Overview of Hydrogen-Powered Railway Motive Power Vehicles (Hydrail)

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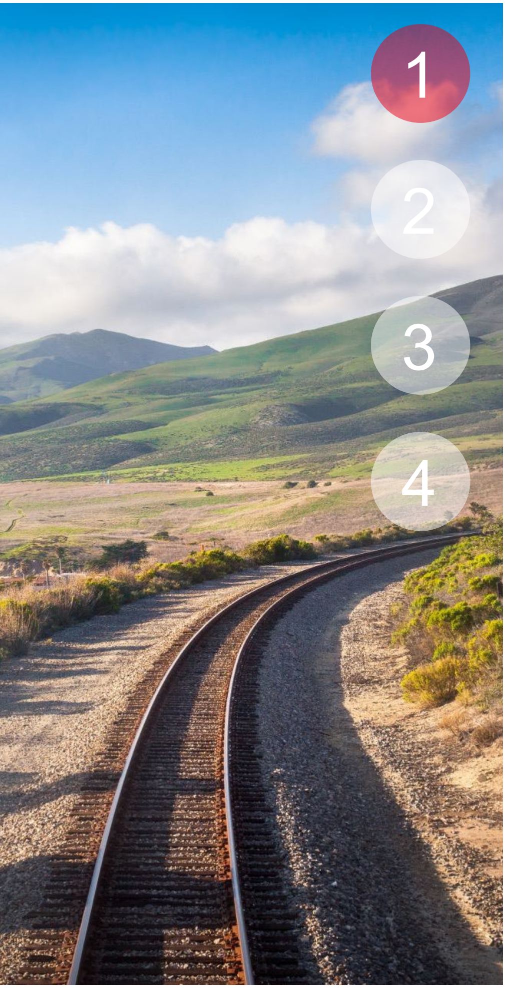
Andreas Hoffrichter, PhD | Lead, Sustainable Motive Power and Zero-Emission Technologies | DB Engineering & Consulting USA Inc.
andreas.hoffrichter@deutschebahn.com | +1-916-841-3947

Agenda

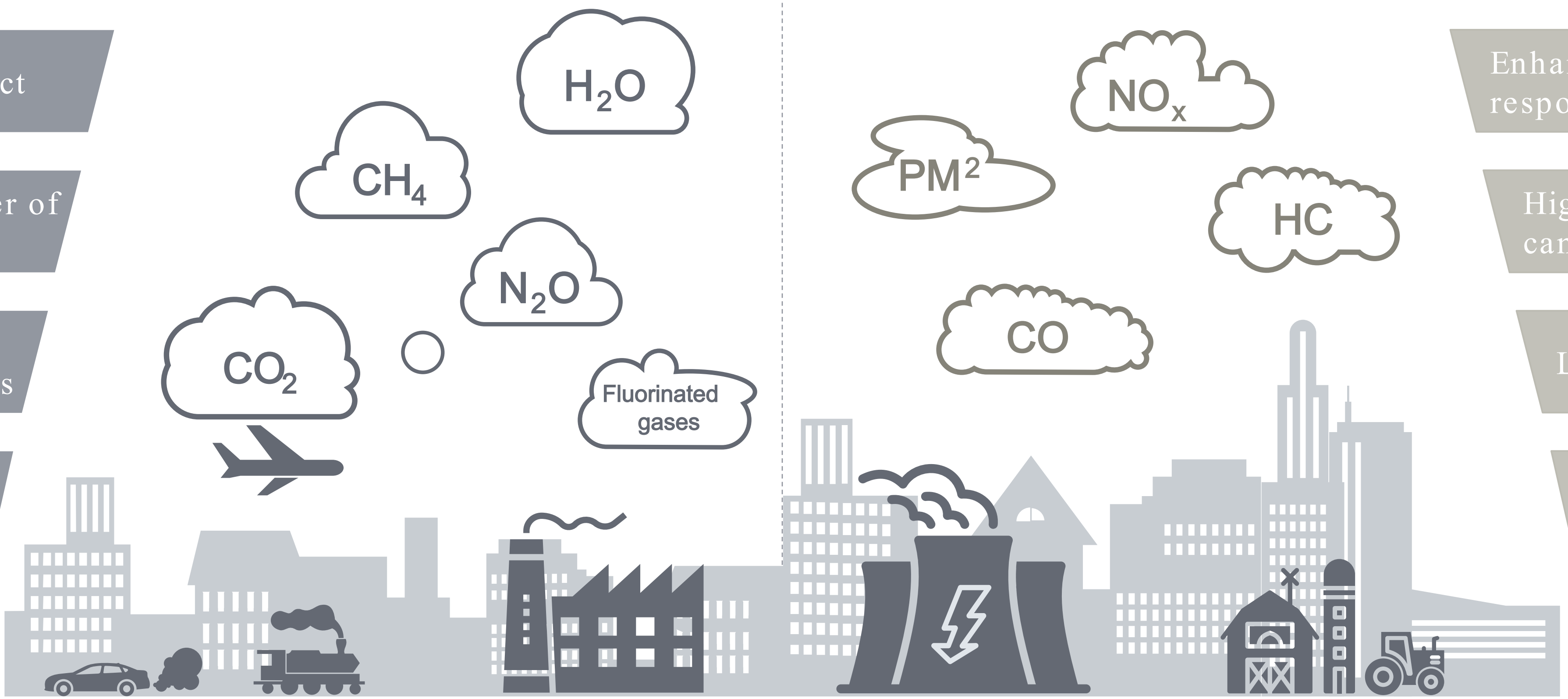


1. Emissions
2. Current Motive Power
3. Energy Carrier Hydrogen
4. Hydrail

Greenhouse gases and air pollutants pose a high risk for the environment and people's health

GHGs produced by human activities accelerate climate change…

- Increased heat, drought and insect outbreaks
- Increased number of wildfires
- Reduced agricultural yields
- Declining water supplies
- …



…and air pollutants from exhaust gases impact people's health

- Enhanced allergic responses
- Higher risk of cancer
- Lung irritations
- Premature death
- …

