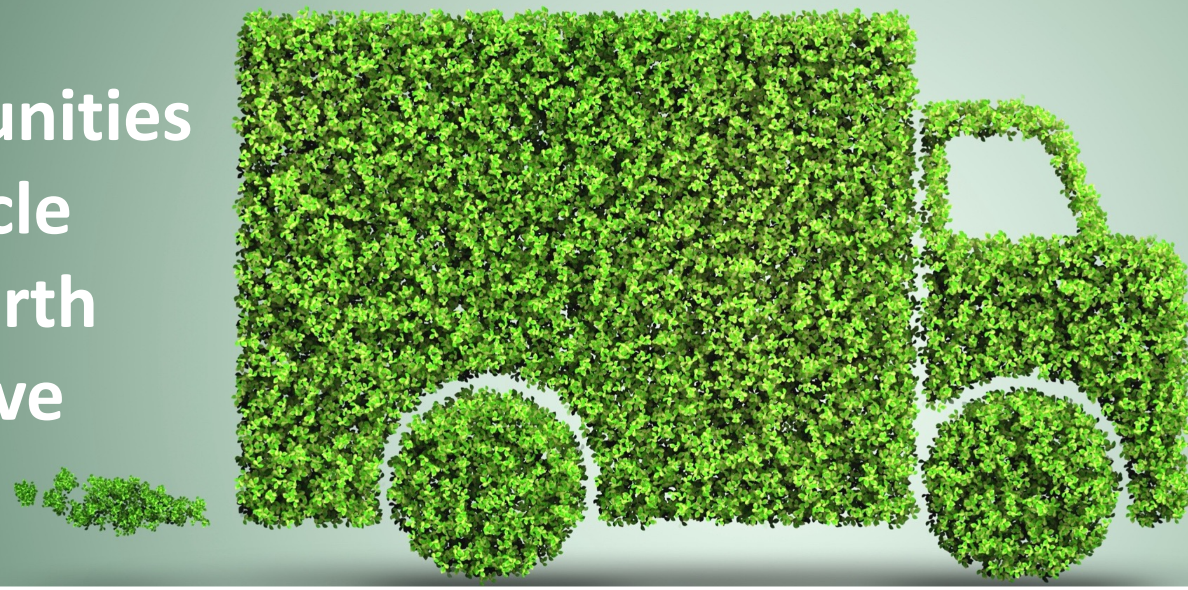
21st Workshop on Automotive Software and Systems

Challenges and Opportunities in Commercial Vehicle Electrification – a North American Perspective



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OUTLINE

BACKGROUND

ENERGY EFFICIENCY

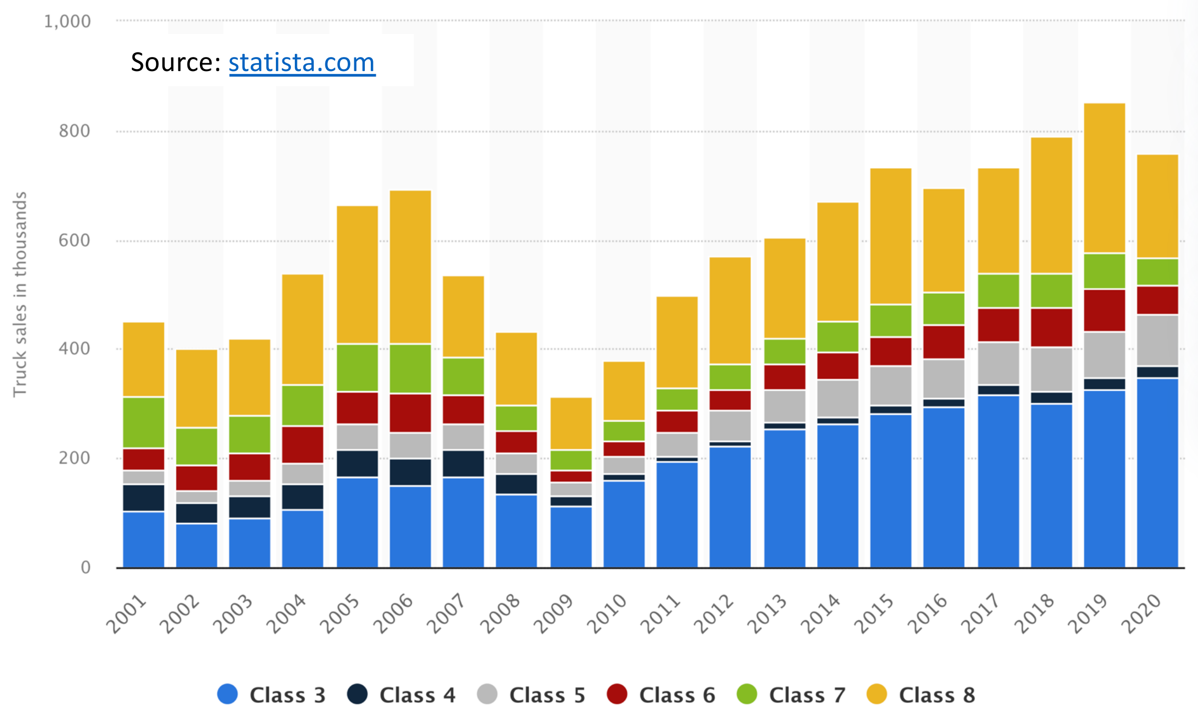
ELECTRIC TRUCKS

BATTERY CHALLENGES

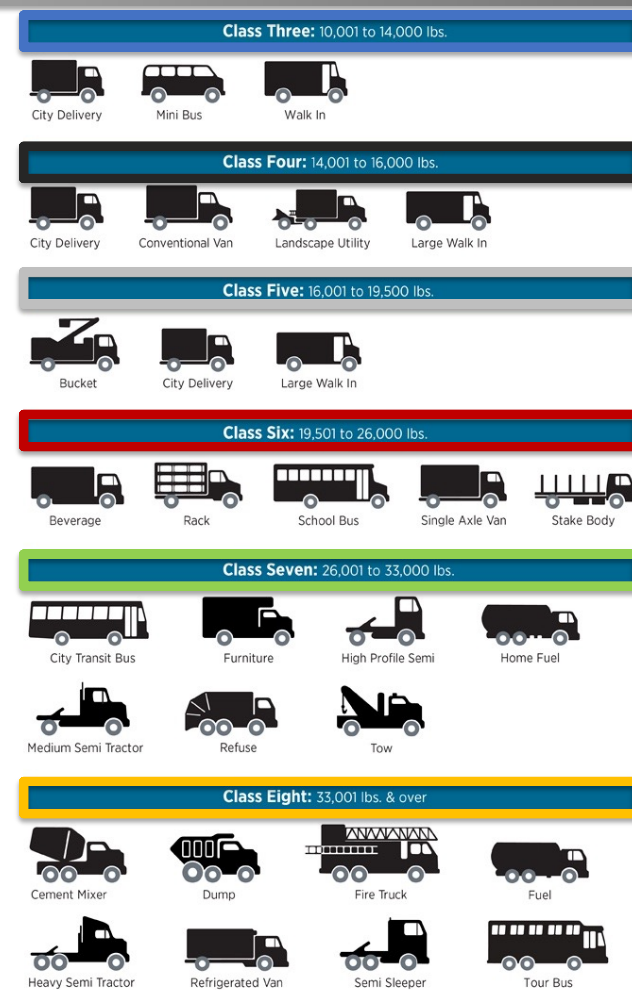
CONCLUSION

Commercial Vehicles in the US Economy

Class 3-8 truck sales in the United States from 2001 to 2020 (in 1,000s)



Work trucks | Transit | Freight



Source: energy.gov

Freight

Revenue:

$875.5 billion in gross freight revenues (primary shipments only) from trucking, representing **80.8% of the nation's freight bill in 2021**.

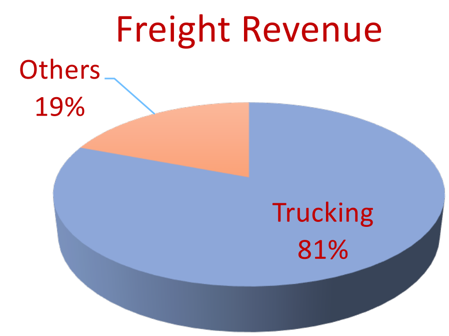
Tonnage:

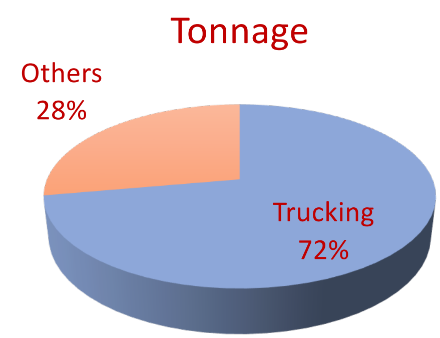
10.93 billion tons of freight (primary shipments only) transported by trucks in 2021, representing **72.2% of total domestic tonnage shipped**.

Employment:

7.99 million people employed throughout the economy in jobs that relate to trucking activity in 2021 excluding the self-employed.

3.49 million truck drivers employed in 2021 (an increase of 3.7% from 2020).

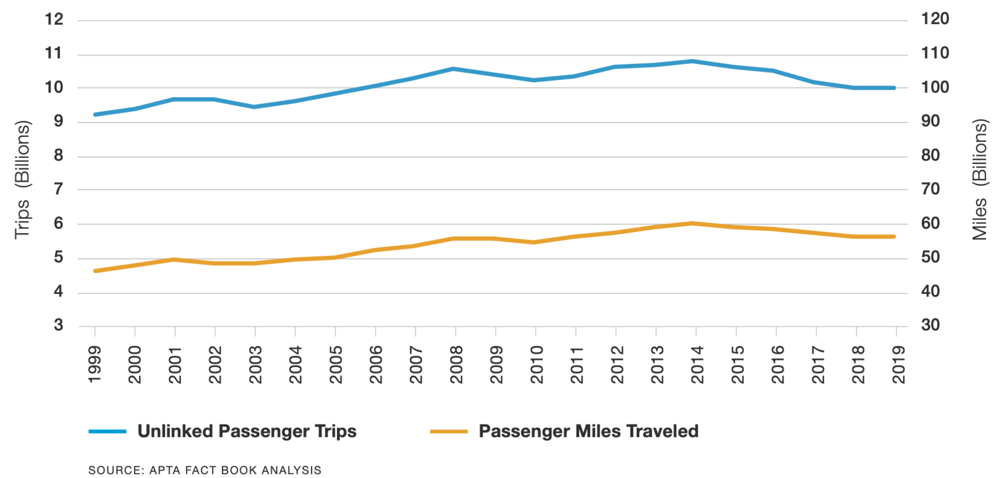




Source: American Trucking Associations

Transit

Ridership and Distance Traveled on Public Transit 1999-2019



Transit Spending in Private Sector

$43.1 billion in 2019.

