Electrification Enabling Technologies

Keynote presentation

Giorgio Rizzoni, The Ford Motor Company Chair In Electromechanical Systems

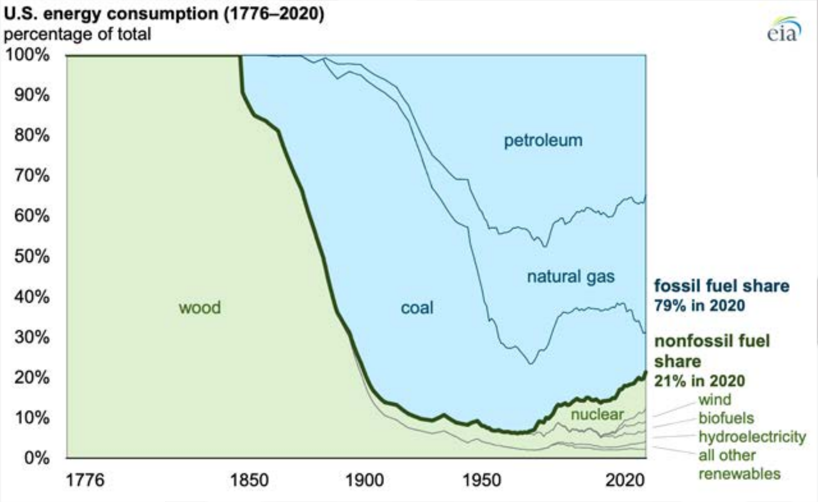
Professor, MAE and ECE Departments, The Ohio State University

OCT. 24, 2023

CHATTANOOGA, TN

SMOKY MOUNTAINS Mobility Conference

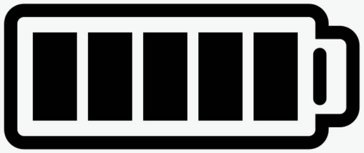
Energy Considerations



Key Elements in a Vehicle

POWERTRAIN/ PROPULSION SYSTEM

A propulsion system or powertrain is the ensemble of components that produce the motive force to push an object forward



ENERGY STORAGE SYSTEM

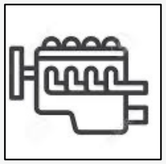
Energy Storage Systems refer to equipment that can store various types of energy to power the propulsion system

Power Technologies

At the beginning of the 20th Century most vehicles' power technologies were already available

STEAM ENGINE

Invented in 1712 by T. Newcomen and improved by J. Watt in 1765. In 1900 steam cars were produce by "Locomobile" and "Stanley Motor Carriage Company" in the United States.



INTERNAL COMBUSTION ENGINE (ICE)

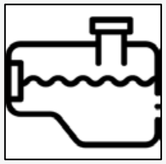
In 1876, Nicolaus Otto patented the first four-stroke cycle engine. In 1879, Karl Benz patented a reliable two-stroke gasoline engine. In 1892, Rudolf Diesel developed the first compression ignition engine.

ELECTRIC MOTOR

T. Davenport invented the first battery-powered electric motor in 1834. The first DC motor was invented by F. J. Sprague in 1886. In 1888, Nikola Tesla patented his AC induction motor.

Energy Storage Technologies

Similarly, most energy storage technologies were first invented in the 18th and 19th Centuries



LIQUID FUELS

In 1891, the Shukhov cracking process became the world's first commercial method to break down heavier hydrocarbons in crude oil to increase the percentage of lighter products.

BATTERIES

Italian physicist A. Volta built and described the first electrochemical battery in 1800. The first mass-produced model dry cell was marketed by the National Carbon Company in 1896.

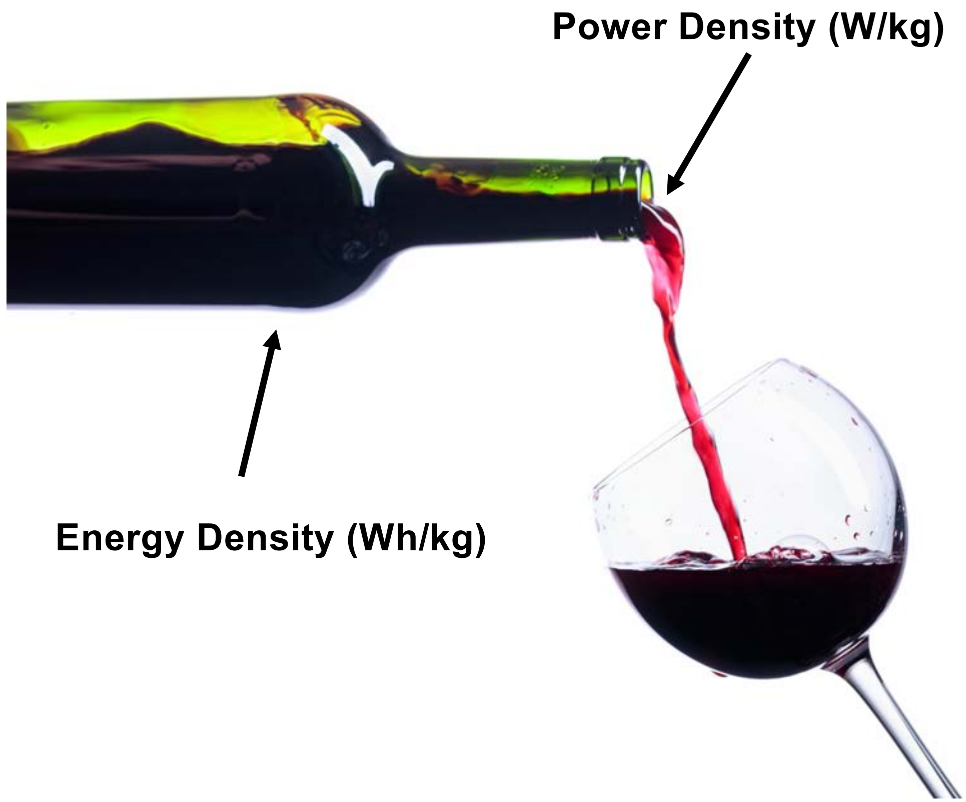
What Makes a Fuel Good for Transportation?

Energy Density:

The amount of energy contained in a specific quantity (mass or volume) of material. It mostly controls the vehicle **range**.

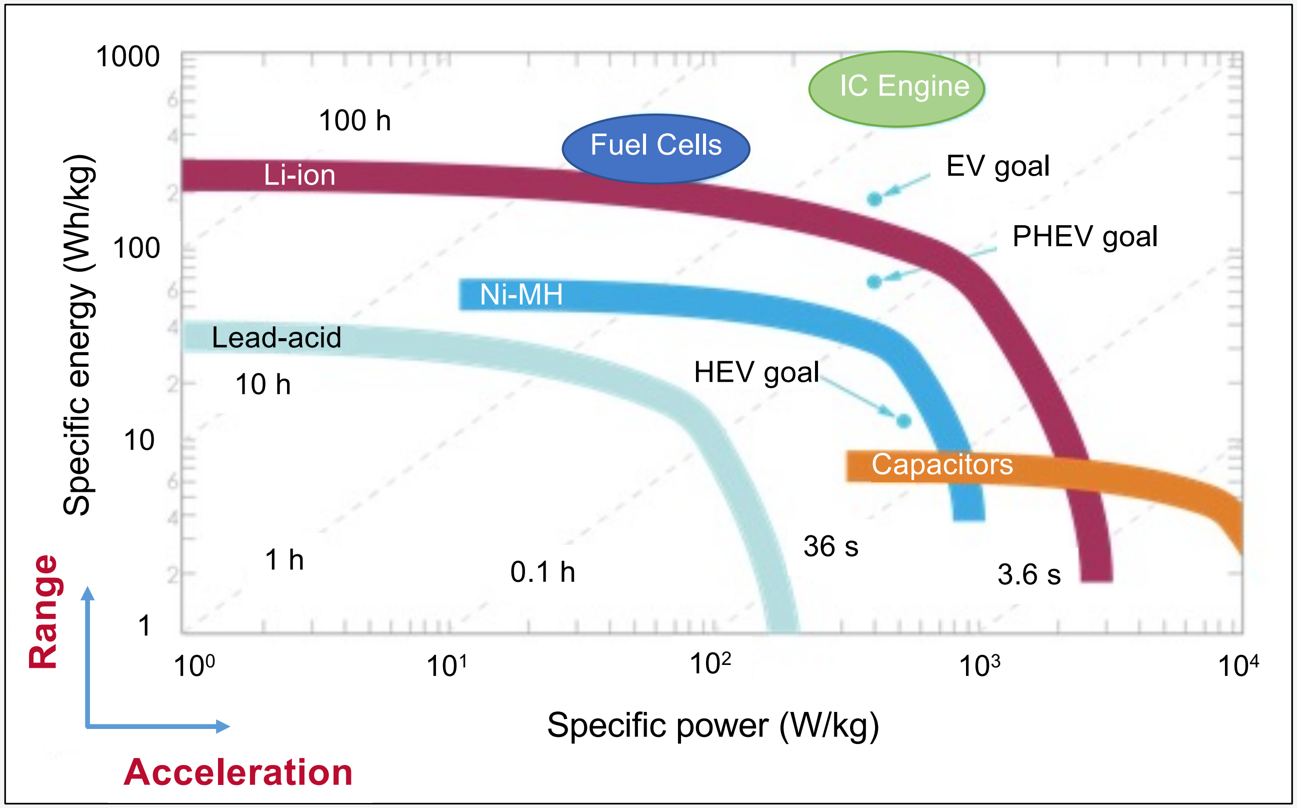
Power Density:

The power density, in the units of power per unit mass, designates the maximum power that can be supplied (in/out) of the power unit per unit weight. It controls the vehicle **performance**.

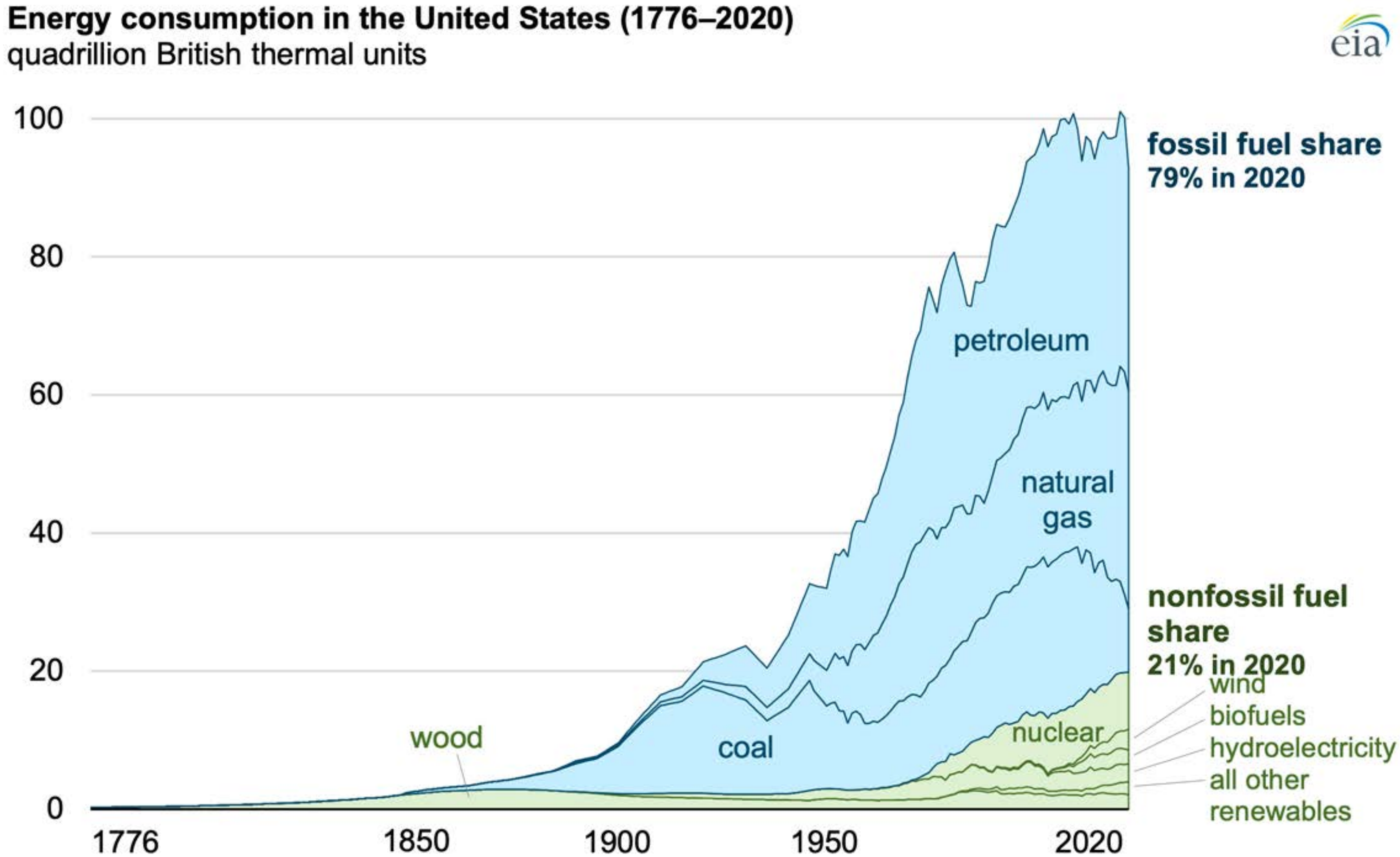


Why IC Engine and Fossil Fuels?

