Pacific Northwest
NATIONAL LABORATORY

Emerging Technologies

Opportunities & Challenges for Washington

January 2020
Washington Energy Strategy Advisory Committee

Angela Becker-Dippmann

Strategy Advisor
Energy & Environment Directorate

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

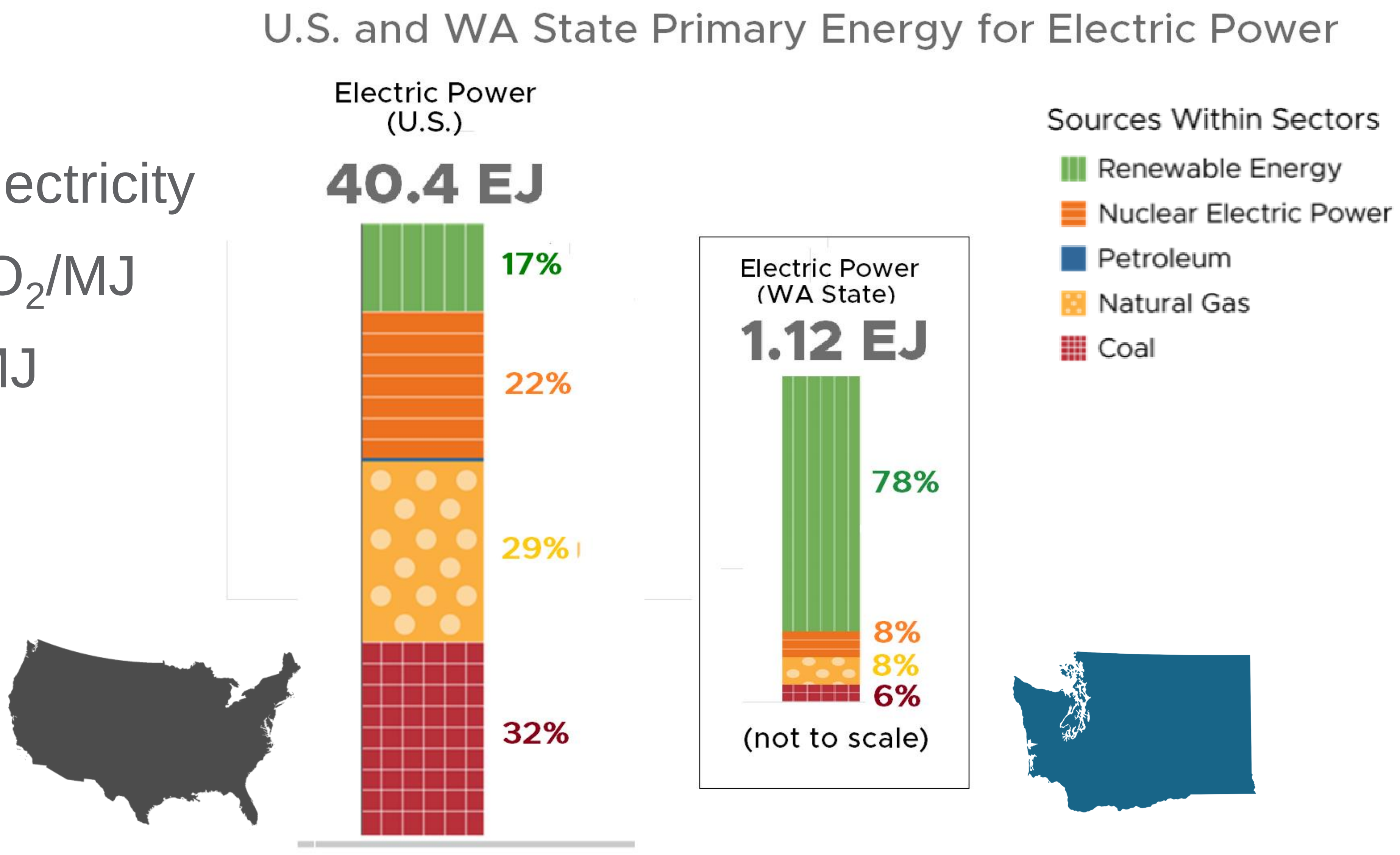
PNNL-SA-143818

Mission-driven locations empower collaboration

The primary energy used to generate electricity in WA State differs dramatically from the nation, and is among the cleanest

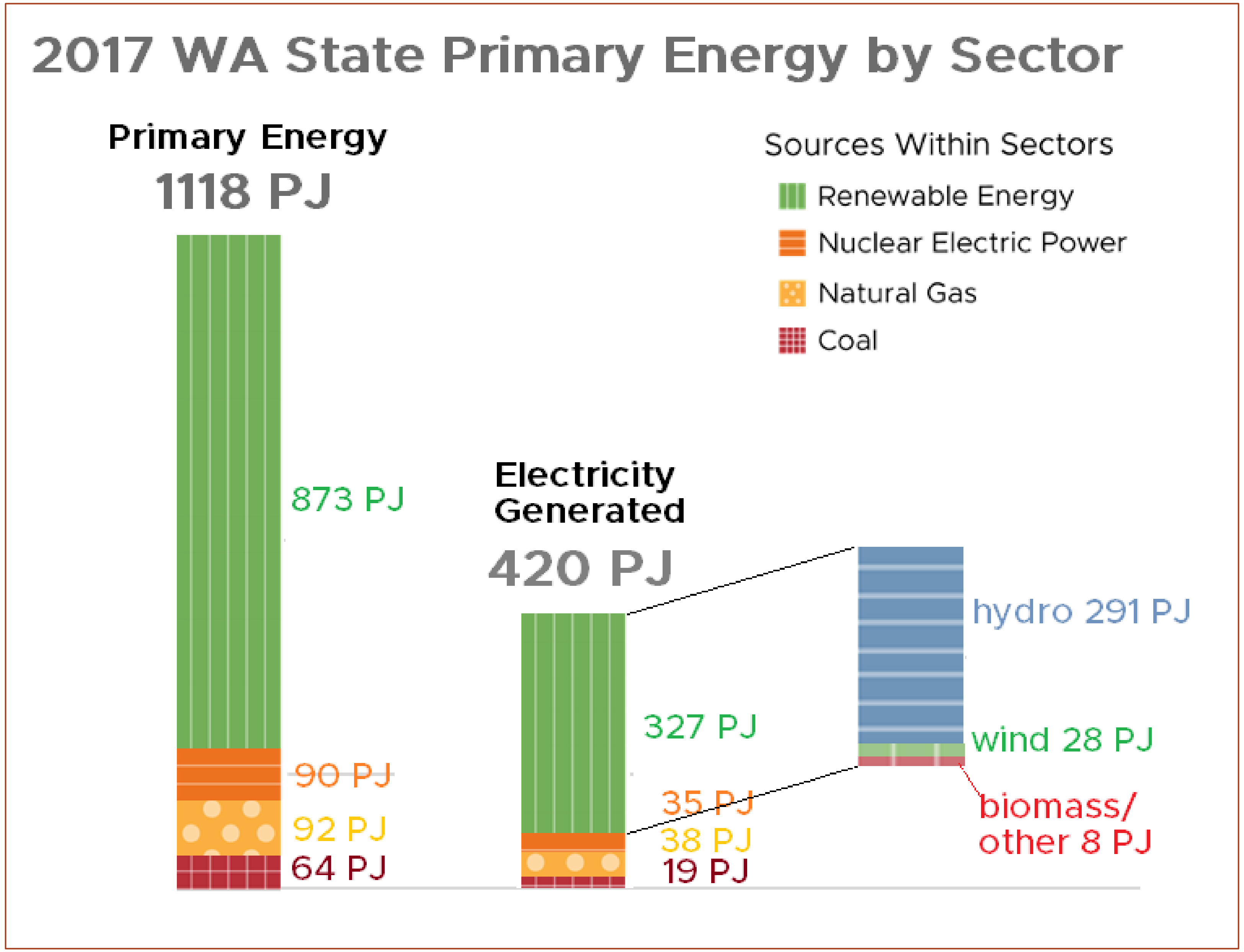
CO_2 from generating electricity

- WA state 25.36 g CO_2/MJ
- U.S. 124.83 g CO_2/MJ

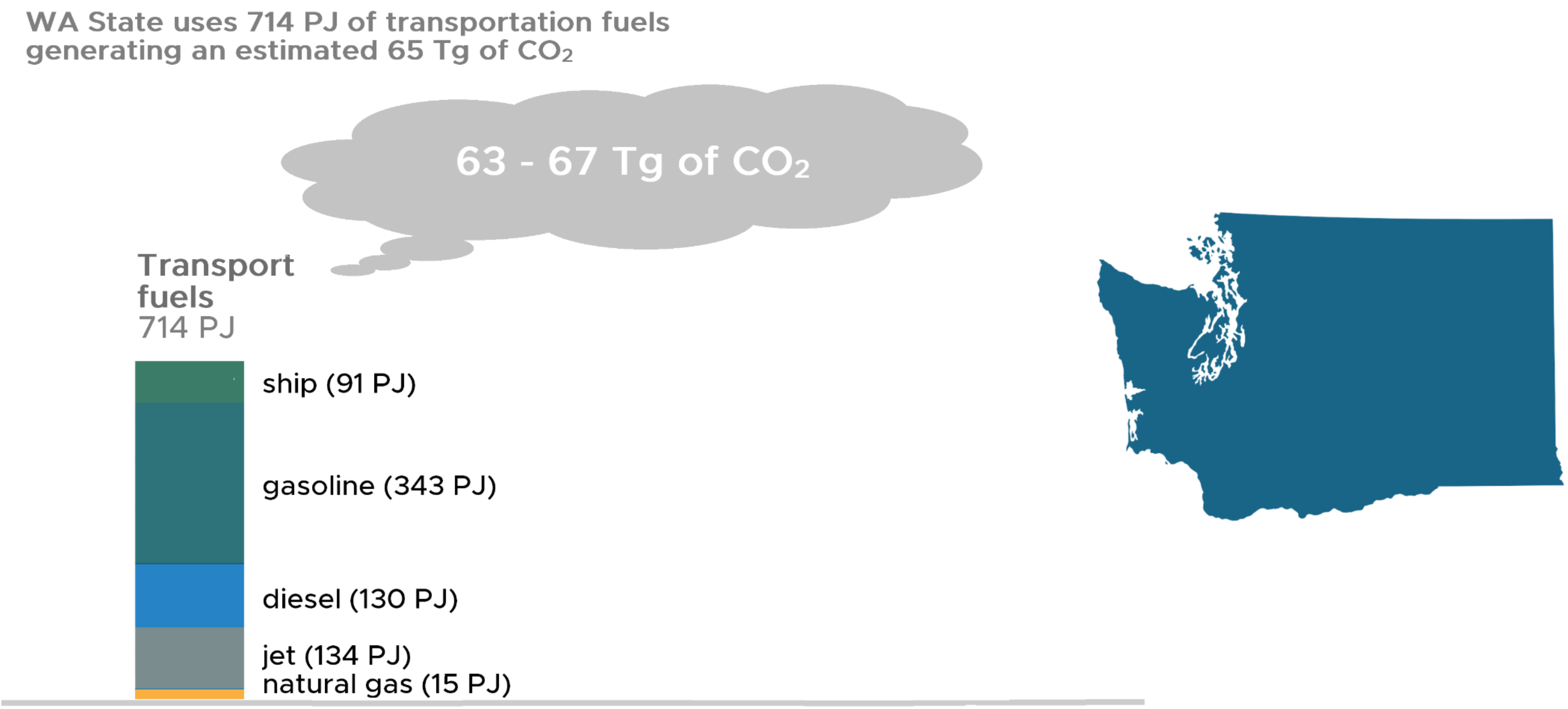


From 1118 PJ of primary energy WA State generates 420 PJ of low cost electricity which also generates 10.7 Tg of CO_2