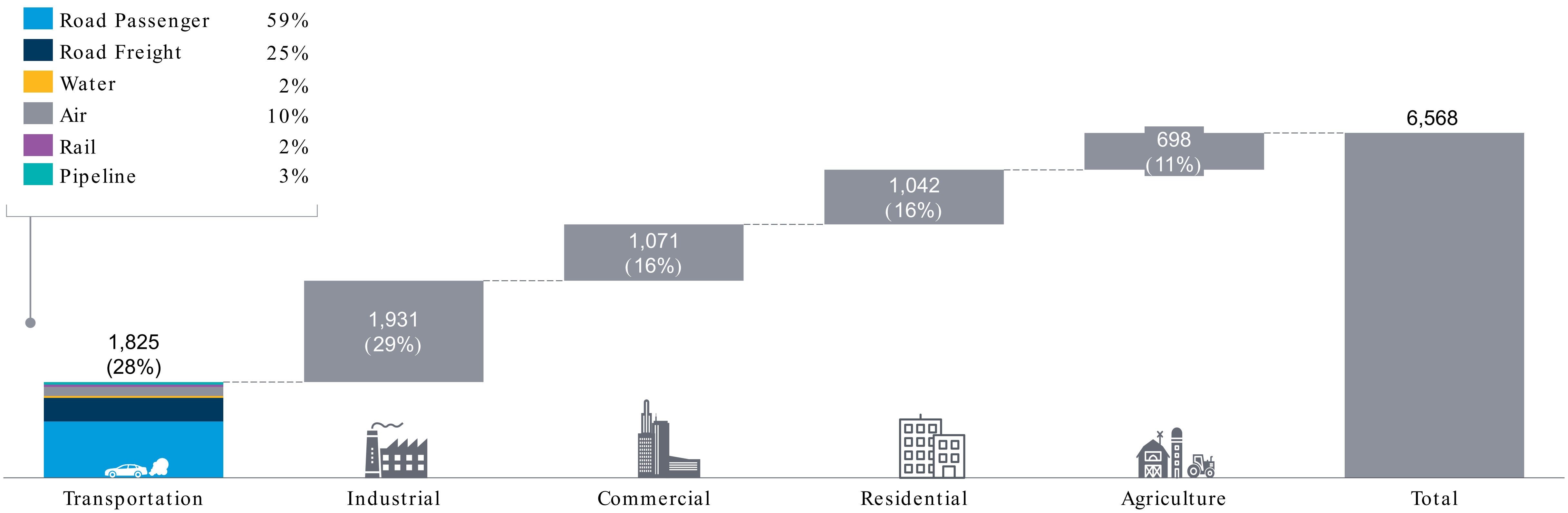
(1) More than 97% of scientists agree that the current rise in global temperatures is due to human activities that release GHGs (2) PM = Particulate Matter

Source: USGCRP 2017, Fourth Climate Assessment

Transportation is the 2nd largest source of GHG in the U.S. – modal shift to rail can significantly reduce emissions

GHG emissions in the US

in $MtCO_2e$ (%) 2018



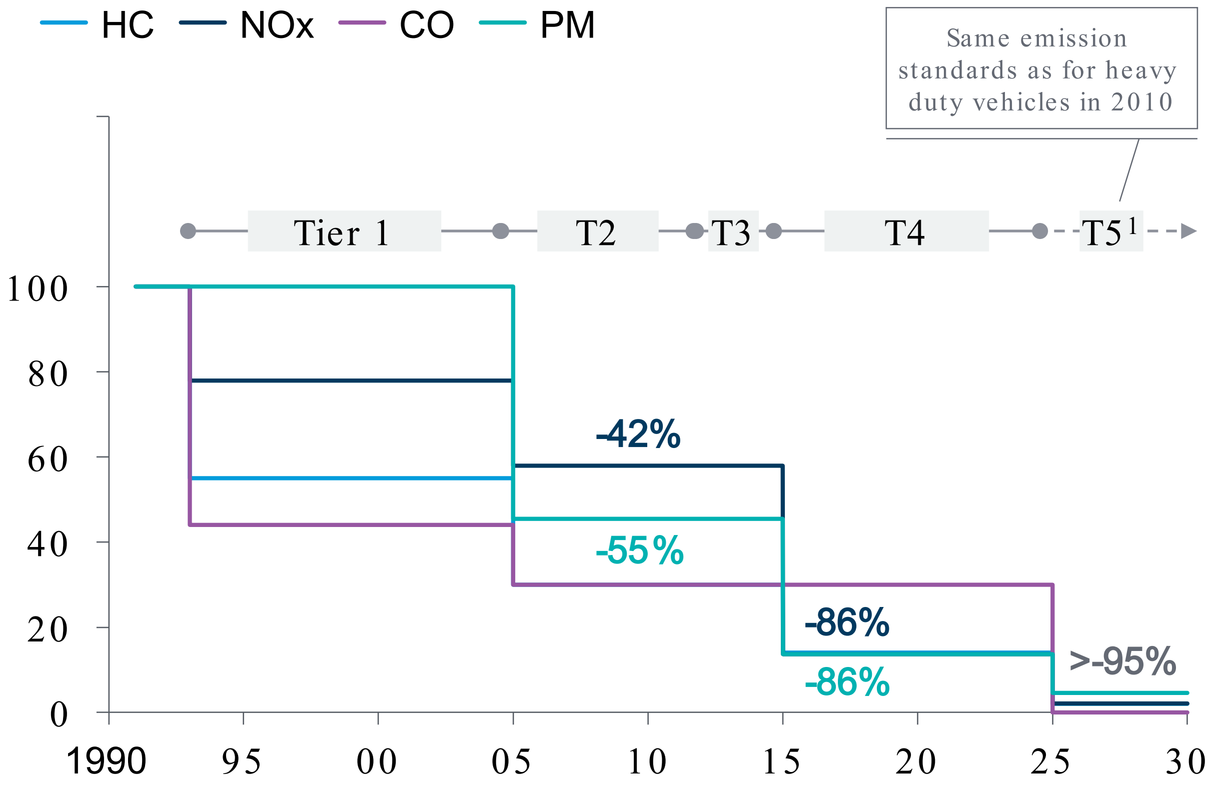
Numbers rounded

Source: Oak Ridge National Laboratory (2020) Transportation Energy Data Book: Edition 38.2

The U.S. Environmental Protection Agency regulates the exhaust emission resulting from railway motive power vehicles

- Four Tiers depending on the production year of the motive power vehicle
- Increasingly more stringent
- Current standard is Tier 4, since 2015
- The California Air Resources Board has proposed a Tier 5 standard to be adopted by the EPA

Tier standards for line -haul locomotives
in % (Tier 0 = 100)



(1) Proposed by CARB, not yet adopted
Source: EPA (2016), CARB (2017), Harris (2019)