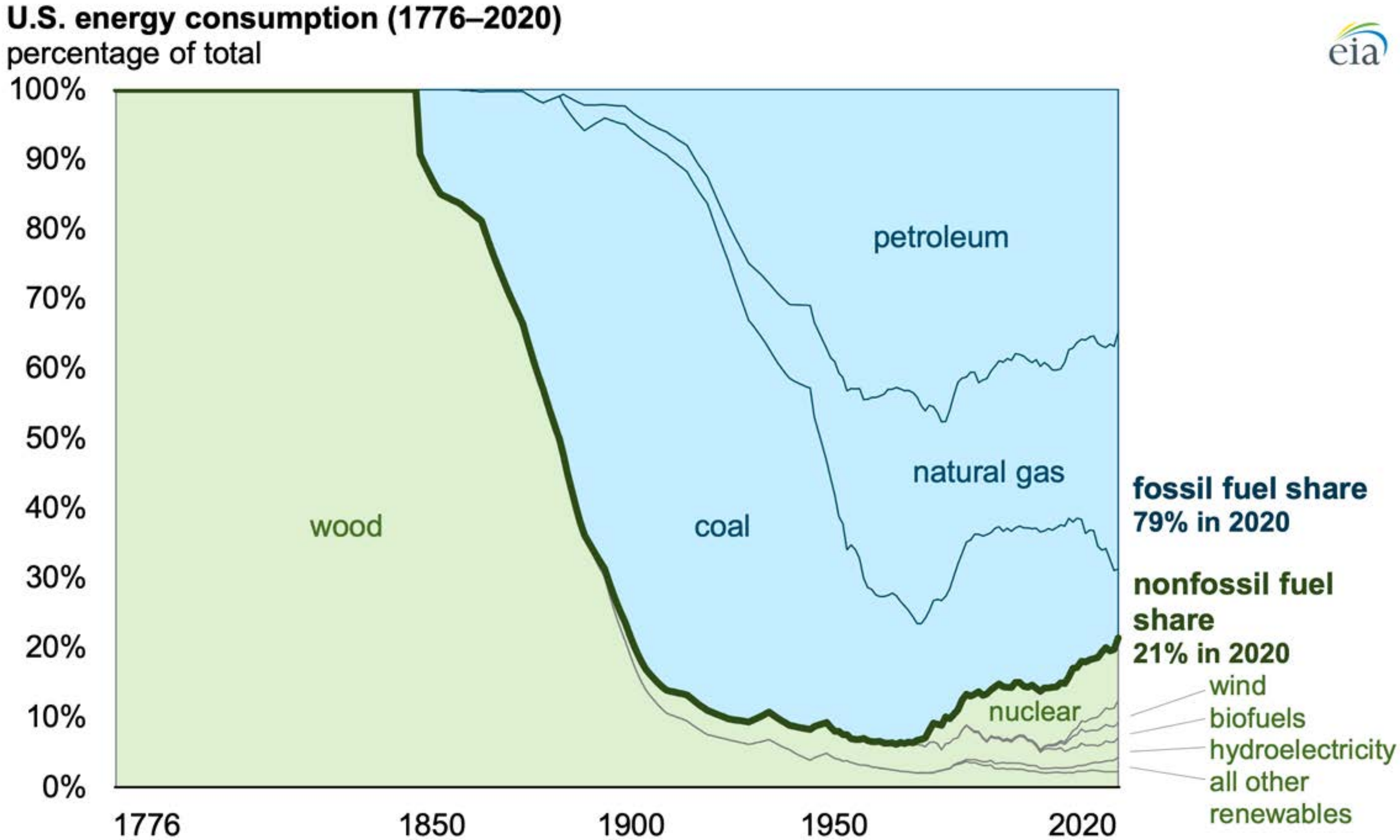
The internal combustion engine still today has the best ***combination of specific energy and power***



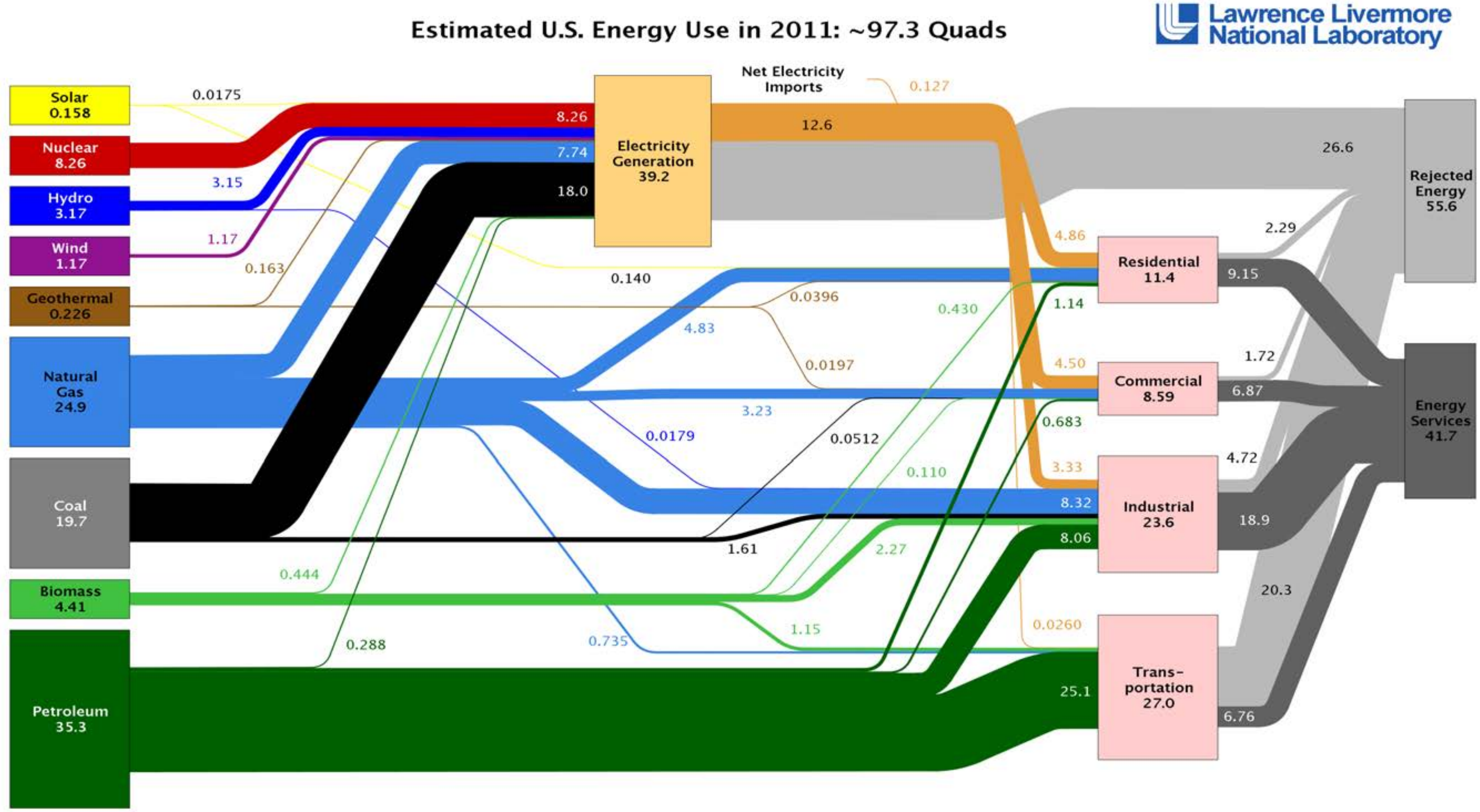
History of Energy Consumption in USA



History of Energy Consumption in USA

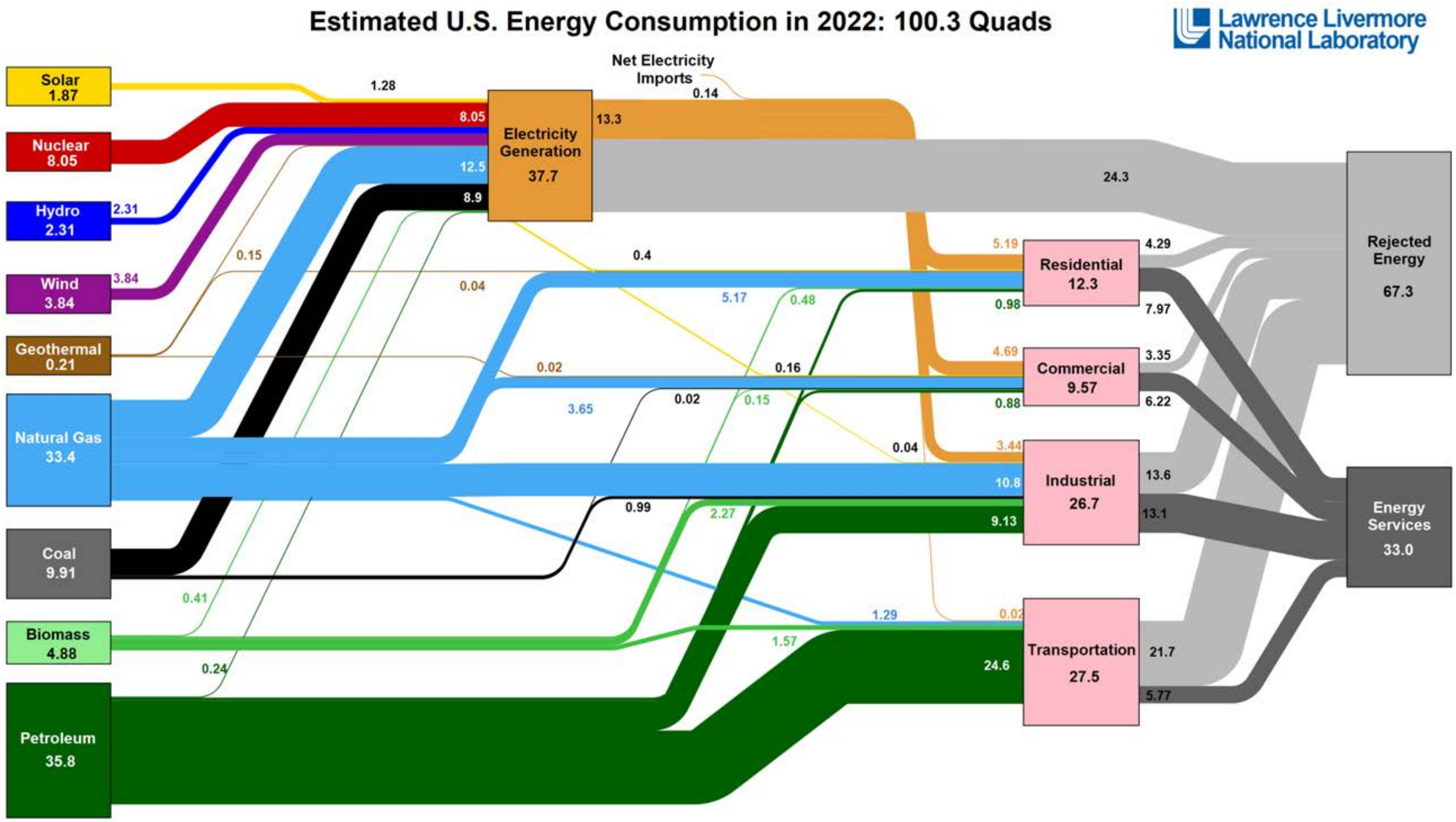


United States' Energy Use in 2011



Source: LLNL 2012. Data is based on DOE/EIA-0384(2011), October, 2012. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