- Hydro, 291 PJ (69%)
- Wind, 28 PJ (7%)
- Other, 8 PJ (2%)
- Nuclear, 35 PJ (8%)
- Natural gas, 38 PJ (9%)
- Coal, 19 PJ (5%)



The transportation sector in WA generates an estimated 65 Tg of CO_2



Based on GREET, Han et al. Fuel 157 (2015) 292-298 (https://doi.org/10.1016/j.fuel.2015.03.038)
(87-95 g CO_2/MJ of energy)

Building-Grid Integration

Realizing benefits beyond energy savings

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Integrating Buildings with the Electric Grid
Fast facts

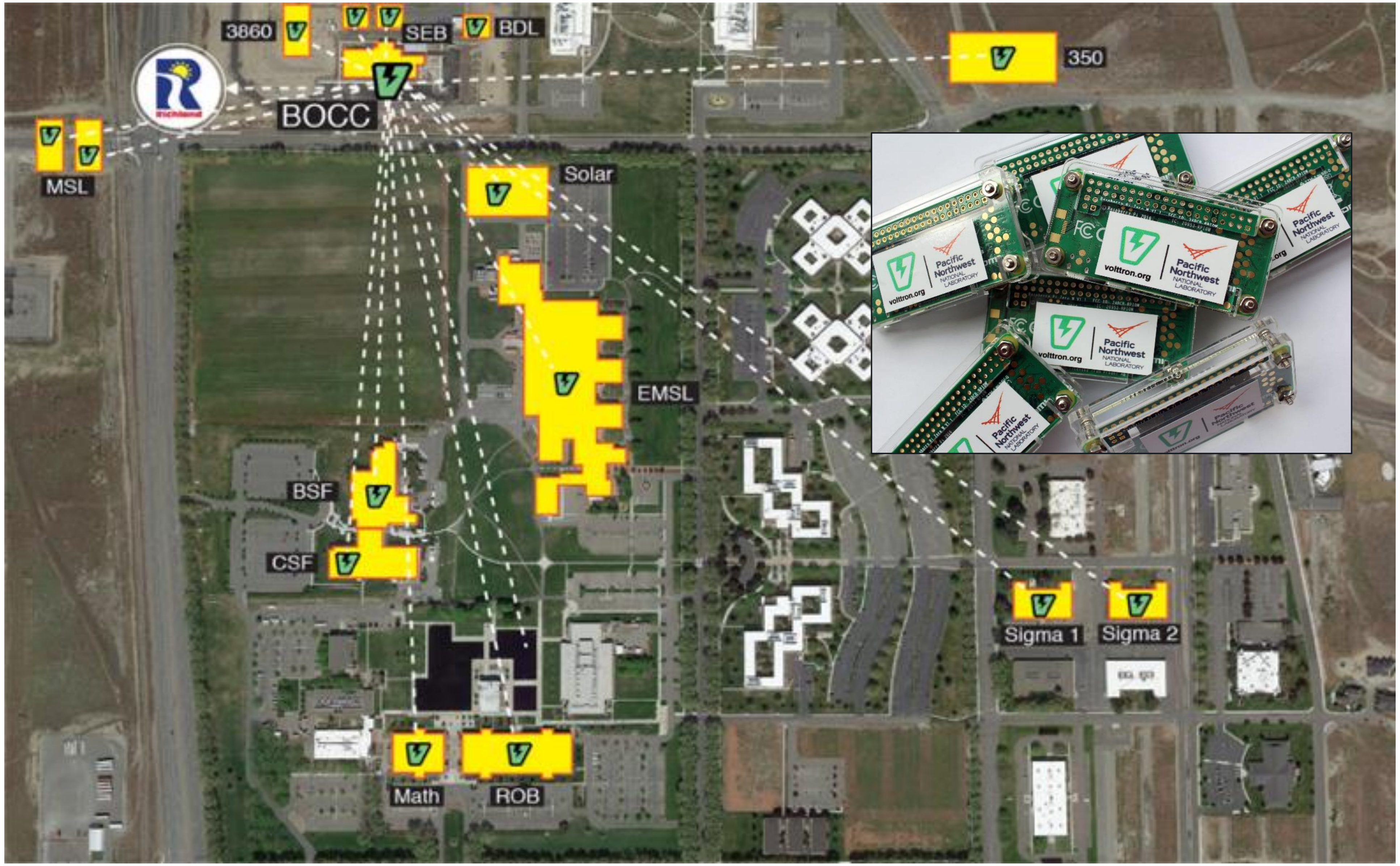
- The U.S. has 125 million homes and more than 5 million commercial buildings
- Nearly 75 percent of all U.S. electricity is consumed within buildings
- Electricity currently goes to functions such as air conditioning and lighting
- Increasingly, buildings will also use electricity to charge electric vehicles and buildings will generate and store electricity onsite with resources such as solar photovoltaic arrays and batteries

How Could Buildings Support or Enhance Electricity Grid Reliability?

Our goal is to develop the technology that enables utilities to cost-effectively and continuously engage up to 70% of their customers as grid assets **and** demonstrate the feasibility of this technology to stakeholders within five years

Challenge: Control & Coordination of Multiple Commercial Buildings and Their Assets

- Coordinate assets with a signal from the utility
- Simultaneously identifying energy efficiency measures
- PNNL campus is a unique experimental platform



Technology Gaps & Key R&D Needs
Informing the future

More advances are required to capitalize on the technology and information revolution around buildings

- Automatic collection of big data for optimizing building operations
- Advanced data analytics and machine learning
- Advanced control theories
- Stakeholder engagement
- Cybersecurity best practices

Pacific Northwest NATIONAL LABORATORY

Grid-Scale Storage

Enhancing System Resilience

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Pacific Northwest
NATIONAL LABORATORY

Grid Storage Efforts at PNNL

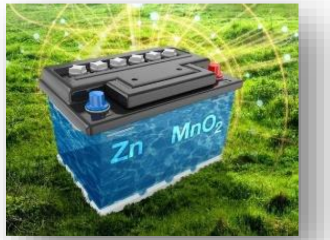
Office of
ELECTRICITY

Cost Competitive Technologies

Redox Flow

Sodium

$Zn-MnO_2$



Regulatory Support

WASHINGTON
UTC
UTILITIES AND TRANSPORTATION COMMISSION

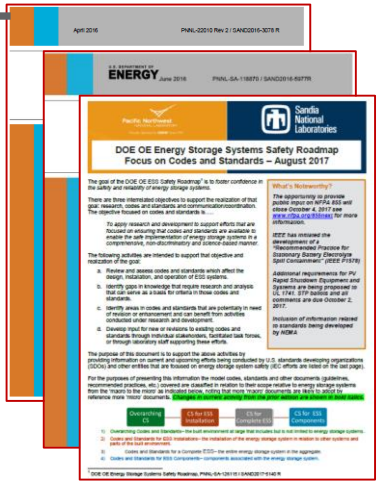
PUCN

PUBLIC UTILITY COMMISSION OF TEXAS

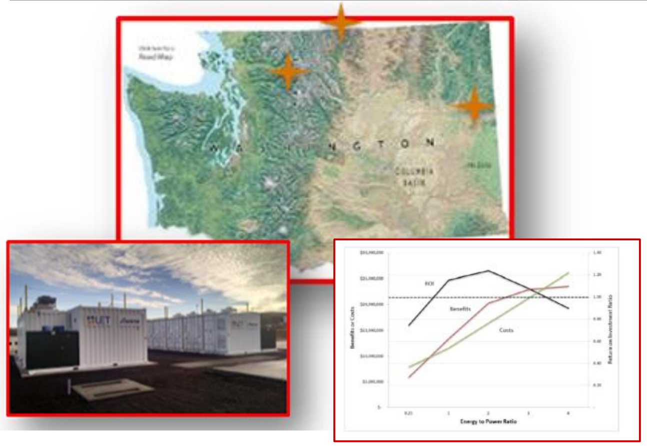
Oregon PUC
Public Utility Commission

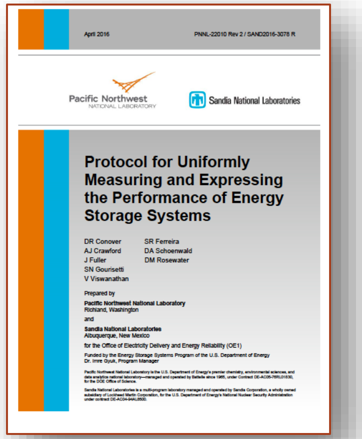
STATE OF HAWAII
1959
STATE OF HAWAII
PUBLIC UTILITIES COMMISSION

Safety and Reliability



Industrial Acceptance





We engage partners across all sectors

- Utilities
- Industry
- State/Regulatory Support
- University Partners
- Partner Laboratories

PNNL Supporting 26MW of Grid Storage Deployed Across the Nation

26 MW 104 MWh at 14 Sites

Funded by:

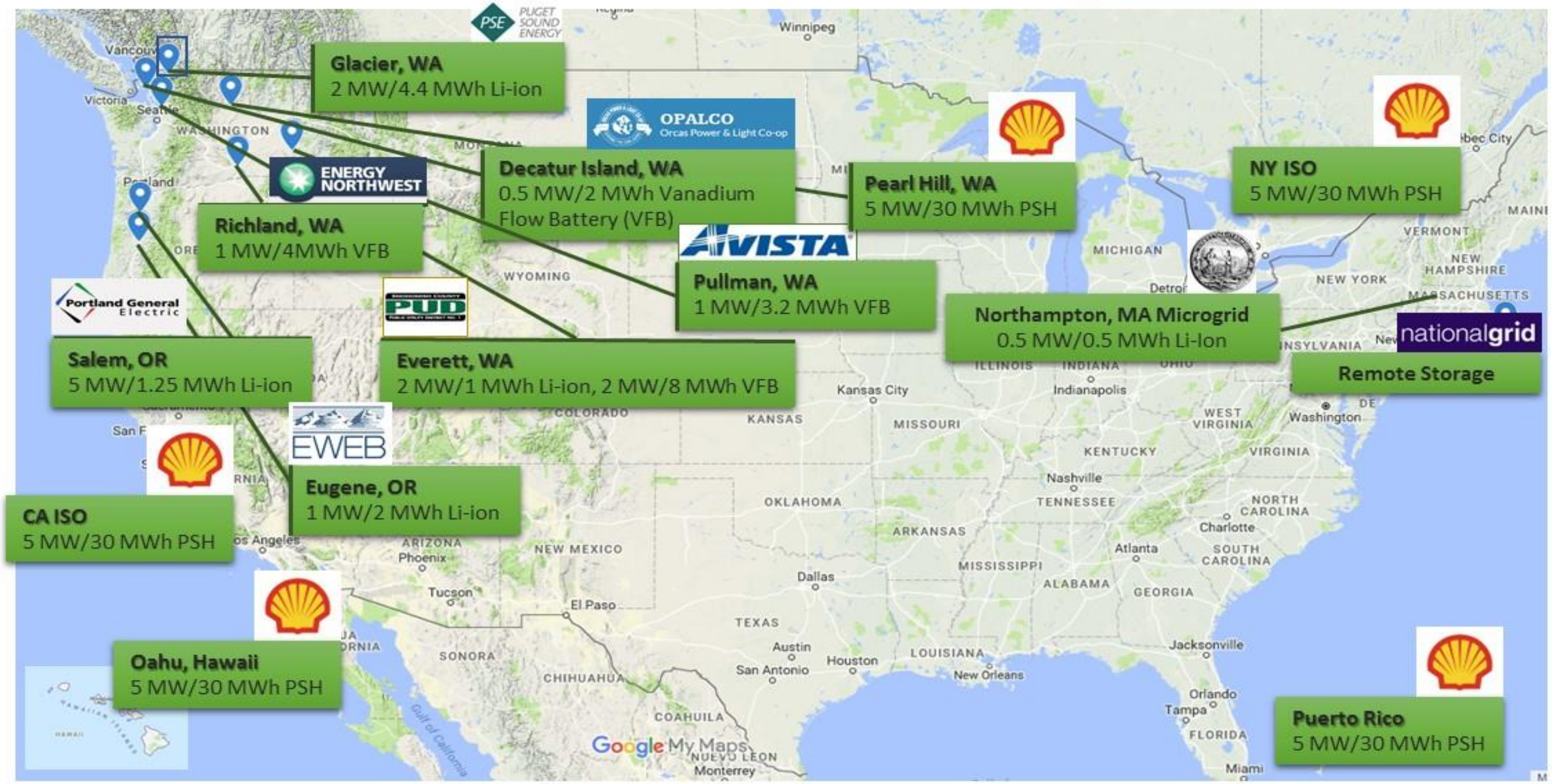
U.S. Department of Energy

Department of Commerce

Energy Northwest

nationalgrid

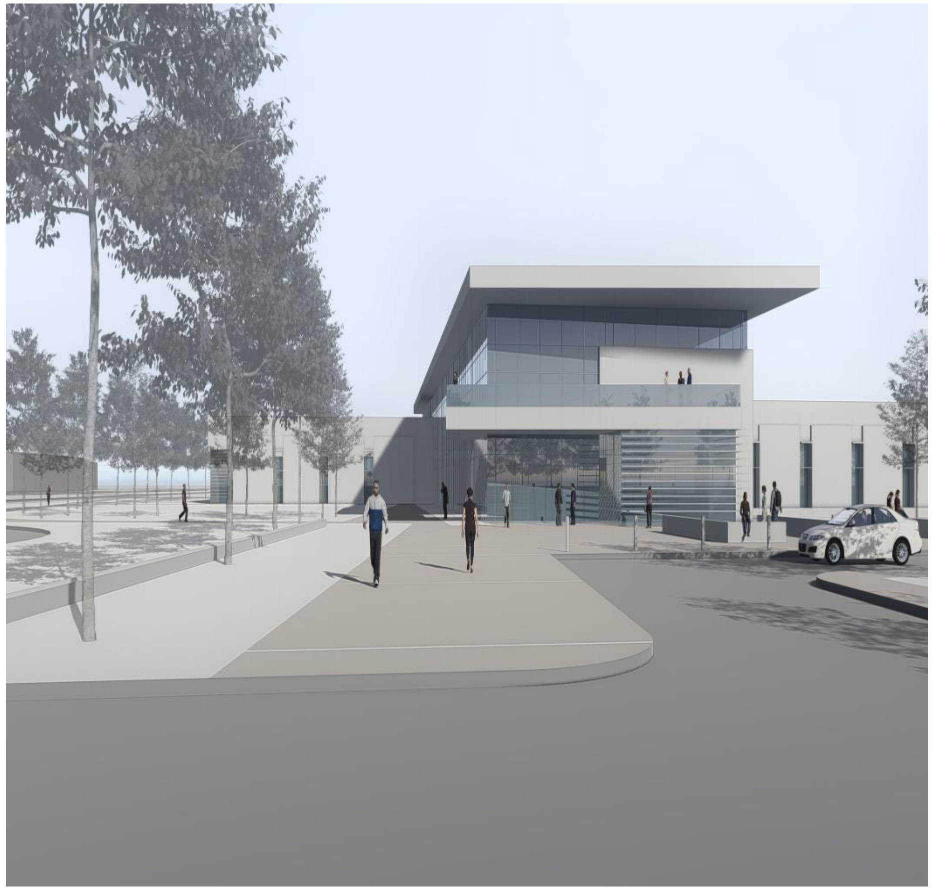
OPALCO



Grid Energy Storage Launchpad

Mission

- **Validation**: This facility will provide independent testing of next generation grid energy storage materials and systems under realistic grid operating conditions
- **Acceleration**: The facility will reduce risk while speeding the development of new technologies by propagating rigorous grid performance requirements to all stages of storage technology development
- **Collaboration**: By linking the DOE and storage R&D communities in a new collaborative facility, this facility will lower barriers to solving key crosscutting industry challenges



Pacific Northwest
NATIONAL LABORATORY

Transportation Electrification

Is the Grid Ready for Loads at Scale?

U.S. DEPARTMENT OF ENERGY BATTELLE

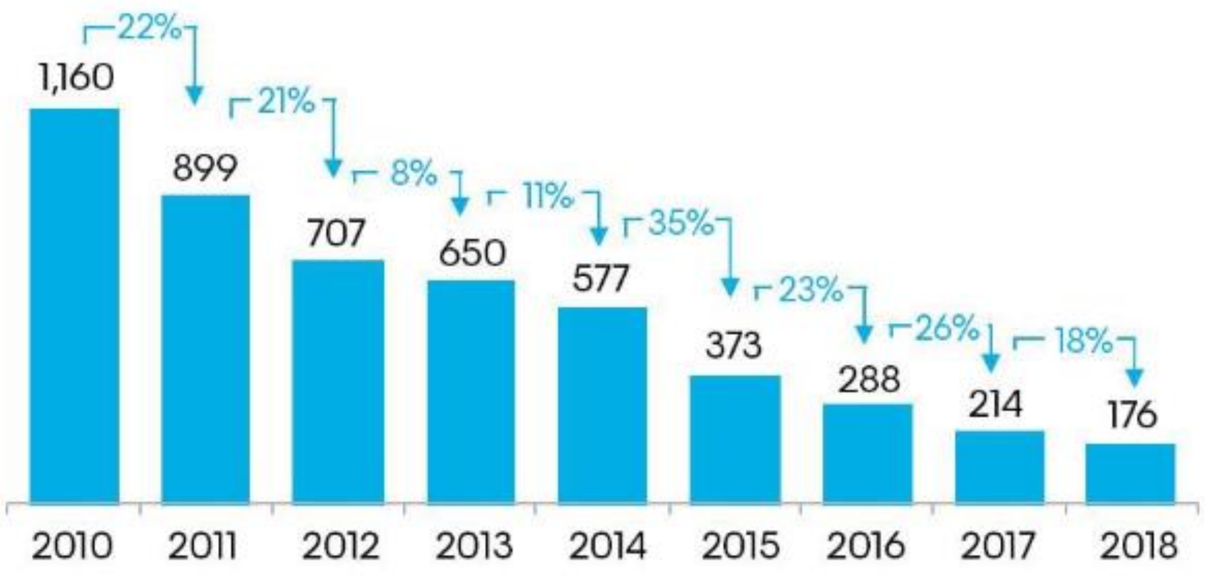
PNNL is operated by Battelle for the U.S. Department of Energy

Globally - It's all about the batteries!

Battery prices keep falling. As a result, we expect price parity between EVs anc internal combustion vehicles (ICE) by the mid-2020s in most segments, though there is wide variation between geographies and vehicle segments.

