Low-carbon hydrogen to decarbonize heavy trucks and other transportation modes

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CENTER FOR SUSTAINABLE SYSTEMS
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MI Hydrogen

- *Integrate UM research expertise to create hydrogen solutions that accelerate clean and just energy transitions*
  - **Hydrogen has the potential to decarbonize industrial, transportation and other sectors** where electrification is problematic
  - Integration across **technology, energy systems analysis, policy and social sciences** will be emphasized in research and engagement activities.

Hydrogen 101

- **Hydrogen is the most abundant element**
  - but limited occurrence in nature as H_2
- **Hydrogen is an energy carrier**
  - serves to connect energy resources (e.g., wind, solar, nuclear) with end-uses (e.g., transportation)
  - clean hydrogen is produced using clean electricity
  - **potential role to decarbonize sectors where electrification is problematic**
- **Hydrogen as a feedstock**
  - used mainly today in petroleum refining and chemical manufacturing
  - **produced by steam methane reforming (SMR)** of natural gas (emitting CO_2)

Hydrogen
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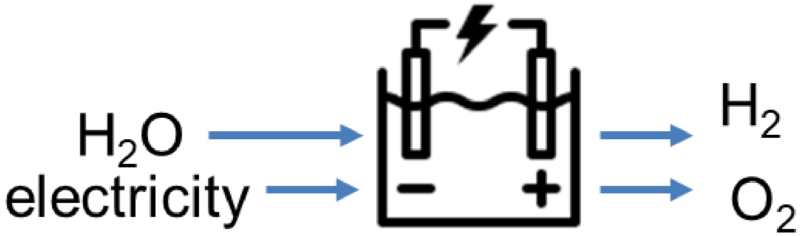
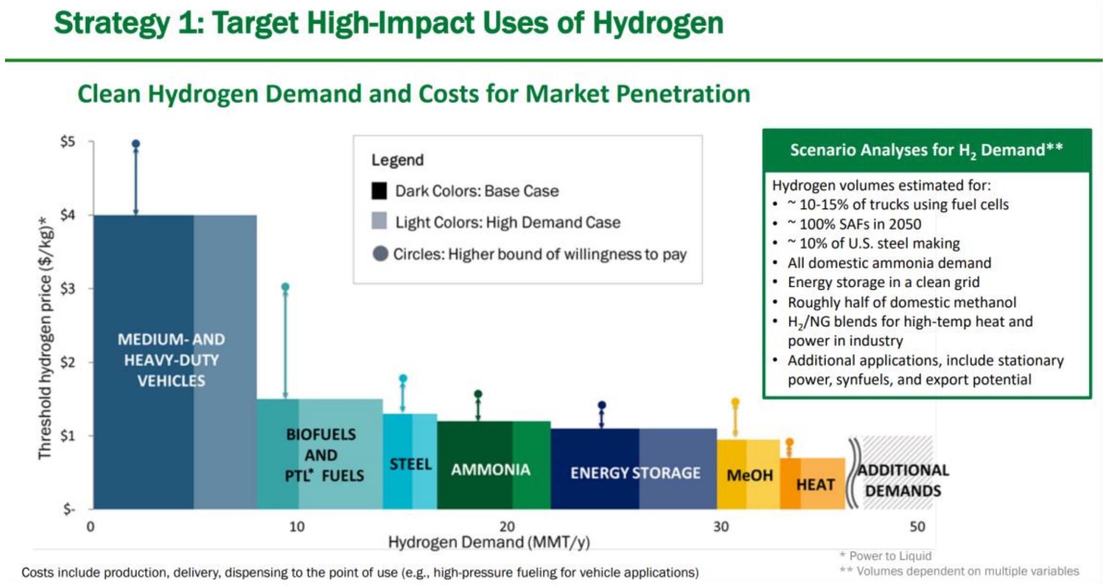


electrolysis

Hydrogen Economics

- **Energy equivalence**
  - Energy content of **1kg H_2 = 1 gallon of gasoline**
- **Production costs**
  - **\$1-2/kg H_2 from steam methane reforming**
  - **\$7.5/kg H_2 from renewable electricity**
    - **DOE target is to lower this to \$1/kg H_2 by 2031.**
  - IRA production tax credit
    - **\$3 /kg H_2 tax credit** when produced from renewable electricity
- **Transport costs** and energy requirements **are high**
  - compressed H_2 7-8 times less dense than gasoline
  - liquid H_2 4-5 times less dense than gasoline



Hydrogen volumes estimated for:

- ~ 10-15% of trucks using fuel cells
- ~ 100% SAFs in 2050
- ~ 10% of U.S. steel making
- All domestic ammonia demand
- Energy storage in a clean grid
- Roughly half of domestic methanol
- H_2/NG blends for high-temp heat and power in industry
- Additional applications, include stationary power, synfuels, and export potential