Passenger Load:

Transit ridership is split between rail and roadway modes: 47% of all (unlinked) passenger trips were made by buses in 2019.

Employment:

In 2019, the public transportation industry employed **448,271 people**. Approximately 96% were operating employees (vehicle operations and maintenance, non- vehicle maintenance, and general administration functions), and less than 4% were capital employees.

Source: [American Public Transportation Association (APTA), 2021 Public Transportation Fact Book]

Work Trucks

The medium-duty market covers many different vocations

- Construction
- Baking & Snack Delivery
- Parcel & Home Delivery
- Linen & Uniform
- Utility Companies
- Municipalities
- Small Tools Sales
- Dry Cleaners
- Gutter Repair & Replacement
- Vending/Food Service
- Florists
- Carpet Installation
- Laundry Services
- Blood Banks
- Salvage
- Swimming Pool Supply
- Libraries & Bookmobiles
- Carpenters
- Plumbing
- Ice Cream
- Airlines
- Locksmiths
- Soft Water & Water Conditioning
- Nurseries & Landscaping
- Small Appliance Repair
- Catering
- Sewer Cleaning
- Electrical Contractors
- Newspaper Delivery
- Audio/Video Production
- Pet Care
- Rug Services
- TV News
- Police & Fire Departments
- Parts Trucks
- HVAC
- Exterminators

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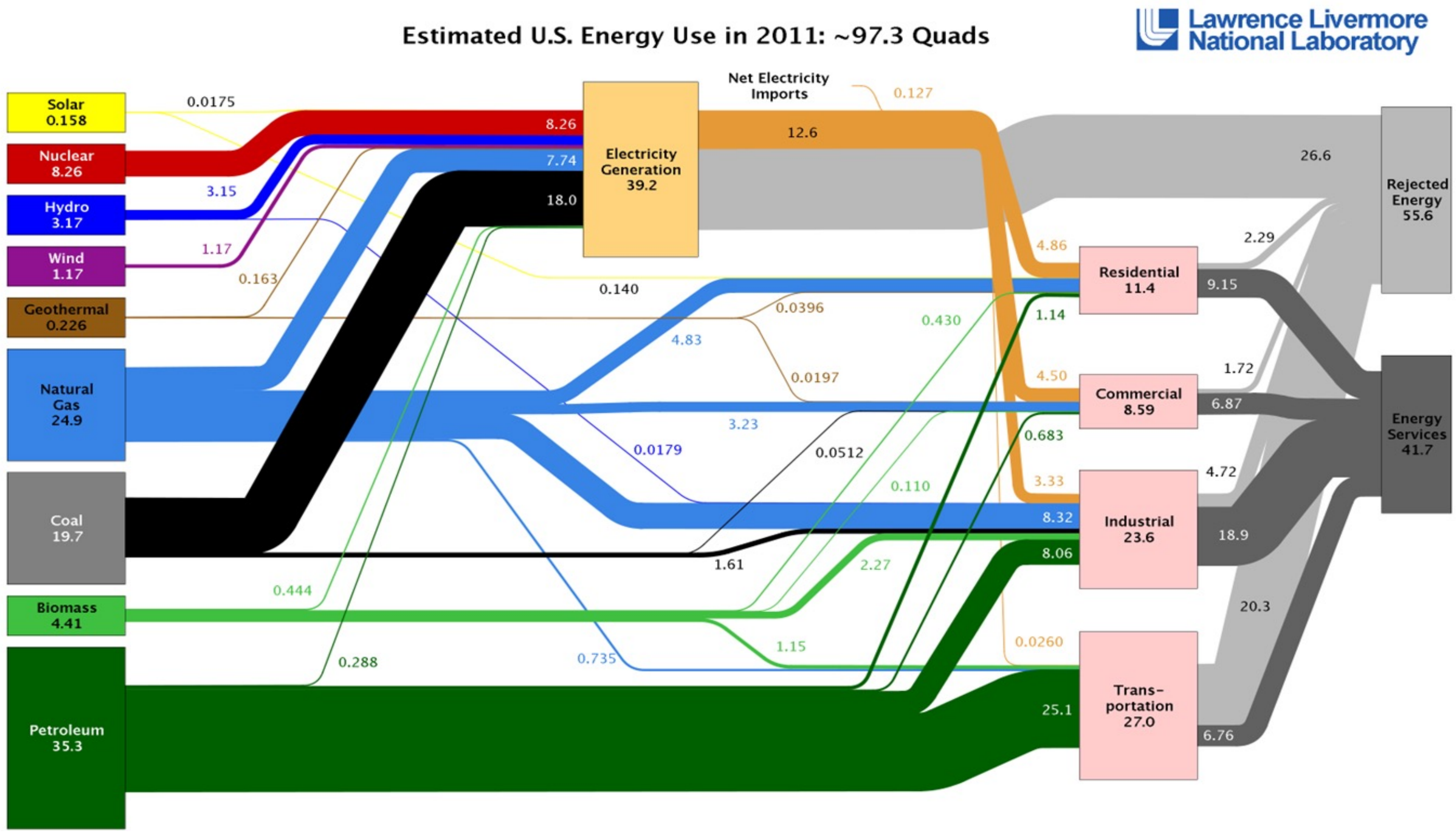
Energy Efficiency in 2011



Source: Lawrence Livermore National Laboratory (LLNL) - *Energy Flow Charts* 2011 https://flowcharts.llnl.gov/commodities/energy.

Energy Efficiency in 2021

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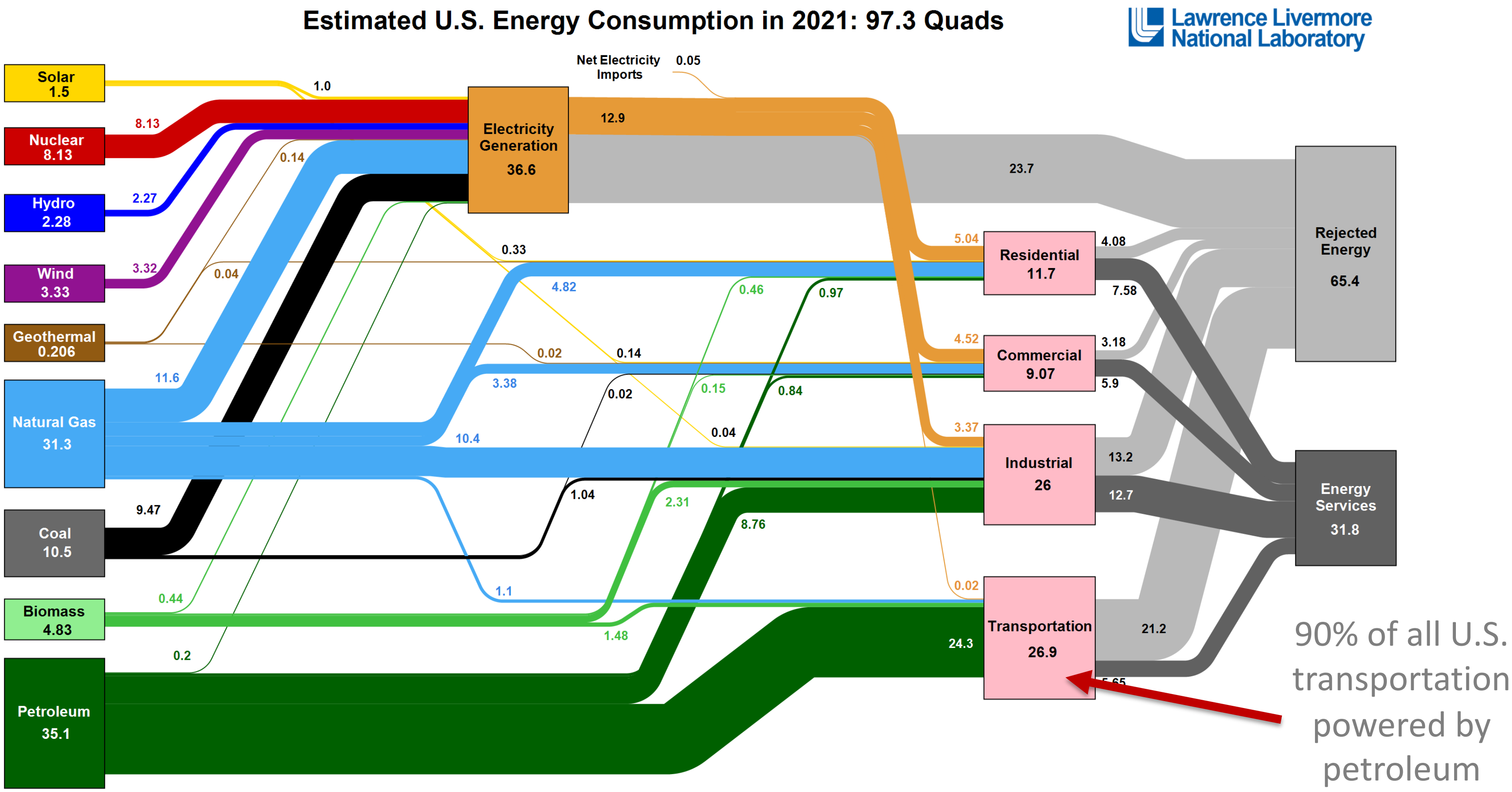
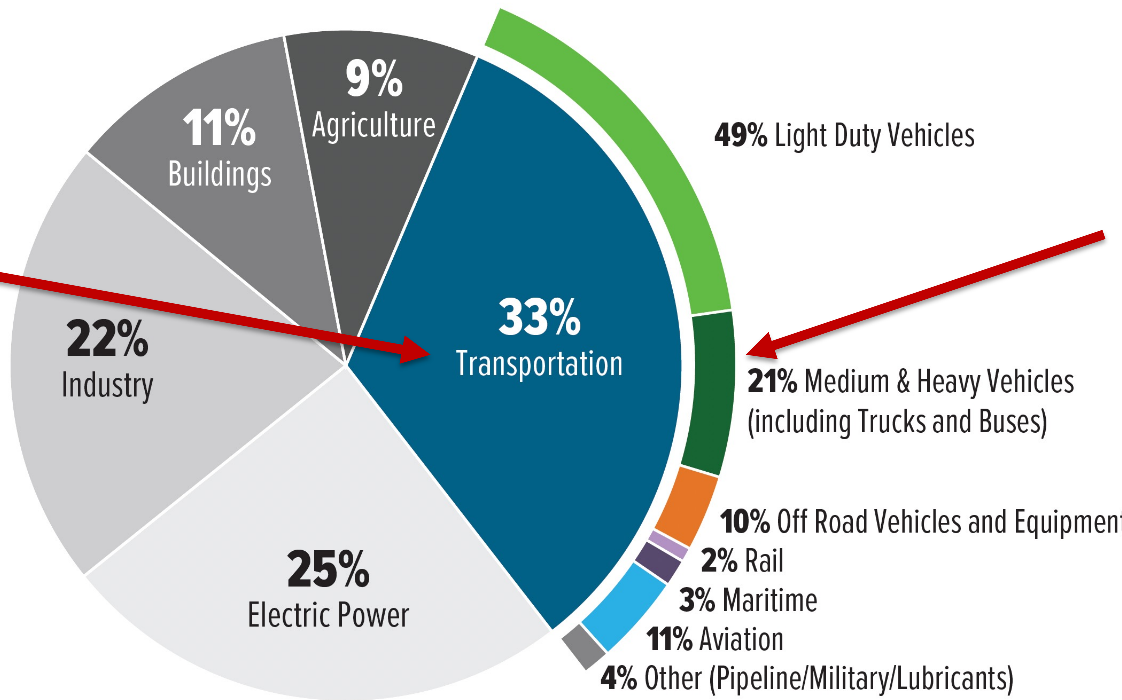


Source: Lawrence Livermore National Laboratory (LLNL) - *Energy Flow Charts* 2021 https://flowcharts.llnl.gov/commodities/energy.

