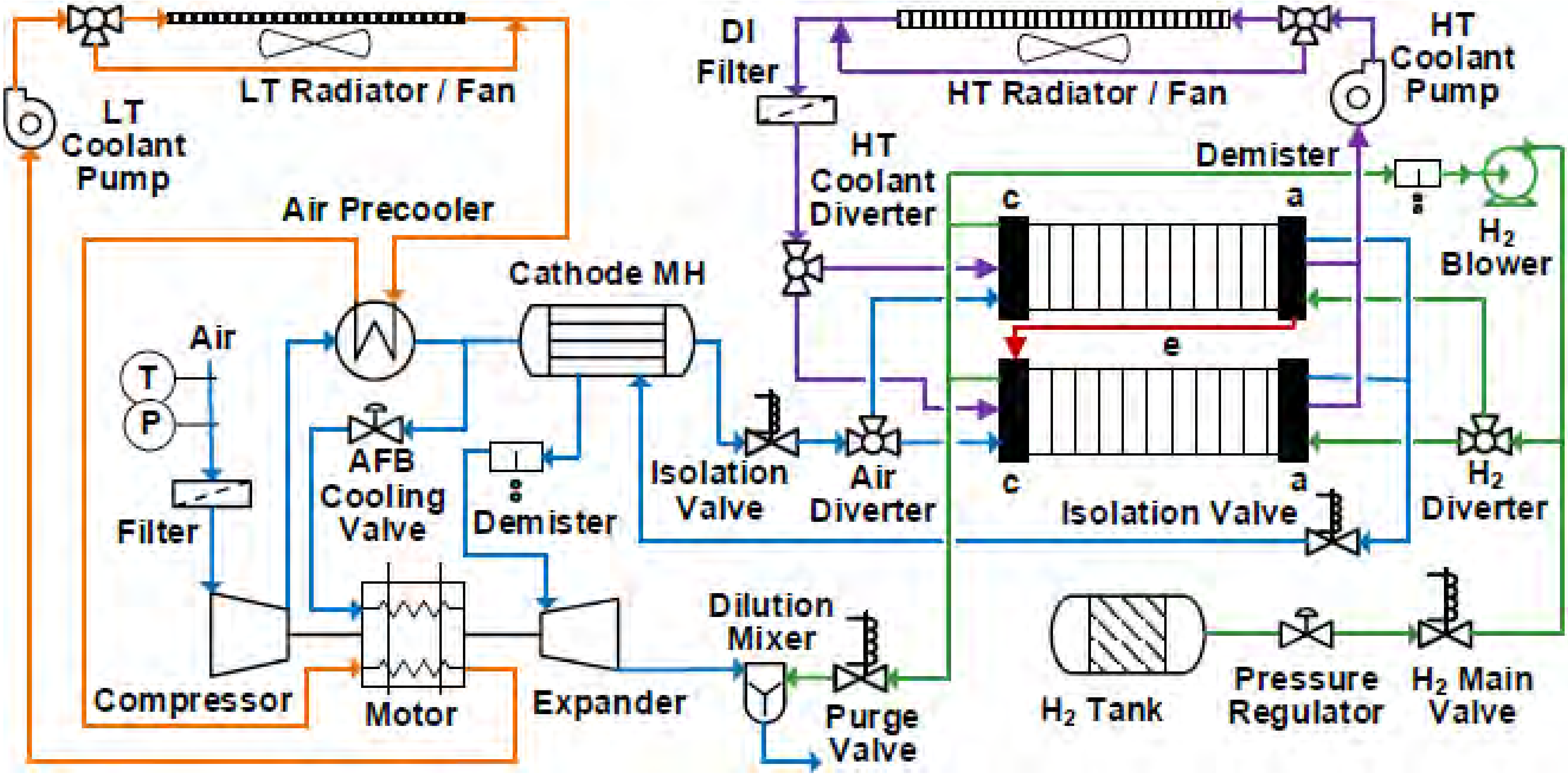
FC Mining Vehicle

South Africa, 2012

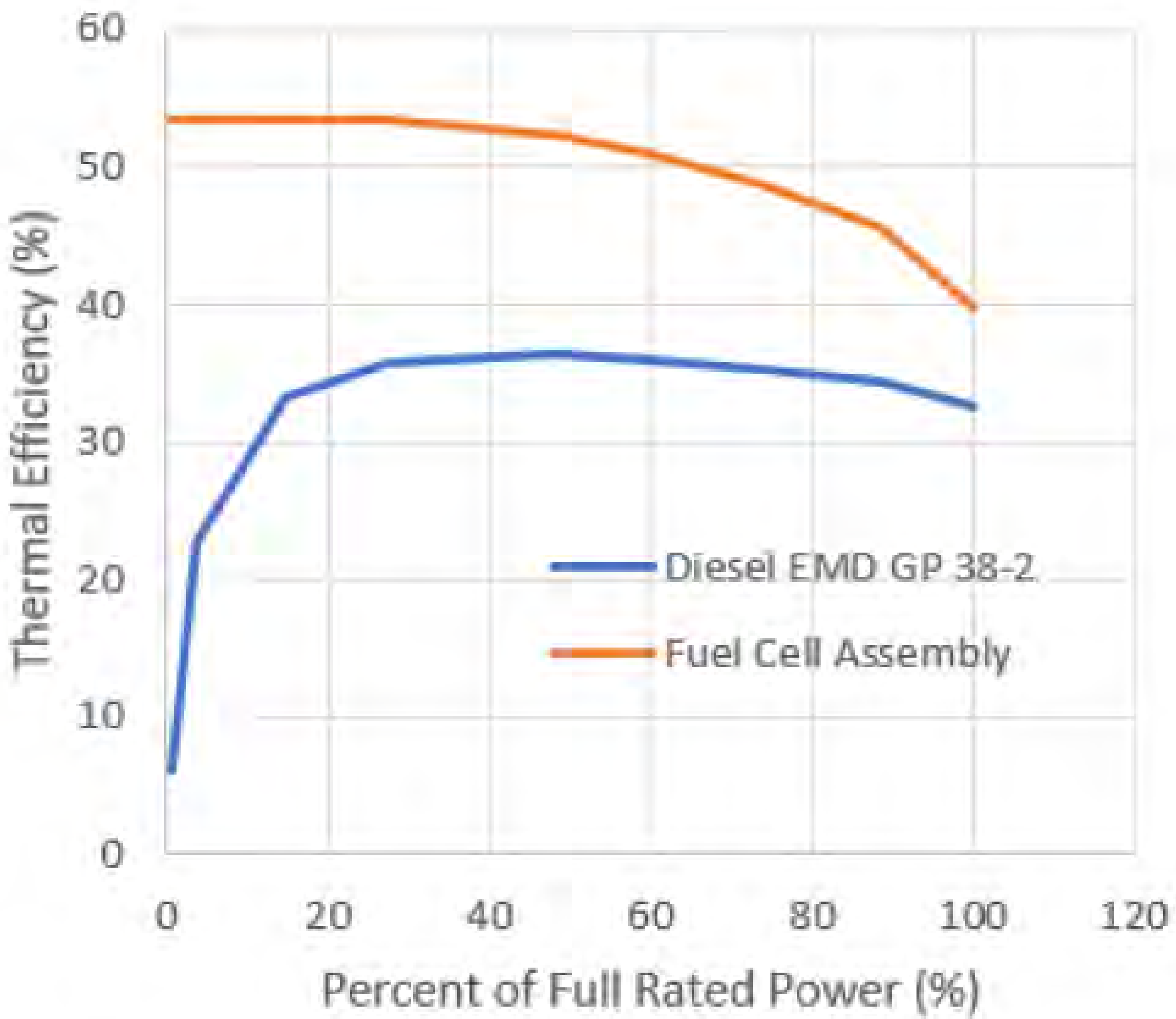
FC Hybrid Railcar

Japan, 2006

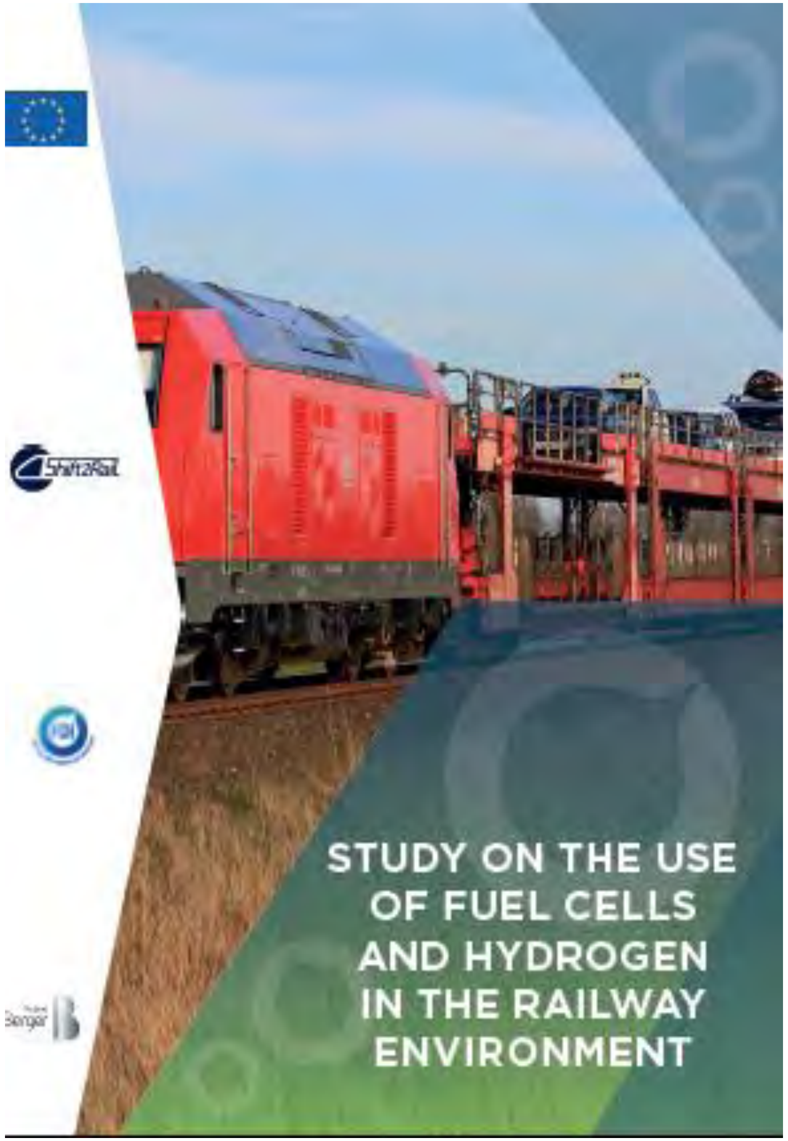
Fuel cell trains - Engine



Fuel cell trains - Performances



Fuel cell trains – Business case



© Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking, 2019.