Costs include production, delivery, dispensing to the point of use (e.g., high-pressure fueling for vehicle applications)

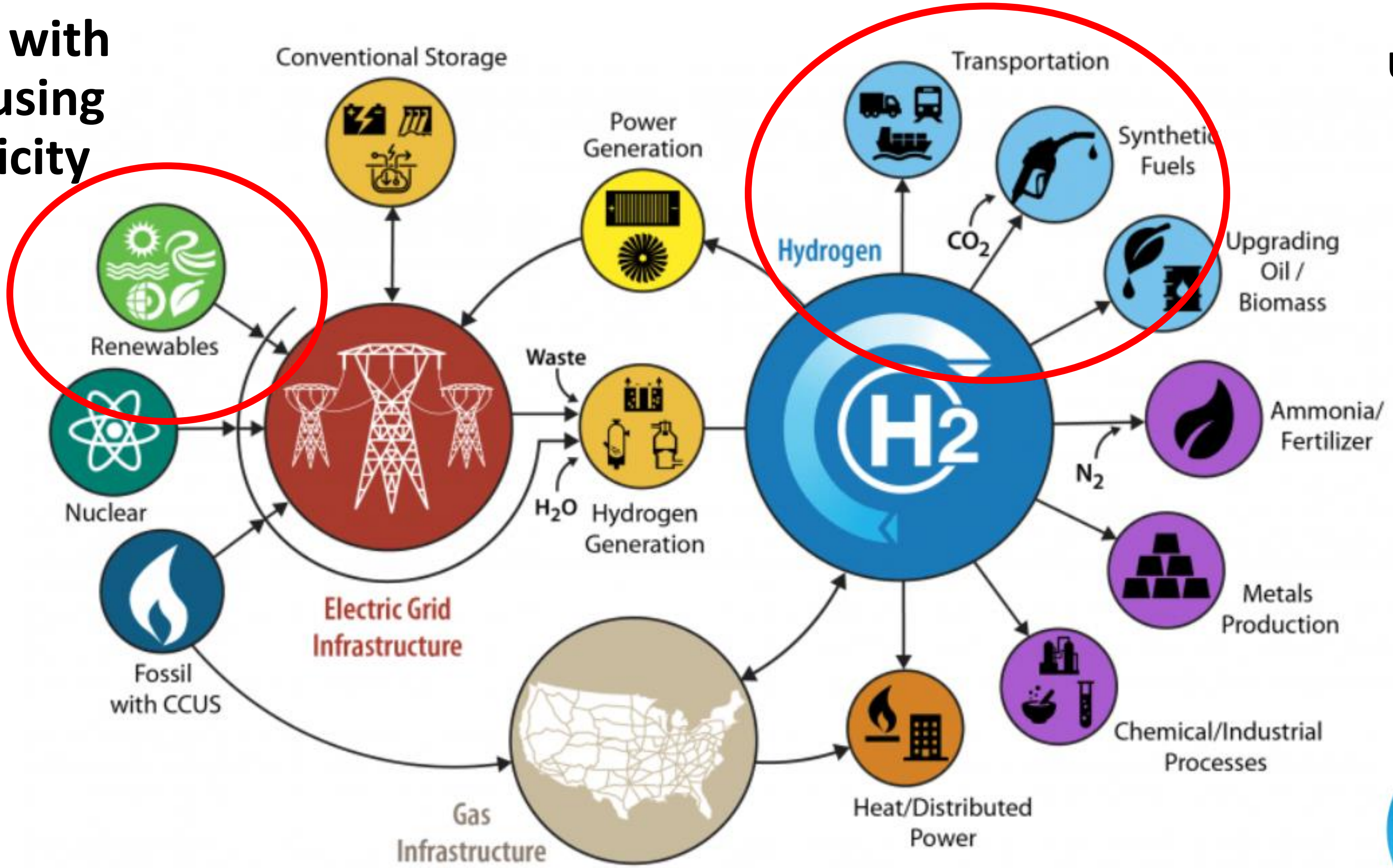
* Power to Liquid
** Volumes dependent on multiple variables