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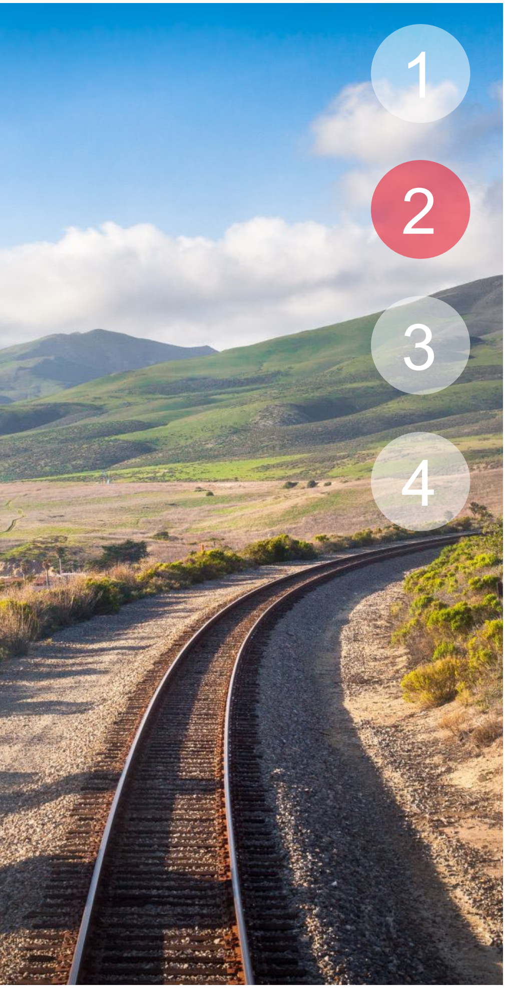


1 Emissions

2 Current Motive Power

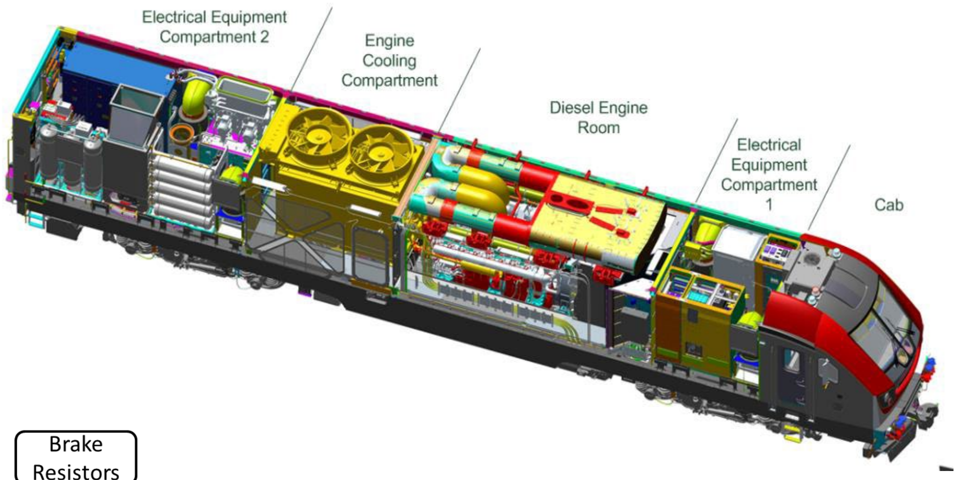
3 Energy Carrier Hydrogen

4 Hydrail

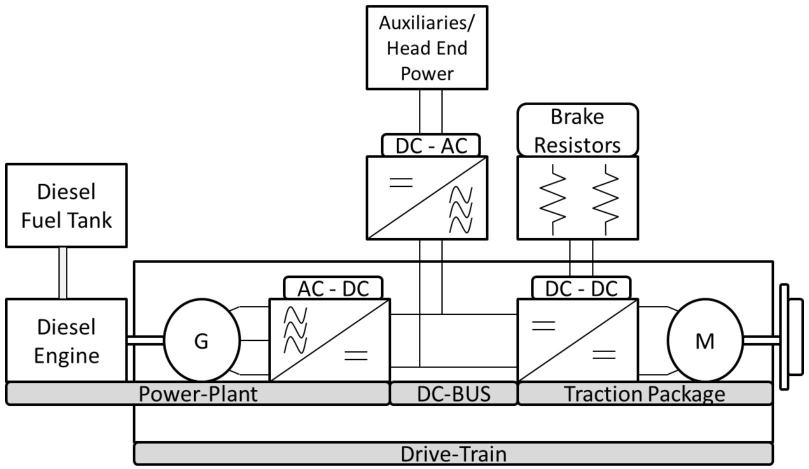
Diesel-Electric Motive Power

- Diesel-electric is the most common powertrain in North America, introduced in the 1920s
- There were ~40,000[1] locomotives in the U.S. in 2018
- An electric vehicle with its own power-plant (diesel generator set)
- Many components the same as in electric motive power vehicle
- Two main types:
  - Direct current (DC) traction motors; ~65%[1] of the fleet in 2018
  - Alternating current (AC) traction motors;~ 35%[1] of the fleet in 2018

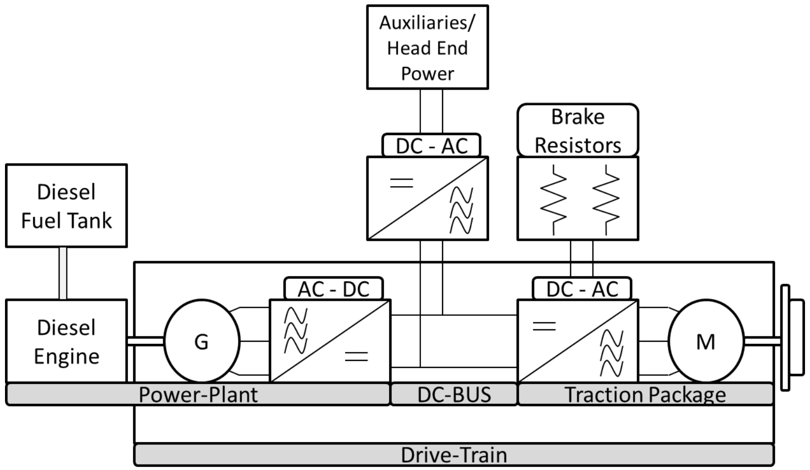
Modern Tier 4, Diesel -Electric Intercity Passenger Locomotive with AC Motors



(2)



DC Traction Motors (legacy)

