JCESR Joint Center for Energy Storage Research

Where is Electric Transportation Going?

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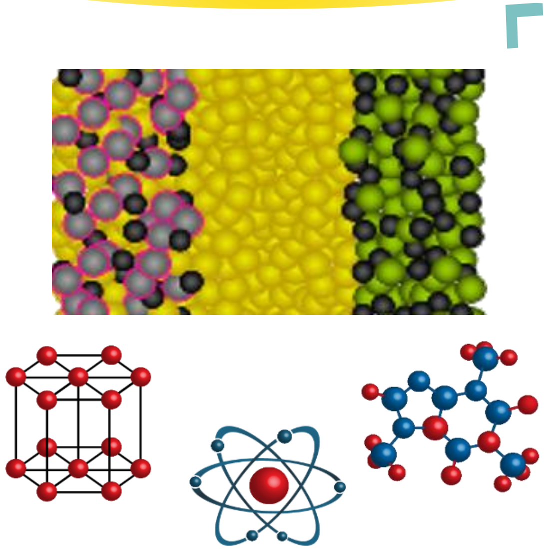
Transformative Materials, Chemistries and Architectures



Build Materials from the Bottom Up

Outline

Megatrends for Transportation

Cars, Trucks, Rail, Shipping, Aviation

Battery or Fuel Cell?

Recycling

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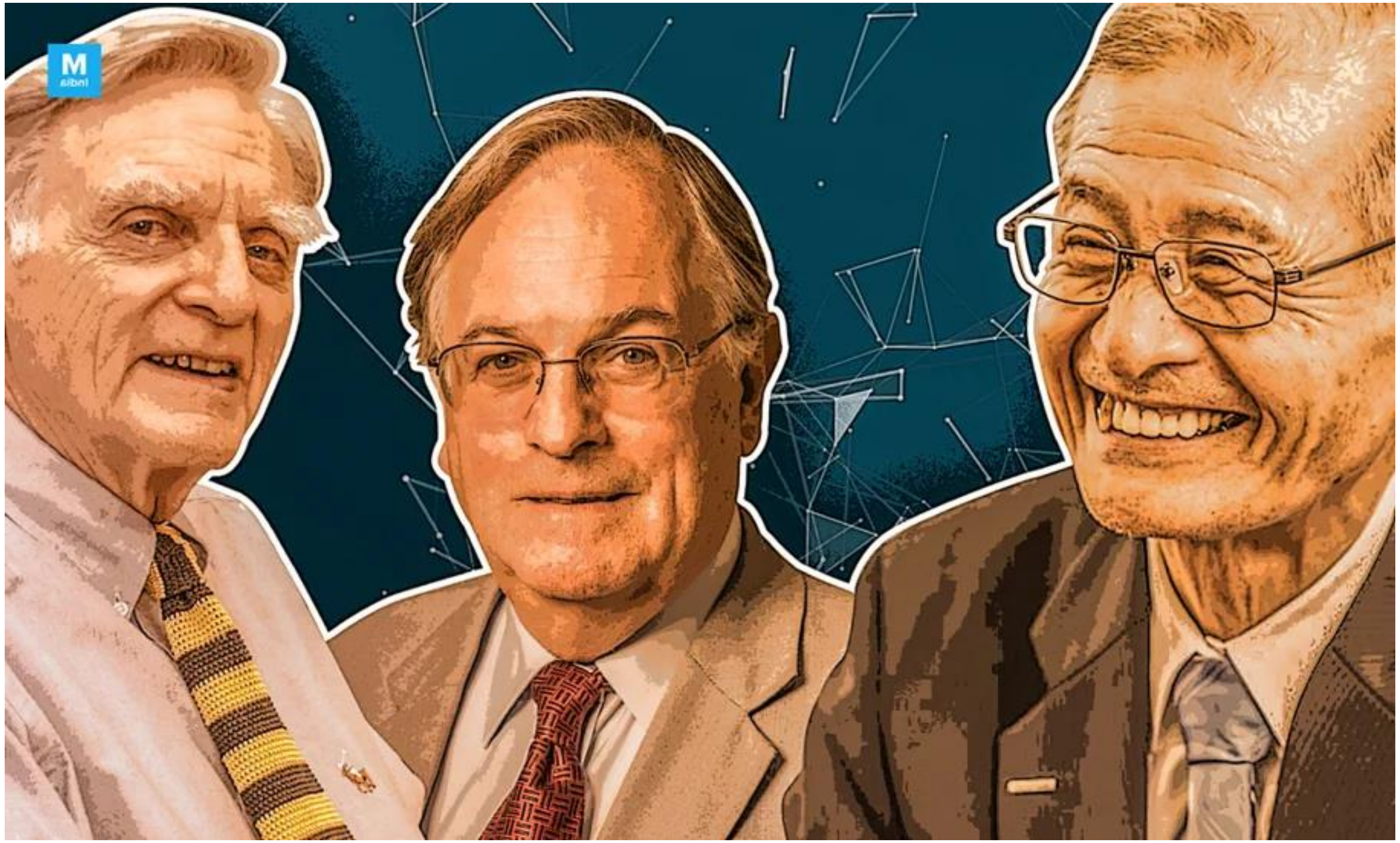
U.S. DEPARTMENT OF ENERGY

A3PS Conference Eco-Mobility
Vienna, Austria
November 19, 2020

2019 Nobel Prize in Chemistry Honors Lithium-Ion Batteries



John B. Goodenough, M. Stanley Whittingham and Akira Yoshino

recognized for research that "laid the foundation of a wireless, fossil fuel-free society."