1 Dollar 1 Kilogram 1 Decade

Hydrogen Ecosystem

replace SMR with electrolysis using clean electricity

used **directly (as H_2)** or **indirectly (in synthetic fuels).**



H2@Scale U.S. Department of Energy

U.S. Transportation GHG Emissions and Energy Use

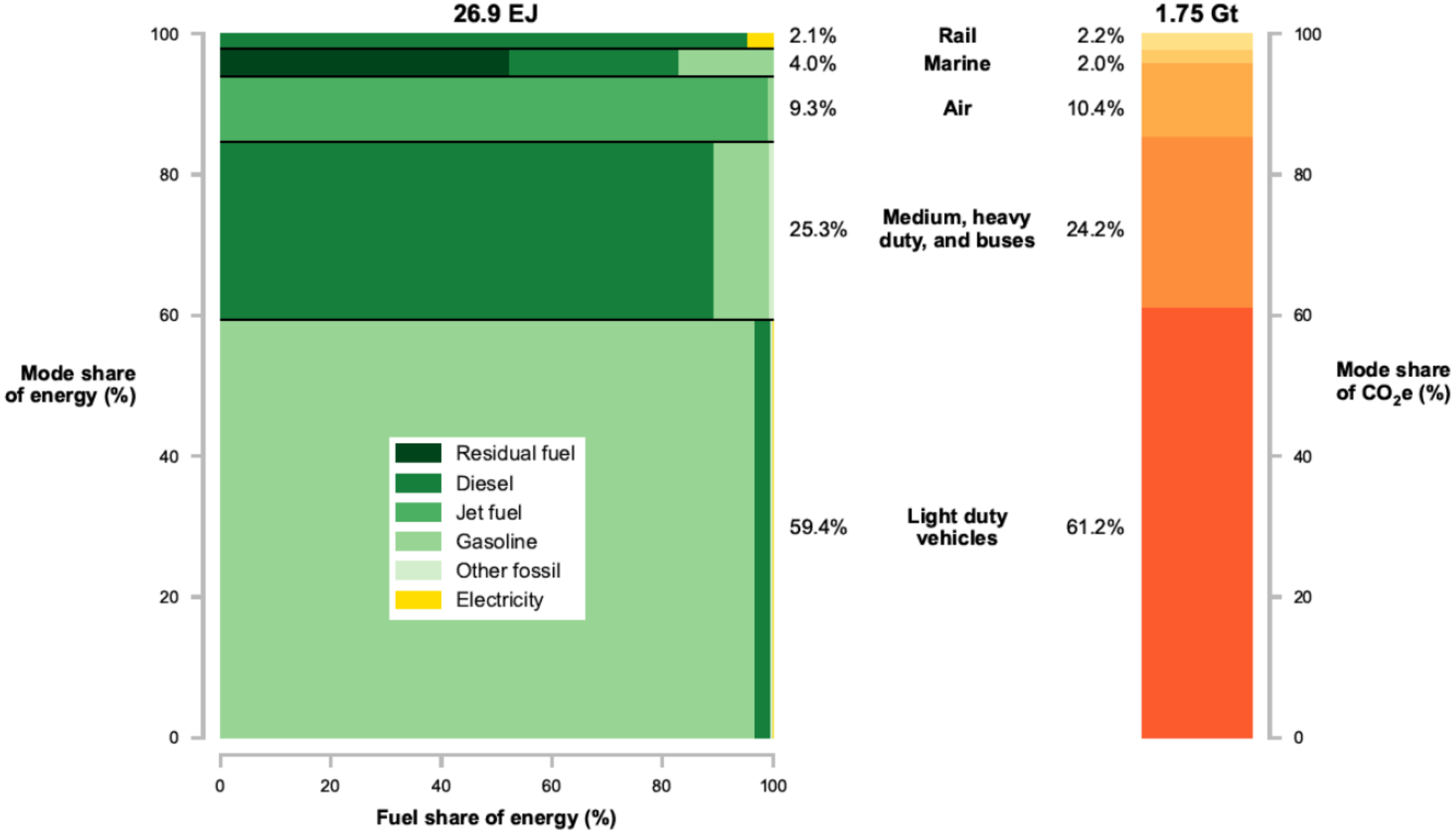


Fig. 1: U.S. Transportation Energy Consumption and CO$_2$ Emissions in 2019

Energy consumed by road, air, marine, and rail transportation in the U.S. broken down by mode share and fuel share and corresponding CO$_2$ emissions.[17,18] *Energy used for transport using pipelines is not included. The total energy consumption was 26.9 EJ and CO$_2$ emissions were 1.75 Gt.*