Volume weighted average lithium-ion pack price

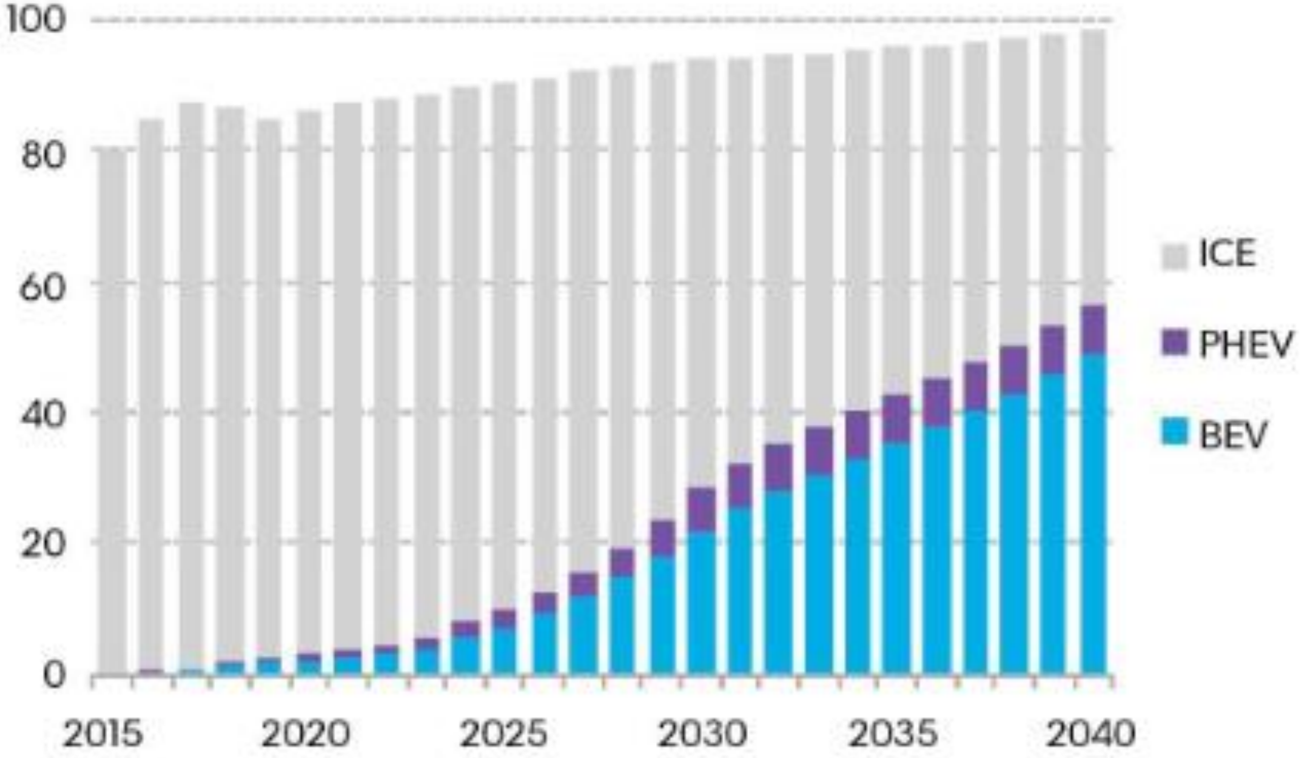
Real 2018 USD



Source: BloombergNEF

Global long-term passenger vehicle sales by drivetrain

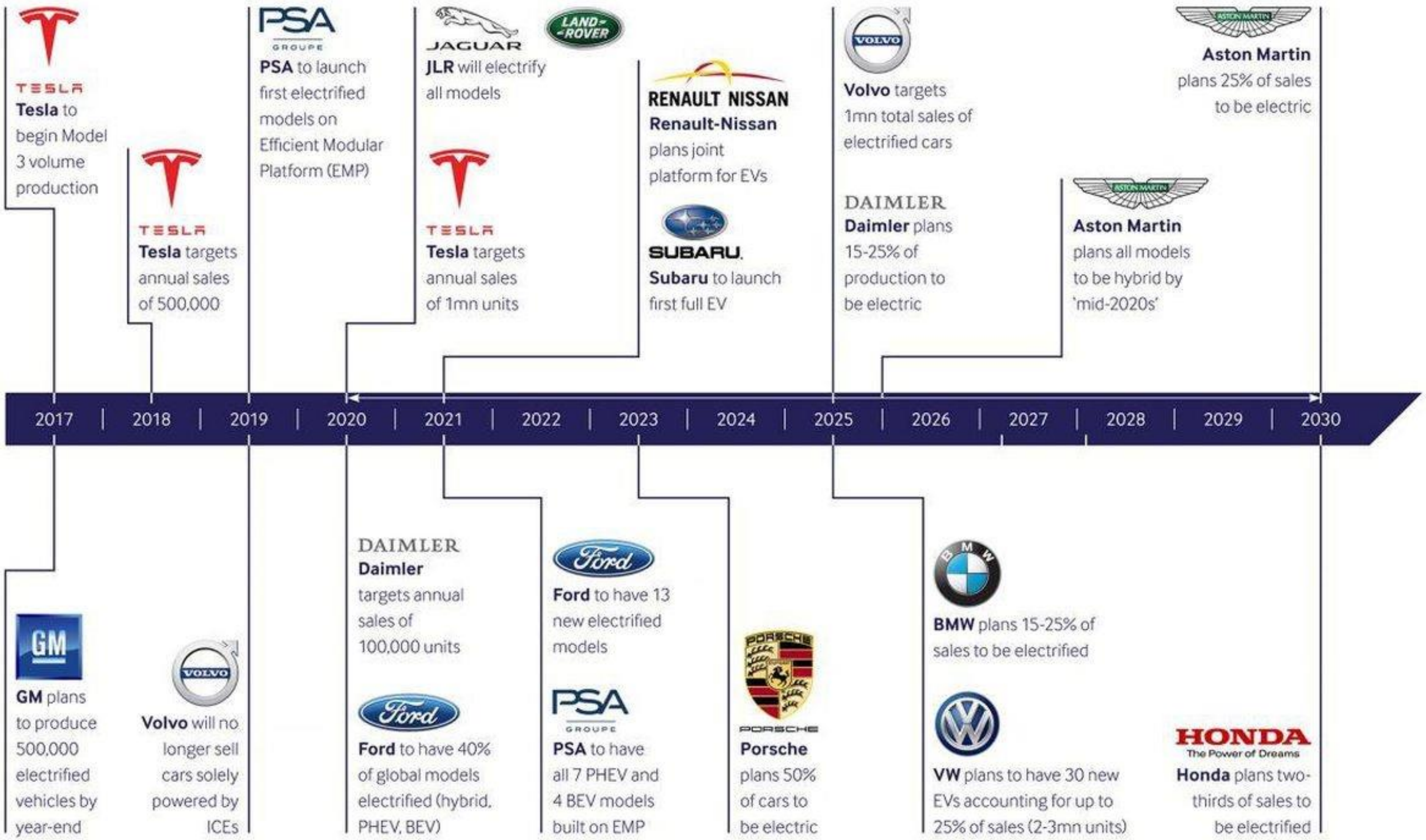
Million vehicles



Source: BloombergNEF

Electric Vehicle Timeline

BMI Research
A FitchGroup Company



Pacific Northwest NATIONAL LABORATORY

Battery500 Consortium

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

BATTERY 500 CONSORTIUM

PNNL Leads Battery500 Consortium

Goal: ***Double the specific energy (to 500 WH/kg)*** *relative to today's battery technology while achieving 1,000 electric vehicles cycles*

Advisory Committee

- TESLA
- IBM
- USABC (United States Advanced Battery Consortium)
- NAATBatt (National Alliance for Advanced Technology Batteries)
- FMC

Materials

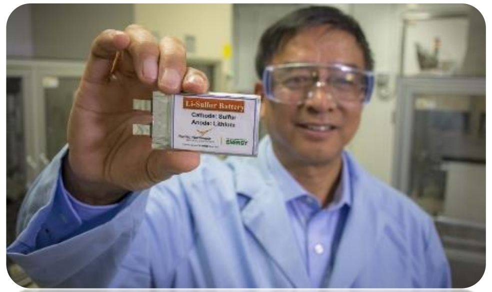
- The University of Texas at Austin
- Pacific Northwest National Laboratory
- Stanford University
- Binghamton University

Architectures

- University of California San Diego
- INL Idaho National Laboratory
- Pacific Northwest National Laboratory
- SLAC National Accelerator Laboratory

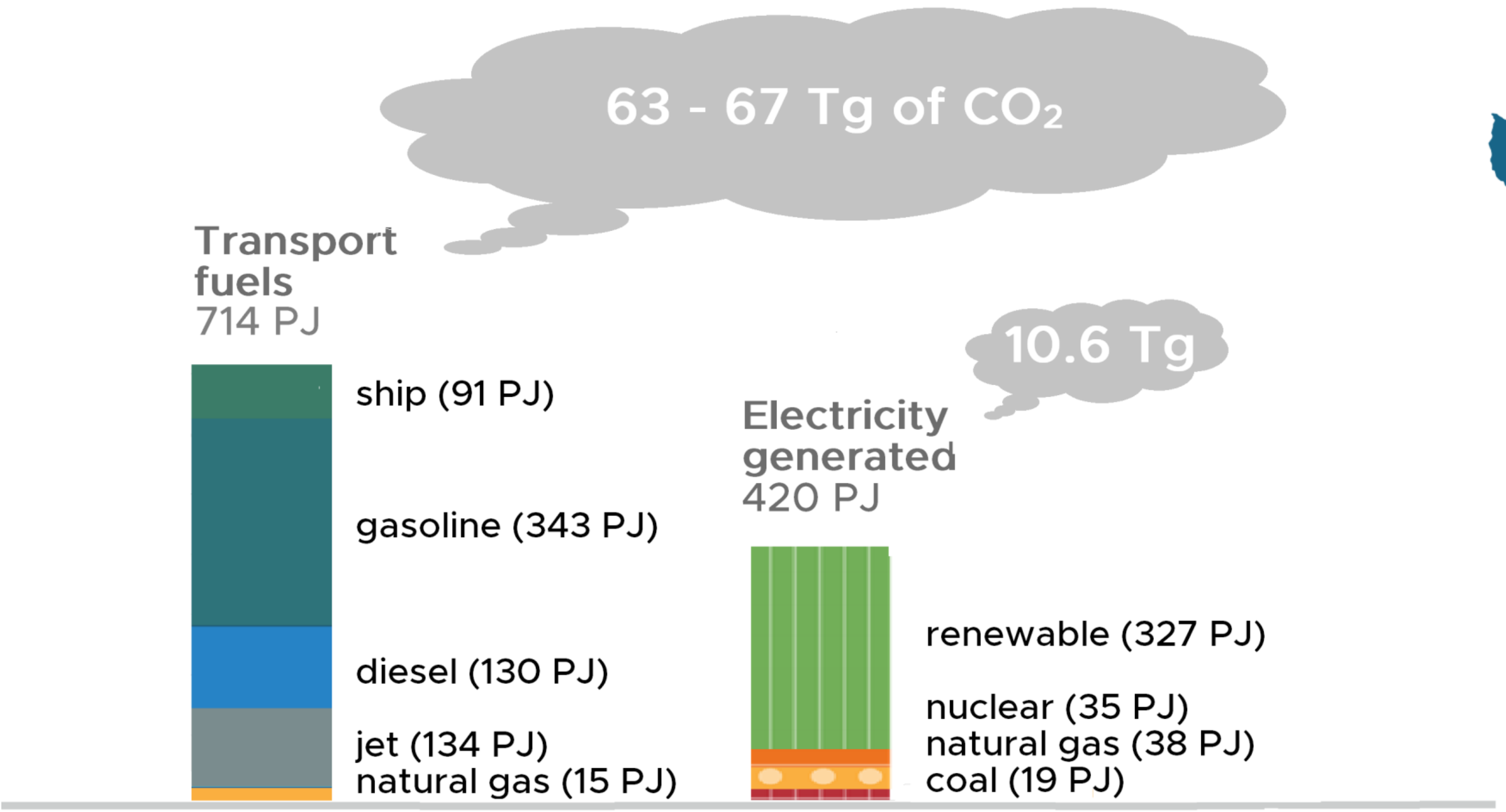
Integration

- University of Washington
- Brookhaven National Laboratory
- Pacific Northwest National Laboratory