A Decade Later … United States’ Energy Use in 2022



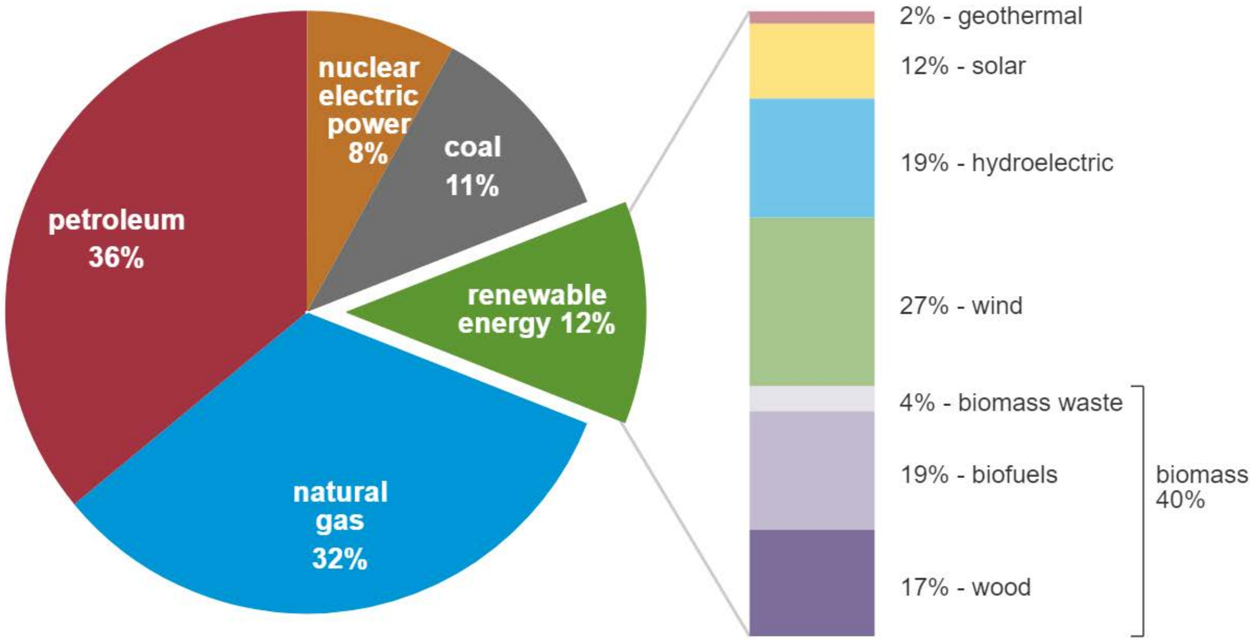
Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Snapshot Today

U.S. primary energy consumption by energy source, 2021

total = 97.33 quadrillion
British thermal units (Btu)

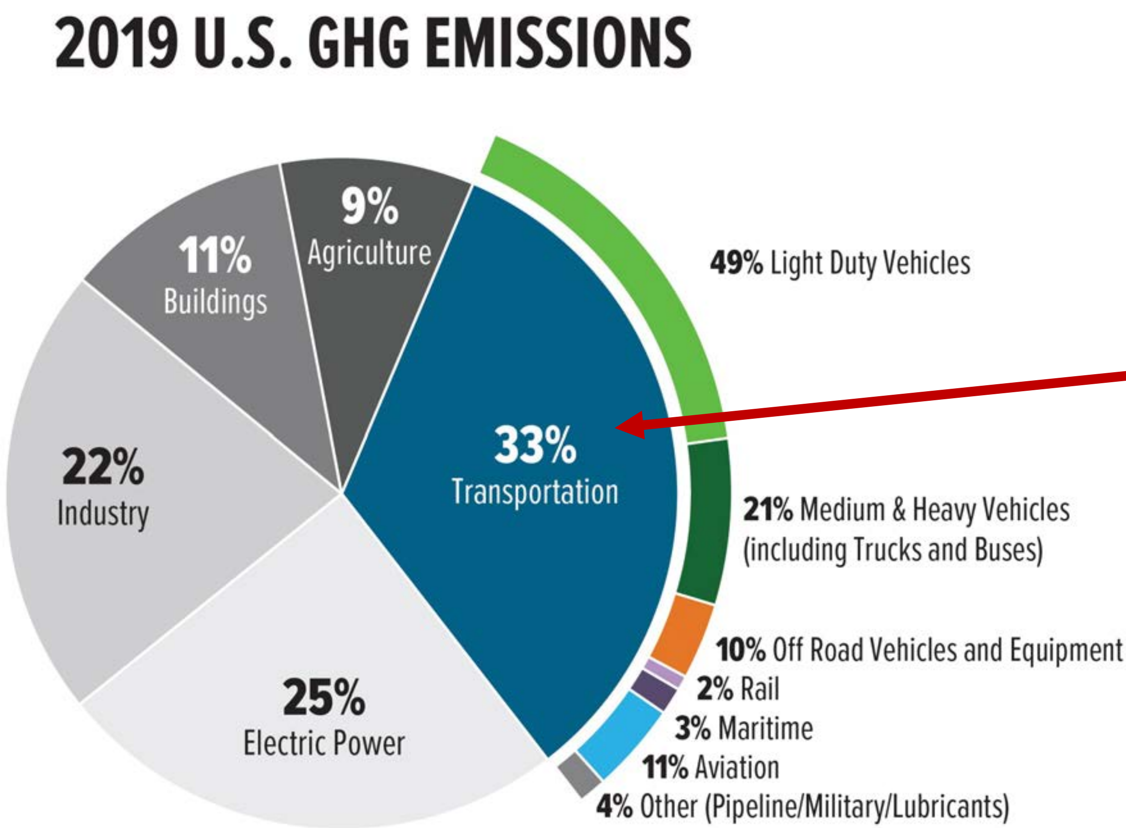
total = 12.16 quadrillion Btu



eia

Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2022, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

Snapshot Today



Transportation accounts for 33% of US GHG emissions

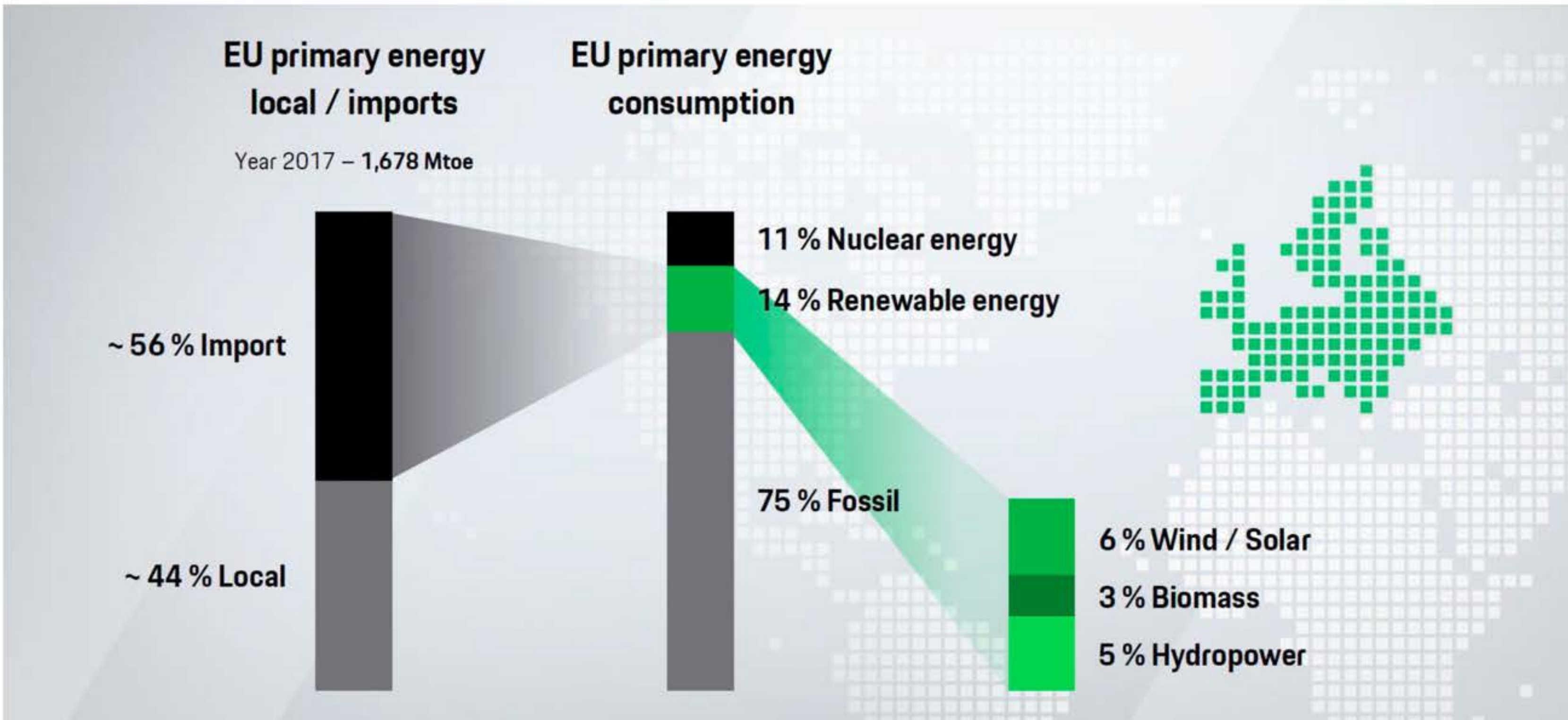
The Ohio State University
Center for Automotive Research

Source: THE U.S. NATIONAL BLUEPRINT FOR TRANSPORTATION DECARBONIZATION A Joint Strategy to Transform Transportation, 2023, https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.

Primary Energy Consumption in Europe

Europe's energy import is 5 times higher than the renewable production

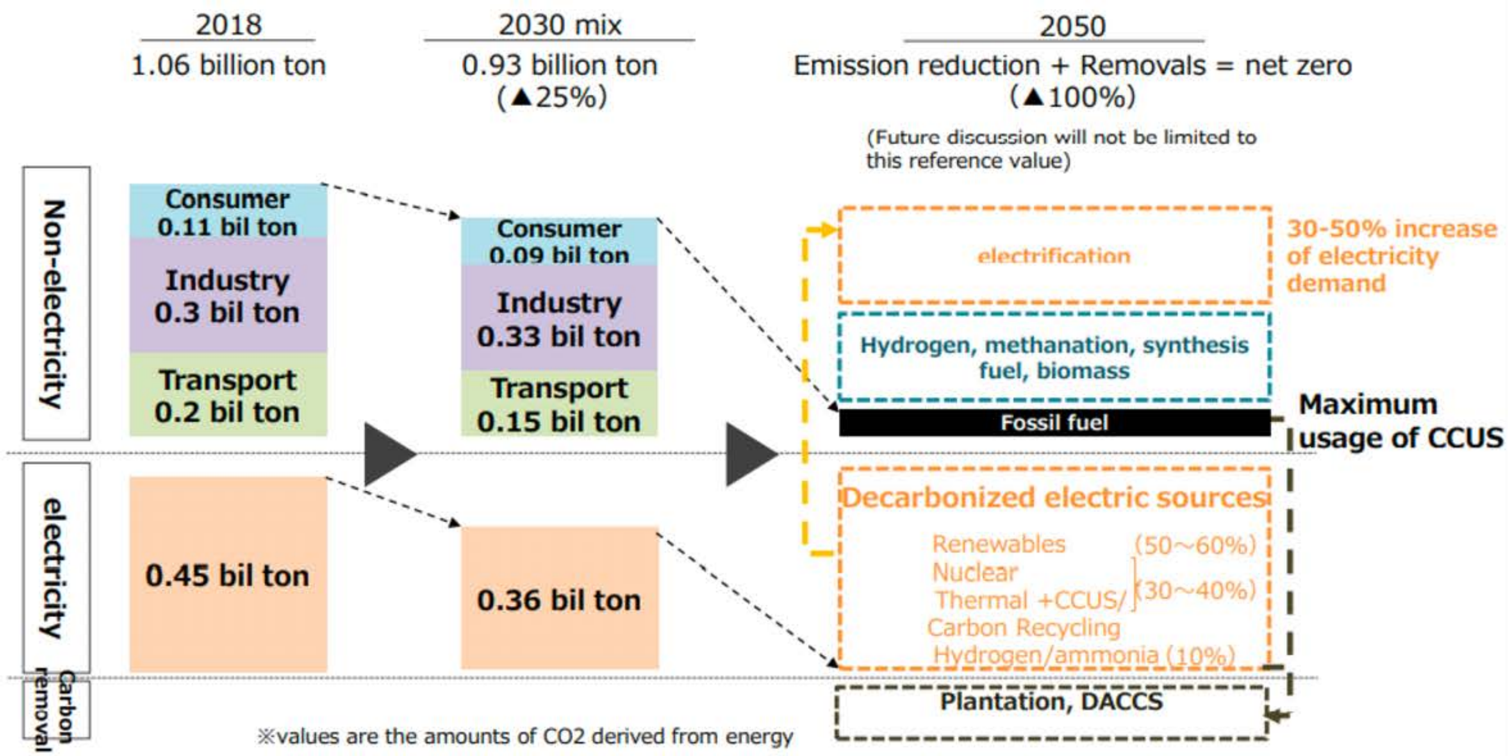
What is the solution of energy import for the future?