Nobel Prize Committee October 9, 2019
https://www.nobelprize.org/prizes/chemistry/

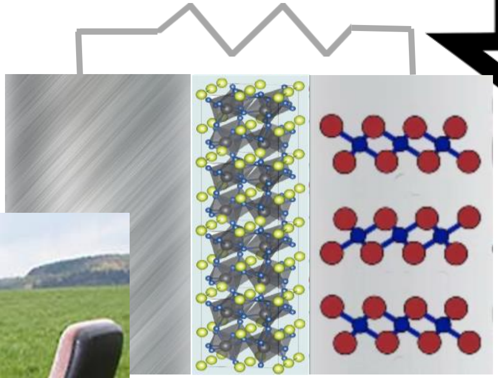
The story behind the Prize:: Martin Winter, Brian Barnett, Kang Xu, *Before Li Ion Batteries*, Chem Rev 118, 11433 (2018)

Megatrends Shaping Transportation

Lower Cost

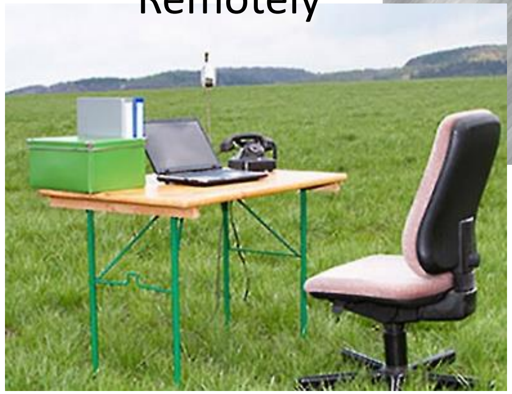
Climate Change

New Technology



Sector Coupling

Working Remotely



Secure Supply Chains (Oil, . . .)

Transportation is on the cusp of historic transformation

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Electrifying Transportation

Light vehicles →

battery electric

faster charging, lower cost, greater safety, longer lifetime

cost and convenience parity with gasoline

Buses →

battery, hydrogen fuel cell electric

Medium and heavy-duty freight trucks →

battery, hydrogen fuel cell electric

Rail (already electric) →

replace diesel generator by hydrogen fuel cell or catenary wire

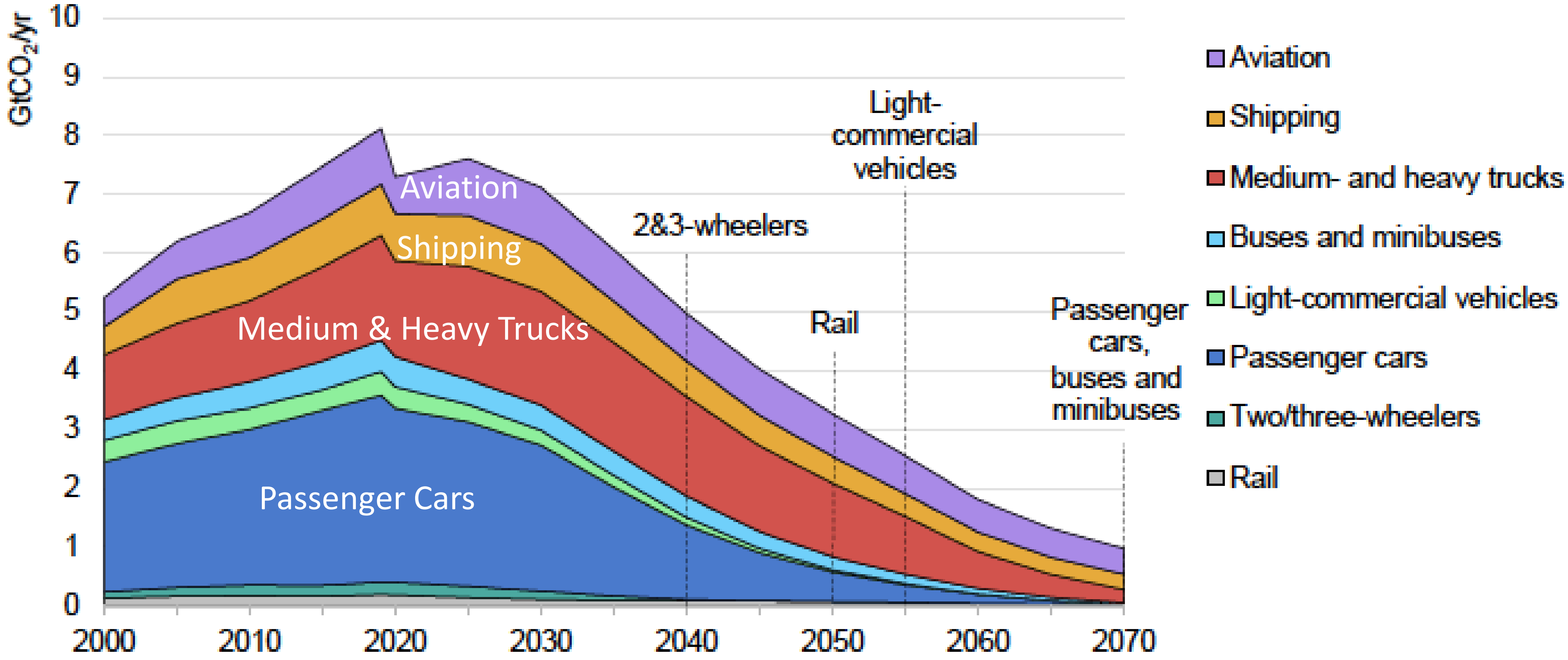
Marine shipping →

hydrogen fuel cell electric, hydrogen combustion

Aviation →

battery, hydrogen combustion, fuel cell, battery-combustion hybrid

Carbon Dioxide Emissions from Transportation



IEA Energy Technology Perspectives 2020

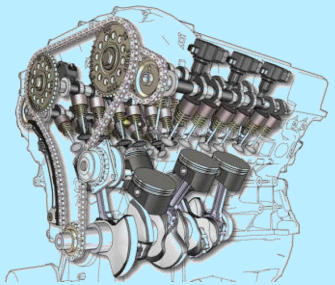
https://www.iea.org/reports/energy-technology-perspectives-2020

Battery and Fuel Cell Electric Vehicles - High or Low Cost?