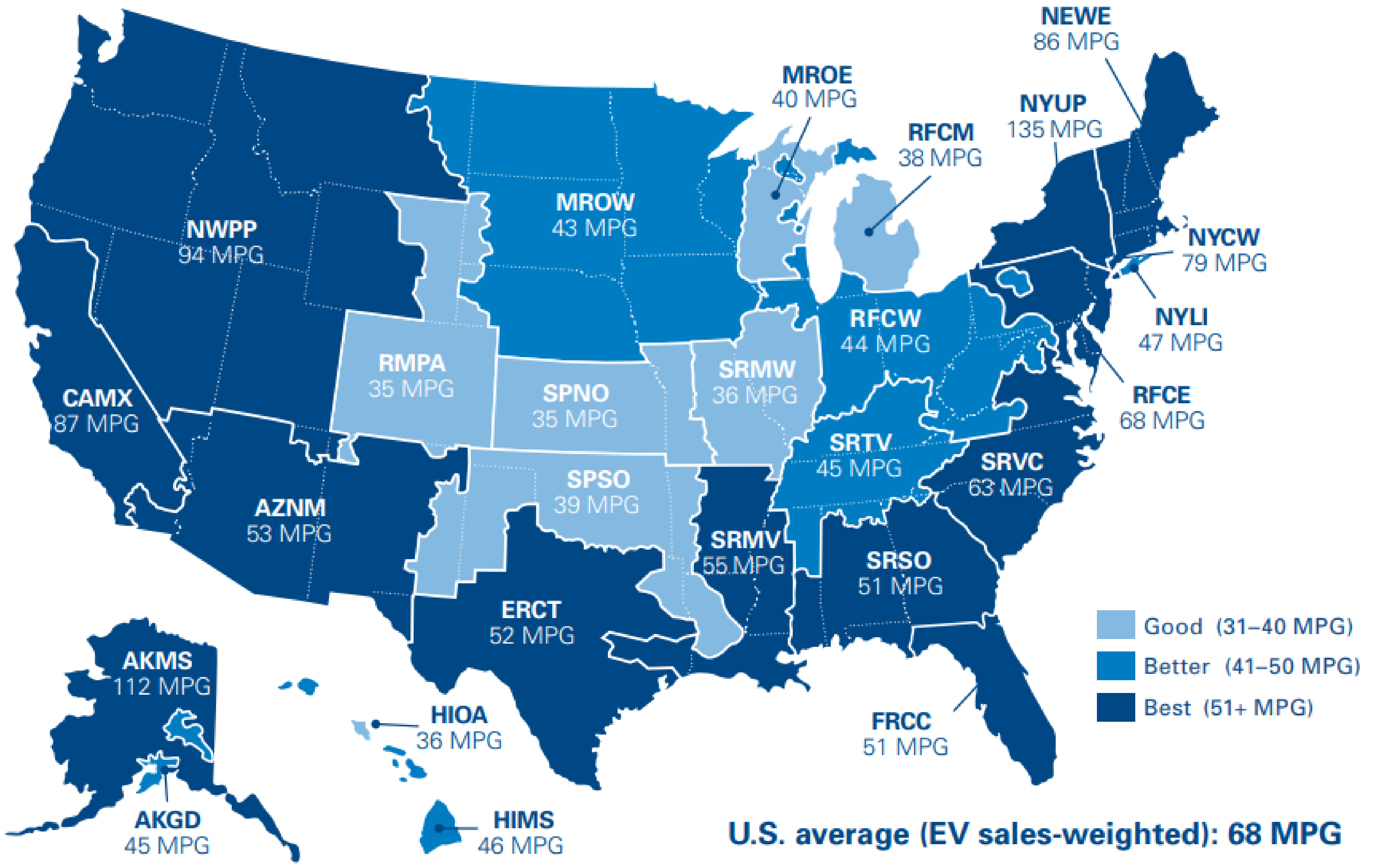
Washington State uses 714 PJ of transportation fuels generating 65 Tg of CO_2 and 420 PJ of electricity generating 10.6 Tg of CO_2

WA State uses 1.7x more transportion fuels than electricity and the transportation sector generates 6x more CO_2



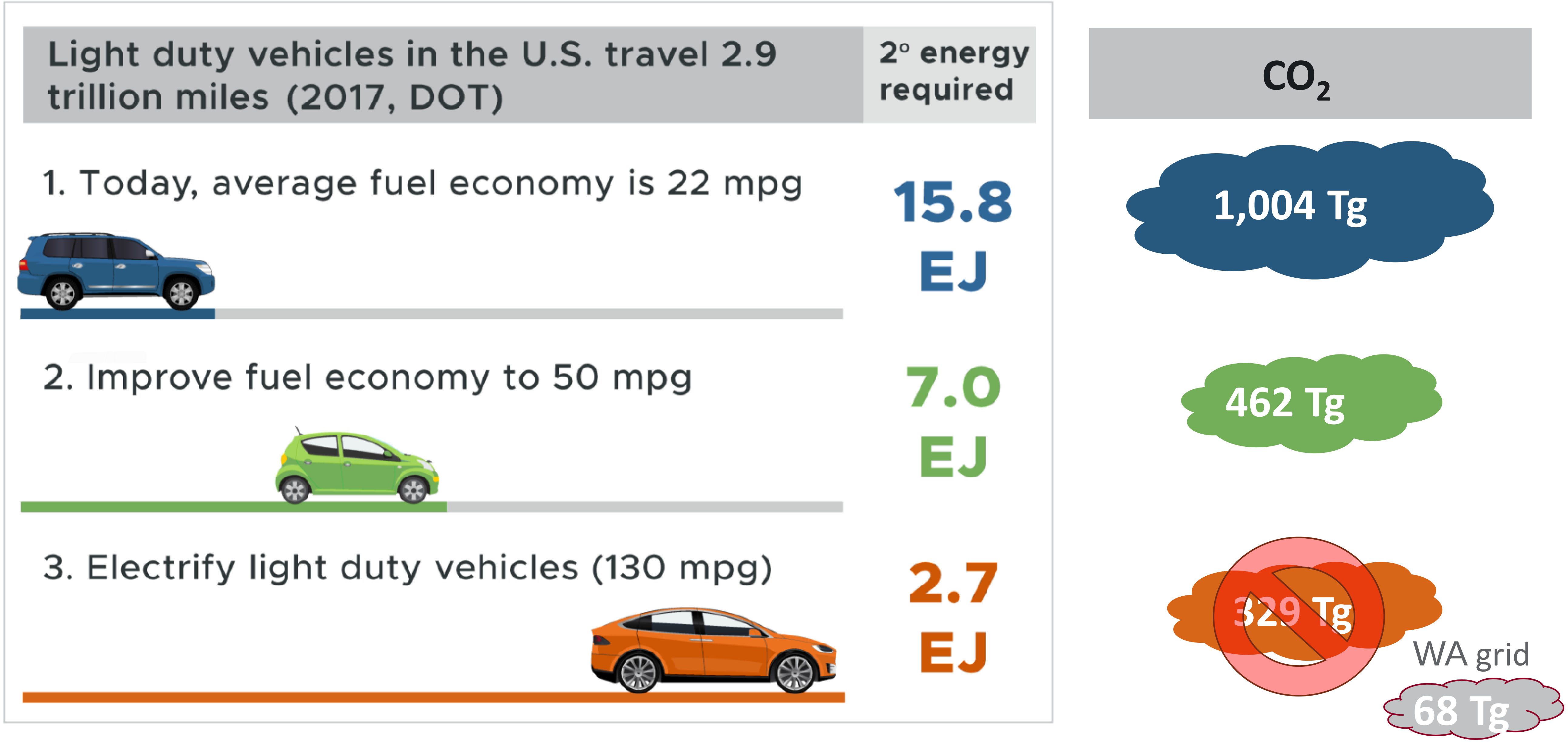
Data from Energy Information Agency, additional analysis from GREET
Han et al. Fuel 157 (2015) 292-298 (https://doi.org/10.1016/j.fuel.2015.03.038)

The fuel economy at which a gasoline vehicle produces CO_2 emissions equivalent to a battery electric vehicle changes by region



source: Figure 19 from ADLittle analysis, https://www.adlittle.com/sites/default/files/viewpoints/ADL_BEVs_vs_ICEVs_FINAL_November_292016.pdf

A cleaner grid can help reduce the CO_2 footprint of transportation upon electrification



1. https://www.bts.gov/archive/publications/national_transportation_statistics/table_01_35_m
2. MPG from https://afdc.energy.gov/data/10310, 121.1 MJ gal^{-1}

EV-Grid Impact Study

<u>OBJECTIVE</u>: As adoption of EVs is accelerating, provide insights into the ability of the U.S. bulk power grid to serve the new EV load

Question 1: Are there sufficient resources in the U.S. bulk power grid to provide electricity to the projected EV fleet?

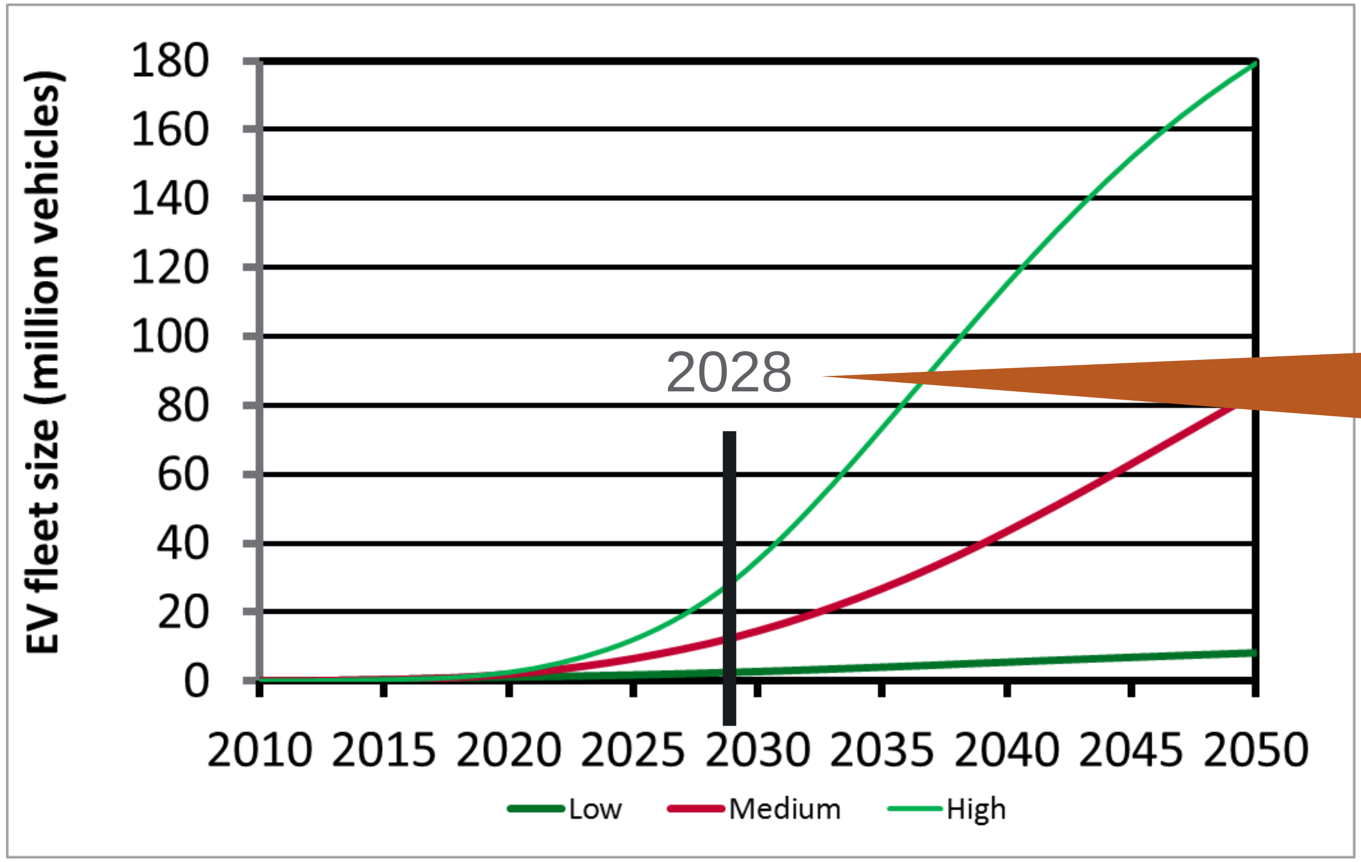
Question 2: How will the generation mix dispatch be impacted by the additional EV load?