Source: IHS, Eurostat, IEA Statistiken, BP Statistical Review, Nationale Statistiken, EU Reference Scenario 2016, Porsche AG

Green Growth Strategy of JAPAN (METI)

- CN scenario for transportation of Green Growth Strategy presupposes a combination of three paths; ①Electrification ②Hydrogen Utilize ③IC engines with CN Fuel



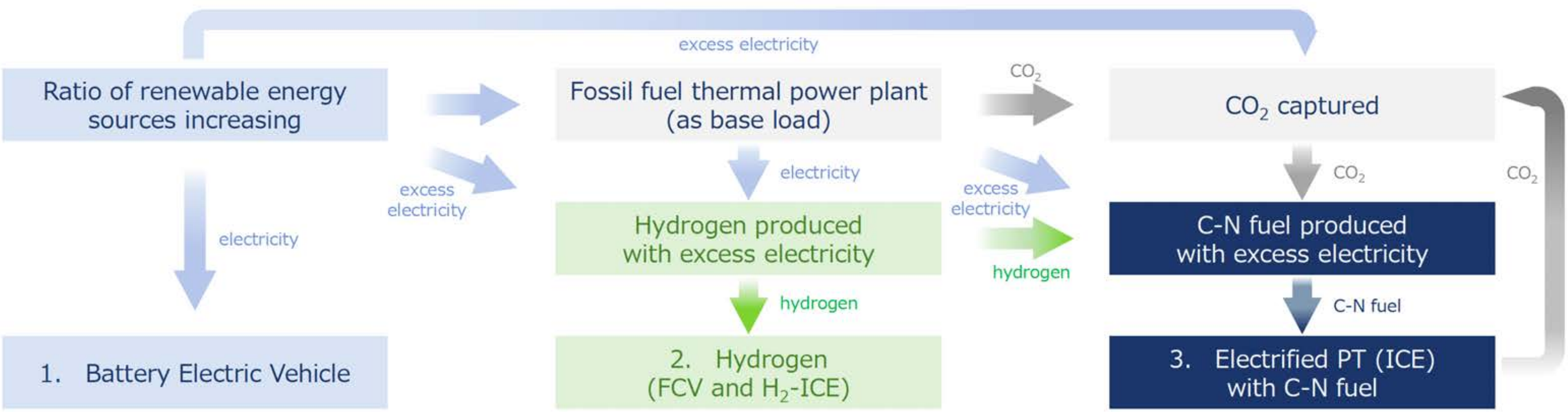
Source：METI "Green Growth Strategy Through Achieving Carbon Neutrality in 2050" Formulated

Pathways toward Carbon Neutrality

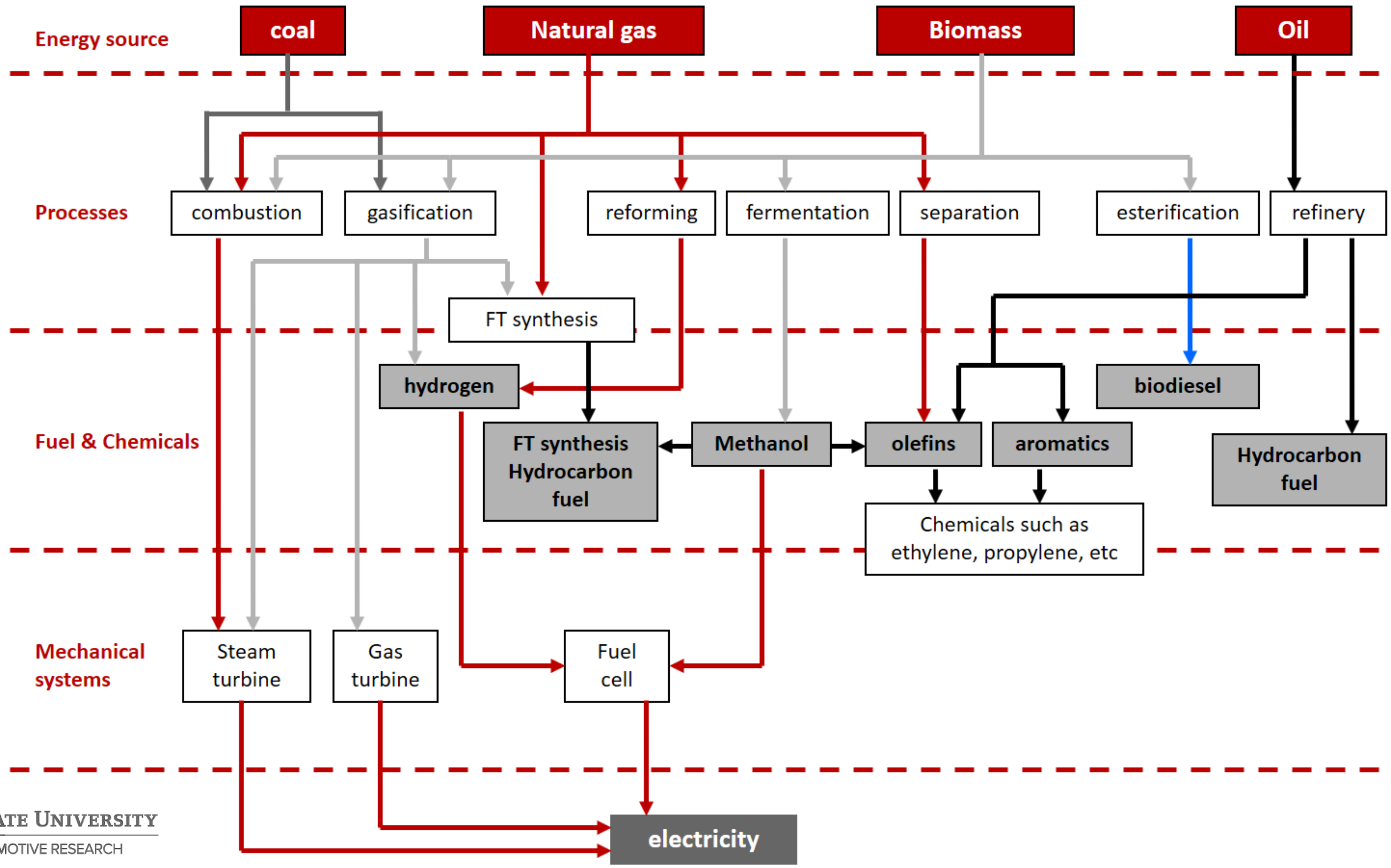
- According to the world trend toward CN, following three paths seems to be realistic as zero emission society by 2050;

  ① Battery Electric Vehicle, ② Hydrogen (FCV or H_2-ICE), ③ ICE with CN fuel

- Pathways are as following;
  1. As renewable electricity ratio increasing, BEV expanding
  2. Excess electricity stored as hydrogen (PtX), and applied to FCV and H_2-ICE
  3. CN fuel produced with hydrogen and captured CO_2, CN for ICE vehicles