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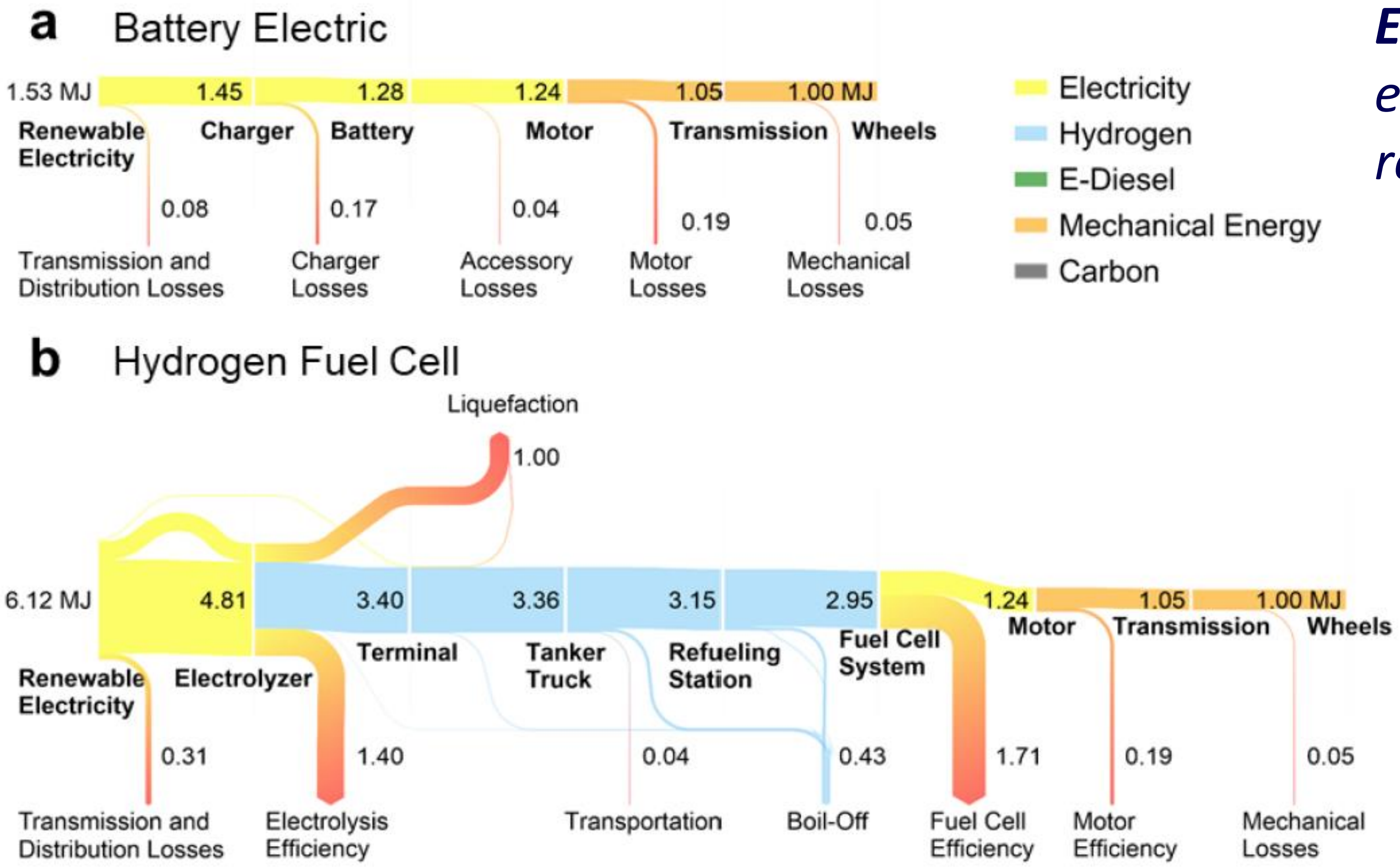
Heavy Duty Vehicles



Energy Efficiency = *energy delivered to wheels/ renewable electricity*

= 0.65 (BEV)

= 0.16 (HFCV)