GHG Emissions

2019 U.S. GHG EMISSIONS

Transportation accounts for 33% of US GHG emissions



M&HD vehicles account for 21% of US GHG emissions from transportation

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.

Heavy duty engines serve diverse vehicle applications
- Decarbonization will require a range of technology solutions

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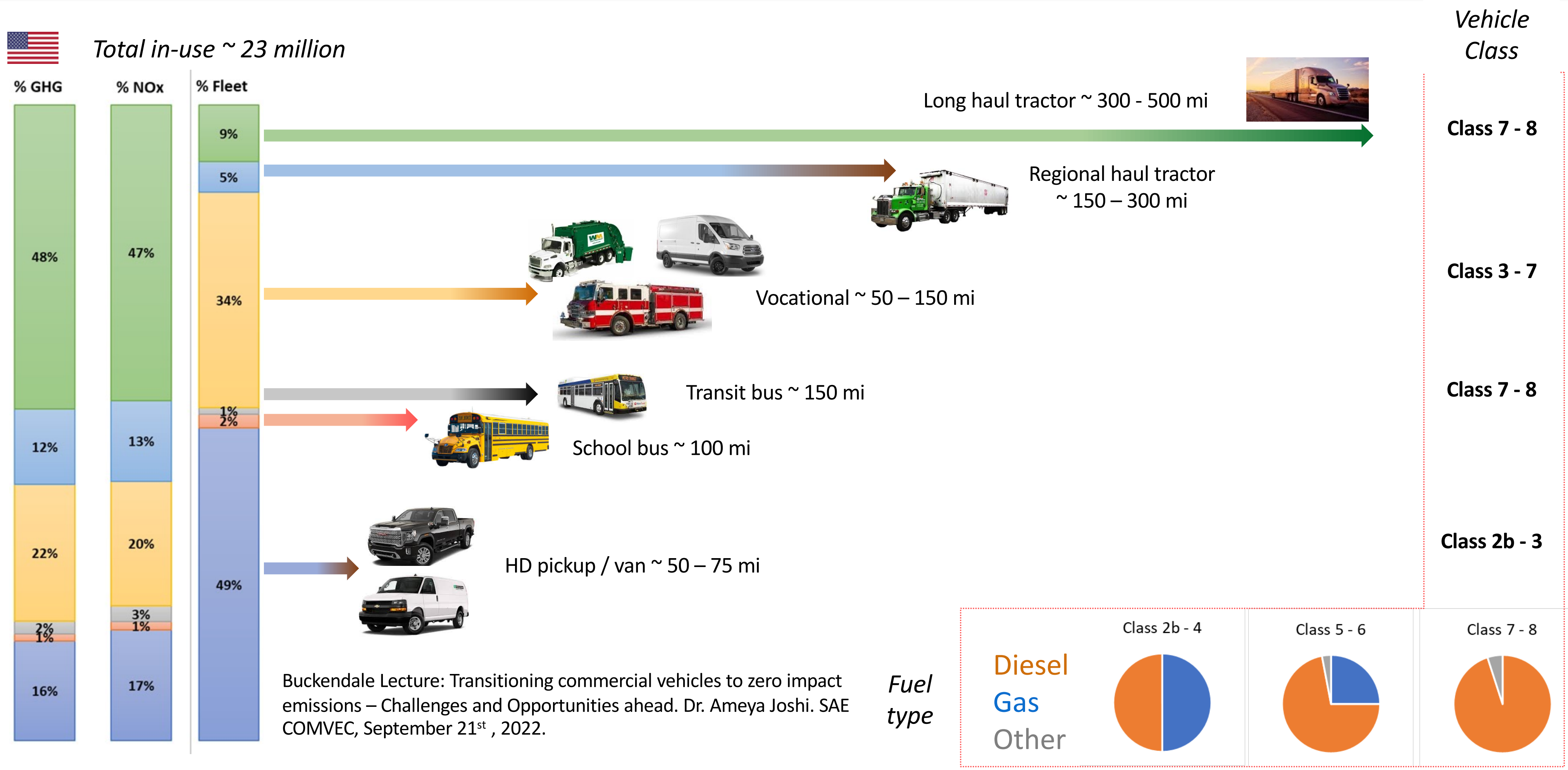
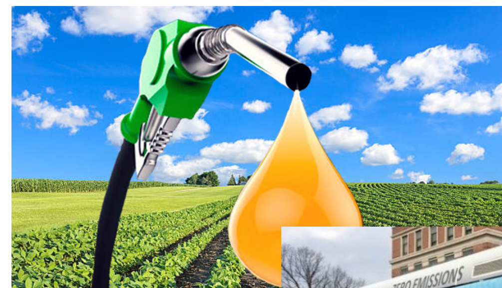


Buckendale Lecture: Transitioning commercial vehicles to zero impact emissions – Challenges and Opportunities ahead. Dr. Ameya Joshi. SAE COMVEC, September 21st , 2022.

Approaches to CO_2 reduction

Alternative Fuels

Power vehicles by fuels produced from non-fossil fuel sources and less carbonaceous fuels.



- **Bio-diesel and Ethanol:**
  - Synthesized from plant sources: Vegetable oil, Corn
  - Waste organic material: Used cooking oil and animal fat

- **Natural Gas and Bio-CNG**:
  - Bio-CNG produced from processing of organic matter
  - NG is important in transit bus and city truck fleets
- **Hydrogen**:
  - Produced from electrolysis of water, powered by the grid or a renewable source.
  - Strong interest in Fuel Cell EVs fueled by H_2, but infrastructure challenges remain

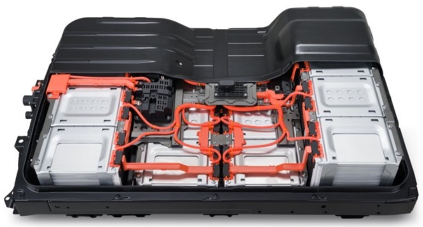
https://afdc.energy.gov/

Electrification

An electric powertrain is more efficient than conventional powertrains over a wider operating range and can additionally recover energy by regenerative braking.

Electrified vehicles have become more cost-competitive due to improvements in:

- Battery technology:
  - Costs have dropped dramatically:
    200-300 $/kWh in 2019 from $1000 in 2010
  - Capacity and durability have also improved



- Charging infrastructure:
  - Fast charging for shorter range applications are already available
  - On-the-fly charging for longer range applications are under development

Vehicle improvement strategies and technology solutions needed to reach a net-zero economy in 2050

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1 icon represents limited long-term opportunity 🔋
2 icons represents large long-term opportunity 🔋🔋
3 icons represents greatest long-term opportunity 🔋🔋🔋

	BATTERY/ELECTRIC	HYDROGEN	SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)*	🔋🔋🔋	—	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	🔋🔋	Ⓗ	⛽
Long-Haul Heavy Trucks (~7%)	🔋	ⒽⒽⒽ	⛽⛽
Off-road (10%)	🔋🔋	Ⓗ	⛽
Rail (2%)	🔋🔋	ⒽⒽ	⛽⛽
Maritime (3%)	🔋	ⒽⒽ†	⛽⛽⛽
Aviation (11%)	🔋	Ⓗ	⛽⛽⛽
Pipelines (4%)	🔋🔋	TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

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.

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- BACKGROUND
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- ELECTRIC TRUCKS
- BATTERY CHALLENGES
- HYDROGEN CHALLENGES
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Complexity of the MD Trucks Market

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- Developers of many of the early electric vehicle powertrains have attempted to **integrate "off-the-shelf" or "best available" battery systems**, motors, and power electronics as opposed to **purpose-built or optimized systems**.

- The MHDV market comprises a vastly **diverse set of vocational uses** compared to the passenger car market. These vehicles must address a broad range of duty cycles and use cases. This often leads them to have highly customized options such as power takeoff, refrigeration, job-site power needs, and hotel/idle loads , which limits standardization.

Electrified Trucks: Examples

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Class 3 – Battery Electric	
Peak Power	198 kW
Battery Capacity	68 kWh
Battery Energy Density	\
Battery Type	\
Range	126 mi
Charging Level	Level 2

Ford e-Transit

SAE Ford F-59 EV

Class 3 to 7 – Battery Electric	
Peak Power	250 kW
Battery Capacity	138 kWh
Battery Energy Density	128 Wh/kg
Battery Type	NMC
Range	200 mi
Charging Level	Level 2

Class 6 – Battery Electric	
Peak Power	390 kW
Battery Capacity	211 kWh
Battery Energy Density	\
Battery Type	LFP
Range	\
Charging Level	Level 3

BYD 6R Refuse Truck

ODYNE

Class 6 – Plug-In Hybrid	
Peak Power	70 kW
Battery Capacity	35.4 kWh
Battery Energy Density	\
Battery Type	\
Range	\
Charging Level	Level 2

https://www.fleet.ford.com/showroom/commercial-trucks/e-transit/2023/
https://en.byd.com/truck/class-6-refuse-truck/
https://www.sea-electric.com/products/f59-ev/
https://www.odyne.com/features-specs/specifications/

Differences

- Fleets in each vocation have their own **unique duty cycles** based on their locations, customers, truck types and business models

Similarities

- Vehicles typically operate:
    - **daily**
    - from a **fixed starting location and return** there at the end of their day
    - in **urban areas** where vehicles see predictable daily mileage and stop-and-go traffic

Example Duty Cycles for Medium-Duty (NREL/ORNL/NACFE)

- **Low daily average speeds** (below 35 mph)
- **Occasional high speeds (**above 60 mph)
- **Vehicles moving a small portion of their daily shift** (below 2.75 hours per day)
- **Vehicles occasionally in use all day (**exceeding 10 hours per day)
- Considerable **stopping events**