- what are the expected production cost impacts?
- what are the challenges and benefits to grid operations?

Question 3: What are the net impacts and benefits to emissions?

Pacific Northwest
NATIONAL LABORATORY

EV Penetration for LDVs in 2028: National



Scenario	Fleet size in No. of EVs in millions
Low	2.3
Medium	10.8
High	23.6

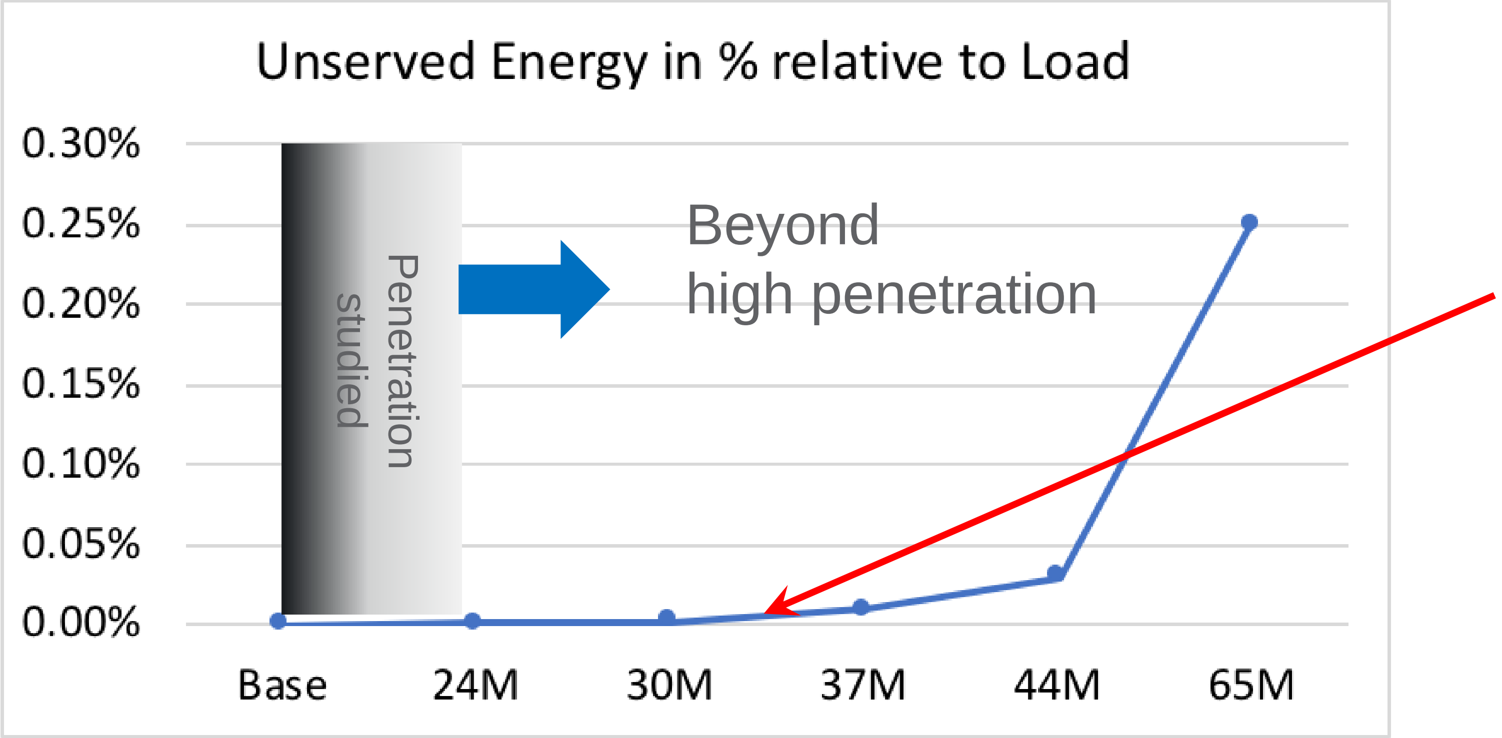
Source: EPRI, 2017: “Plug-in Electric Vehicle Market Projections. Scenarios and Impacts”. 3002011617. Technical Update, November 2017. Electric Power Research Institute, Palo Alto, CA.

Preliminary Results: Reliability Perspective

- Resource Adequacy addresses **generation and transmission** resources necessary to meet additional EV loads.

Even at high LDV Penetration Scenario (24 Mill.), no expected resource adequacy issues with any of the charging strategies **under normal system conditions and all lines in service**

- At what penetration beyond 24 million could we expect potential reliability issues?



Onset of unserved energy indicating outages

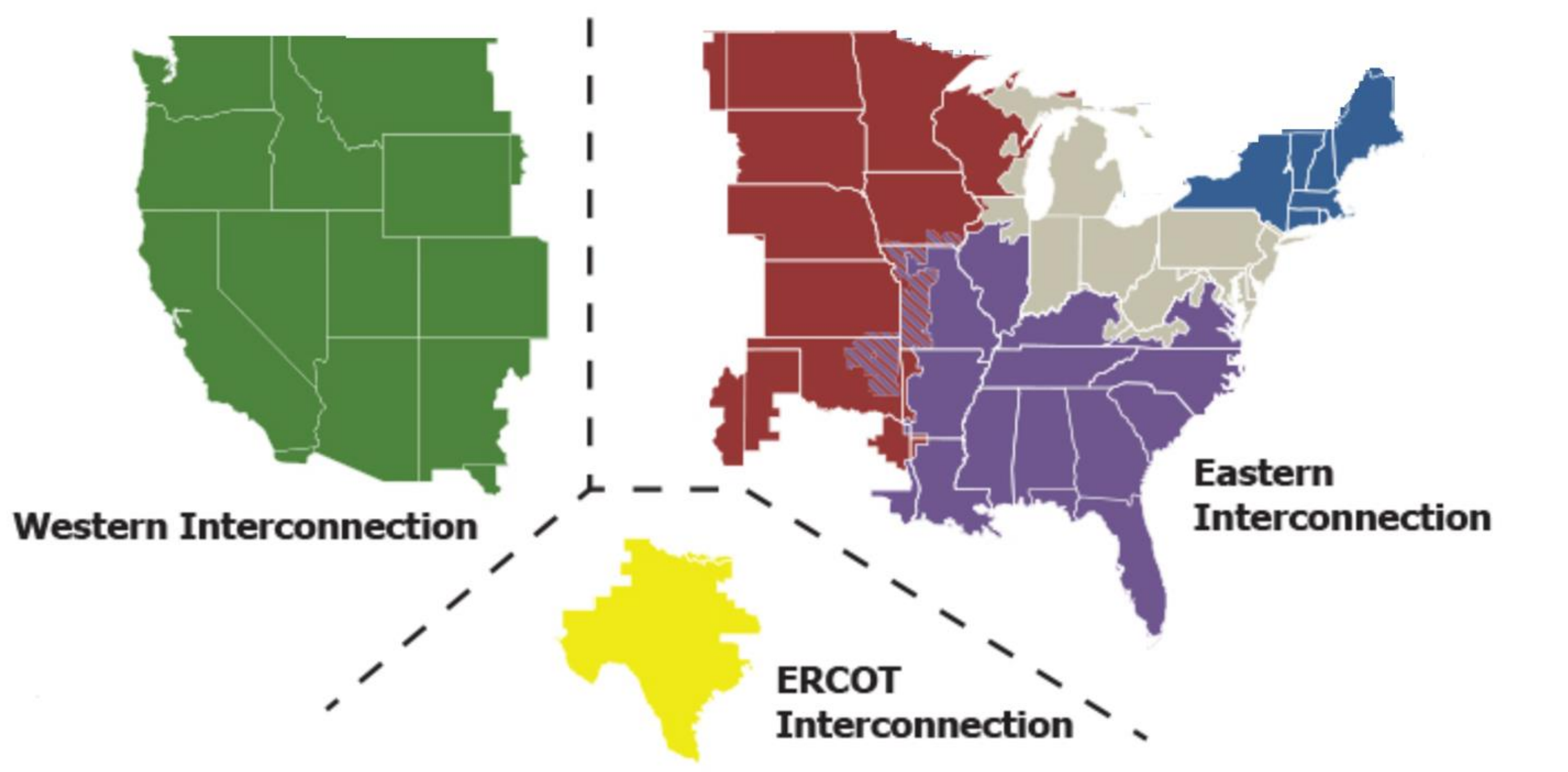
Between 30-37 Mill. LDVs

Electric vehicles will compete for electrons needed for other uses, so important to understand the implications

Considering mode (LD, MD, HD), time of charging, location on U.S. 1.1 TW capacity

WECC-US
Installed Capacity: ~214GW
Peak Load: ~137GW

EI-US
Installed Capacity: ~761GW
Peak Load: ~544GW



ERCOT
Installed Capacity: ~104GW
Peak Load: ~73GW

24 Million new electric vehicles

- Resiliency (capacity) manageable
- Evening loads stress system the most
- At 30 million LDVs, encounter operational issues—with transmission as foremost limiting factor
- Natural gas combined cycle to carry bulk of the load
- Changes in hydro dispatch in WA
- Emissions benefits vary by location and season
- Average production cost increase of 13 percent in the WECC
- Reduce renewable curtailment by 70%

Power to Liquids?

SeaTac uses 63% of the jet fuel in the state, replacing it would use 36% of the electricity generated in WA or require 5,000 new turbines

SEA (Seattle Tacoma)

640 mil gallons (2018)

Electricity required

Power-to-Liquids (ideal)

Would require 36% of total generation from WA State

Potential CO_2 saving is less than 50% (based on grid)

Capital for turbines adds \$530,000 BOE^{-1} day^{-1} (to capital for conversion)

Wind farm

- Shepherds Flat Wind Farm (Columbia Gorge) is rated at 0.85 GW and could produce 6-10 PJ
- It cost $2 billion to build (the turbines cost $1.6 billion with service contract)
- Fifteen equivalent-sized wind farms would be needed

Pacific Northwest
NATIONAL LABORATORY

Jet Fuel From Industrial Waste

- First commercial flight on recycled waste gas
- LanzaTech developed process to convert waste gas to ethanol
- PNNL developed catalytic process to upgrade ethanol to jet fuel

The October 2018 Virgin Atlantic flight took off from Orlando and landed in London.