Document prepared by Roland Berger for the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the Shift2Rail Joint Undertaking (S2R JU).
• More information on the FCH JU is available on the Internet: www.fch.europa.eu
• More information on the S2R JU is available on the Internet: www.shift2rail.org
• More information on the European Union is available on the Internet: www.europa.eu

Authors: Yvonne Ruf, Thomas Zorn, Pinar Akcayoz De Neve, Patrick Andrae, Svetlana Erofeeva, Frank Garrison, Andreas Schwilling
Contact: Yvonne Ruf (yvonne.ruf@rolandberger.com)

Fuel cell trains – Business case

Business case considering the whole supply chain (train, energy supply, infrastructure)

Diesel MU	Electric MU	Hydrogen MU
		
Diesel Fueling Infrastructure Mature Energy Supply Chain Operator Storage and Dispensing	**Overhead Catenary System** Operator builds entire system—catenary wires, traction power system and grid interconnection	**Hydrogen Fueling Infrastructure** Build-out H2 Prod'n and Distribution Operator Onsite Hydrogen Storage and Dispensing

Fuel cell trains – Case study in EU – H_2 Train

Usage profile[1] for TCO model

- **Passenger** operation in regional transport – **Medium-sized operator** assumed purchasing and operating a batch of **15 FCH trains**
- **Typical daily mileage of 800 km** per train and **8 h to 10 h in operation** – Refuelling overnight at **central depot**
- **Flat topography** with about **8 stops per hour** and **10 stops per 100 km**
- Average **seat load factor of 50%, availability of 97% (incl. planned maint.)**

Power rating
800-1,000 kW
- Typical power rating[2] ranges from 800 to 1,600 kW

Acceleration
0.8-1.0 m/s²

Tractive effort
90 kN

Pass. capacity
120 seats
(2 units)
- Typical seating capacity[2] ranges from 100 to 270

Max. speed
140 km/hour
- Typical maximum speed[2] ranges from 100 to 160 km/hour
- Over longer distances usually higher speed

Hydrogen tank
~250 kg
- Typical tank volume[2] for a 2-car MU approx. 1,600 l of diesel