	Weight Class & Type					
Factor	Food Delivery Truck (Class 3)	Parcel Delivery Step Van (Class 4)	Parcel Delivery Walk-In (Class 4)	Linen Delivery Van (Class 5)	Food Delivery Truck (Class 5)	Parcel Delivery Walk In (Class 6)
Average Drive Disitance (mile/day)	37	52	46	66	40	36
Annual Travel Mileage[a]	9,620	13,471	11,911	17,160	10,400	9,404
Max Drive Distance (mile/day)	79	132	232	141	81	88
Average Drive Time (hr/day)[b]	1.12	2.75	2.18	2.42	1.18	2.03
Max Drive Time (hr/day)[b]	2.14	4.56	6.17	4.21	2.05	4.16
Average Vehicle On Time (hr/day)[c]	1.60	6.73	5.50	6.18	2.98	3.48
Max Vehicle On Time (Hr/day)[c]	3.29	11.38	8.78	12.63	18.16	8.40
Average Drive Speed (mph)[b]	33	19	20	27	34	16
Max Drive Speed (mph)[b]	70	71	81	70	71	70
Average Vehicle On Speed (mph)[c]	22.84	8.30	10.92	11.87	18.23	8.91
Average Stops per Mile	0.97	4.04	3.11	1.56	0.92	6.33
Max Stops per Mile	3.03	6.87	6.45	3.02	3.04	16.75
Average Stops per Day[d]	30.26	181.83	147.53	97.72	30.46	147.00
Max Stops per Day[d]	49	284	242	183	65	277

GUIDANCE REPORT: Medium-Duty Electric Trucks Cost Of Ownership, North American Council for Freight Efficiency (NACFE), 2018
https://nacfe.org/wp-content/uploads/2018/10/medium-duty-electric-trucks-cost-of-ownership.pdf

Jobsite Power Demand

Jobsite power demand fulfilled through hydraulic or electrical systems can range **from 10 kW to over 100 kW**. In some application, stationary jobsite operations may be responsible for the majority of the fuel consumption. Duty cycles for a given application may show **significant variation from day to day**.

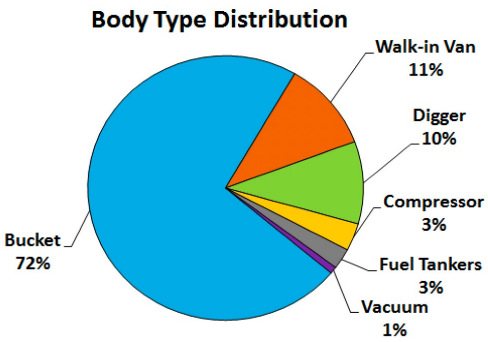
Application	Power Demand (kW)
Milk Tanker	10
Vehicle Transporter	15 ÷ 20
Dump	20 ÷ 60
Bucket / Ladder	18 ÷ 30
Refrigerated Van	20
Chemical Tanker	20 ÷ 30
Terminal Tractor	30 ÷ 60
Crane	35 ÷ 70
Refuse	30 ÷ 40

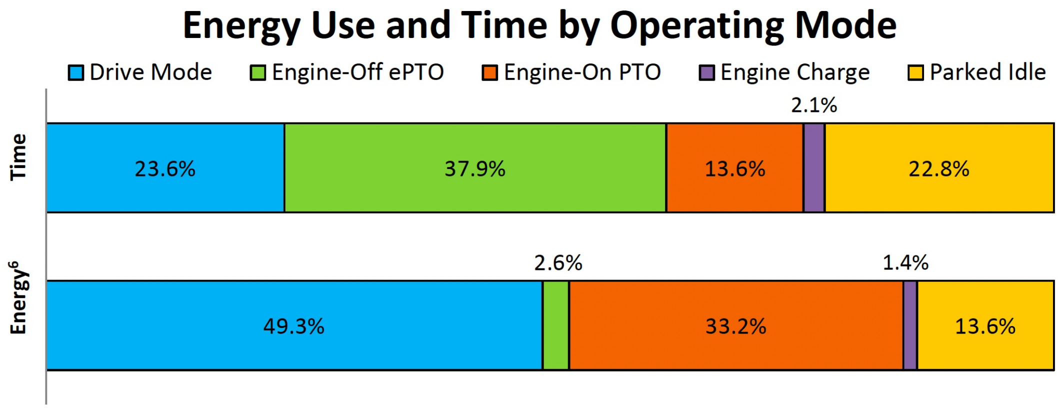
Application	Power Demand (kW)
Lift Dump	45 ÷ 55
Dumpster / Roll Off	45 ÷ 55
Bulk	40 ÷ 60
Sewage	30 ÷ 80
Sewage, Jet-washing	110
Cement Mixer, mixing	15 ÷ 20
Cement Mixer, discharging	40 ÷ 90
Concrete Pumper	100 ÷ 160
Concrete Pumper, extreme	220

Alicia K. Birky, Michael Laughlin, Katie Tartaglia, Rebecca Price, Zhenhong Lin, Transportation Electrification Beyond Light Duty: Technology and Market Assessment, ORNL/TM-2017/77-R1,

Operating Data from Utility Trucks

Odyne deployed 119 **plug-in hybrid electric medium-duty utility trucks** with a parallel hybrid system that were operated by a variety of companies in diverse climates across the country.





NREL Odyne PHEV System Performance Evaluation – Cumulative, 2016 https://www.nrel.gov/transportation/assets/pdfs/67116.pdf

Can Work Trucks Be A Good Fit For Electrification?

Predictable range and the ability to take advantage of regenerative braking are key factors for implementing battery electric trucks

Fuel Economy Comparison

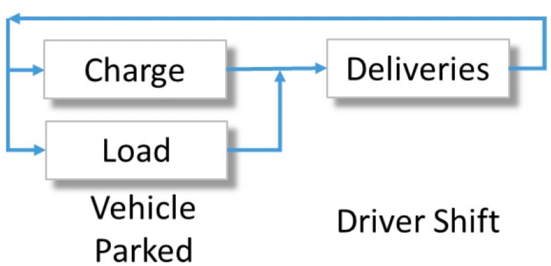
The EV saves energy to a 44% reduction for school buses

For diesel fuel:

$$\left[\frac{kg}{m^3}\right]\left[\frac{kJ}{kg}\right]\left[\frac{l}{gal}\right]\left[\frac{m^3}{l}\right]\left[\frac{kWh}{kJ}\right]\eta_{power}\eta_{charge}\eta_{serv}=\left[\frac{mi}{gal}\right]$$

	ICE	Battery Electric		
Vehicle	**Conventional Fuel Economy [mpg]**	**Battery Energy [kWh/mi]**	**Equivalent Fuel Economy [mpge]**	**Energy Use Reduction [%]**
Class 3 – Bucket	9.8	0.8	16.4	40%
Class 4 – Parcel Delivery	9.5	0.9	14.3	34%
Class 5 – Food Delivery	7.8	1.1	12.8	39%
Class 6 – School Bus	7.8	1.1	13.9	44%
Class 7 – Food Delivery	5.7	1.6	9.5	40%

Steven Nadel and Eric Junga, Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers, American Council for an Energy-Efficient Economy ACEEE, January 2020



One-shift-per-day Recharging Strategy

The driver starts and ends his shift at a depot facility, where the driver's only charging responsibility is unplugging the vehicle at the start of the shift and plugging the vehicle in at end of shift

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- **BATTERY CHALLENGES**
- HYDROGEN CHALLENGES
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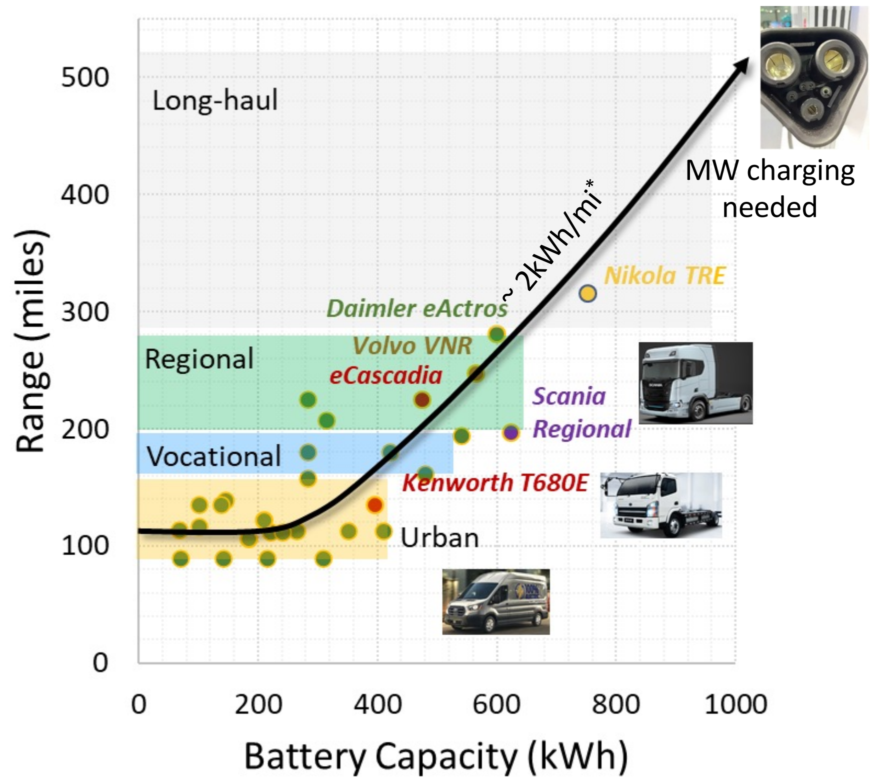
Battery Challenges

- Range (energy density and specific energy)
- Recharge times (and infrastructure)
- Climate sensitivity
- Equivalent emissions
- Durability (ageing)
- Material (minerals)
- Cost

Range

- Vocational and regional delivery trucking is well poised for electrification
- Long-haul: need to address battery weight, charging time, infrastructure