Electric Vehicles

Fewer Moving Parts

Engine + Transmission



Hundreds

Electric Motor

One

Lower Maintenance Cost

Higher Efficiency

25% >90%

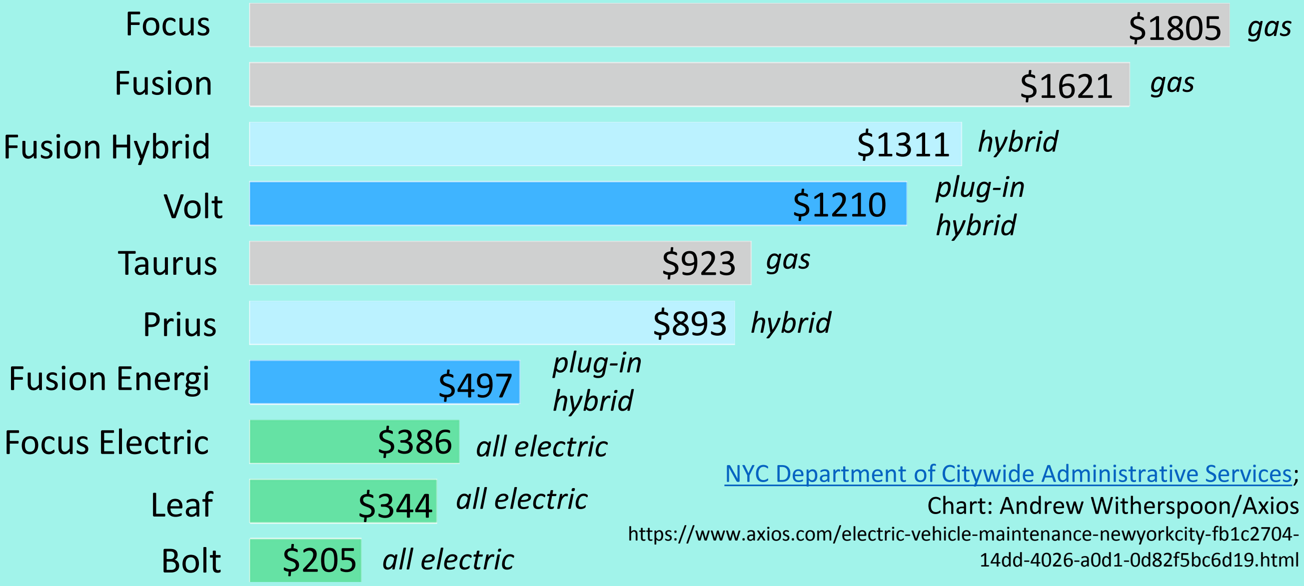
Lower Fuel Cost

Gasoline / mile $0.08 -$0.12

Electricity / mile $0.04 -$0.06

EVs are the economic choice for high mileage vehicles

Average maintenance cost for NYC municipal vehicles in 2018



[NYC Department of Citywide Administrative Services](); Chart: Andrew Witherspoon/Axios https://www.axios.com/electric-vehicle-maintenance-newyorkcity-fb1c2704-14dd-4026-a0d1-0d82f5bc6d19.html

Electric Vehicle Battery Cost:

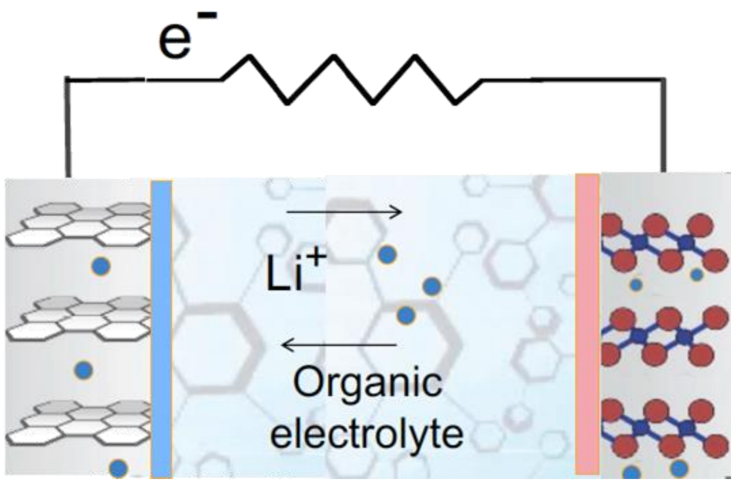
Barrier to Entry, Benefit for High Mileage and Fleet Use

Fleet vehicles switch to electric – high impact on sales and grid

Amazon will order 100,000 electric delivery vans from EV startup Rivian, delivery 2021-2024

https://www.theverge.com/2019/9/19/20873947/amazon-electric-delivery-van-rivian-jeff-bezos-order

Batteries or Fuel Cells?



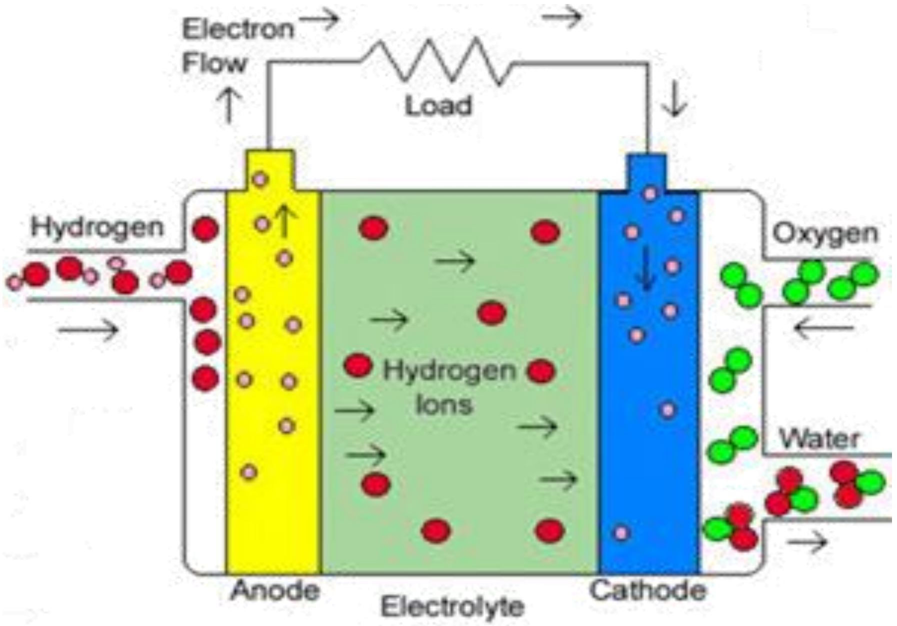
Li-ion Battery

Electricity in - Electricity out

>90% round trip efficiency

No carbon emissions if charged from renewable electricity

Heavy weight: Specific Energy ~ 0.2kWh/kg



Hydrogen Fuel Cell

"One-way battery without electrodes"

$2H_2 + O_2 \rightarrow 2H_2O$

No carbon emissions if fed "green" hydrogen from water electrolysis with renewable electricity

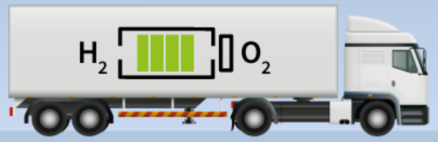
Light weight: Specific Power ~ 1.6 kW/kg

Battery or Fuel Cell for Heavy Duty Applications?