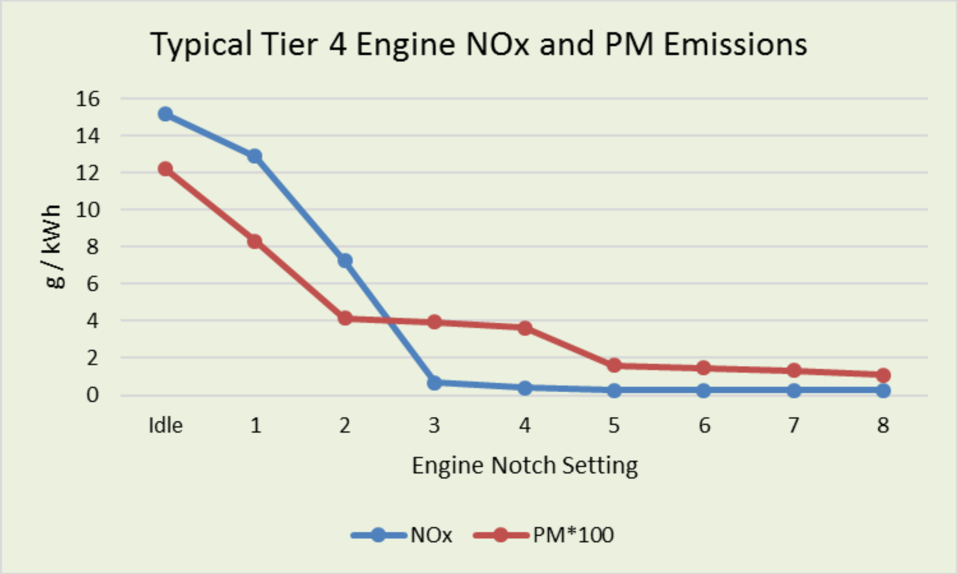


AC Traction Motors (modern)

(1) Humphrey, D. (2019). North American Locomotive Review. Cary, NC: Railinc; (2) Bloedt, M. (2019) Benefits of diesel/battery hybrid propulsion for passenger locomotives. TRB Annual Meeting.

Locomotive Diesel Engine Efficiency and Emissions

- In North America, motive power vehicles/ locomotives are typically driven in notches
- Each notch represents a specific power output
- There are typically eight notches and idle setting(s)
- There are additional losses in the powertrain after the diesel engine conversion
- Typical the duty cycle efficiency of the powertrain of a modern locomotive is ~85% (in addition to the losses in the diesel engine)
- Duty cycle efficiency for a diesel-electric locomotive varies ~18% to ~30%
- Fuel consumption and efficiency are related but not the same
- Fuel consumption at lower notch setting / power output is lower than at most efficient point BUT
- At low notch setting the output generated from the corresponding fuel is significantly lower (i.e., lower efficiency)
- Efficiency shows the ratio between input and output
- In modern locomotives with aftertreatment, there are lower emission per energy unit at higher notch settings



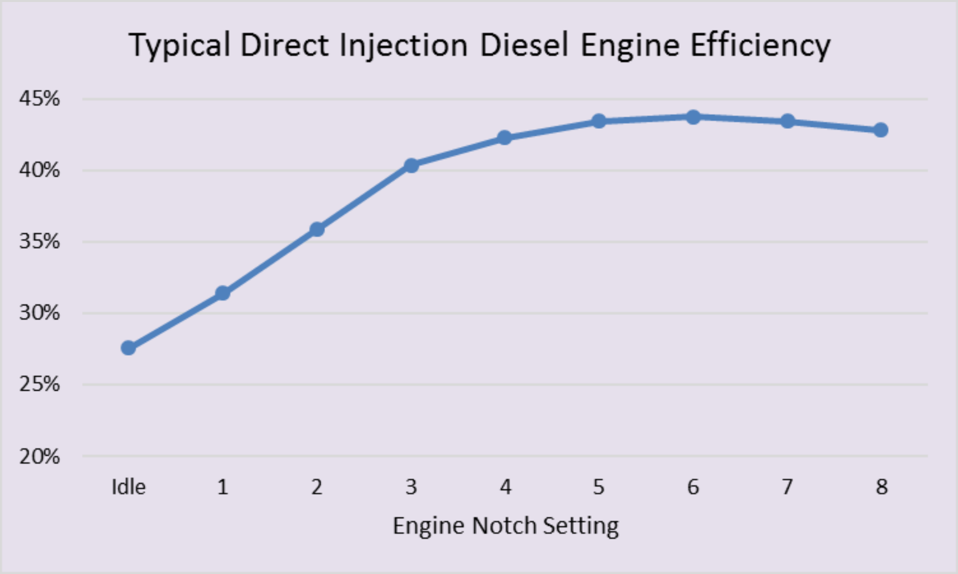


Illustration source: Bloedt, M. (2019) Benefits of diesel/battery hybrid propulsion for passenger locomotives. TRB Annual Meeting.

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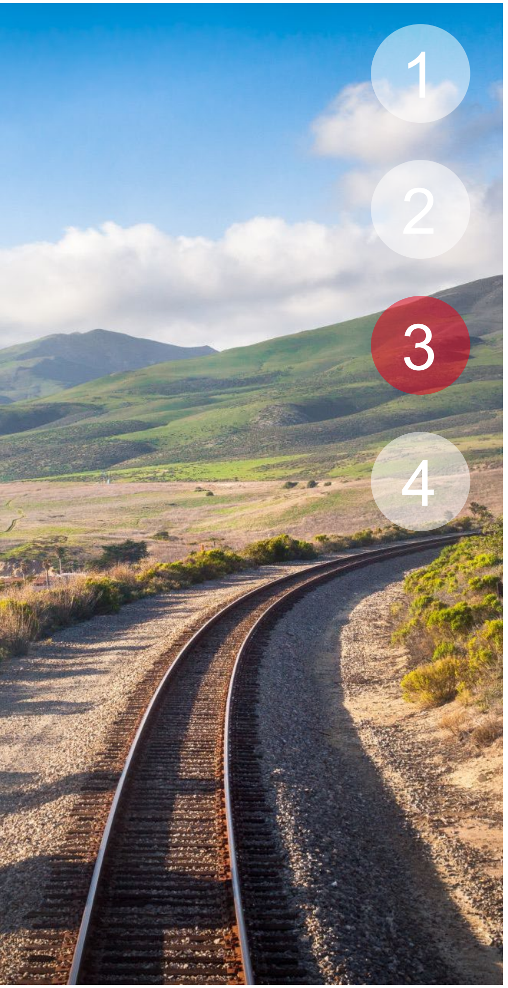