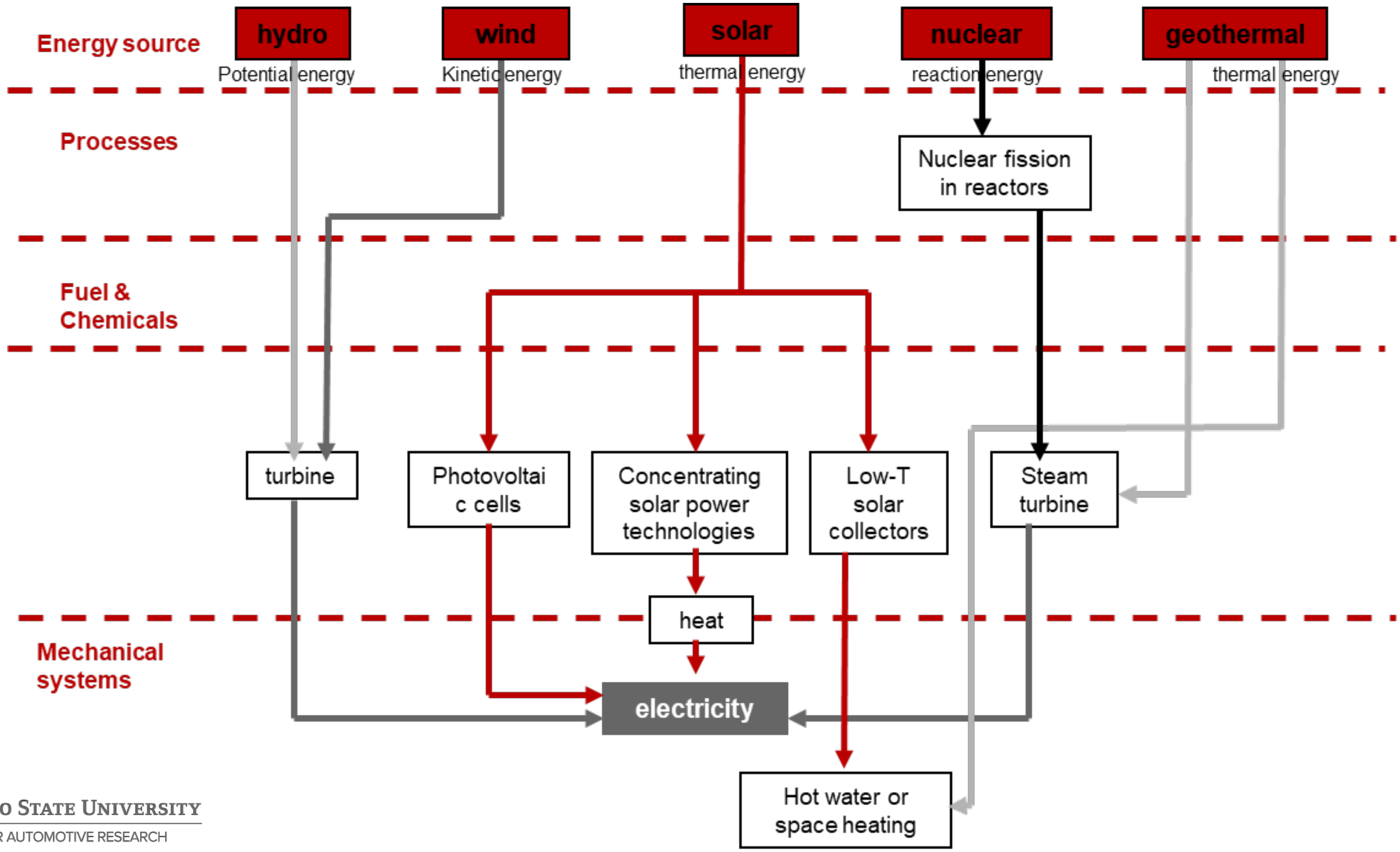


Carbon Based Energy Sources



THE OHIO STATE UNIVERSITY
CENTER FOR AUTOMOTIVE RESEARCH

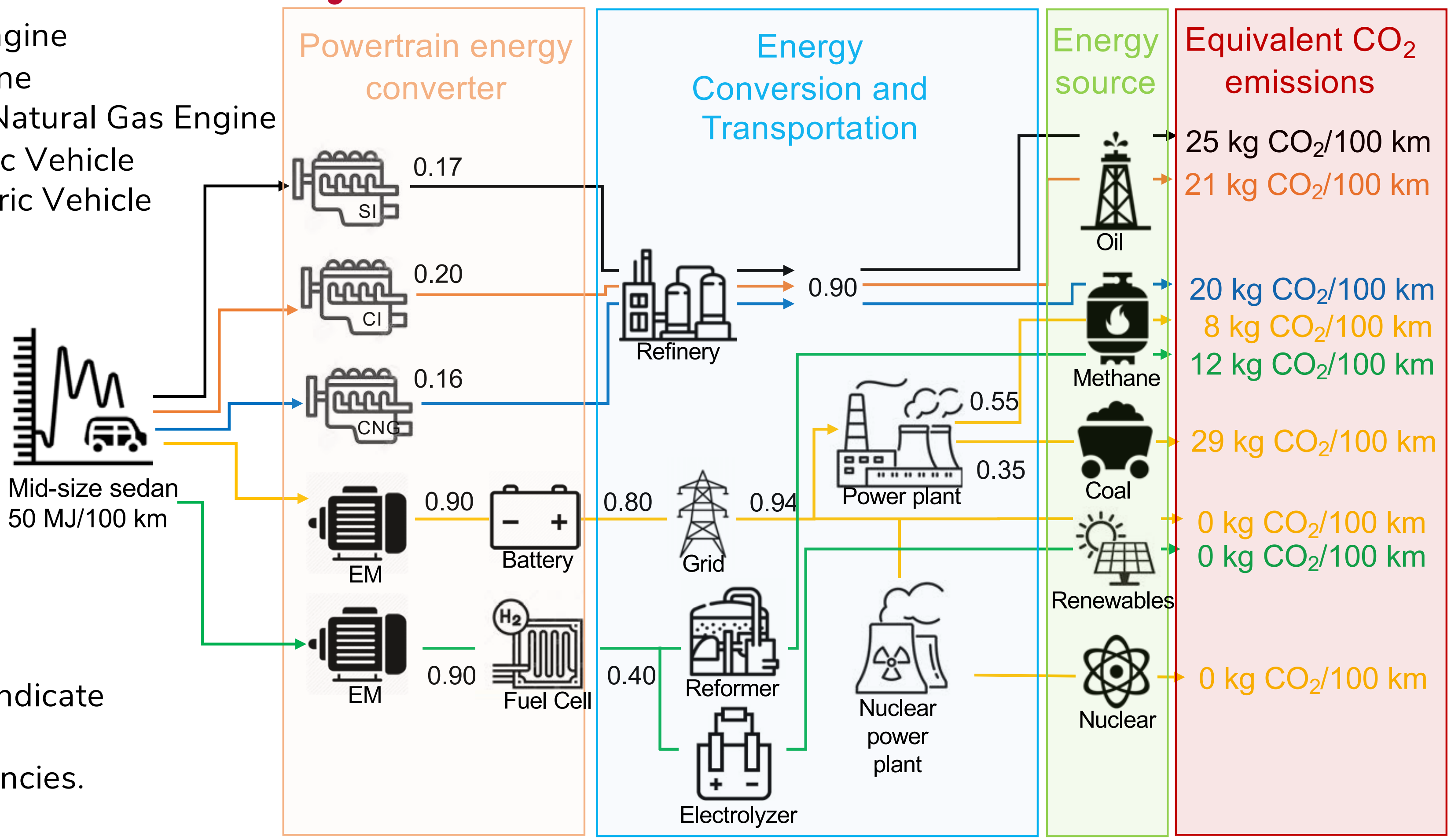
Non-Carbon Based Energy Sources



THE OHIO STATE UNIVERSITY
CENTER FOR AUTOMOTIVE RESEARCH

Well-to-Wheels Analysis

- SI Gasoline Engine
- CI Diesel Engine
- Compressed Natural Gas Engine
- Battery Electric Vehicle
- Fuel Cell Electric Vehicle



NOTE: numbers indicate estimated energy conversion efficiencies.

Source: adapted from Guzzella and Sciarretta "Vehicle Propulsion Systems - Introduction to Modeling and Optimization", 2007

Petroleum has fueled transportation for 100 years...

... what next ?

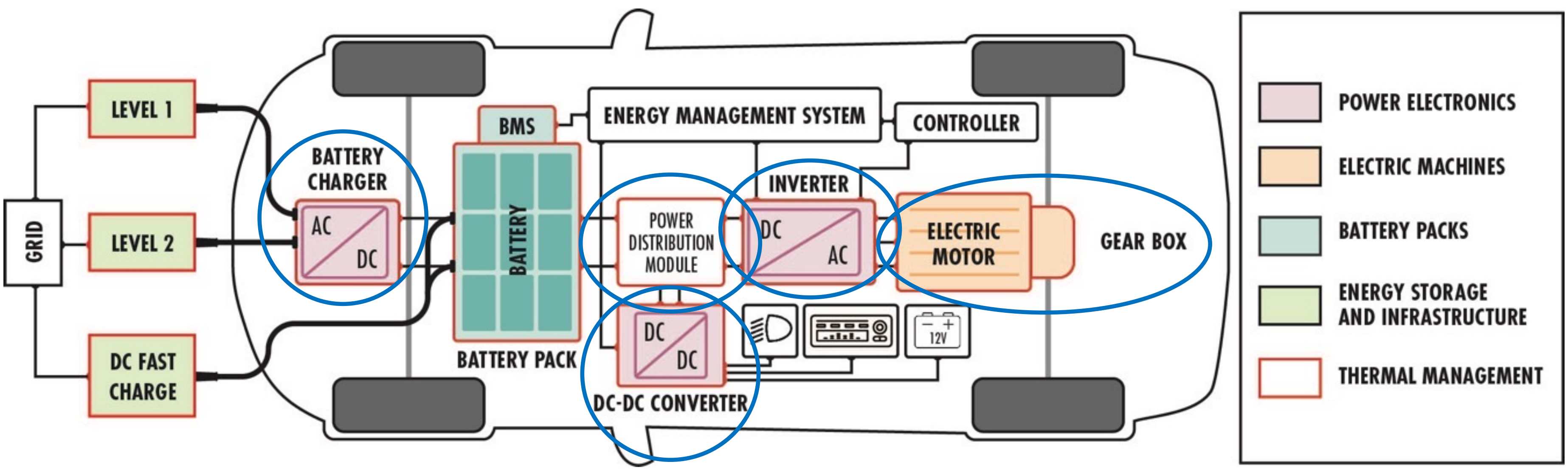
1918, first gasoline delivery truck at OSU

The Ohio State University Archives

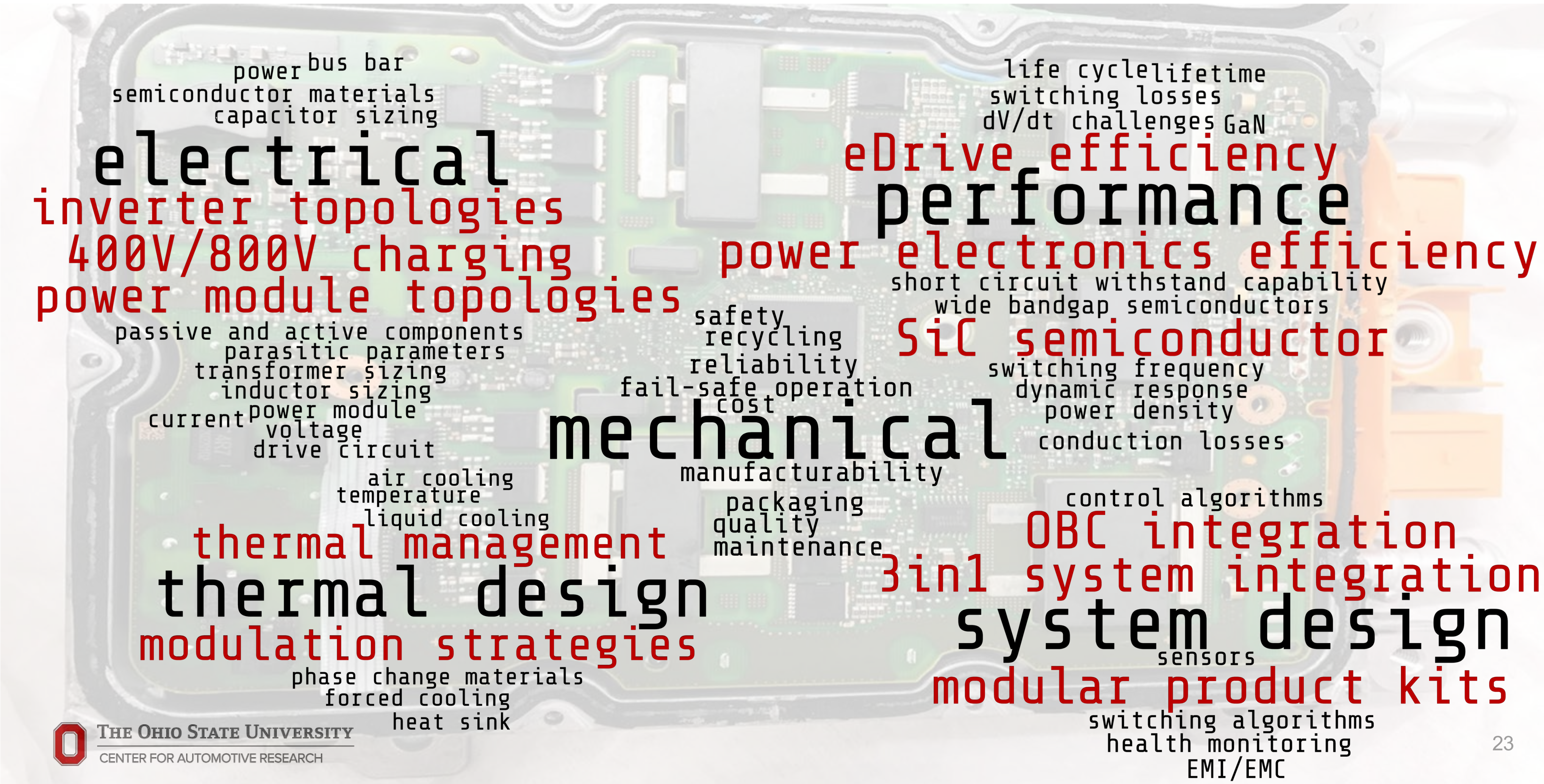
Electric Vehicle Technology

It's More Than Just the Battery!

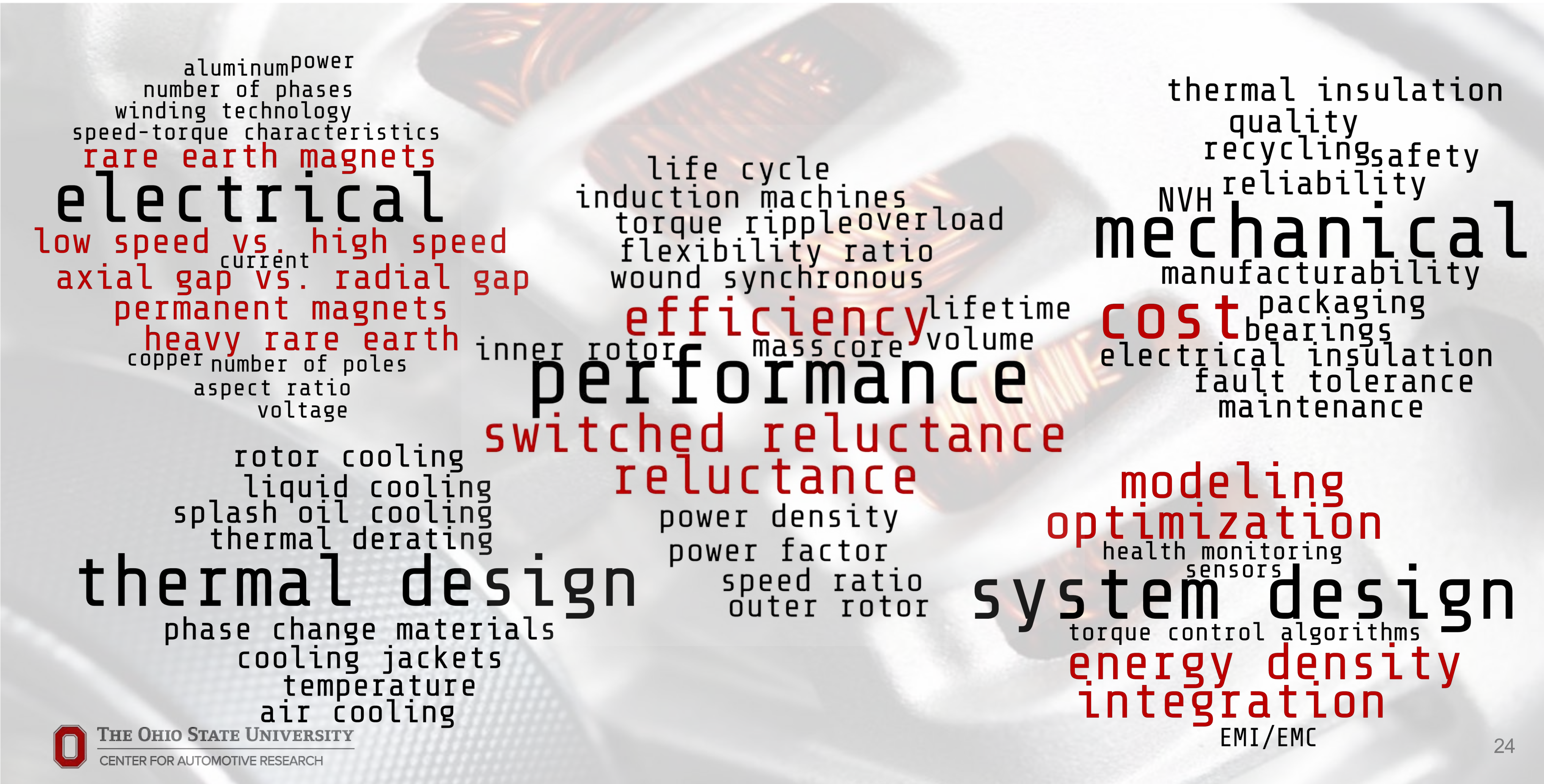
- We will discuss challenges related to the development of power electronic systems, electric machines, and the integration of e-propulsion systems.
- These subsystems, highlighted in the figure below, represent over 20% of the total cost of a BEV.
- If EVs are to be successful in the market, we must get these right…