Pacific Northwest NATIONAL LABORATORY

Maritime Trends - Emissions

Heavy fuel oil (HFO), or bunkers, and to a lesser extent marine gas oil (MGO), are the traditional sources of energy to power ships. Shipping is consuming around 3.2 million barrels per day of HFO and 800,000 bpd of MGO – totaling more than $100 billion a year, or about 5% of global demand.

Pacific Northwest
NATIONAL LABORATORY

Alternative Fuels and Propulsion

- Fully Electric or Hybrids
- Hydrogen Fuel Cells
- Wind Turbines
- Biofuels
- Solar PV

Vessel operators are investigating alternative fuels and methods of propulsion, largely in response to industry trends.

Pacific Northwest
NATIONAL LABORATORY

Wildcards

Understanding Implications of Wildfire & Hydro Variability

U.S. DEPARTMENT OF ENERGY BATTELLE

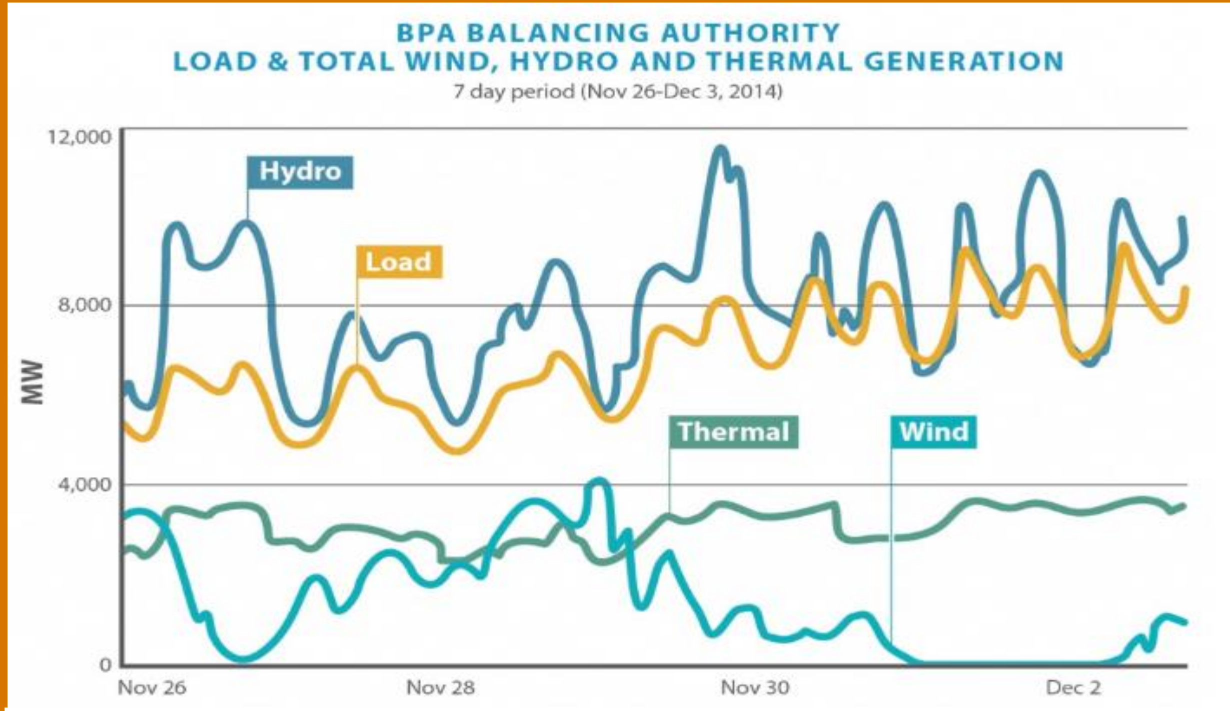
PNNL is operated by Battelle for the U.S. Department of Energy

Sustainable Biomass, Grid & Wildfire Resilience

- **Challenge:** Fire suppression, land management and climate variables have resulted in greatly increased forest density which increases mega-fire frequency, and alters multiple hydrologic processes including streamflow patterns, and reduced water availability.
- **USFS/DOI/States response:** implement strategic thinning and prescribed burning across the U.S.
  - Air quality standards, forest economic sustainability and budgets limit amount of annual restoration
- **Goal:** Develop and demonstrate an analysis framework **to prioritize how and where to target forest restoration (timber harvest and thinning) and fuels reduction to have the greatest benefit for bioenergy, reduce severe wildfire risk, increase water yield, and improve ecosystem services.**
  - Multi-agency collaboration between DOE-BETO (PNNL, ORNL) and USFS R&D

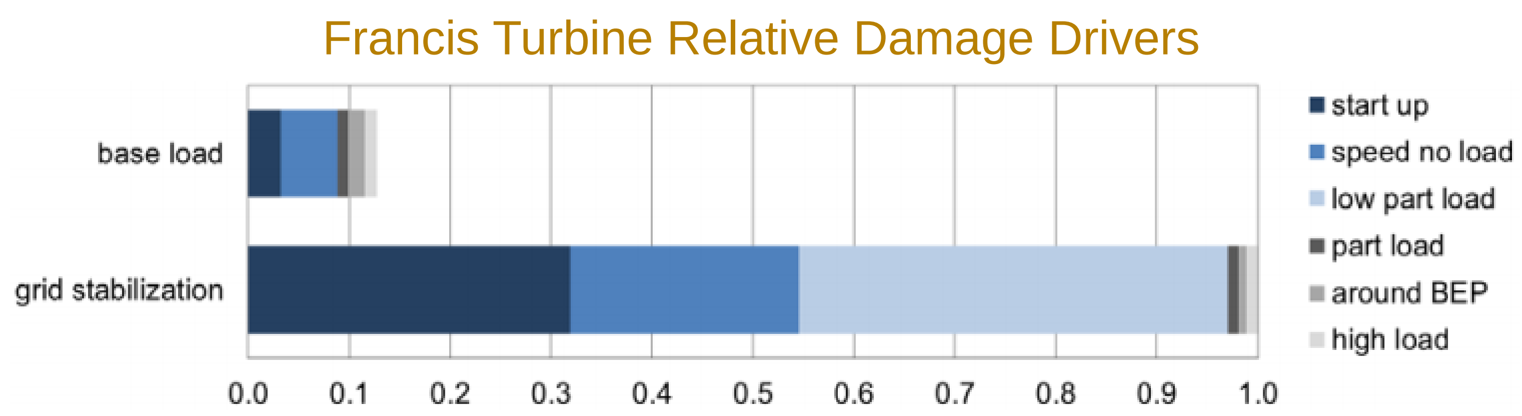
Hydro Dynamics: Impacts of Intensifying Dispatch Variability

Drivers of Variability



Source: BPA Balancing Authority: Load and Total Wind, Hydro and Thermal Generation, Nov. 26-Dec. 23, 2014

Implications



Source: Dynamic Loads on Francis Runners and their impact on fatigue live, Seidel et al, 2014

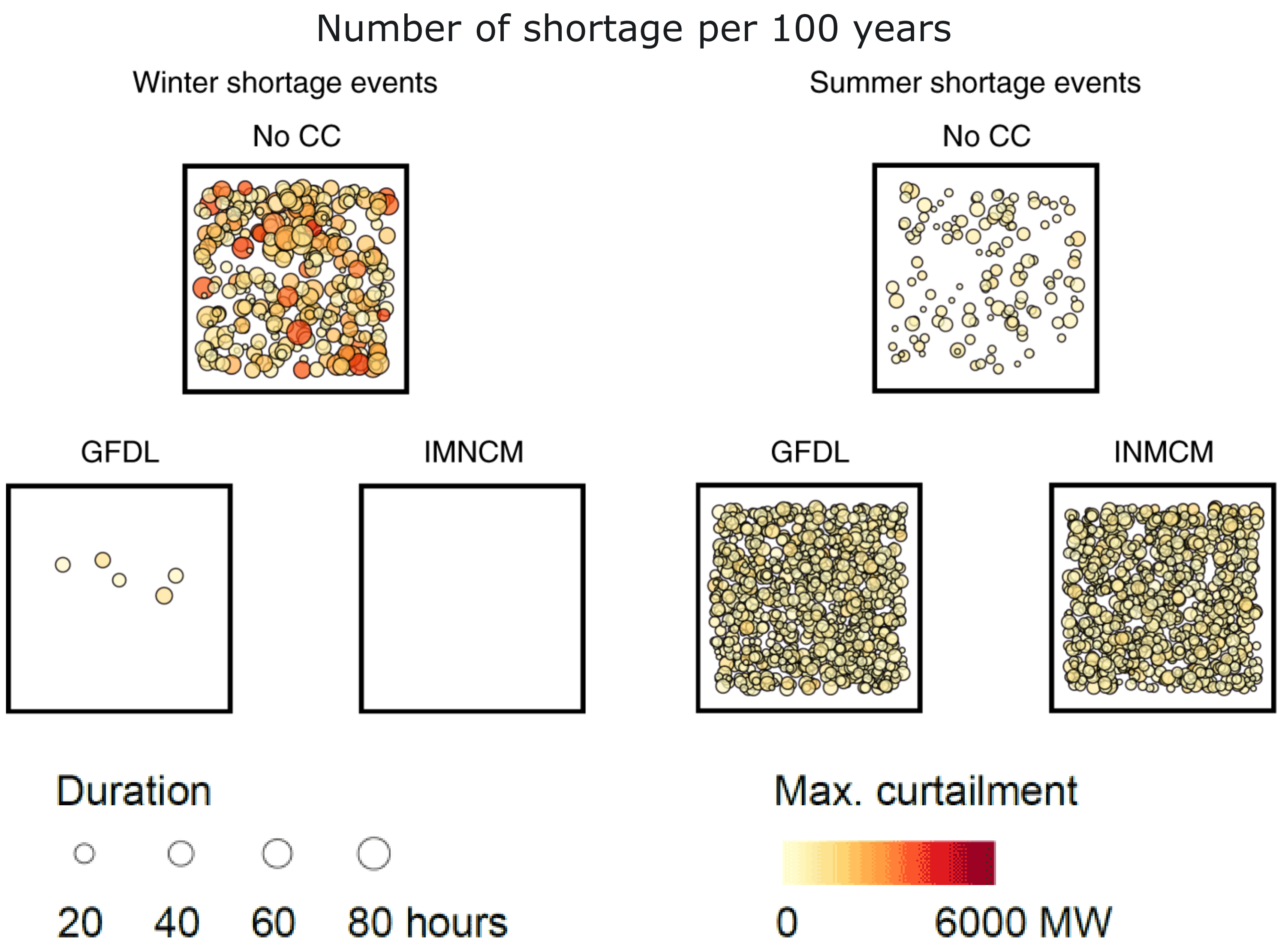
Potential Questions We Can Answer:

- How can operational variability/cycling be classified?
- Is operational variability changing? If so how/where?
- Is there a measureable maintenance/cost impact of operational variability?
- How can plants be run to minimize maintenance requirements?