	Battery Electric	Fuel Cell Electric
Carbon Emissions	Zero if charged from emissions-free electricity Zero emission grid by 2050?	Zero if run on green H from water electrolysis Cost of electrolyzers and renewable electricity?
Range	Less: requires heavyweight batteries on truck: ~ 2 kWh/mi ~ 10 kg/mi	More – depends on lightweight H storage capacity on truck
100% refueling	8 hours conventional 1 hour at high power	10-20 min – high pressure filling of H tanks
Power	Less: slower battery chemical reaction	More: faster fuel cell chemical reaction
Infrastructure	Charging stations, electricity readily available	Green hydrogen cost and deployment, not commerially available
Sector Coupling Flexibility	Less: Grid+storage+transportation	More: Grid+storage+hydrogen
Supply Chain	Foreign sources of Li, Co, Ni, Mn, processed graphite	Water, renewable electricity, FC components - mostly domestic

Hydrogen vs battery electric trucks - Long distance

Trips up to 400 km represent 62% of EU truck activity

Parameters	Fuel cell electric truck	Battery electric truck
		
	2030	
Total cost of ownership over first 5-year user period (based on France)	**€ 459 k**	**€ 393 k**
Vehicle purchase costs	€ 139 k	€ 167 k
Annual renewable fuel costs[1]	€ 38 k	€ 22 k
Cost parity with diesel without subsidies	**Mid 2040s**	**Early 2030s**
Economies of scale with cars	**Low**	**High**
Max range without refuelling / recharging	**1200 km**	**800 km**
Refuelling / recharging time (full)	**10-20 minutes**	**8 hours (overnight) 60 minutes (opportunity)**
Net payload loss (weight)[2]	**None**	**None**

1: Renewable fuel costs are incl. taxes, levies and charges, transport and distribution costs for electricity and fuel; assuming renewable hydrogen cost for the end user of € 5.40/kg (2030) and renewable electricity cost for the end user of €-cent 15.26/kWh (2030).

2: Additional weight from the onboard battery pack (assumed energy density of 318 Wh/kg in 2030) of 4.2 t is compensated for by the additional ZEV weight allowance (2 t) under the EU Weights & Dimensions Directive and net savings from replacing a conventional with an electric drivetrain (2.4 t).