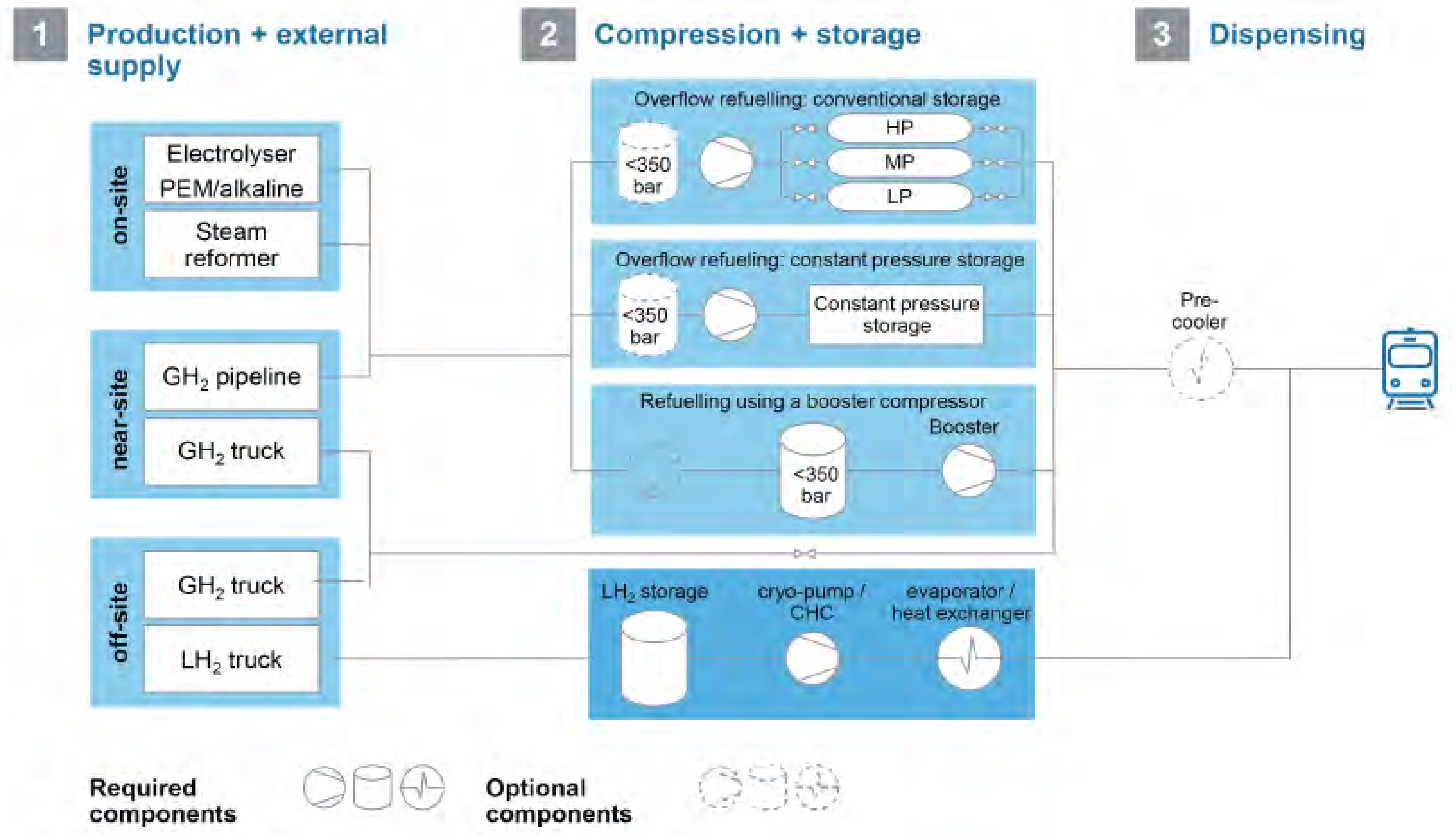
Consumption
0.25-0.3 kg/km

Max. range
1,000 km
- Typical range[2),3)] of approximately 1,000 km
- Depends e.g. on passengers on board, stops and topography

Price
EUR 4.0-5.5 m
- Typical price[2] ranges from EUR 2.0 to 9.6 m

Lifetime
30 years[4]

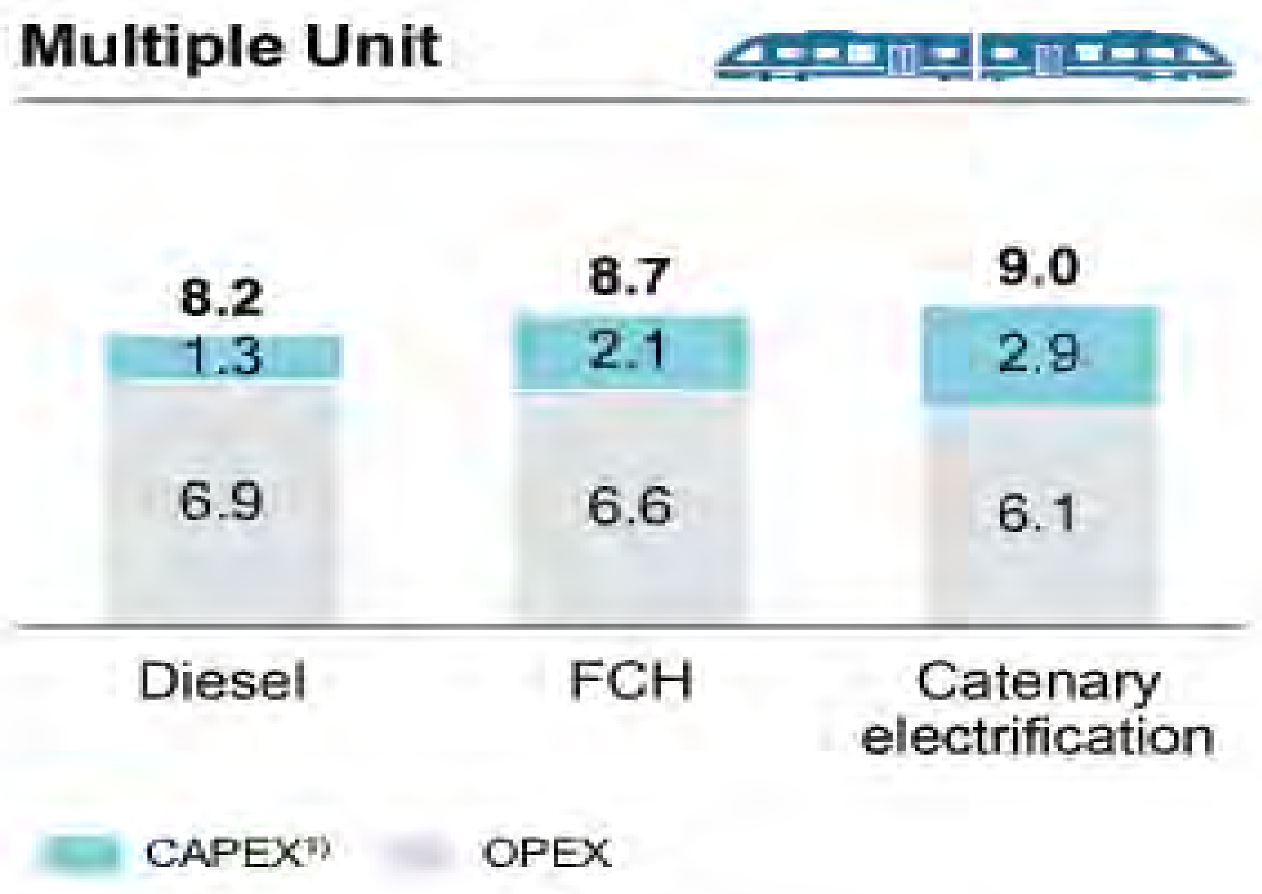
Fuel cell trains – Case study in EU - HRS