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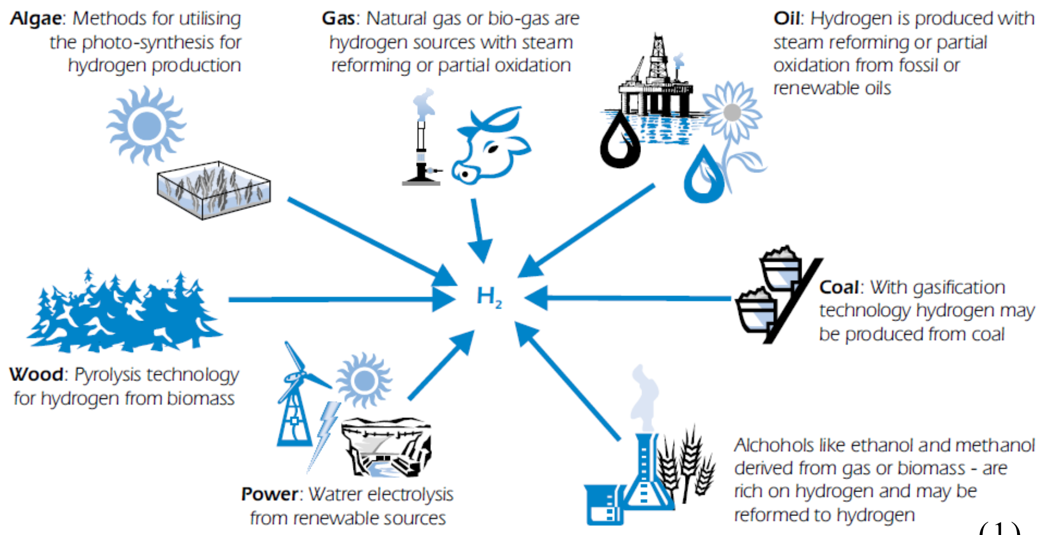
Hydrogen Characteristics

H_2

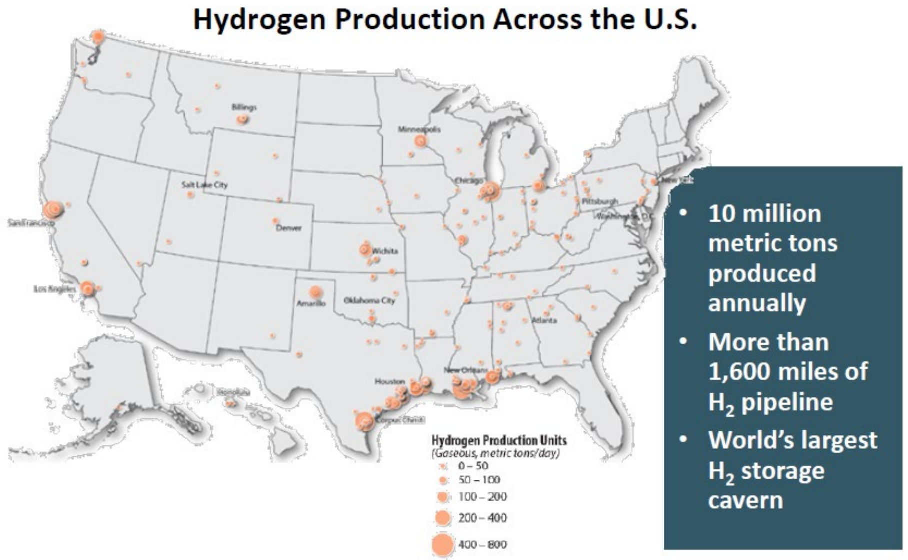
- Colorless, Odorless, Tasteless, Non-toxic, Not a GHG
- Very low harmful emissions if combustion with air (small amount of NOx)
- Most abundant element in the Universe
  - Very common on Earth, but usually in compounds (e.g., water, hydrocarbons)
- Lightest element on Earth
  - Dissipates quickly (e.g., rises into air and dilutes, eventually escapes into space)
  - Leads to low energy density by volume
  - Requires compression, liquification, or other storage method for vehicle applications
- Highest energy density by mass
  - 120MJ/kg or ~33kWh/kg LHV (Diesel 42.6MJ/kg or ~12kWh/kg LHV)
  - 142MJ/kg or ~40kWh/kg HHV (Diesel 45.6MJ/kg or ~12.6kWh/kg HHV)
  - 1kg of H2 ≈ 1gallon of diesel (energy content basis)
- Combustion range in air is 4% to 75% concentration
  - Minimum concentration in air is four times higher than gasoline for combustion
- Low radiant heat during combustion

Hydrogen Production

- On Earth, hydrogen rarely occurs in its pure but is common as part of compounds
- Has to be produced from something else
  - Similar to electricity, which also has to be produced from something else
  - Hydrogen is an energy carrier (aka energy vector)
- Many production pathways and feedstock available
  - Production will depend on local circumstances and priorities
  - Currently, most hydrogen in the U.S. is produced from natural gas (~95%)
  - Primarily for petrochemical industry (e.g., desulfurize fuel in refineries)
  - Major feedstock for fertilizer production (ammonia)
- ~10million metric tons of H2 produced annually in the U.S.