> 1MWh battery pack needed for 500+ mile range



* 2kWh/mi → 6 hrs overnight depot charging @ 100 kW for 300 mi

Sensitivity to Climate Conditions

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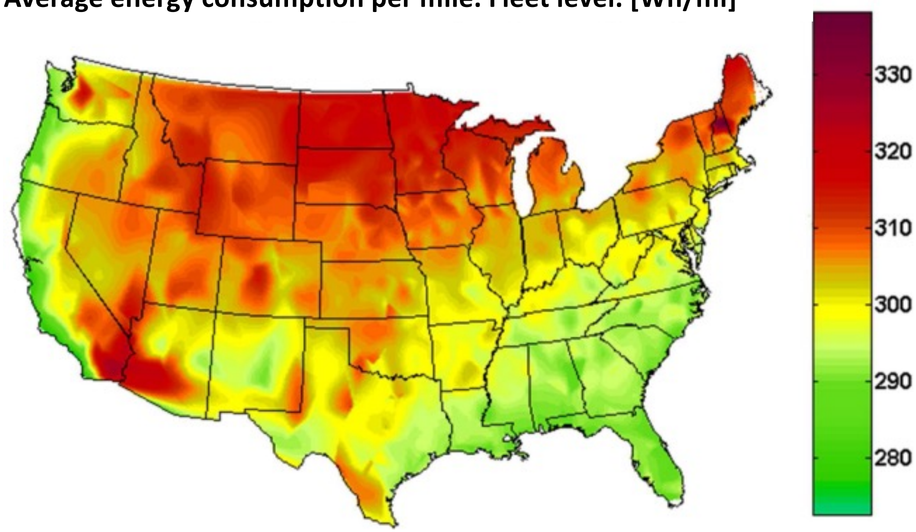
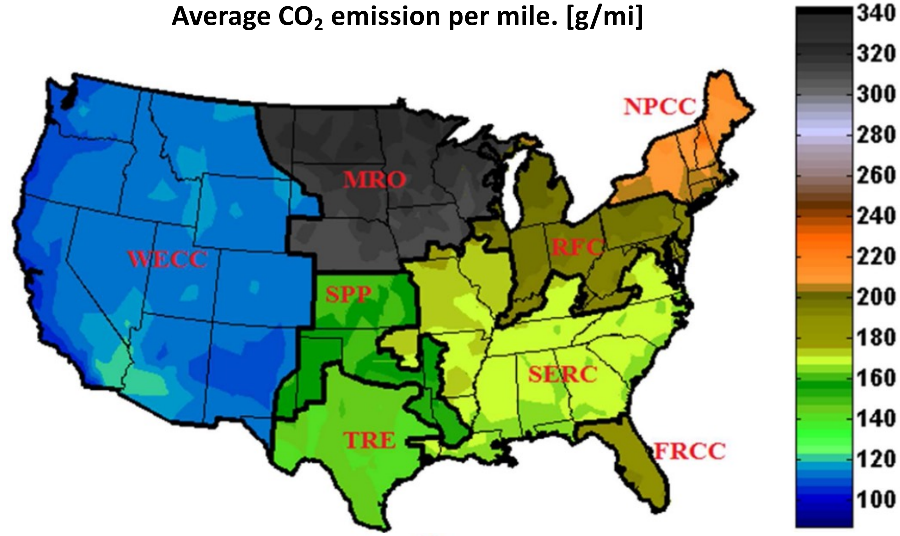
Climate, outside **temperature, energy production system** have a **direct impact** on the BEV:

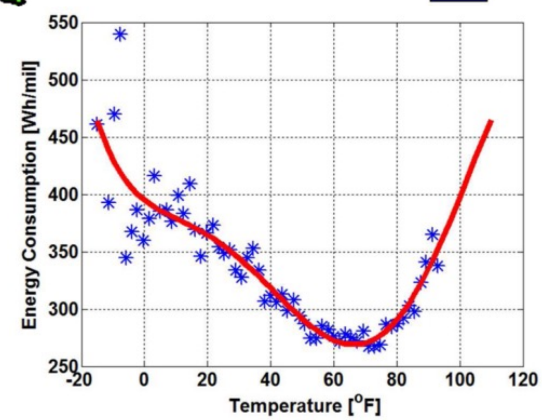
- Energy Consumption
- CO_2 emissions

Average energy consumption per mile. Fleet level. [Wh/mi]



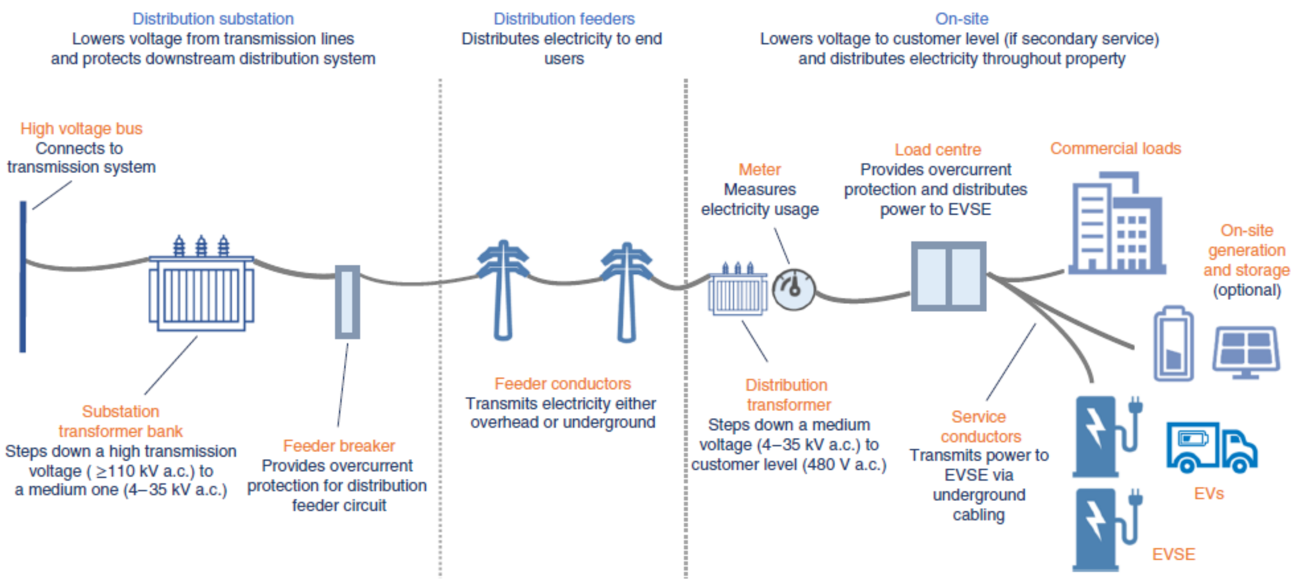
Average CO_2 emission per mile. [g/mi]



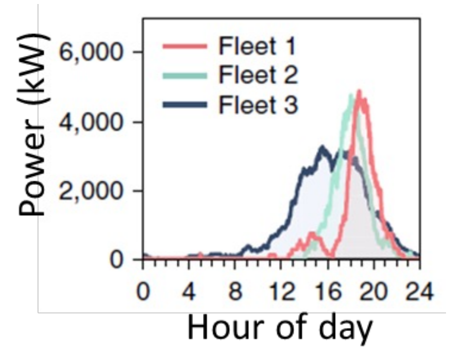


Tugce Yuksel and Jeremy J. Michalek, Effects of Regional Temperature on Electric Vehicle Efficiency, Range, and Emissions in the United States, *Environmental Science & Technology* 2015 *49* (6), 3974-3980, 10.1021/es505621s