Fuel cell trains – Cost per km (€/km)

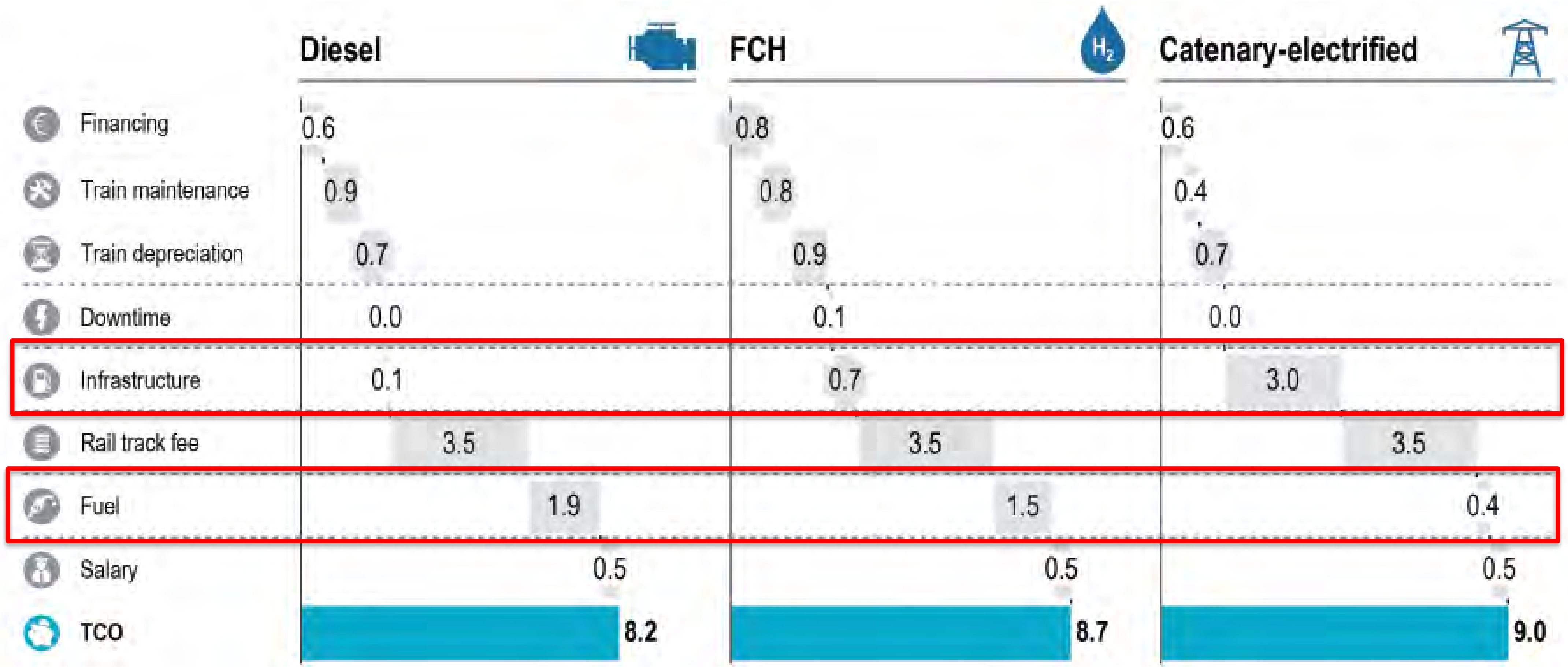
CASE STUDY IN EU

- Route length (100 kilometres)
- Diesel price (EUR 1.3 per litre of diesel)
- Energy consumption (1.45 litre of diesel per kilometre and 0.27 kg H2 per kilometre).
- Electricity price (EUR 90 per MWh)
- Hydrogen produced at the on-site production facility using an electrolyser: cost of 5.6 EUR/kgH_2
- The infrastructure cost includes the hydrogen refuelling station and the production facility.
- For the catenary electrification it was assumed that 100 km of rail track are being electrified (1 MEUR/km)



Fuel cells and H_2 technologies are already interesting in EU

Fuel cell trains – Cost per km (€/km)