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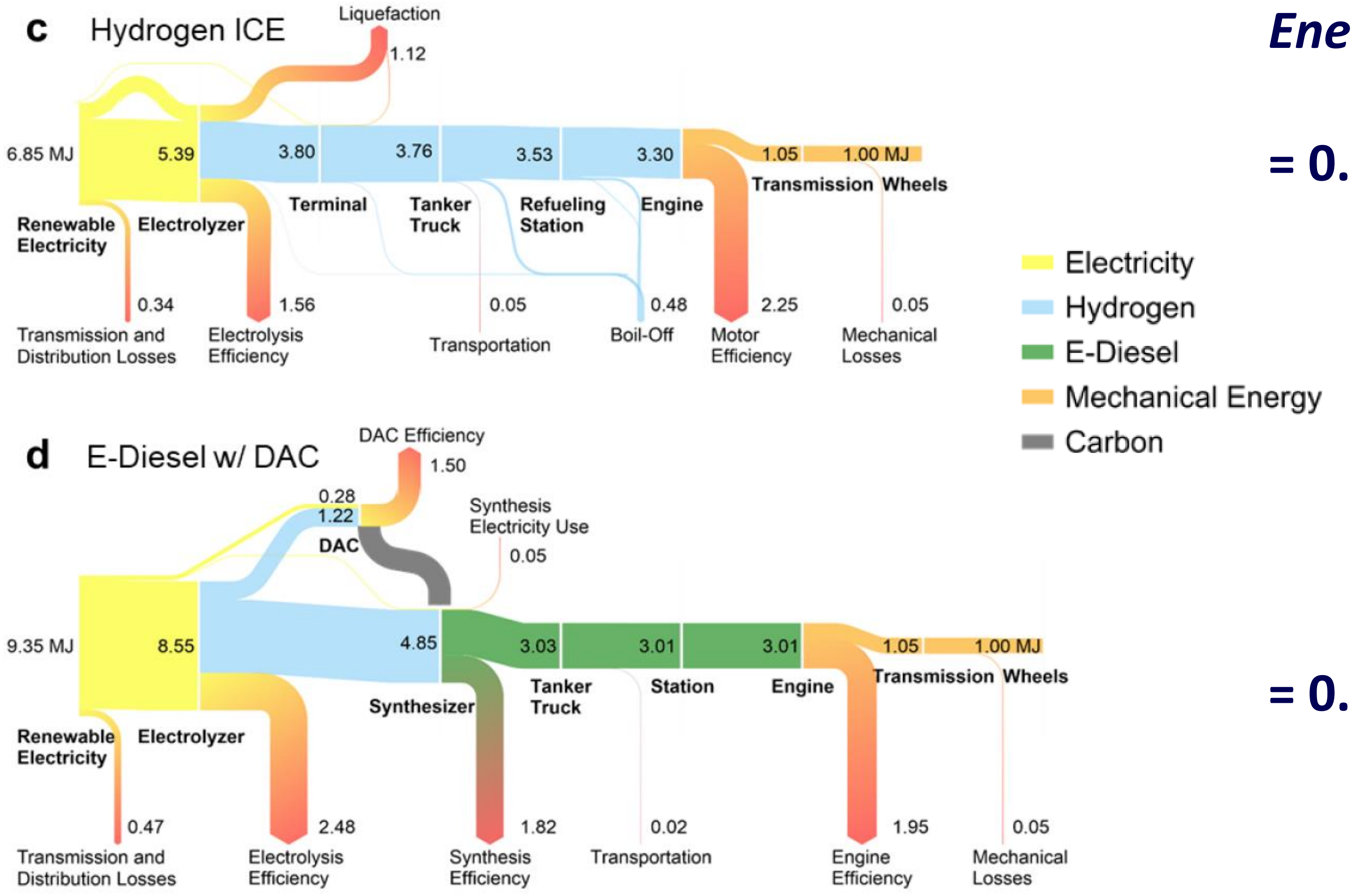
Heavy Duty Vehicles



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Energy Efficiency:

= 0.15 (HICE)

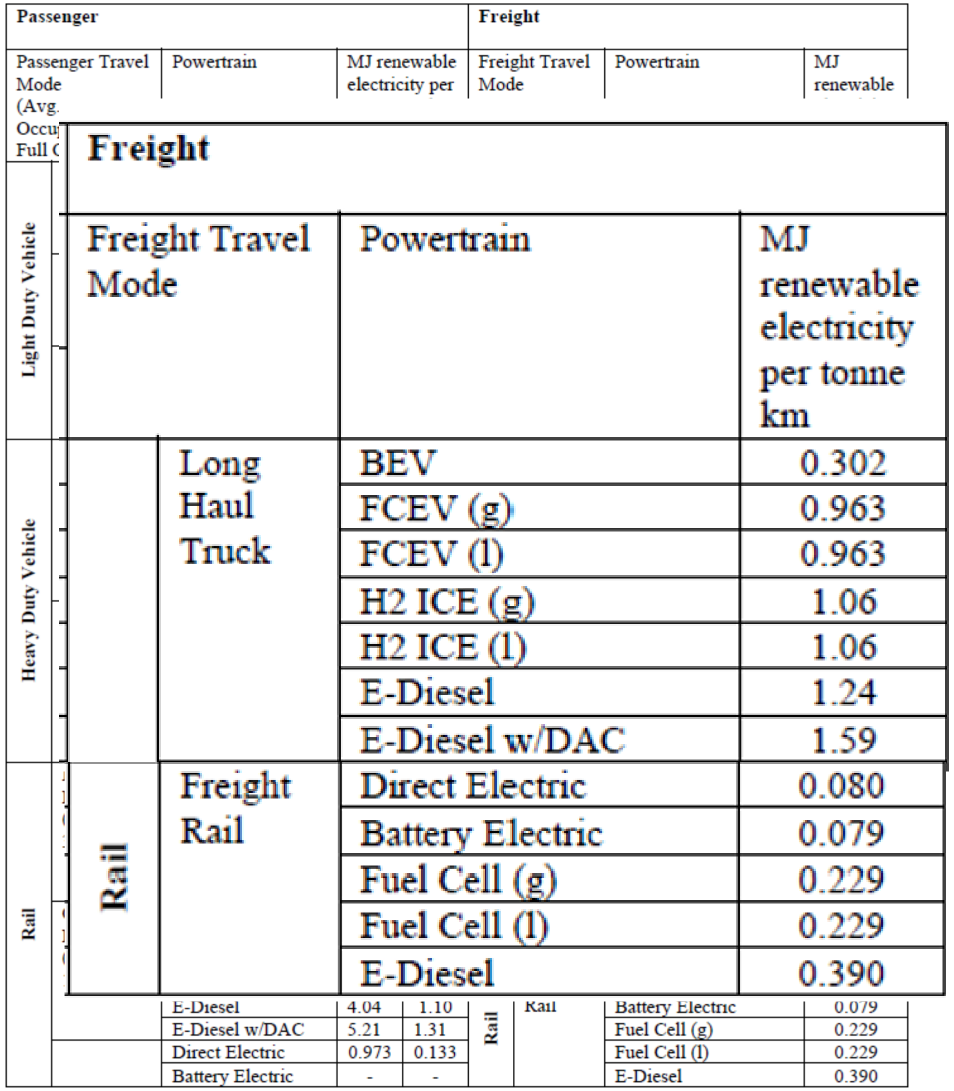
= 0.11 (E-Diesel w/DAC)