Charging infrastructure will have to be developed



NREL https://doi.org/10.1038/s41560-021-00855-0



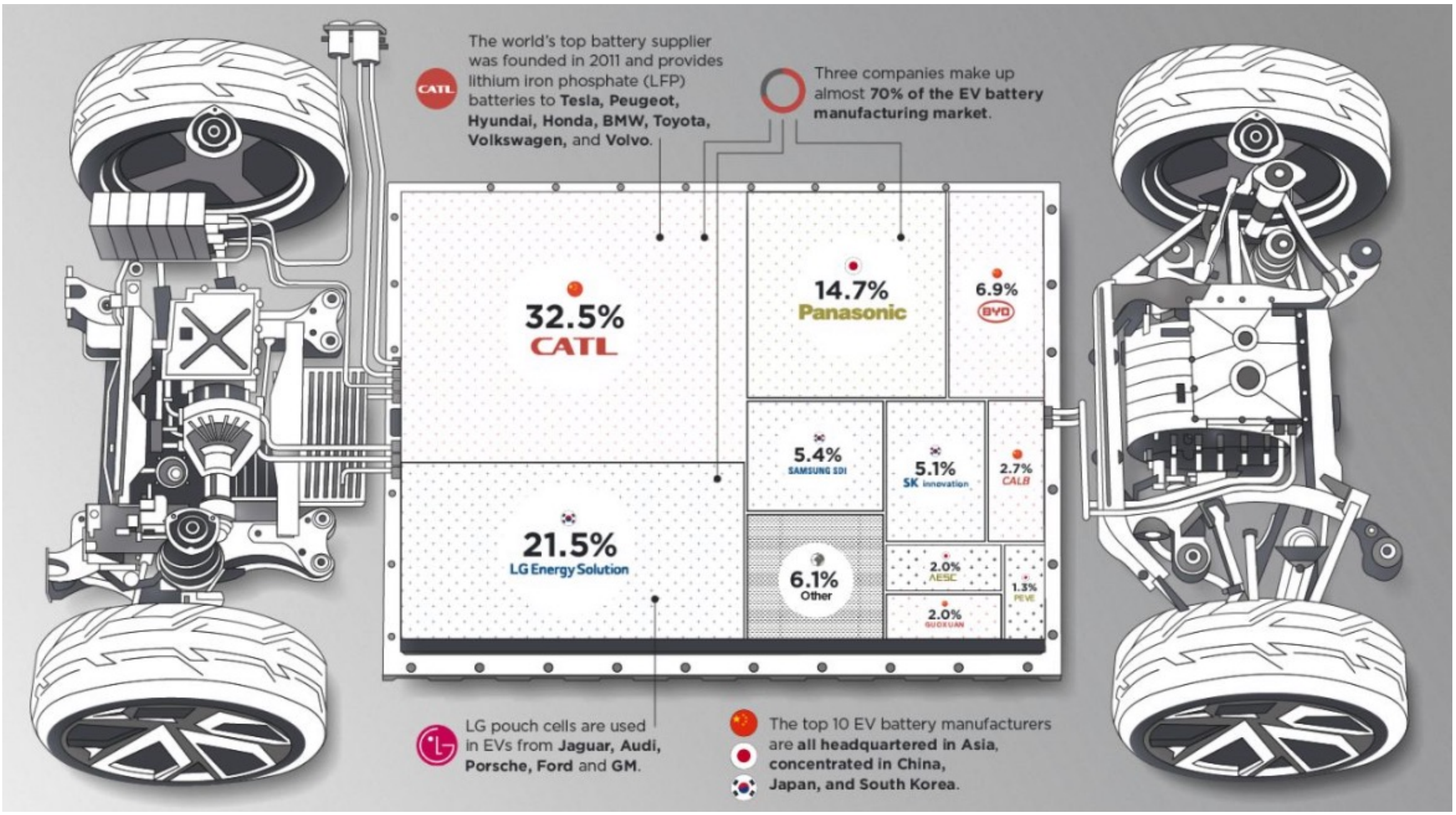
<u>Case study</u>

Fleet of 100 vocational EV trucks

4.5 MW peak power for immediate (end-of-shift) charging at 100 kW

78 – 86% substations can supply without any upgrades

EV Battery Manufacturers



50 battery plants needed – 8 planned or operational

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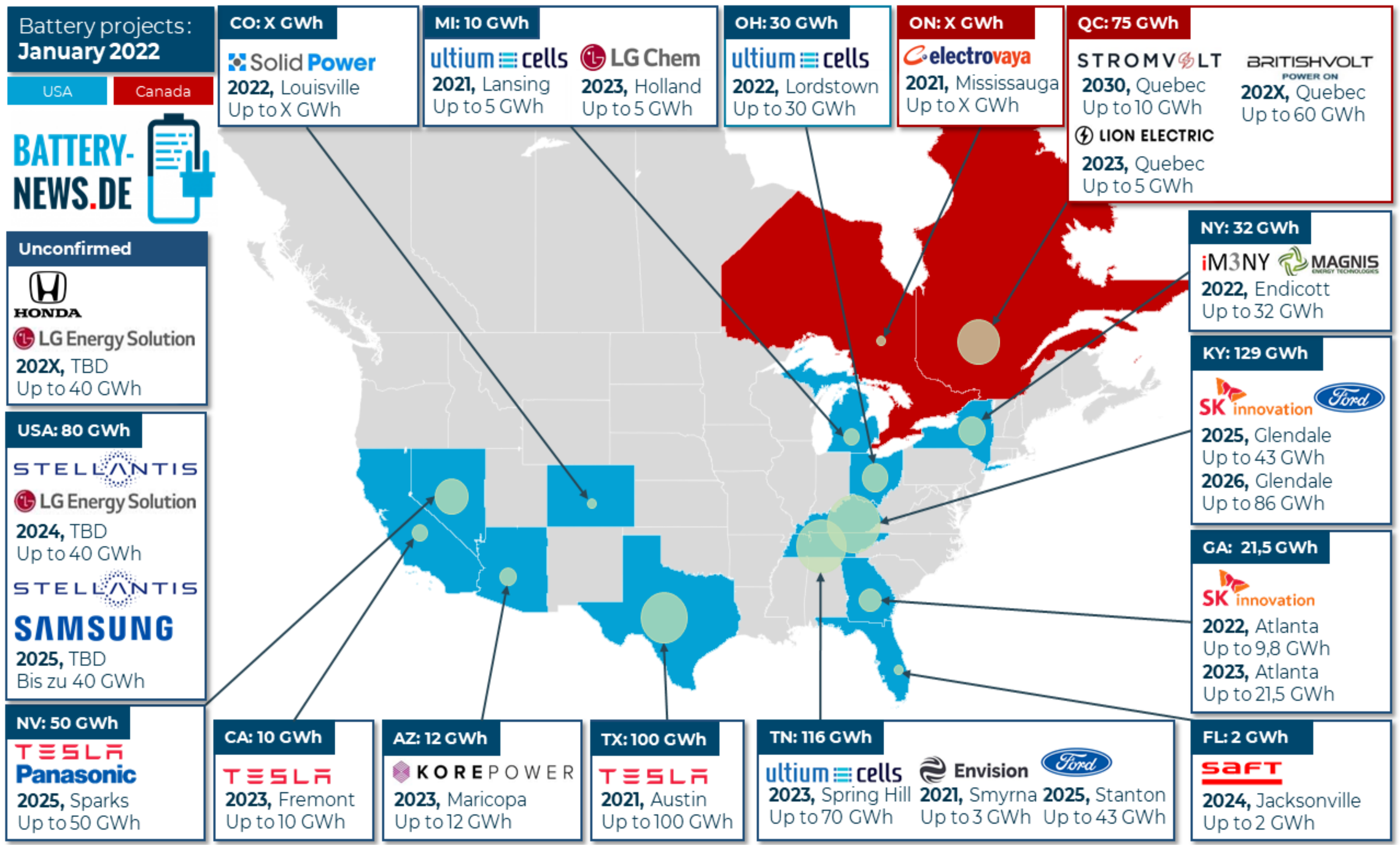
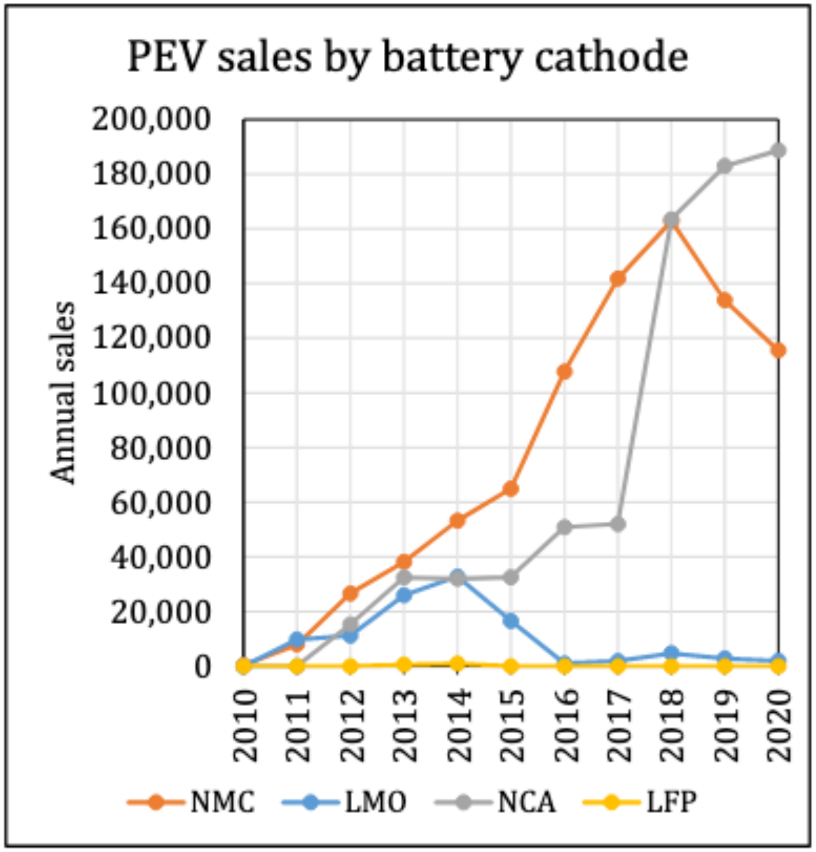


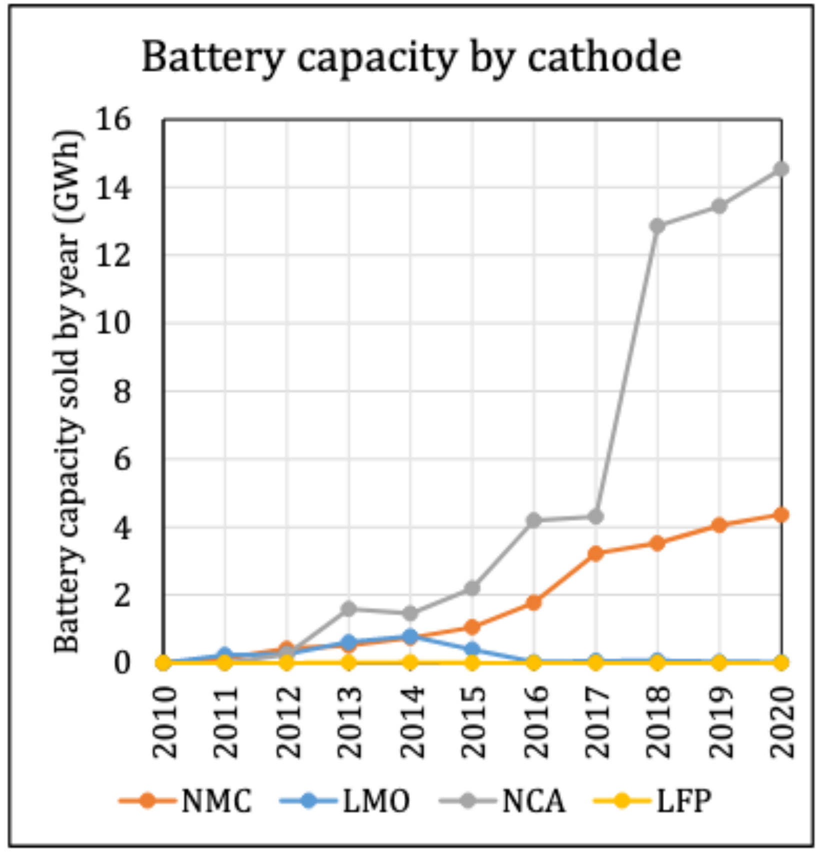
Critical Minerals

Critical Minerals List

		Net Import Reliance	
▲	BERYLLIUM	14%	*Alloying agent in aerospace and defense*
	MAGNESIUM	47%	*Furnace linings for manufacturing steel*
▲	GERMANIUM	50%*	*Fiber optics, night vision applications*
▲	LITHIUM	50%*	*Batteries*
▲	TUNGSTEN	50%*	*Used in wear-resistant metals*
	ZIRCONIUM	50%*	*High-temperature ceramics production*
	ALUMINUM	61%	*Used in almost all sectors of the economy*
▲	PLATINUM-GROUP METALS	68%†	*Catalytic agents*
▲	CHROMIUM	69%	*Stainless steel, other alloys*
▲	COBALT	72%	*Rechargeable batteries, superalloys*
▲	TIN	75%	*Coatings and alloys for steel*
	BARITE	75%*	*Cement and petroleum industries*
	TELLURIUM	75%*	*Steelmaking, solar cells*
	RHENIUM	80%	*Lead-free gasoline, superalloys*
	ANTIMONY	85%	*Batteries, flame retardants*
	TITANIUM	91%	*White pigment, metal alloys*

	TITANIUM	91%	*White pigment, metal alloys*
	POTASH	92%	*Fertilizer*
	BISMUTH	96%	*Used in medical and atomic research*
	VANADIUM	100%	*Used for titanium alloys*
	CESIUM	100%	*Used in research and development*
	FLUORSPAR	100%	*Aluminum manufacturing, gasoline, uranium fuel*
	GALLIUM	100%	*Integrated circuits, optical devices (e.g. LEDs)*
	GRAPHITE	100%	*Lubricants, batteries, fuel cells*
	INDIUM	100%	*LCD screens*
▲	MANGANESE	100%	*Steelmaking*
▲	NIOBIUM	100%	*Steel alloys*
▲	RARE EARTHS	100%	*Batteries, electronics*
	RUBIDIUM	100%	*Research and development in electronics*
	SCANDIUM	100%	*Alloys, fuel cells*
	STRONTIUM	100%	*Pyrotechnics, ceramic magnets*
▲	TANTALUM	100%	*Electronic components (e.g. capacitors)*