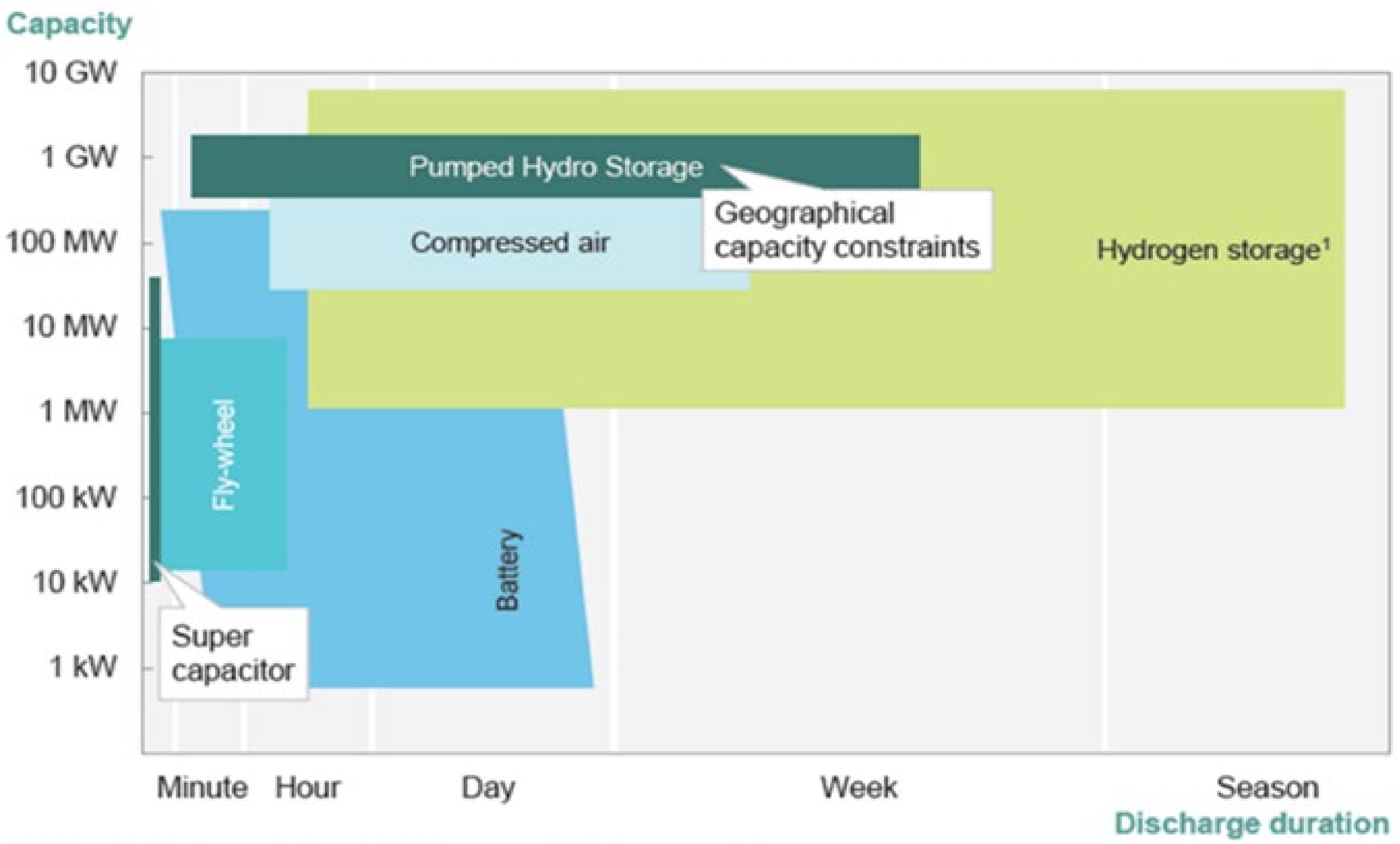
(1)



(2)

(1) International Energy Agency (2006) Hydrogen Production and Storage; (2) Satyapal (2020) U.S. Department of Energy Hydrogen and Fuel Cell Technology Overview

Utility -scale energy storage



Source: Satyapal (2019) Hydrogen and Fuel Cell Program Overview

Hydrogen storage as a liquid

- Used for longer-distance transportation/ distribution by road
- Used for longer-term storage at plants or refueling stations
- Can be an option for high-energy demand rail applications
  - Hydrogen as on-board storage (e.g., mainline long-distance freight)
  - Hydrogen delivery to refueling station
- Requires very low temperature -253°C (-423.4 °F)
- Energy intensive to produce (~30% loss); has to be evaluated compared to more frequent delivery as a gas or additional space requirements

Hydrogen storage as compressed gas

Most popular way to store hydrogen

- For transportation (often in pipelines)
- For use on vehicles
- Storage at refueling stations

Typical pressures

- 200 bar, metal cylinders, e.g., for occasional low-volume use, relatively short-distance delivery
- 350 bar, popular for on-vehicle storage for heavy-duty applications, e.g., busses, trucks, rail
- 500 bar, for transportation in cryo-compressed delivery vehicles
- 700 bar, popular in cars and some trucks; possibility for rail




Fuel Cell System

– Hydrogen combines with oxygen from air to create DC electricity, heat, and water

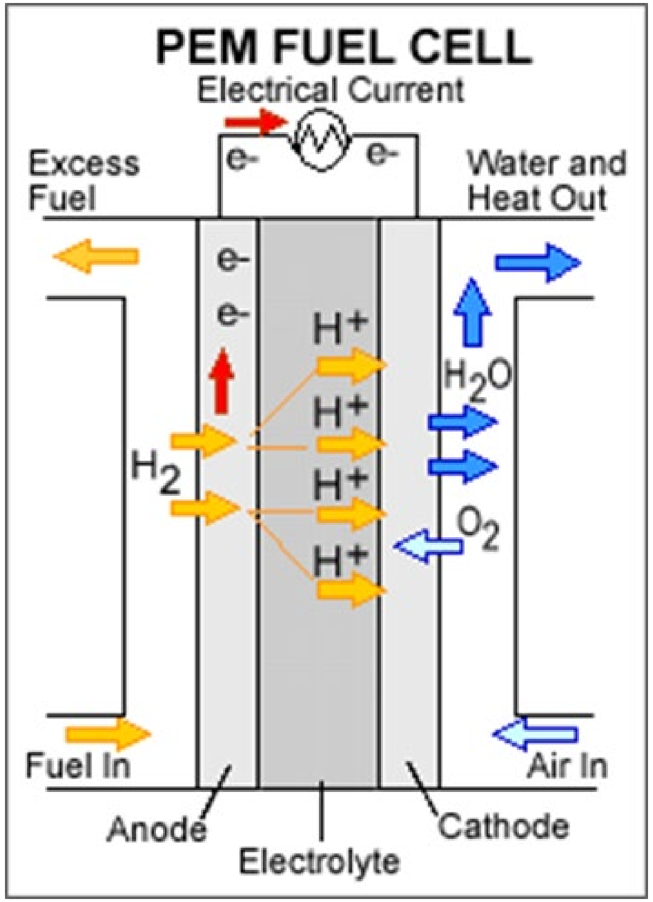
– Several different types but in vehicle applications typically proton exchange membrane (PEM) aka polymer electrolyte membrane

– Single PEM fuel cell has typically power of 120W to 700W

– Several cells combined in a stack for higher power

– Several stacks combined with balance-of-plant components (e.g., air and fuel delivery system) to create a fuel cell system with typical power of 100kW to 200kW for heavy-duty applications