Energy Efficiency Results

Hydrogen options (direct and indirect) have about 10-20% overall energy efficiency and are about 3-7 times less efficient than direct electricity use.

	Road Light Duty	Road Heavy Duty	Rail	Marine	Aviation
Battery Electric	65.4%	65.4%	70.9%, 72.5%[a]	51.5%	53.5%
Hydrogen Fuel Cell (gas)	22.2%	16.3%	17.1%	17.3%	
Hydrogen Fuel Cell (liquid)		16.3%	17.1%	15.0%	15.8%
Hydrogen ICE (gas)		14.6%			
Hydrogen ICE (liquid)		14.6%			
Hydrogen Turbofan (liquid)					18.0%
E-gasoline	8.4-10.8%				
E-diesel		10.6-14.6%	8.9-11.5%		
E-jet-fuel					10.3-12.8%
E-methanol ICE				10.5-13.7%	
E-methanol Fuel Cell				8.9-11.5%	
E-ammonia ICE				11.9%	
E-ammonia Fuel Cell				8.7%	

Energy Intensities (MJ per passenger km or per tonne km)



Passenger			Freight		
Passenger Travel Mode (Avg. Occu… Full (	Powertrain	MJ renewable electricity per	Freight Travel Mode	Powertrain	MJ renewable

Light Duty Vehicle

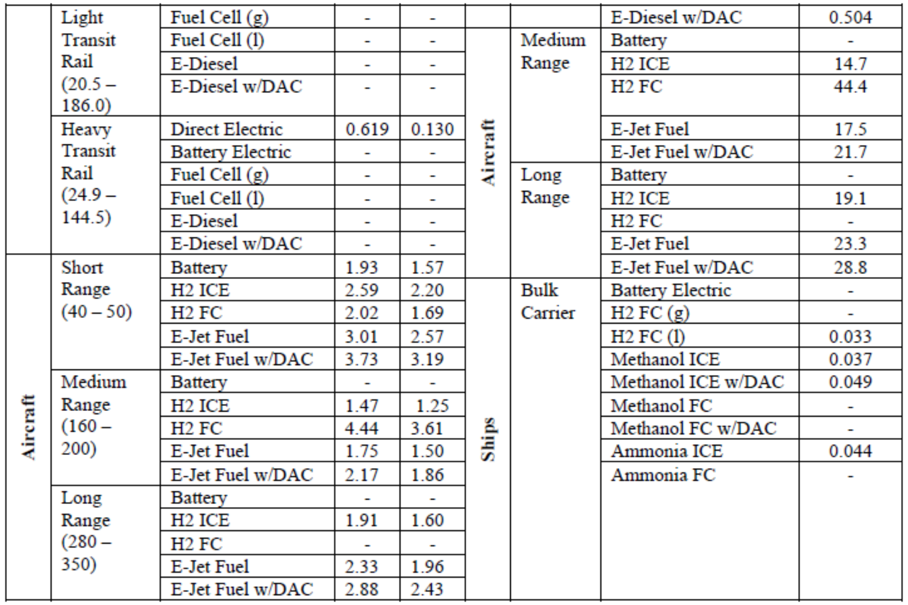
Heavy Duty Vehicle

Rail

Freight

	Freight Travel Mode	Powertrain	MJ renewable electricity per tonne km
	Long Haul Truck	BEV	0.302
		FCEV (g)	0.963
		FCEV (l)	0.963
		H2 ICE (g)	1.06
		H2 ICE (l)	1.06
		E-Diesel	1.24
		E-Diesel w/DAC	1.59
Rail	Freight Rail	Direct Electric	0.080
		Battery Electric	0.079
		Fuel Cell (g)	0.229
		Fuel Cell (l)	0.229
		E-Diesel	0.390