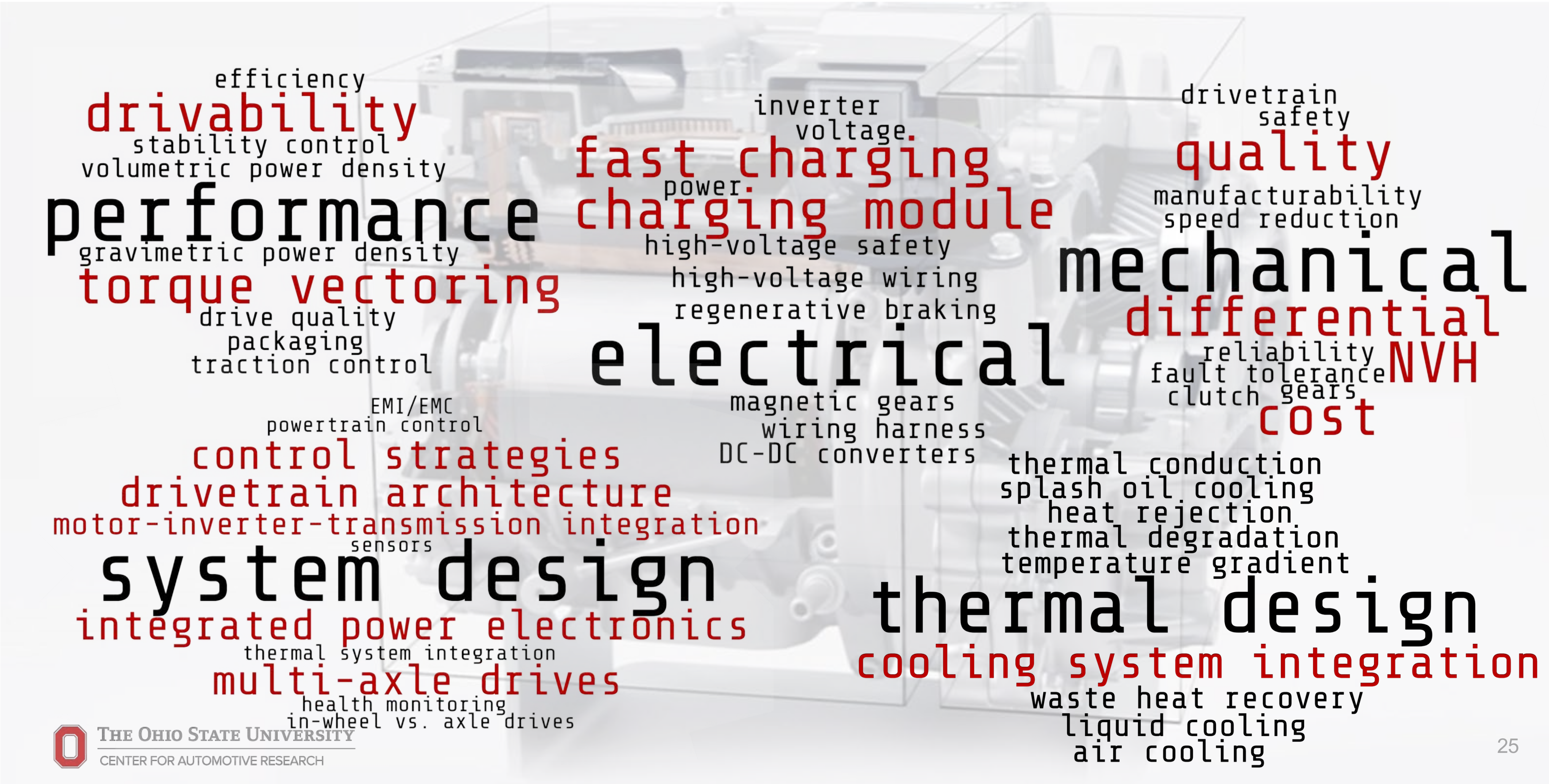
Power Electronics



Electric Machines



Drivetrain Integration



Technical Targets (Proposed DOE VTO)

Electric Drive

Year	2025	2030	2035
Peak Power Level (kW_peak)	100	150	225
Voltage (V)	600	800	800
Cost ($/kW_peak)	6	4	2.67
Power Density (kW_peak/L)	33.3	50	75

Power Electronics

Year	2025	2030	2035
Cost ($/kW_peak)	2.70	1.80	1.20
Power Density (kW_peak/L)	100	150	225

Electric Motor

Year	2025	2030	2035
Cost ($/kW_peak)	3.30	2.20	1.47
Power Density (kW_peak/L)	50	75	112.5

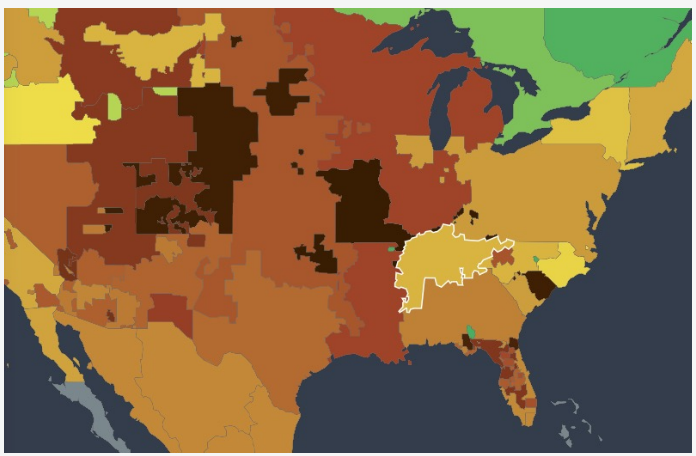
Emissions of Electric Vehicles

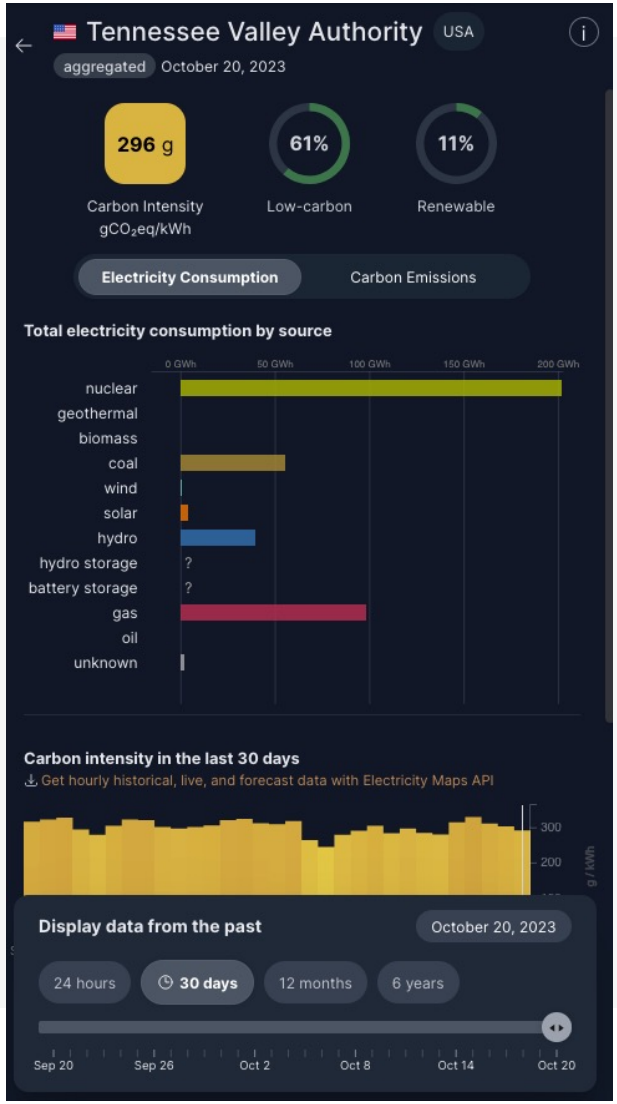
Electricity?

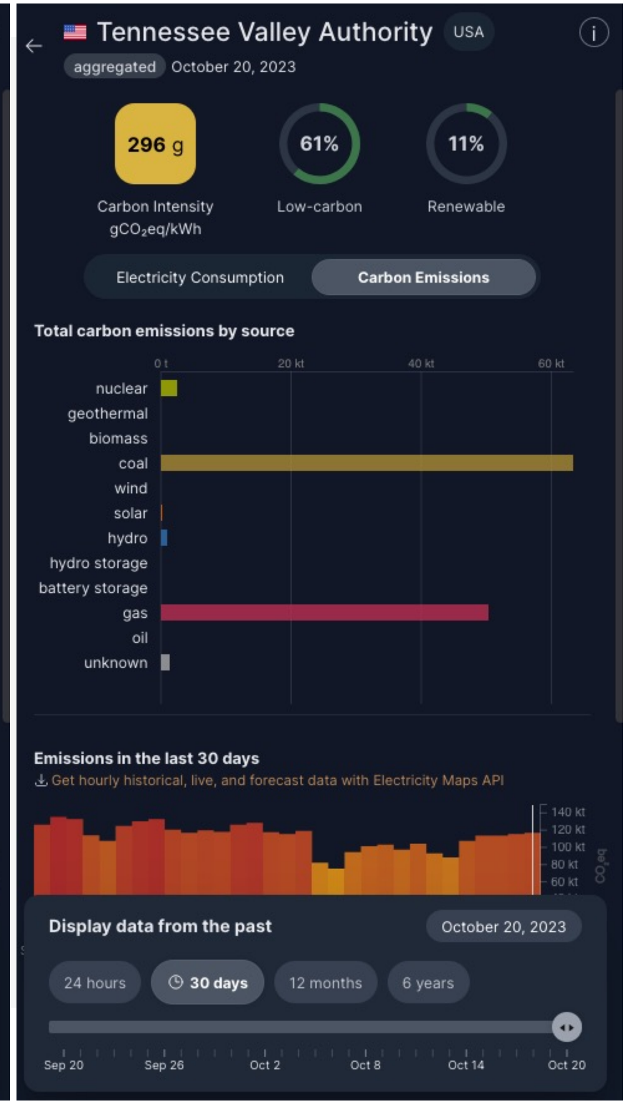
- Infrastructure already exists (home charging).
- Lowered cost per vehicle mile.
- Can use renewable energy, driving demand for renewables.

The Carbon Cost of Charging EVs

TVA example (one of the better ones)







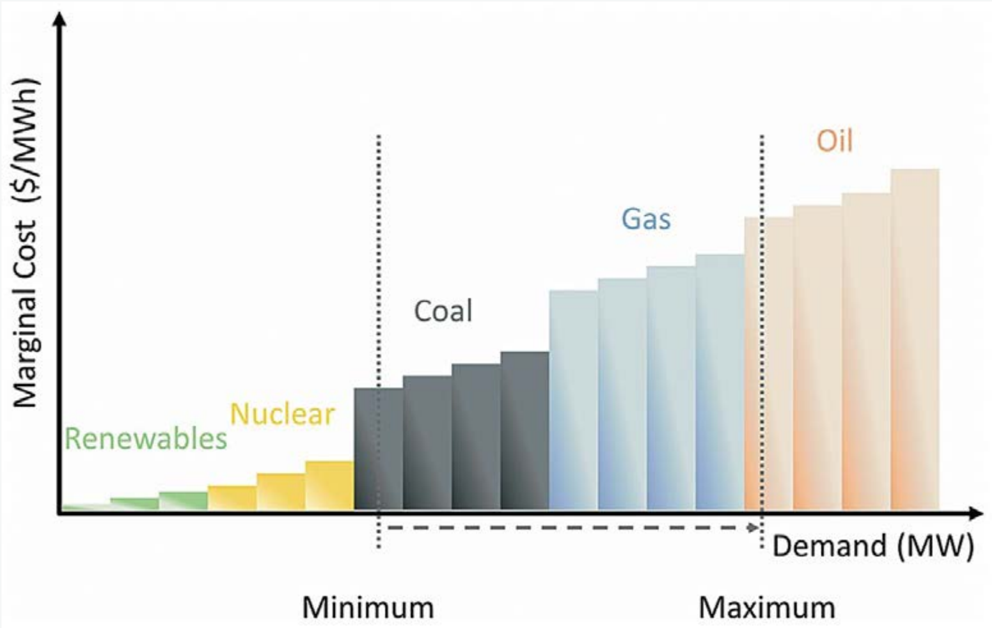
The Carbon Cost of Charging EVs

When a consumer is asking for more electricity, that additional electricity will come from the cheapest power plant that still has spare capacity at that time. This power plant is called the **marginal power plant**.

Typically, the marginal plant is a system that can react quickly to changes in electricity demand, such as a gas turbine. It however cannot be a wind turbine or solar panels, as you can't command them to produce more.