– Several fuel cell systems can be combined for more power



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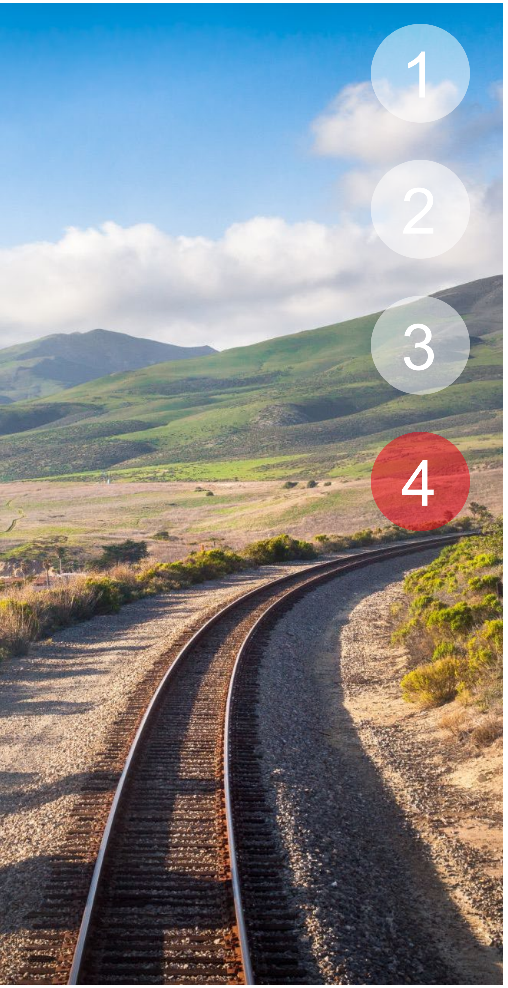


Emissions

Current Motive Power

Energy Carrier Hydrogen

Hydrail

Hydrogen (Hydrail)

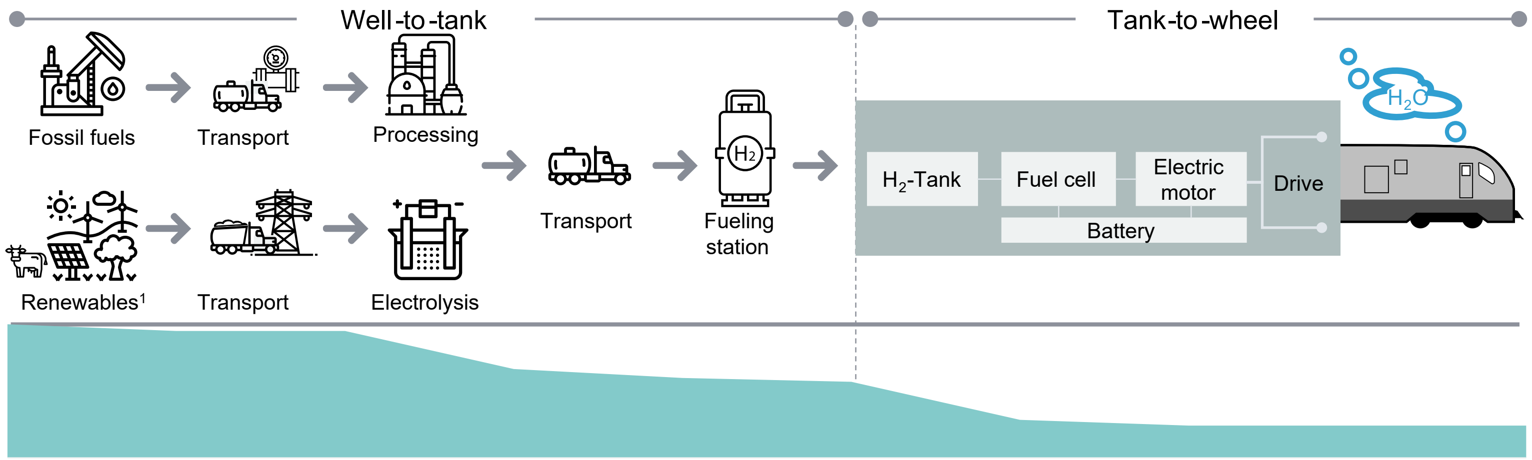
General Overview

De-scription

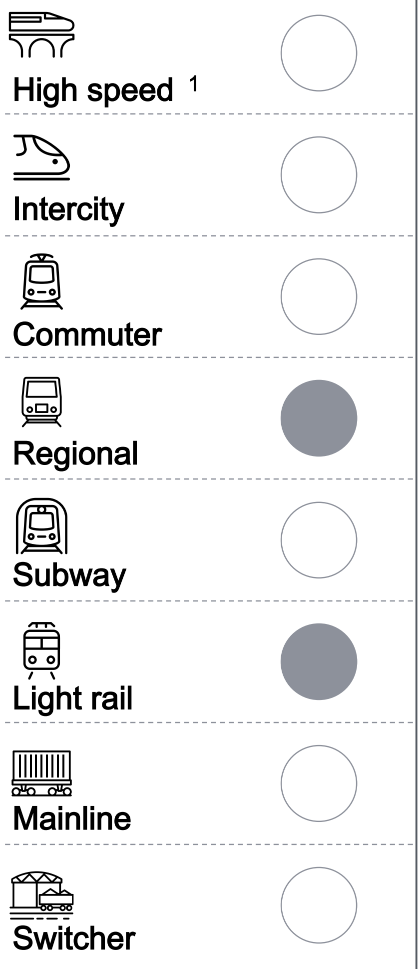
- Offers good technical performance with similar flexibility and versatility as diesel.
- Most hydrail vehicles have a hybrid powertrain with batteries.
- Often economically attractive on routes longer than 20 miles, especially compared to electrification, and where batteries are not practical.
- Can be competitive with diesel when low price hydrogen is available. Low-priced hydrogen is already available at high consumption; renewable hydrogen prices are becoming increasingly competitive and are already very attractive in some locations, leading to lower operating cost than conventional diesel vehicles.
- The technology has great potential for most railway applications; for long ranges combined with relatively infrequent refueling a tender might be required. Hydrogen could be stored on-board as a gas (the option in most vehicles, including current rail motive power), liquid, or through other means, e.g., metal hydrides.
- Refueling time is similar to diesel, for example, ~15min for a regional train.
- Significant cost reduction for powertrain components and refueling infrastructure expected.
- System effects with other sectors, especially renewable power generation (wind, solar) can be realized.