Powertrain				Mode	Powertrain	
E-Diesel	4.04	1.10	Rail	Rail	Battery Electric	0.079
E-Diesel w/DAC	5.21	1.31			Fuel Cell (g)	0.229
Direct Electric	0.973	0.133			Fuel Cell (l)	0.229
Battery Electric	-	-			E-Diesel	0.390



	Light Transit Rail (20.5 – 186.0)	Fuel Cell (g)	-	-
		Fuel Cell (l)	-	-
		E-Diesel	-	-
		E-Diesel w/DAC	-	-
	Heavy Transit Rail (24.9 – 144.5)	Direct Electric	0.619	0.130
		Battery Electric	-	-
		Fuel Cell (g)	-	-
		Fuel Cell (l)	-	-
		E-Diesel	-	-
		E-Diesel w/DAC	-	-
Aircraft	Short Range (40 – 50)	Battery	1.93	1.57
		H2 ICE	2.59	2.20
		H2 FC	2.02	1.69
		E-Jet Fuel	3.01	2.57
		E-Jet Fuel w/DAC	3.73	3.19
	Medium Range (160 – 200)	Battery	-	-
		H2 ICE	1.47	1.25
		H2 FC	4.44	3.61
		E-Jet Fuel	1.75	1.50
		E-Jet Fuel w/DAC	2.17	1.86
	Long Range (280 – 350)	Battery	-	-
		H2 ICE	1.91	1.60
		H2 FC	-	-
		E-Jet Fuel	2.33	1.96
		E-Jet Fuel w/DAC	2.88	2.43

		E-Diesel w/DAC	0.504
Aircraft	Medium Range	Battery	-
		H2 ICE	14.7
		H2 FC	44.4
		E-Jet Fuel	17.5
		E-Jet Fuel w/DAC	21.7
	Long Range	Battery	-
		H2 ICE	19.1
		H2 FC	-
		E-Jet Fuel	23.3
		E-Jet Fuel w/DAC	28.8
Ships	Bulk Carrier	Battery Electric	-
		H2 FC (g)	-
		H2 FC (l)	0.033
		Methanol ICE	0.037
		Methanol ICE w/DAC	0.049
		Methanol FC	-
		Methanol FC w/DAC	-
		Ammonia ICE	0.044
		Ammonia FC	-

Direct use of electricity is less energy intense than using hydrogen, which is less energy intense than using e-fuels. Results highlight opportunities to use renewable electricity more efficiently: mode shifting and increasing occupancy.