The difference with catenary is the infrastructure

Fuel cell trains – Needs for parity with diesel

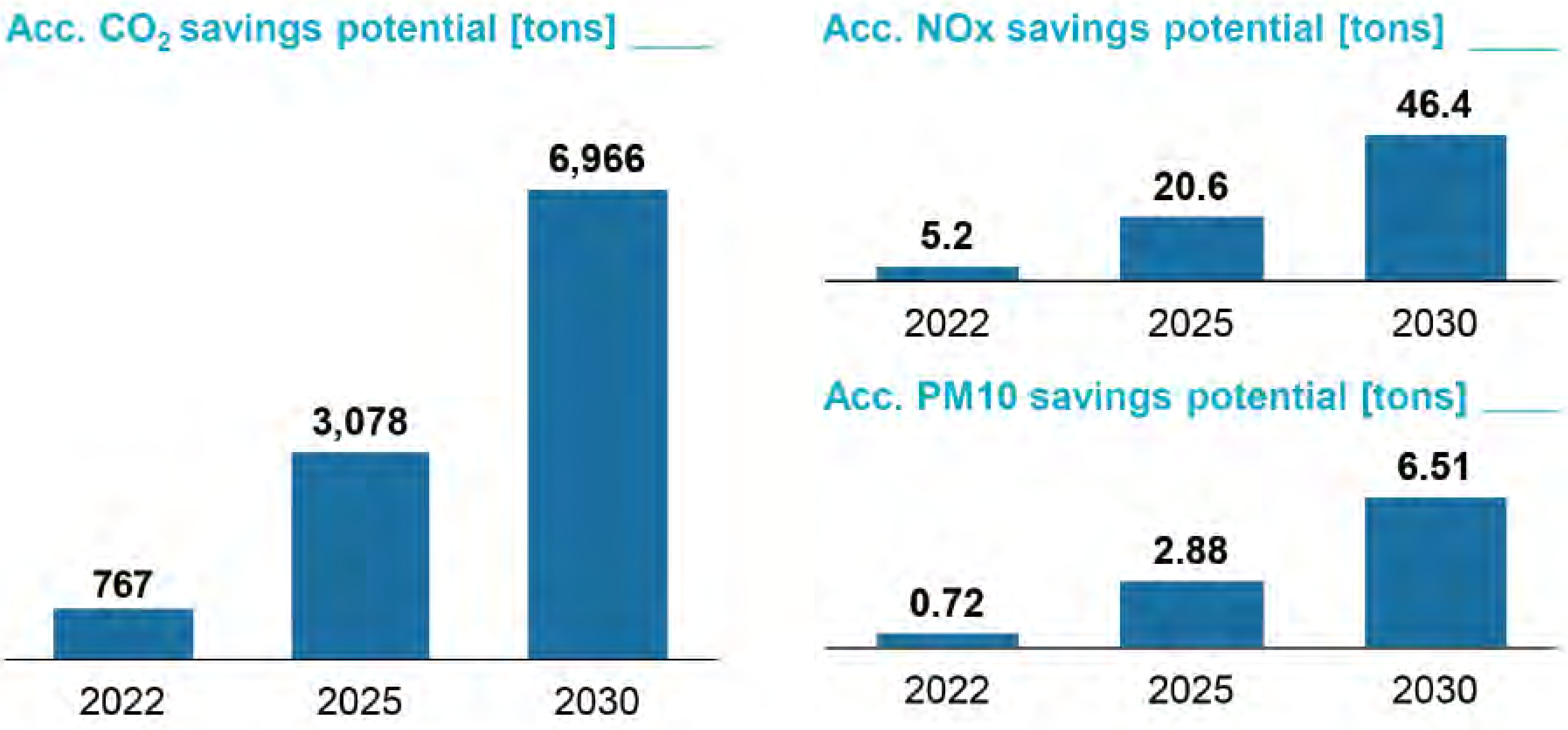
Key levers	Required % change to reach par with diesel	Required absolute change to reach par with diesel
Decrease in hydrogen consumption	- 37.8%	- 0.1 kg H_2/km
Increase in diesel cost	+ 29.8%	+ EUR 0.35 per l
Decrease in electricity price	- 37.8%	- EUR 0.03 per kWh
Decrease in FCH train purchasing cost	- 32.1%	- EUR 1.8 m

Parity with diesel reached at cost of H_2 of 3.4 EUR/kg
(obtained by electrolysis @ electricity price EUR 60 per MWh)
With trucked-in hydrogen, parity at cost of H_2 of 5.0 EUR/kg