Energy supply chain

Efficiency



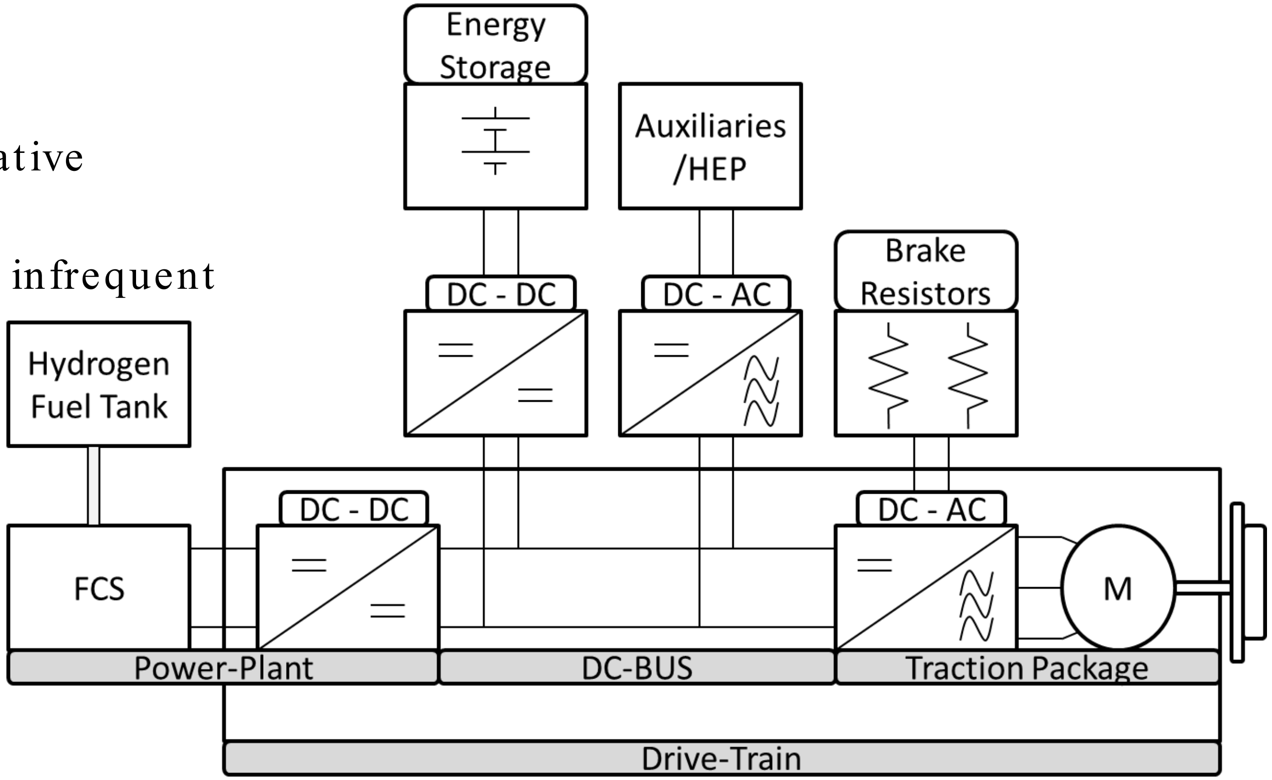
Current application



(1) >125 mph

Hydrogen Fuel Cell Hybrid Powertrain

- Hybrid drive system
  - Fuel cell system power plant
  - On-board energy storage, e.g., batteries
- Power plant meets average power
- Energy storage (e.g., batteries) allows regenerative braking and meets peak power
- Hydrogen storage for long range and relatively infrequent fueling (e.g., once per day)



Hydrail Example :
Alstom Coradia iLINT 54

Description	– 2-car multiple unit regional train operating in Northern Germany – Current route, Buxtehude-Cuxhaven, Germany (~62 miles) – 40% CO_2 reduction if hydrogen from natural gas – zero CO_2 if renewable, 'green' hydrogen used

Key facts

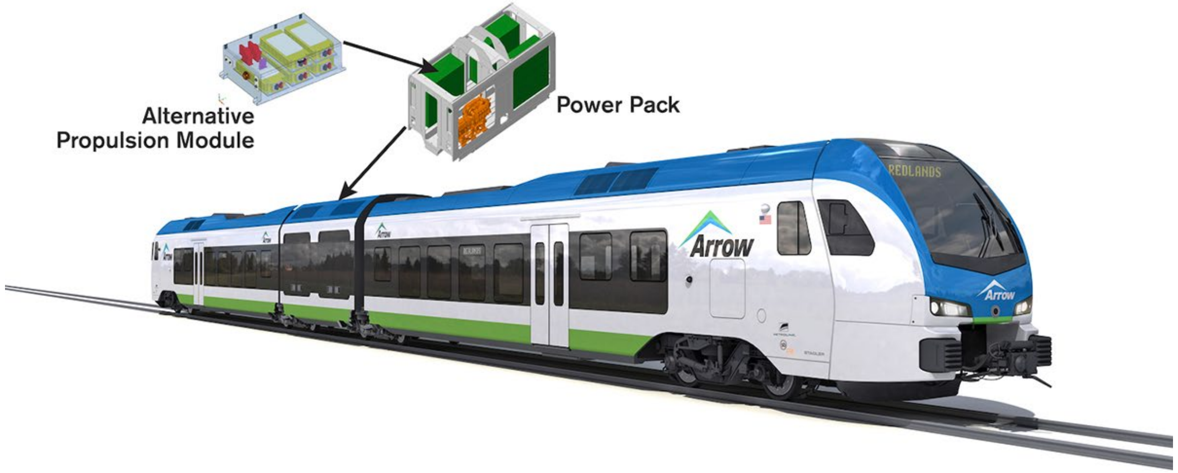
Year introduced	2018	**Project location**	Northern Germany
Supplier	ALSTOM	**Project type**	In Service
Size (# vehicles)	2 (>100 ordered)	**Range**	~600 mi

Hydrail Example :
ZEMU by San Bernardino CTA & Stadler, supported by DB E&C USA

Description	– First commercial hydrail project in North America; project is in design stage, commercial operation planned for 2024 – Multiple unit regional train (~4 cars) based on Stadler FLIRT – Operating in San Bernardino County, CA with plans to extend route to L.A. Union Station (60 mi)

Key facts

Year introduced	2024	Project location	California
Supplier	STADLER	Project type	In design
Size (# vehicles)	1 (4 planned)	Range	~16 hours+



Source: SBCTA (2020) Current Projects – Diesel Multiple Unit to Zero-Emission Multiple Unit Pilot

High -level assessment

Suitability of motive power technology depends on the application

	Passenger						Freight	
	High speed [1]	Intercity	Commuter	Regional	Light rail	Subway	Mainline	Switcher
	●	●	●	●	●	●	●	●
Diesel	○	●	●	●	●	○	●	●
H_2	○	●	●	●	●	○	●	●

● Suitable ○ Not suitable

(1) >125 mph. Very limited with diesel. Hydrail might be an option with tender cars and some impact on operations

Source: DB E&C USA assessment

Summary

- Railways have to reduce exhaust emissions
- Hydrogen can be applied to the railway sector, offering a solution without harmful emissions at the point-of-use
- Hydrail technology is suitable for many railway services
- Higher-power demonstration projects are required

Thank You