PEV sales by battery cathode
Annual sales
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
NMC
LMO
NCA
LFP


Battery capacity by cathode
Battery capacity sold by year (GWh)
16
14
12
10
8
6
4
2
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
NMC
LMO
NCA
LFP

Lithium-Based Battery Supply Chain

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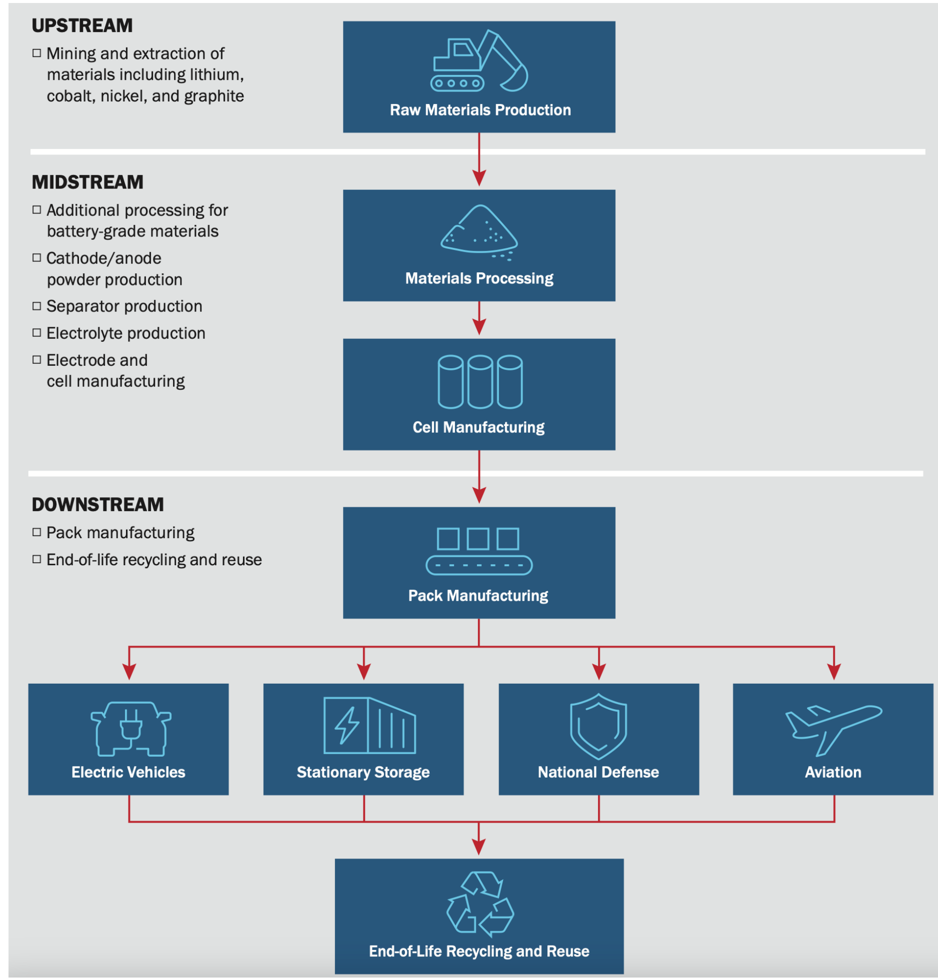
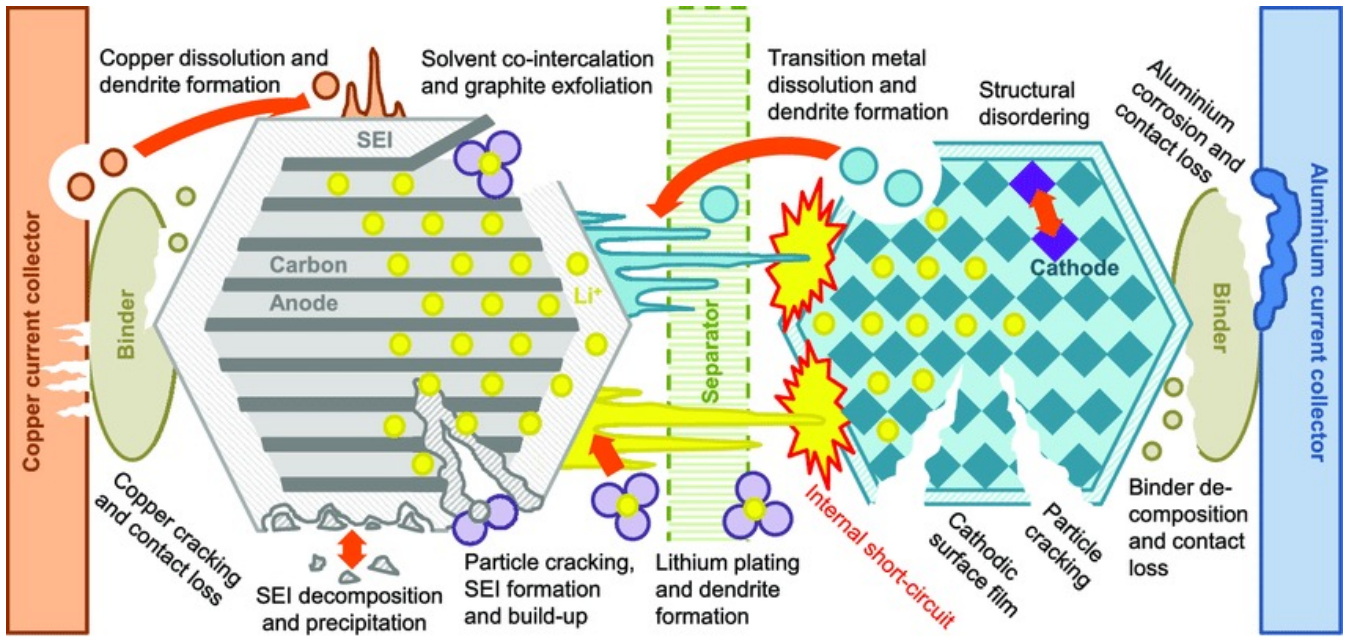


Overview Of Aging Mechanisms in Batteries

A lithium –ion battery incurs a variety of degradation mechanisms, but the major ones can be categorized into:

- SEI layer Formation
- Loss of Active Material
- Lithium Plating



Birkl CR, Roberts MR, McTurk E, Bruce PG, Howey DA. Degradation diagnostics for lithium ion cells. Journal of Power Sources. 2017 Feb 15;341:373-86.

Capacity Fade and Resistance Increase

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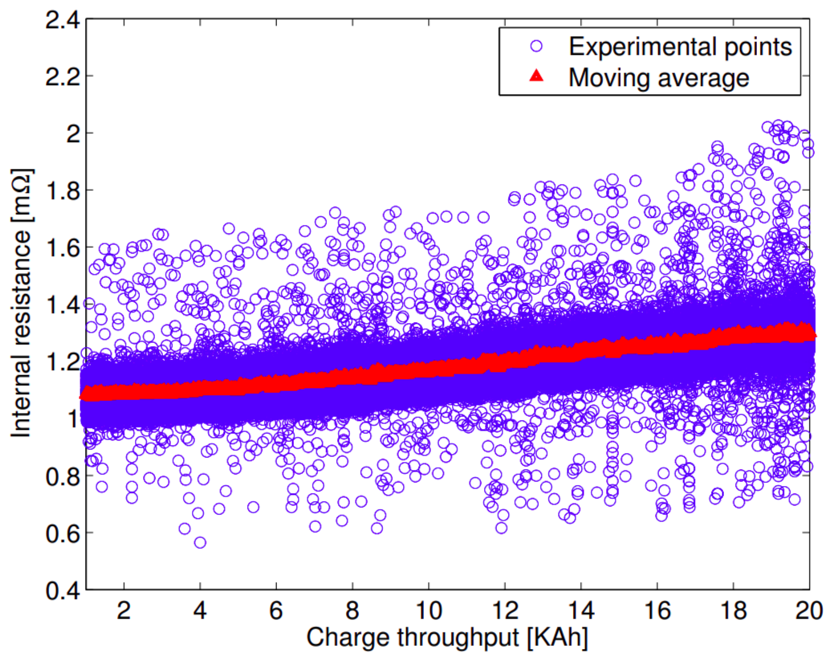
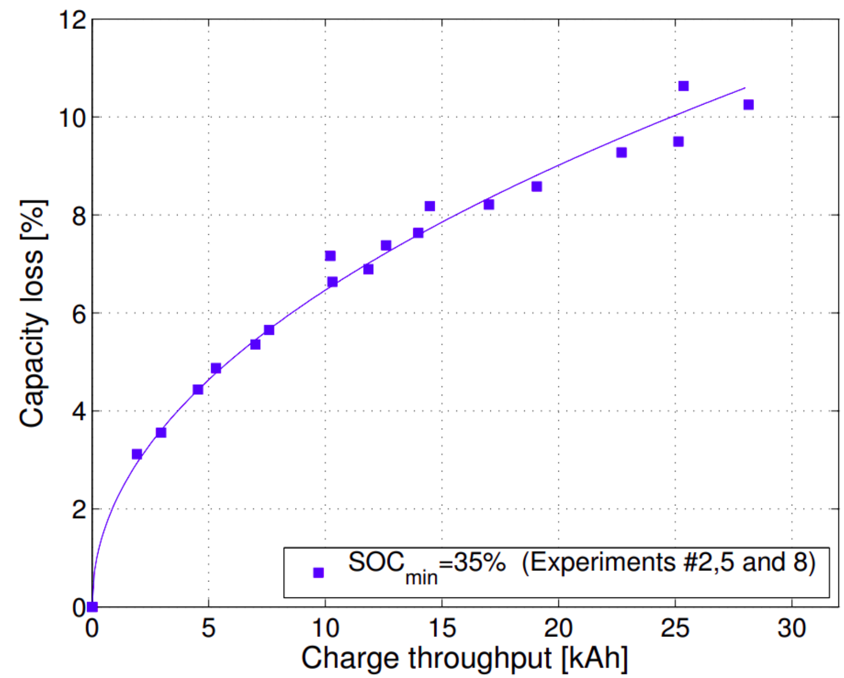
Battery cycling causes both resistance increase and capacity fade