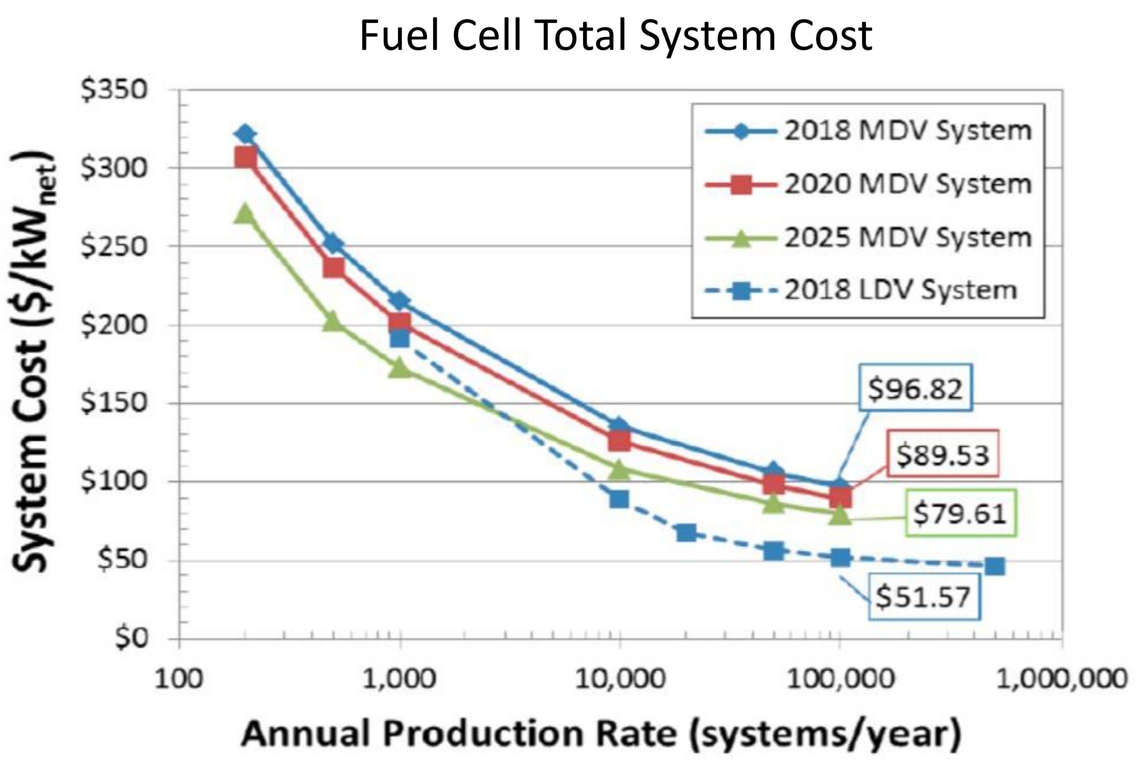
Better →

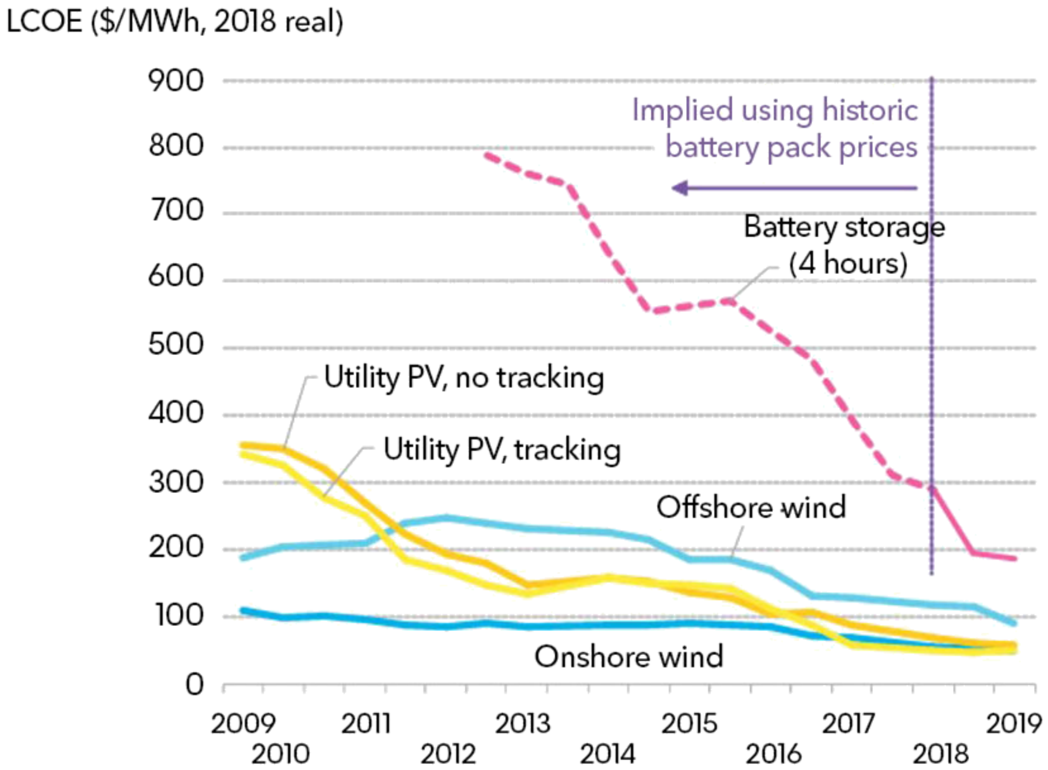
TRANSPORT & ENVIRONMENT
transportenvironment.org

For methodology and sources see also:
https://www.transportenvironment.org/sites/te/files/2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf

Transport and Environment: Comparison of Hydrogen and Battery Electric Trucks
https://www.transportenvironment.org/sites/te/files/publications/2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf

Fuel Cell and Battery Costs Follow Similar Paths





Source: BloombergNEF. Note: The global benmark is a country weighed-average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system running at a daily cycle and includes charging costs assumed to be 60% of whole sale base power price in each country.

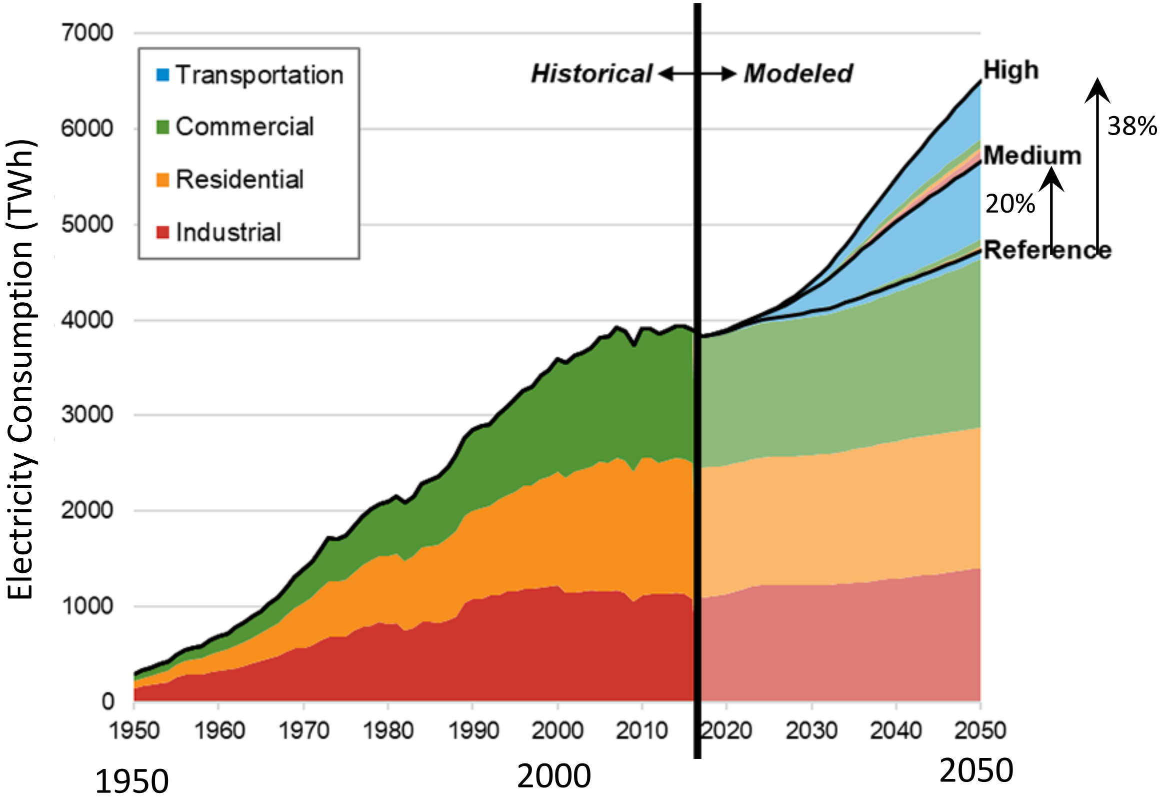
Source: Burke and Sinha, *Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040*, National Center for Sustainable Transportation, UC Davis, March 2020, *https://escholarship.org/uc/item/7s25d8bc*

https://about.bnef.com/blog/battery-powers-latest-plunge-costs-threatens-coal-gas/

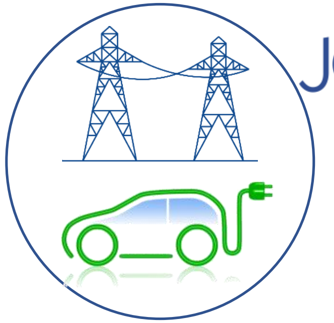
High Production → Low Cost

Electric Vehicles Enable Sector Coupling Flexibility

EVs could increase electricity demand by 20% - 38% in 2050



Source: NREL, https://www.utilitydive.com/news/evs-could-drive-38-rise-in-us-electricity-demand-doe-lab-finds/527358/