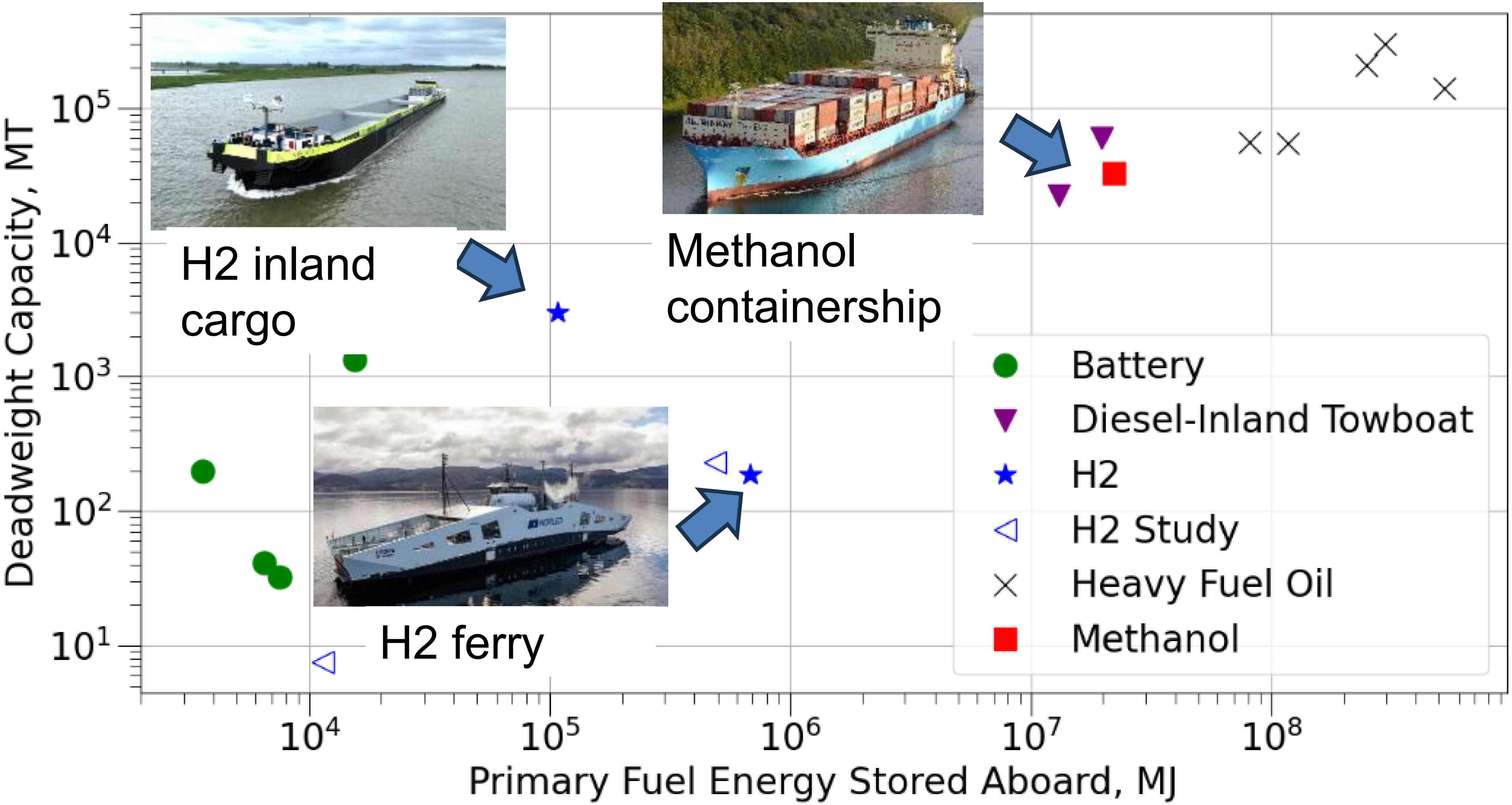
Joule journal article in review

Fuel cell aircraft can be a solution beyond 200 mi where battery weight becomes limiting

Brelje and Martins. **Aerostructural wing optimization for a hydrogen fuel cell aircraft**. *AIAA 2021-1132*

Adler and Martins. **Blended wing body configuration for hydrogen-powered aviation**. *AIAA 2023-4020*

Currently, hydrogen fills a gap between all-electric vessels and hydrocarbon vessels


H2 inland cargo

Methanol containership

H2 ferry

Hydrogen Outlook for Transportation

1. Limited/strategic role for the direct use of hydrogen; electrification (batteries) offers greater energy efficiencies.
    - MDT/HDT (long distance), Rail (long distance where electricity infrastructure is problematic)
    - Ships: Ferries and inland barges (longer distance and where charging time could be a factor)
    - Aviation – Flights where battery electrification range and battery weight are a limitation (< 200 miles)
2. Carbon-based e-fuels are less attractive than direct hydrogen pathways from an energy efficiency perspective butcan pose fewer infrastructure challenges.
3. Hydrogen production and transport costs are a major challenge for adoption in transportation and the industrial sectors
    - IRA investment of $8 billion expected to drive down costs; DOE target is $1/kg H_2
    - Abatement costs are estimated to be over $500-1000/t CO_2e
4. Renewable and nuclear electricity opportunity cost for producing hydrogen
    - Clean hydrogen production for domestic demand has the potential to scale from < 1 to 10 million metric ton per year in 2030; up to 200 GW of new renewable energy sources would be needed in 2030
    - Potentially greater environmental benefits to displace fossil-based electricity generation
    - Proposed rules for 45 V tax credit could limit nuclear sources for hydrogen production; delaying hydrogen demonstration and scale up, however, until the grid is fully decarbonized (US target is 2035), would also be problematic
5. Given challenges with fueling options sustainable transportation requires demand reduction and modal shifts and other strategies (e.g., trip chaining, rightsizing, increased occupancy, denser development, telework).

Acknowledgements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(1) Green Hydrogen: Energy Efficiency and Intensity in Ground, Air, and Marine Transportation (in review *Joule*).

(2) Hydrogen as a Sustainable Ground, Air, and Marine Transportation Fuel: A Critical Review (in prep to submit to *Renewable and Sustainable Energy Reviews*).

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