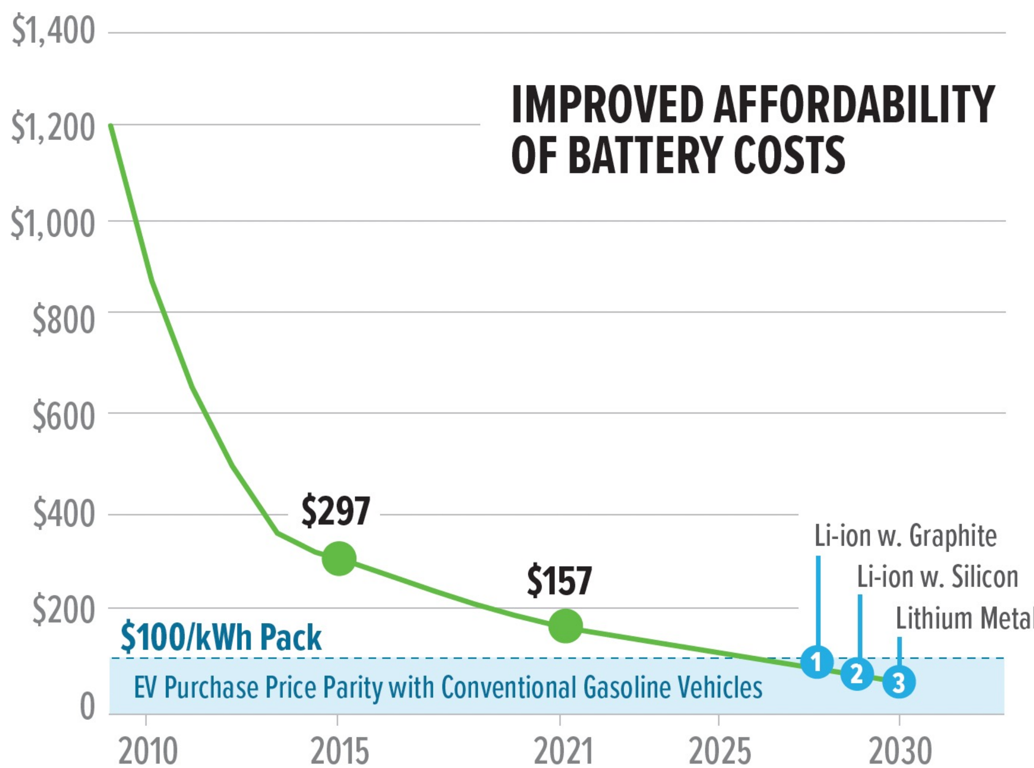




Cordoba-Arenas 2015

Battery costs are going down

Over the last 10 years, battery performance has improved and battery costs have been reduced substantially, making electrification of MHDVs more attractive



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.

Total Cost of Ownership (TCO)

TCO includes both the **capital expense** to purchase the vehicle and the **operating costs** (e.g., driver compensation, fuel, maintenance and repair, and insurance) over either the vehicle lifetime or the ownership period. If a business adds plug-in vehicles to its fleet and installs charging equipment, the amortized cost of the recharging system may be included in the TCO as well.

Argonne National Laboratory identified **8 key factors** as most important **cost components** for quantifying **TCO**

Cost Components	Major Gaps Addressed
Vehicle	Depreciation; Retail markup
Financing	Loan terms
Fuel	Charging infrastructure
Insurance	Annual & per-mile costs
Maintenance & repair	Annual & per-mile costs
Tax & fees	Registration; taxes
Payload changes	Estimation of payload loss
Labor	Cost of EV charging

https://www.energy.gov/sites/default/files/2021-07/van038_Gohlke_2021_o_5-27_455pm_LR_ML.pdf

Total Cost of Ownership TCO: Maintenance Break Down

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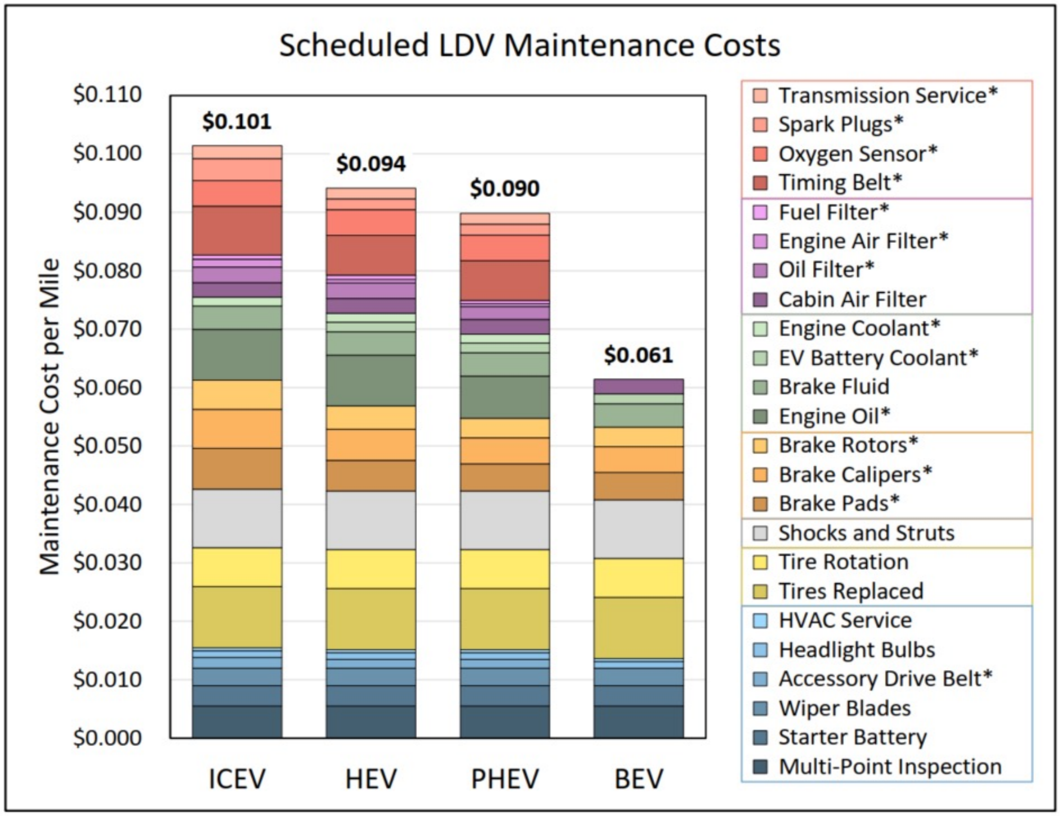


https://www.energy.gov/sites/default/files/2021-07/van038_Gohlke_2021_o_5-27_455pm_LR_ML.pdf

Energy Costs and Payback

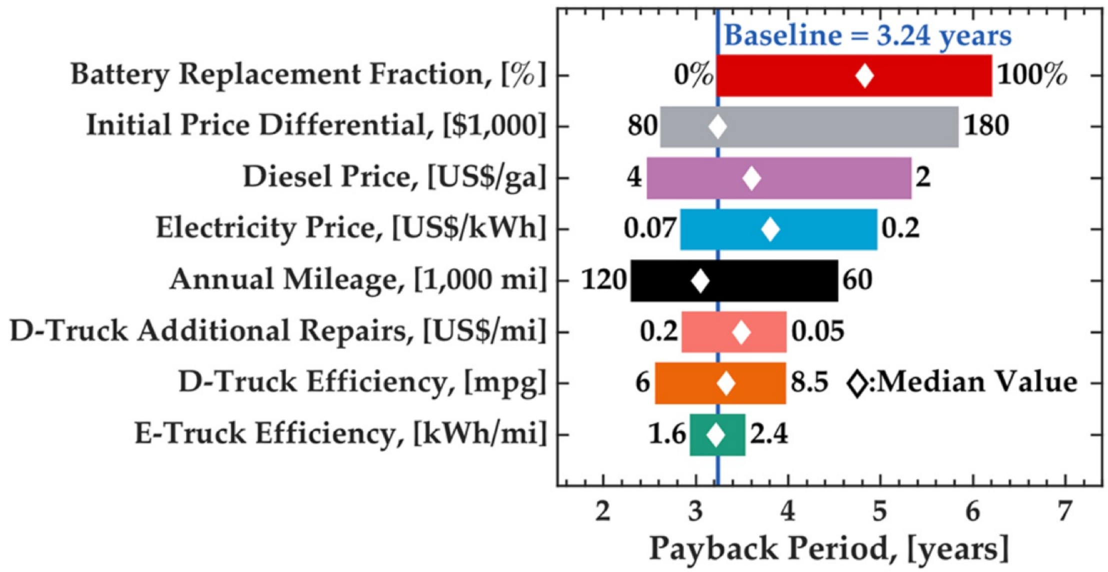
- With high annual vehicle miles traveled in the MHDV sector and high fuel consumption per mile, fuel costs will typically exceed the purchase price of the vehicle in a few years. This places high priority on the overall vehicle efficiency, even with EVs, to accrue fuel savings that will pay back the very high cost of energy storage in 2–3 years
- Based on the California Air Resources Board (CARB 2019), the reduction in operating costs can pay off an electric truck's higher initial purchase cost in few years

	Upfront Cost [US$]	Annual Miles	Fuel Economy [mpg | mi/kWh]	Consumption [gal | kWh]	Annual Energy Cost [US$]	Payback [years]
Class 2b – 3 Diesel	50,000	23,725	12.5	1,898	5,755	3.7
Class 2b – 3 Electric	67,000		2.0	11,863	1,151	
Class 4 – 5 Diesel	55,000	36,500	9.3	3,946	11,964	3.3
Class 4 – 5 Electric	85,500		1.3	23,077	2,723	
Class 6 – 7 Diesel	85,000		7.0	5,214	15,810	3.5
Class 6 – 7 Electric	125,000		0.8	45,625	4,426	

Steven Nadel and Eric Junga, Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers, American Council for an Energy-Efficient Economy ACEEE, January 2020

Payback Period Risk Factors for EVs

There are insufficient field data to establish a baseline for comparison against alternative truck types, including maintenance and repair costs, battery and vehicle expected lifetime, and vehicle residual value. Each unknown represents a risk for fleet owners.



Source: Shashank Sripad and Venkatasubramanian Viswanathan, “Quantifying the Economic Case for Electric Semi-Trucks,” ACS Energy Lett., 2019, 4 (1), pp 149–155)

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OUTLINE

BACKGROUND

ENERGY EFFICIENCY

ELECTRIC TRUCKS

BATTERY CHALLENGES

CONCLUSION

Organizations you should know

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APTA AMERICAN PUBLIC TRANSPORTATION ASSOCIATION

NTEA THE ASSOCIATION FOR THE WORK TRUCK INDUSTRY

National Truck Equipment Association

NACFE NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

North American Council for Freight Efficiency

Under the US Department of Transportation (DOT):

- Federal Highway Administration (FHWA)
- Federal Transit Authority (FTA)
- Federal Motor Carrier Safety Administration (FMCSA)

FMCSA Federal Motor Carrier Safety Administration

US Environmental Protection Agency (EPA)

CALIFORNIA AIR RESOURCES BOARD

California Air Resources Board (CARB)

Under the US Department of Energy (DOE)

- Vehicle Technology Office (VTO)
- Advanced Research Projects Agency – Energy

arpa·e

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