Integrates transportation and the electricity grid into a single universal energy system

Frees transportation from dependence on foreign oil

Path to decarbonize transportation along with electricity grid

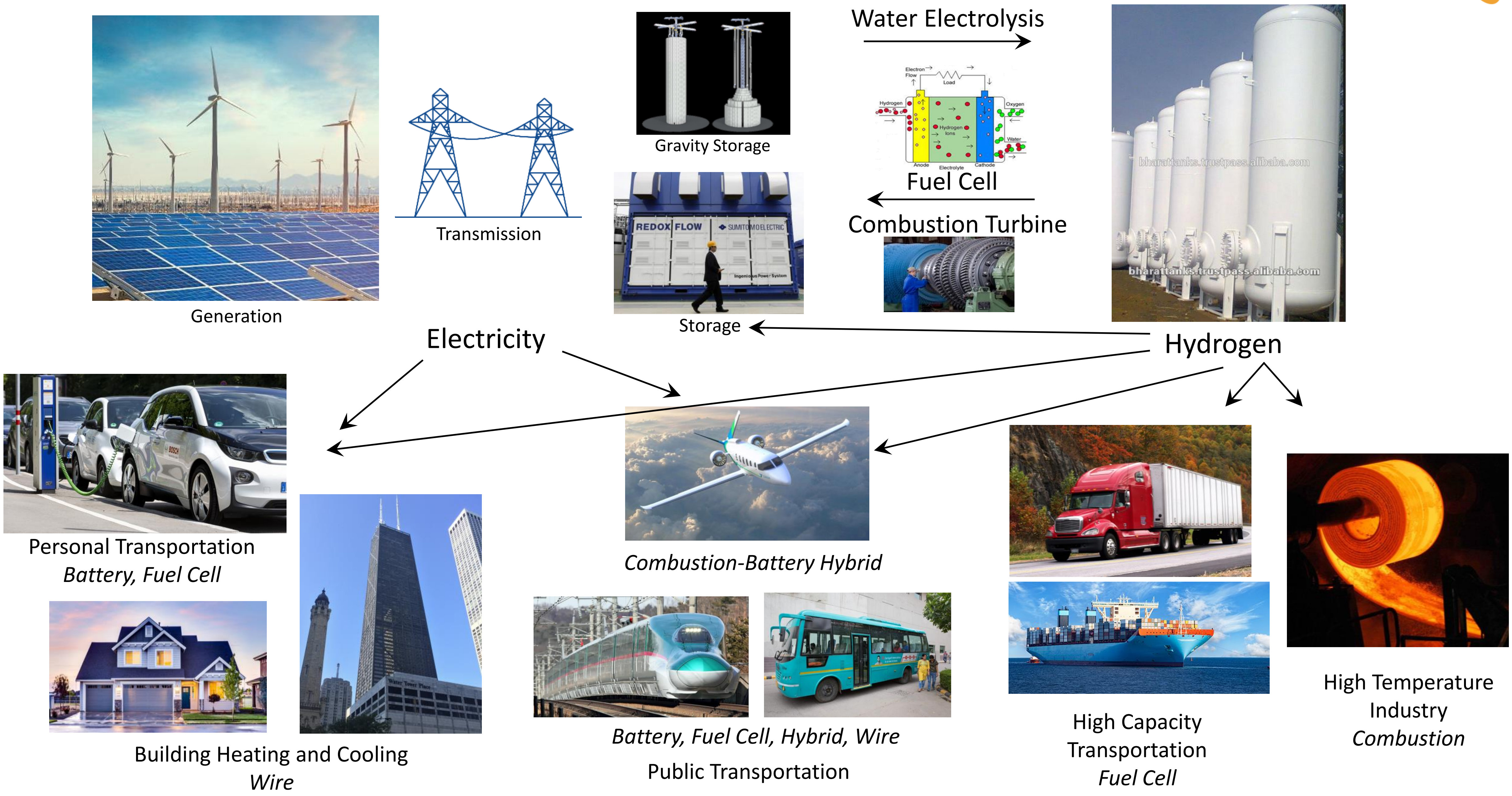
How to meet additional demand?
- *Charge off peak to avoid building new generation capacity*

Off-peak capacity is typically idle gas peaker plants

→ *Significantly greater carbon emissions than renewable charging*

Solution: Charge EVs only with renewable electricity
Replace gas peaker plants with storage

Electricity+Storage+Hydrogen: A Fully Integrated, Flexible, Decarbonized Energy System



Two Kinds of All-Electric Flight

Scale up prototype all-electric air taxis

Urban Air Taxi
Boeing's first autonomous air taxi flight ends in fewer than 60 seconds. Jan 19, 2019
https://www.cnn.com/2019/01/23/tech/boeing-flying-car/index.html

Expected deployment 2020-2025

Eviation Aircraft "Alice" https://www.eviation.co/alice/
9 passengers, 650 mile range, 275 mph, 10 000-30 000 ft, Li-ion 900kWh, propellers on tail and wingtips, $4M
Planes bought by Cape Air, Barnstable MA, for short hop coastal flights

Electrify full size plane

Hybrid-electric passenger flight

VoltAero Cassio
https://en.wikipedia.org/wiki/VoltAero_Cassio
Ampaire Electric EEL
https://en.wikipedia.org/wiki/Ampaire_Electric_EEL

https://robbreport.com/motors/aviation/hybrid-electric-airplane-rewrite-aviation-two-years-2919373/

4 to 6 passengers
1 fossil engine 170 kW (230 hp)
5 electric motors 60 kW (80 hp) each
Speed: 370 km/h (230 mph, 200 kn)
Hybrid range: 1,200 km (750 mi, 650 nmi)
Electric range: 200 km (110 nmi)