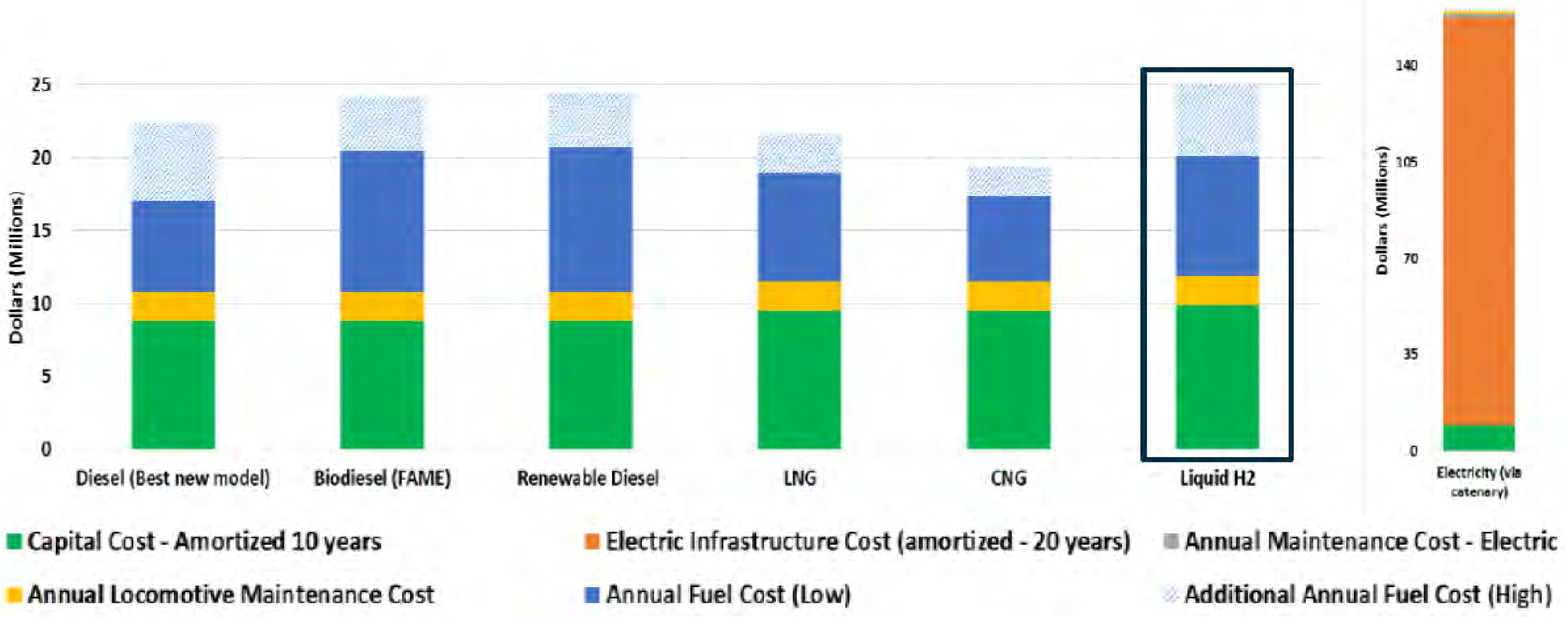
Fuel cell trains – Some case studies in EU

Multiple unit case studies	Montréjeau – Luchon, France	Aragon, Spain	Groningen & Friesland, Netherlands
Overview of route specifications			
Track length	140 km	165 km	300 km
Rolling stock	3x 4 car trains (bi-mode)	2x 4 car trains (bi-mode)	70x 3 car trains
H_2 consumption	0.36 kg/km	0.31 kg/km	0.22 kg/km
	245 kg/day	240 kg/day	16,500 kg/day
Total CAPEX	EUR 25 m	EUR 14 m	EUR 398 m
Characteristics	Partly electrified route with a low utilisation on 36 km	Cross border connectivity and long route without electrification	Fast trains for intercity connections
Total cost of ownership [EUR/km$_{train}$]			
Diesel	18.5	9.3	4.8
FCH	**21.2**	**12.4**	**5.0**
Catenary	27.5	22.6	4.5
Battery	19.9	13.7	5.3
Environmental analysis			
CO_2 savings [tons per year]	1,334 t	767 t	56,389 t

Fuel cell trains – Saving of contaminants in the case-study of Aragon (Spain)