Merit Order Curve:

Generation systems are called upon in a specific order of increasing cost (in order to minimize overall cost).



https://www.electricitymaps.com/blog/marginal-carbon-intensity-of-electricity-with-machine-learning

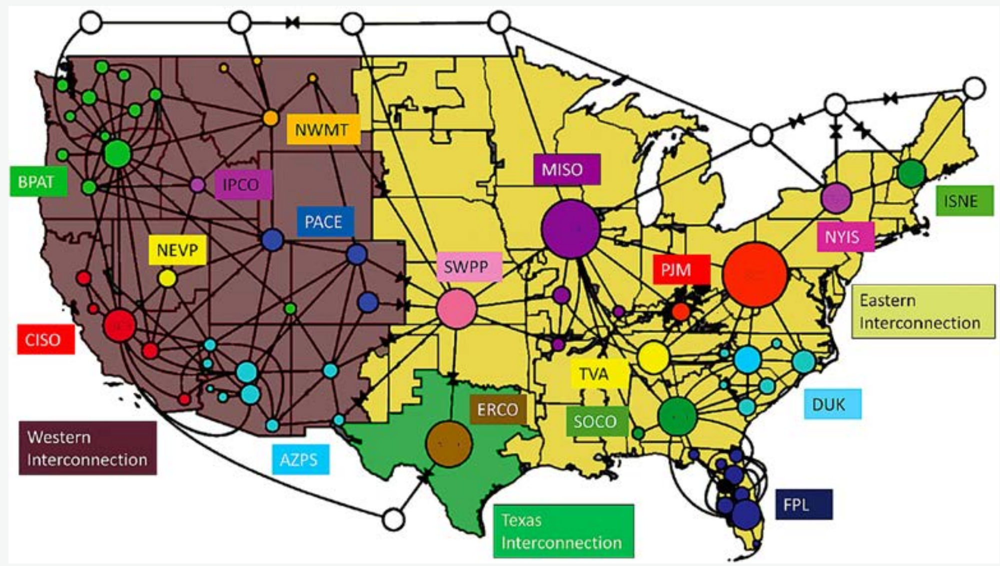
Burton, T., Powers, S., Burns, C., Conway, G. et al., "A Data-Driven Greenhouse Gas Emission Rate Analysis for Vehicle Comparisons," SAE Int. J. Elect. Veh. 12(1):91–127, 2023, doi:10.4271/14-12-01-0006.

The Carbon Cost of Charging EVs

Charging an electric vehicle at a given time, will cause the marginal plant to produce more, and therefore, charging will be responsible for the carbon emissions associated to it. Those emissions are called **marginal carbon emissions**.

Contiguous U.S. Grid Interconnections

To attribute carbon emissions, we need to trace back the area that generated the marginal electricity.



https://www.electricitymaps.com/blog/marginal-carbon-intensity-of-electricity-with-machine-learning

Burton, T., Powers, S., Burns, C., Conway, G. et al., “A Data-Driven Greenhouse Gas Emission Rate Analysis for Vehicle Comparisons,” SAE Int. J. Elect. Veh. 12(1):91–127, 2023, doi:10.4271/14-12-01-0006.

Petroleum has fueled transportation for 100 years...

...what next ?

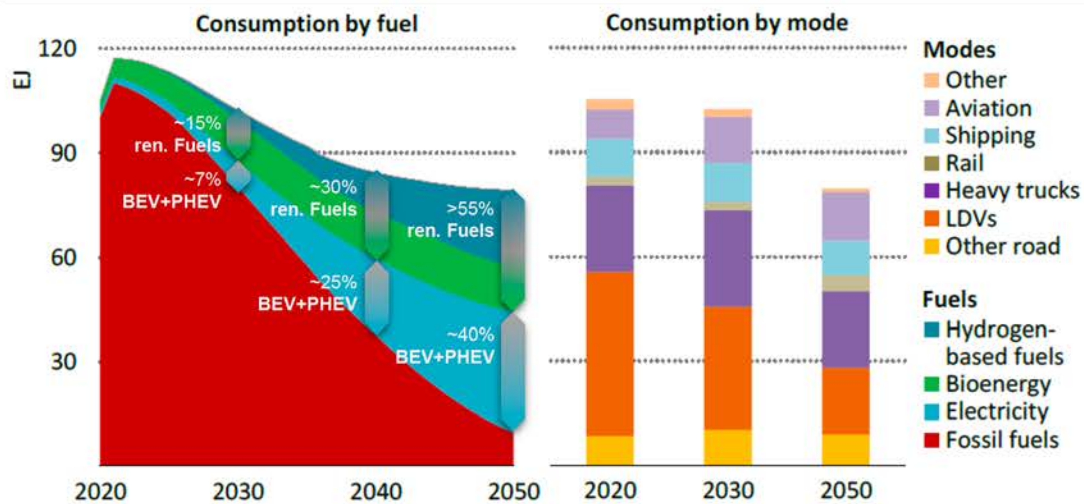
1918, first gasoline delivery truck at OSU

The Ohio State University Archives

IEA 2021 Report: Worldwide Global Pathway to Net Zero CO_2 by 2050

Sustainable mobility will be possible by electrification + renewable fuels$_{\text{CO2-neutral}}$

Figure 3.22 ▷ Global transport final consumption by fuel type and mode in the NZE global pathway to net-zero CO_2 emissions in 2050



Electricity and hydrogen-based fuels account for more than 70% of transport energy demand by 2050

Note: LDVs = Light-duty vehicles; Other road = two/three wheelers and buses.

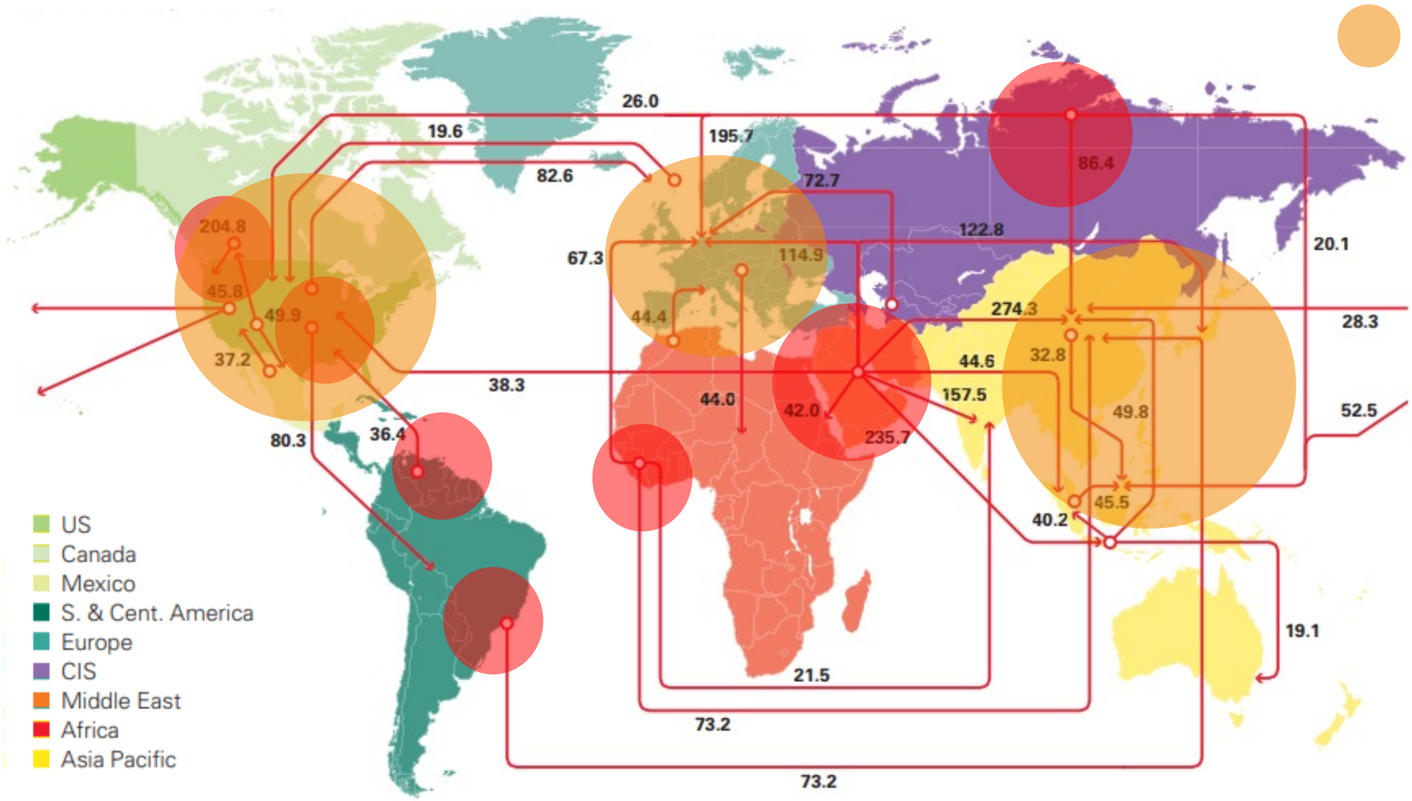
Source: International Energy Agency, 2021 Report
*renewable Fuels: CO_2-neutral bioFuels and eFuels

Global Fossil Energy Trading System

Crude Oil Transport in Million Tons p.a. (2020)

Supply regions

Demand regions



Todays energy trading is based nearly 100% on fossil fuels.

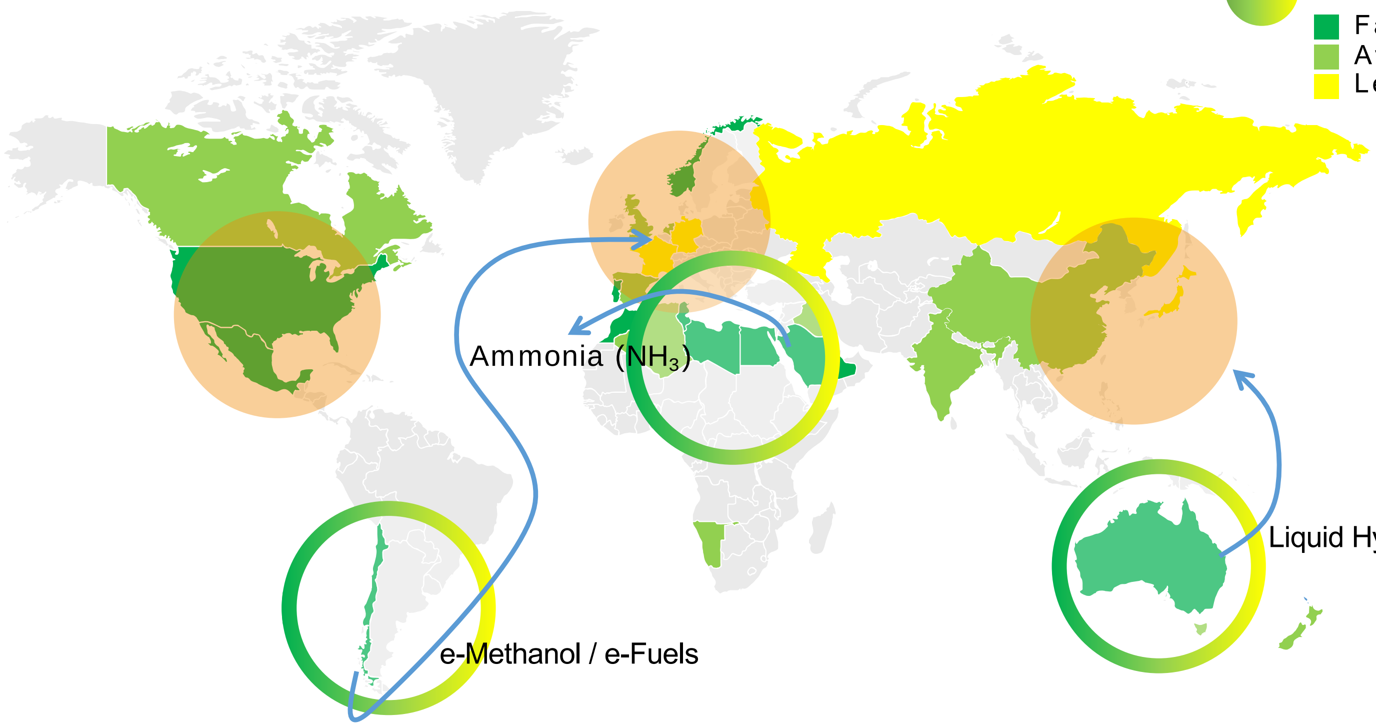
Global Energy Trading System in the Future

Energy trading with sustainable energy carriers

Demand regions
USA, Asia, Europe

Supply regions
- Favorable conditions
- Average conditions
- Less favorable conditions