Paris Air Show
Le Bourget, Paris, June 17-23, 2019

Li-ion Recycling – a Ripe Opportunity

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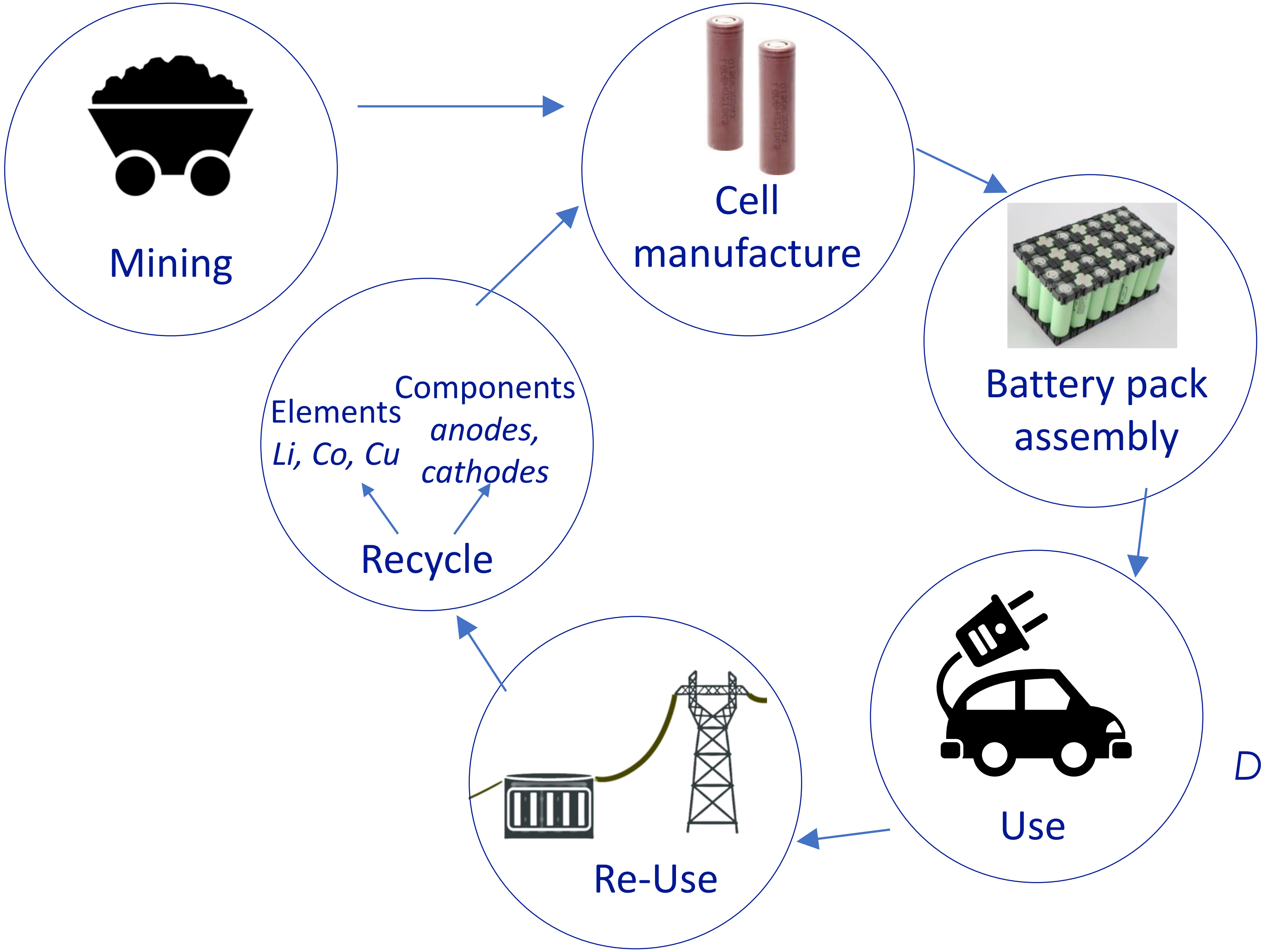


> 99% of lead-acid batteries recycled

< 5% of Li-ion batteries recycled

Growing EV market → Li-ion recycling

Design for re-use and recycle

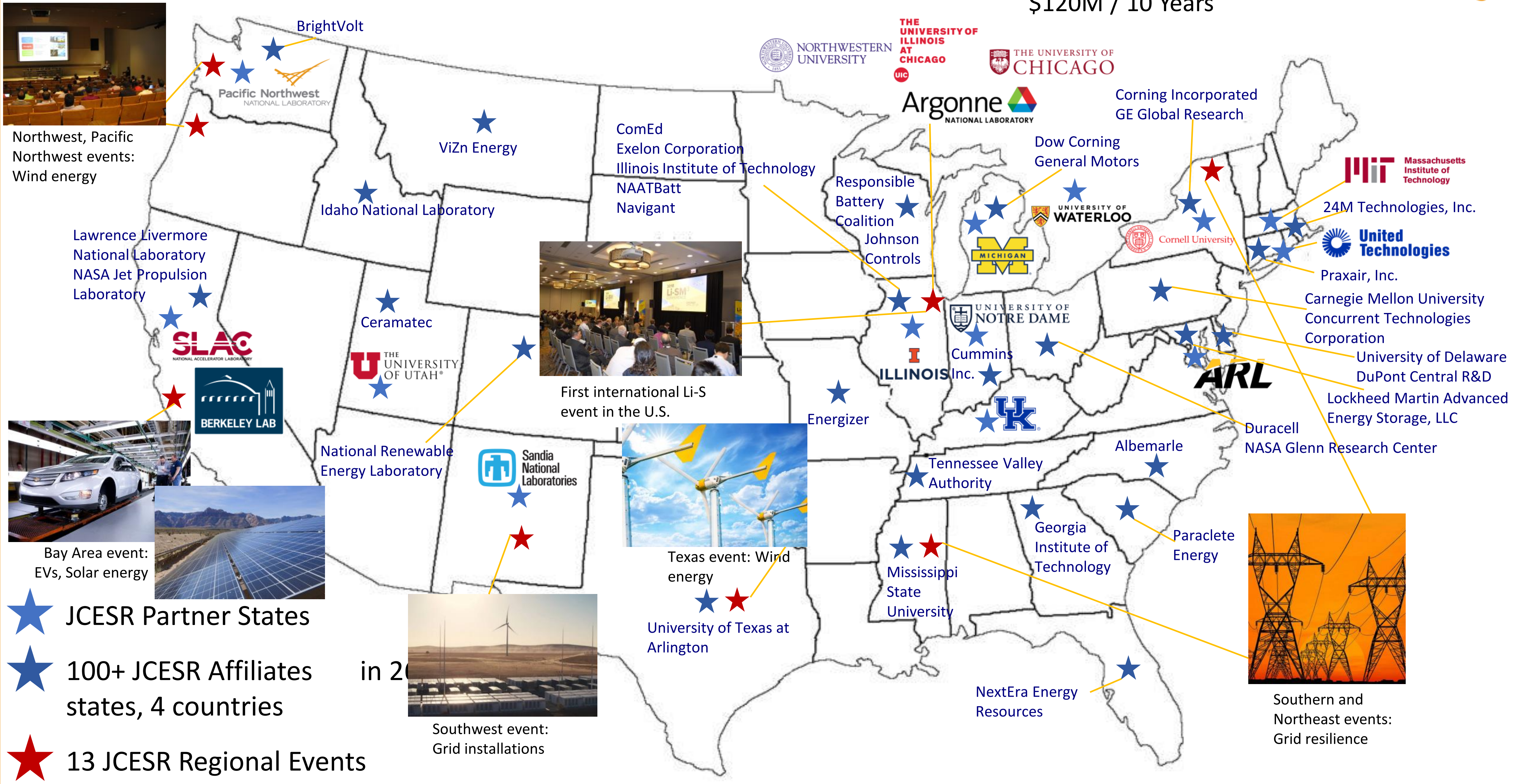
DOE launches first lithium-ion battery recycling R&D center
Feb 15, 2019