US case – Full cost comparison

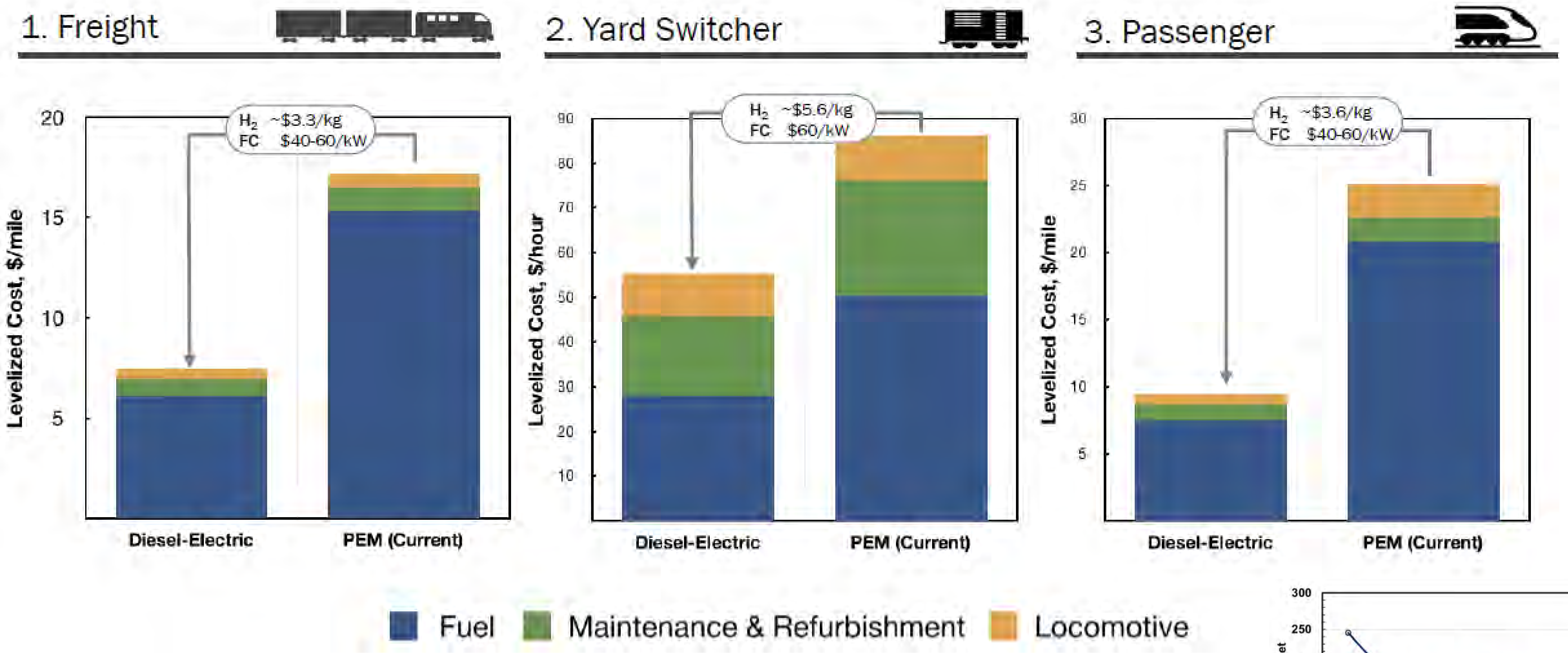


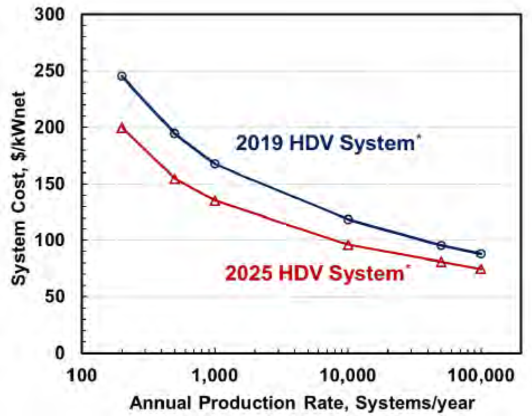
Assumptions:
Liquid Hydrogen Cost: $5.16-$9.03/gallon
Vehicle Cost: $8.05-$9.95 million/locomotive + Tender car

Source: Isaac, Raphael et al. UC Davis (2016)

H_2 fuel technology cost is, at present, still higher than diesel, biodiesel, LNG and CNG, but already lower compared to catenary electric technology

Fuel cell trains – Cost per mile

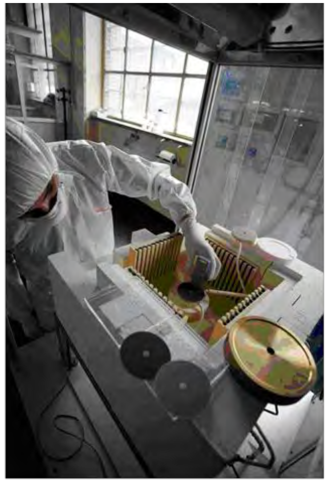




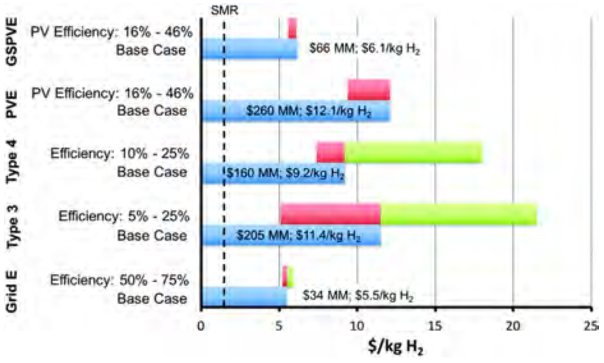
If fuel cells and H_2 technologies performances and cost projections are met, they will compete pretty soon with diesel rail

R&D at several TRLs: from concept to market

Services @ POLITO

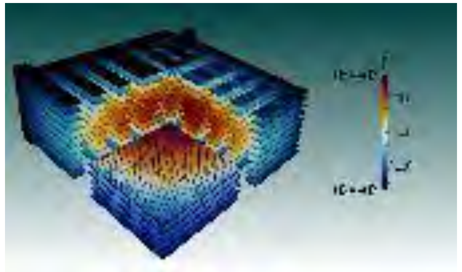


Test and experimental services



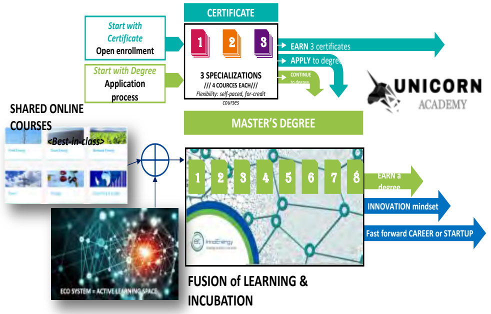
Feasibility studies, strategic consultancy, scenario analysis

Modeling



Prototyping

Training



Thank you for your attention

Prof. Massimo Santarelli
Politecnico di Torino
massimo.santarelli@polito.it