Pilot Projects



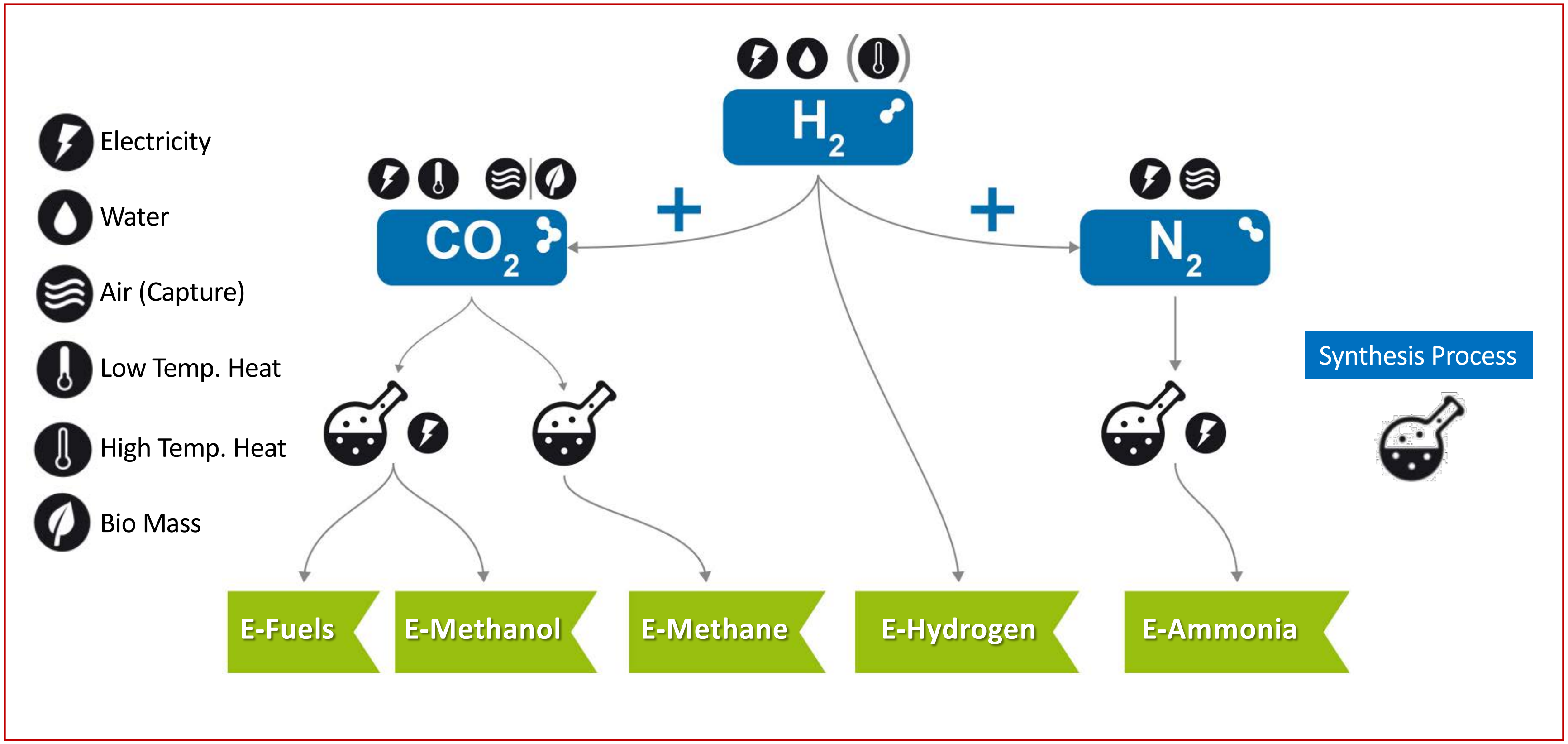
Global Trading with “green” molecule based energy carriers

Considered:
- PV and wind potential
- Political support
- Financial resources
- Political stability

It‘s all about energy

Which energy carriers have a chance in the future for a global transport of energy?

"Green" Production Paths for Synthetic Fuels (Ptx)



Courtesy: Prof. Dr.-Ing. Michael Bargende

Source(s): Öko-Institut e.V., 2020

Candidates to Become Future Energy Carriers

Positive and negative aspects due to efficiency, infrastructure and suitability as a fuel

Hydrogen (H_2)
Synthetic

Positive:
- No C Atom (no CO_2 emissions when burnt)

Negative:
- Transport only liquid (LH_2) with efficiency losses
- High material demands
- High laminar burning speed

Ammonia (NH_3)
Synthetic from H_2

Positive:
- No C atom (no CO_2 emissions when burnt)
- Is already produced in larger quantities

Negative:
- Transport only liquid with efficiency losses (much lower than H_2)
- Low energy density
- Low ignitability

LNG (CH_4)
Synthetic from H_2

Positive:
- Infrastructure exists (Ships, terminals and grid)
- Relatively high energy density

Negative:
- CO_2 emissions when burnt
- Transport only liquid with efficiency losses (lower than H_2)

Methanol (CH_3OH)
Synthetic from H_2

Positive:
- Liquid (only very low efficiency losses due to transportation)
- Infrastructure exists (gas stations)
- High laminar burning speed

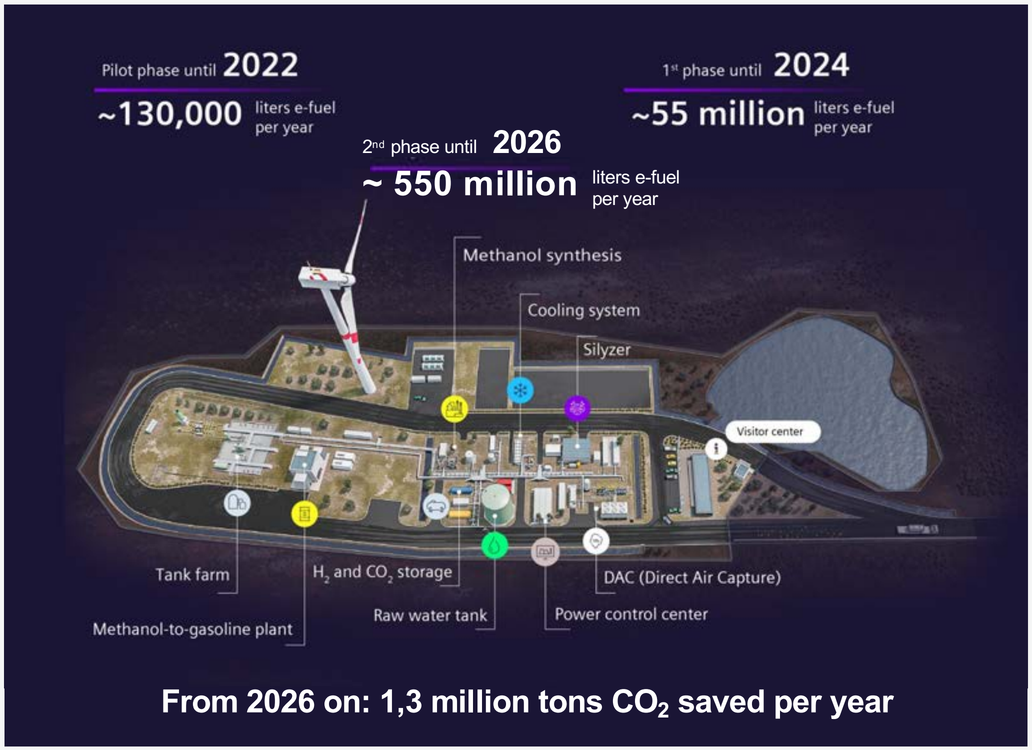
Negative:
- CO_2 emissions when burnt
- Low energy density

Source(s): https://www.offshore-energy.biz/worlds-1st-lh2-carrier-suiso-frontier-departs-for-australia/, https://www.en-former.com/en/is-ammonia-the-future-of-shipping/, https://marine-digital.com/article_10biggest_lng_shipping_companies, https://www.globaltrademag.com/methanol-carrier-cajun-sun-delivered/

Courtesy: Prof. Dr.-Ing. Michael Bargende

eFuels: Porsche and Siemens Energy Step Forward

Porsche and Siemens Energy step forward: Haru Oni – a Project of HIF (Highly Innovative Fuels)



Pilot plant for technology verification of the interlinked process steps:

- Technology path: From power supply to finished eGasoline.
- Process steps: Wind power, direct air capture, electrolysis, methanol, synthesis, gasoline synthesis.

Courtesy: Prof. Dr.-Ing. Michael Bargende

Source(s): Siemens Energy/Porsche, 2021

Passenger Cars In The World

Number and production of all cars on earth

1.434.500.973

In **2030**, if the rate of increase remains the same, the world's car population will increase to **1.6 billion**.

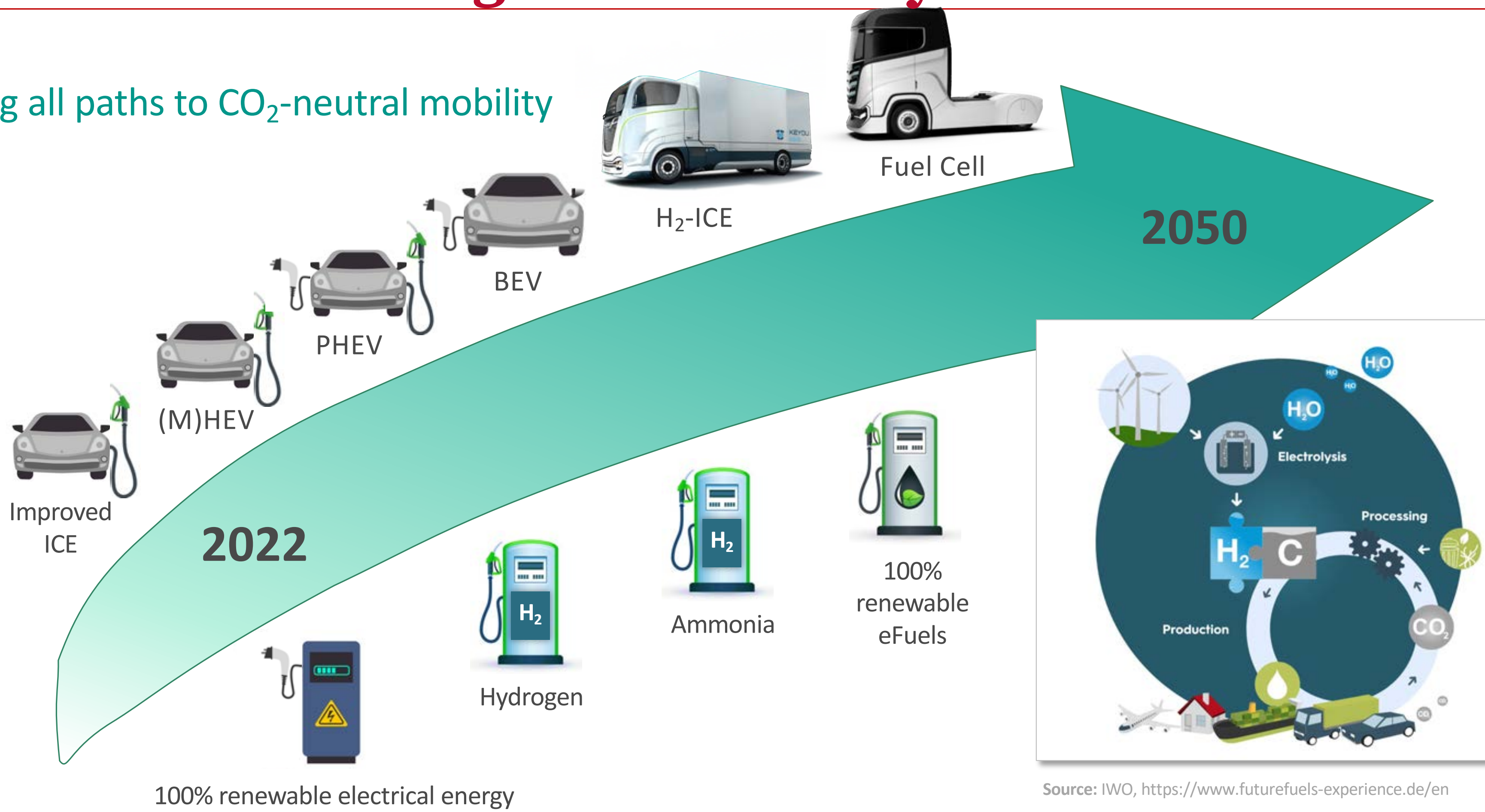
2.7 billion cars by 2050?
According to the latest studies, there will be up to **2.7 billion** cars on earth in **2050**.

Status: Oct. 19, 2023 at 13:35 at http://live-counter.com

Courtesy: Prof. Dr.-Ing. Michael Bargende

Conclusion: Reaching GHG Neutrality

Using all paths to CO_2-neutral mobility



Source: IWO, https://www.futurefuels-experience.de/en

Thank You For Your Kind Attention

Electrification Enabling Technologies

Keynote presentation

Giorgio Rizzoni, The Ford Motor Company Chair In Electromechanical Systems

Professor, MAE and ECE Departments, The Ohio State University

OCT. 24, 2023

CHATTANOOGA, TN

SMOKY MOUNTAINS Mobility Conference