ReCell
ADVANCED BATTERY RECYCLING

https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell

JCESR's National Presence

18 Partner Institutions
>150 researchers
$120M / 10 Years



Three Primary Directions

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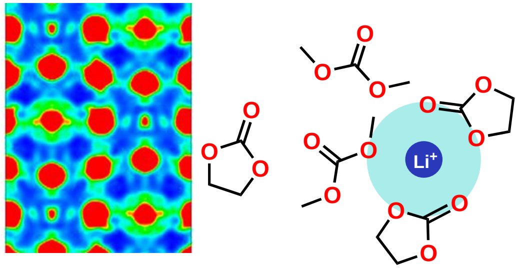
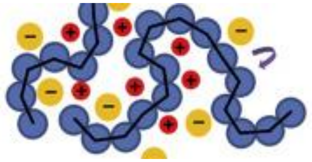
Liquid and Solid Solvation



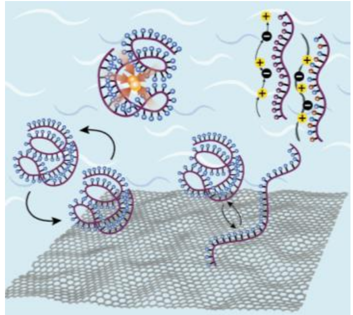


Solids, Liquids, Polymers, Membranes

Motivation

Solvation controls nearly every electrochemical phenomena required to store and release energy in batteries

Redoxmer Design

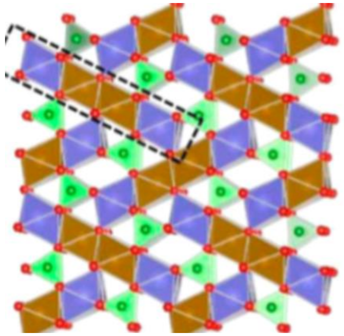


Redox-active polymers for flow batteries

Motivation

Immense untapped design space for disruptive redox-flow battery performance

Multivalent Ion Materials Design



Mg^{++}, Ca^{++}, Zn^{++} working ions

Motivation

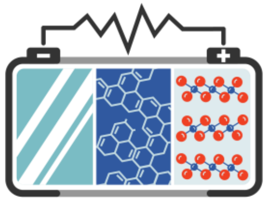
High energy density

Unexplored new MV solvation, reaction, and interfacial phenomena

Extensive use of Electrolyte Genome, Materials Project and Machine Learning

End Users

A diversity of batteries for a diversity of uses



Meet all performance requirements simultaneously

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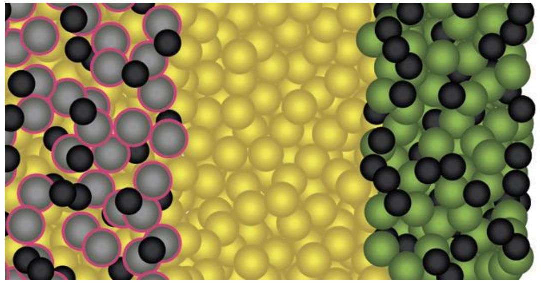
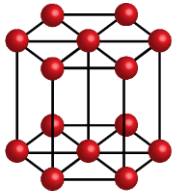
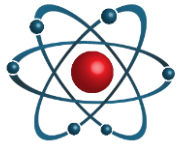
Transformative Materials, Chemistries, and Architectures



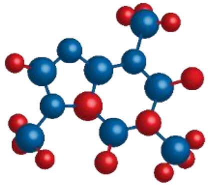
Build Batteries from the Bottom Up



Crystals



Atoms



Molecules

Trahey et al, Energy Storage Emerging: A Perspective from JCESR, PNAS 117, 12550 (2020)

Further Reading

Energy Storage Outlook

Arbabzadeh et al, *The role of energy storage in deep decarbonization of electricity production*, Nature Communications 19, 3413 (2019)

Albertus et al, Long-Duration Electricity Storage Applications, Economics, and Technologies, Joule 4, 1 (2020)

Ziegler et al, Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization, Joule 3, 2134 (2019)

Electric Vehicles

Crabtree, *The Coming Electric Vehicle Transformation*, Science 366, 422 (2019)

International Energy Agency, *Global EV Outlook 2019* (May 2019), https://www.iea.org/reports/global-ev-outlook-2019

Transport and Environment, *Electric Surge-Carmakers Electric Car Plans Across Europe, 2019-2025*, https://www.transportenvironment.org/sites/te/files/publications/2019_07_TE_electric_cars_report_final.pdf

Hydrogen

Staffell et al, The role of hydrogen and fuel cells in the global energy system, Energy Environmental Science 12, 463 (2019)

Recycling Li-ion Batteries

Mayyas et al, *The case for recycling: Overview and challenges in the materials supply chain for automotive Li-ion batteries*, Sustainable Materials and Technologies 19, e00087 (2019)

Thank You!