Climate Events Create Compound Challenges for Electricity Planning

"The paper explores how climate-driven variations in both energy demand and water availability affect the power system, showing that combined climate change impacts on loads and hydropower generation may have a transformative effect on the nature and seasonality of power shortfall risk in the Pacific Northwest."

https://www.nwcouncil.org/news/climate-change-impacts-electricity-loads-and-hydropower-generation



Key Takeaways

- **Efficiency** remains the resource of first resort in the PNW
- **Buildings can become responsive grid assets,** bolstering system resilience
- **Grid-scale storage** can improve system resilience and operational flexibility, in response to emerging trends
- **LDV electrification & integration** manageable for bulk power system
- **Maritime & aviation** pose technical challenges at scale, require continued innovation
- **Wildfire & hydro system dynamics** require additional, ongoing consideration

Thank you!

angela.becker-dippmann@pnnl.gov

Pacific Northwest
NATIONAL LABORATORY

BACKUP SLIDES

Energy in universal units

Energy (J)

- Energy is the ability to do work
- $1\ J = kg\ m^2\ s^{-2}$

Power (W)

- Energy over time
- $1\ W = kg\ m^2\ s^{-3}$

Energy units

1 kJ = 0.95 Btu

1 kJ = 0.278 Wh

1kJ = 0.239 kcal

1 Quad = 1.055 EJ

1 gal of jet = 134 MJ

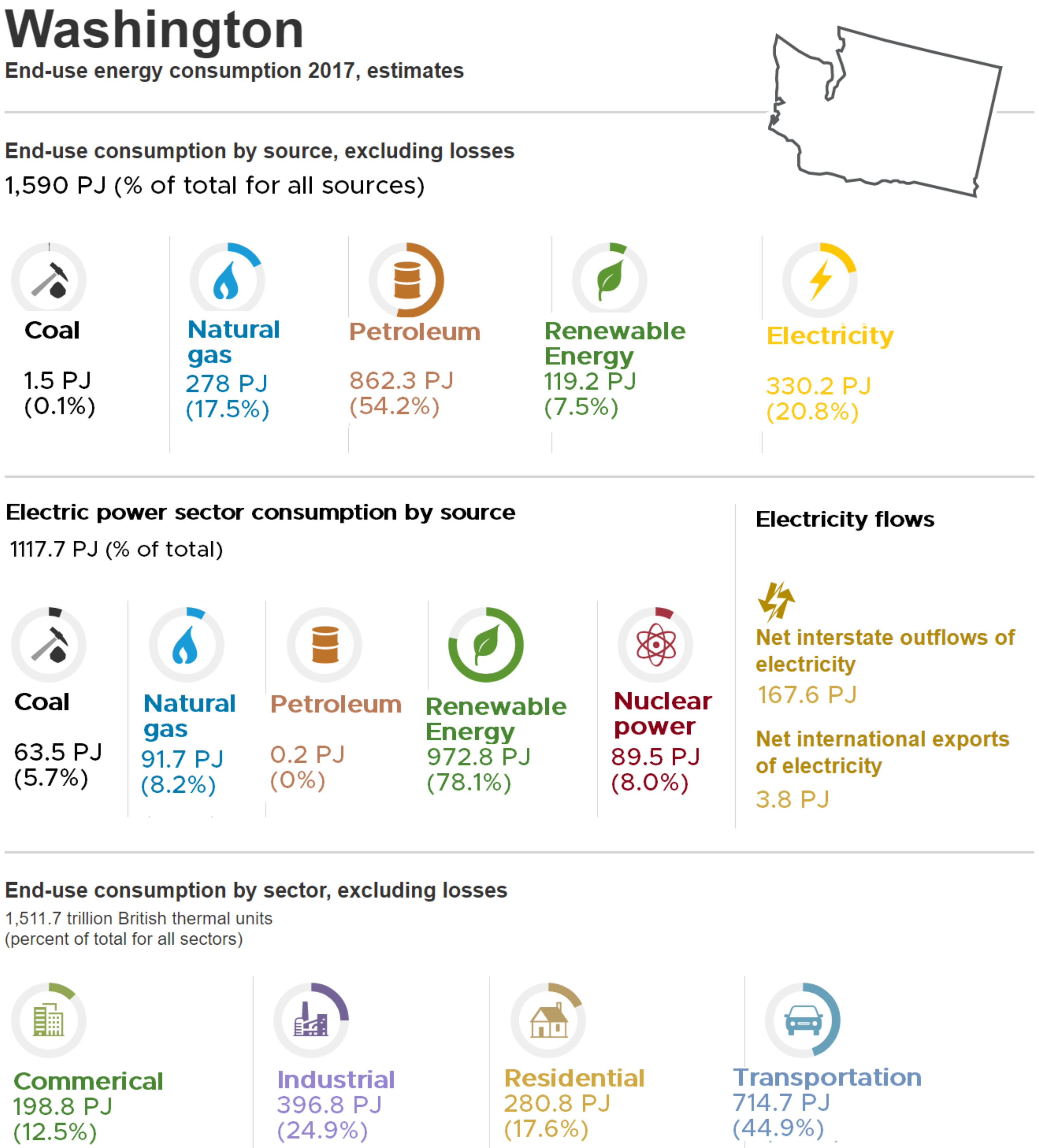
Kilo (k) = 10^3 (thousand)
Mega (M) = 10^6 (million)
Giga (G) = 10^9 (billion)
Tera (T) = 10^{12} (trillion)
Peta (P) = 10^{15} (quadrillion)
Exa (E) = 10^{18} (quintillion)

Pacific Northwest
NATIONAL LABORATORY

Washington at a glance

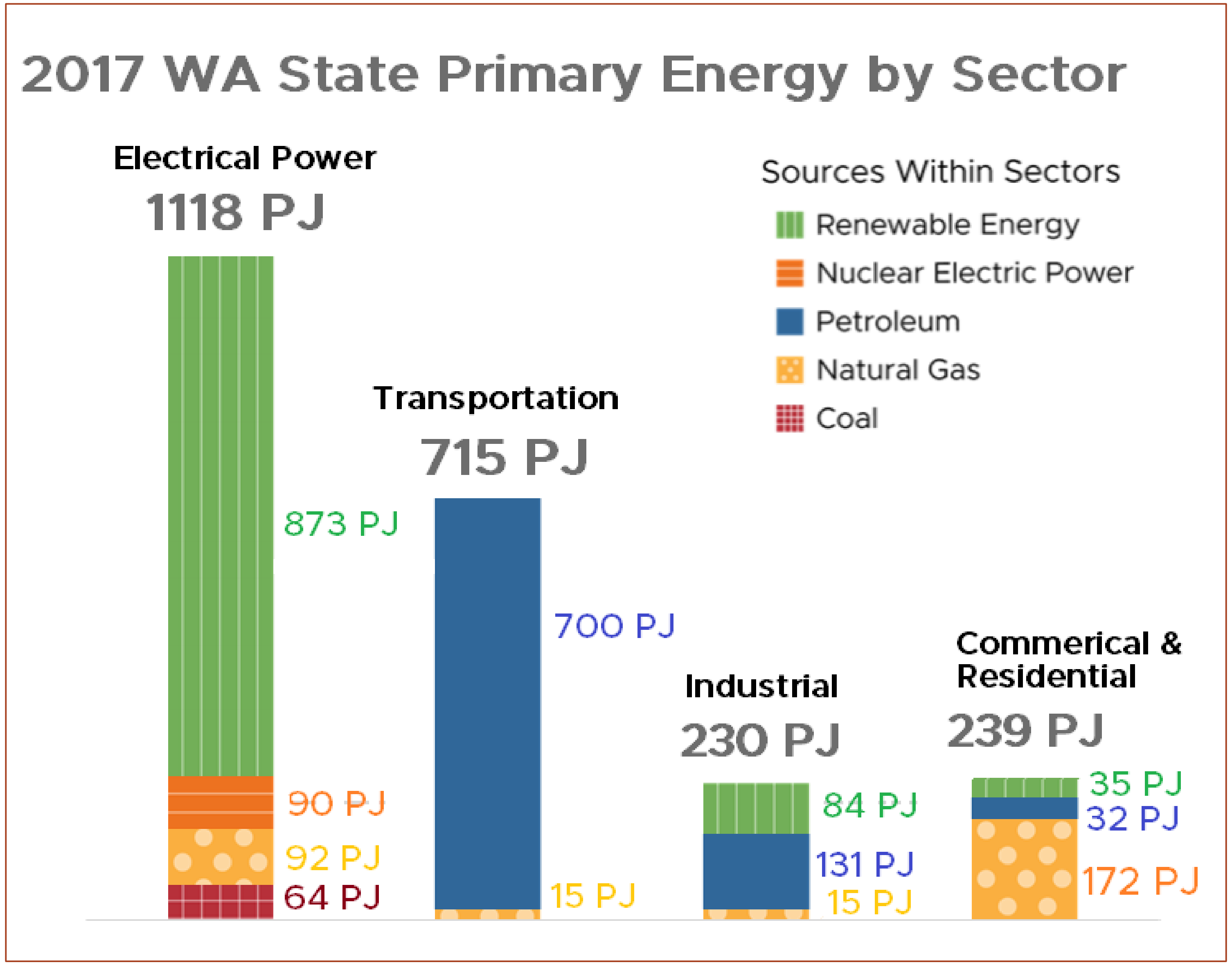
- The Grand Coulee Dam on Washington's Columbia River is the largest hydroelectric power plant in the United States by generation capacity, and can provide electricity to 2.3 million households a year.
- Washington is the top U.S. producer of electricity from hydroelectric sources and routinely accounts for 25% of the nation's annual utility-scale net hydroelectricity generation.
- Although not a crude oil producing state, Washington has the fifth largest U.S. oil refining capacity for making petroleum products with the ability to process 638,000 barrels of oil a day at the state's five refineries.
- Just over one-half of Washington households rely on electricity as their primary heating fuel and one-third of households depend on natural gas.
- Because of the relatively low operating costs of hydroelectric power generation, Washington had the nation’s second lowest average retail electricity price, after Louisiana, in 2017.

https://www.eia.gov/beta/states/states/wa/overview



WA State uses 2.3 EJ of primary energy (2017), dominated by renewables and petroleum

- Renewables, 992 PJ
- Petroleum, 862 PJ
- Natural gas, 293 PJ
- Nuclear, 89 PJ
- Coal, 65 PJ



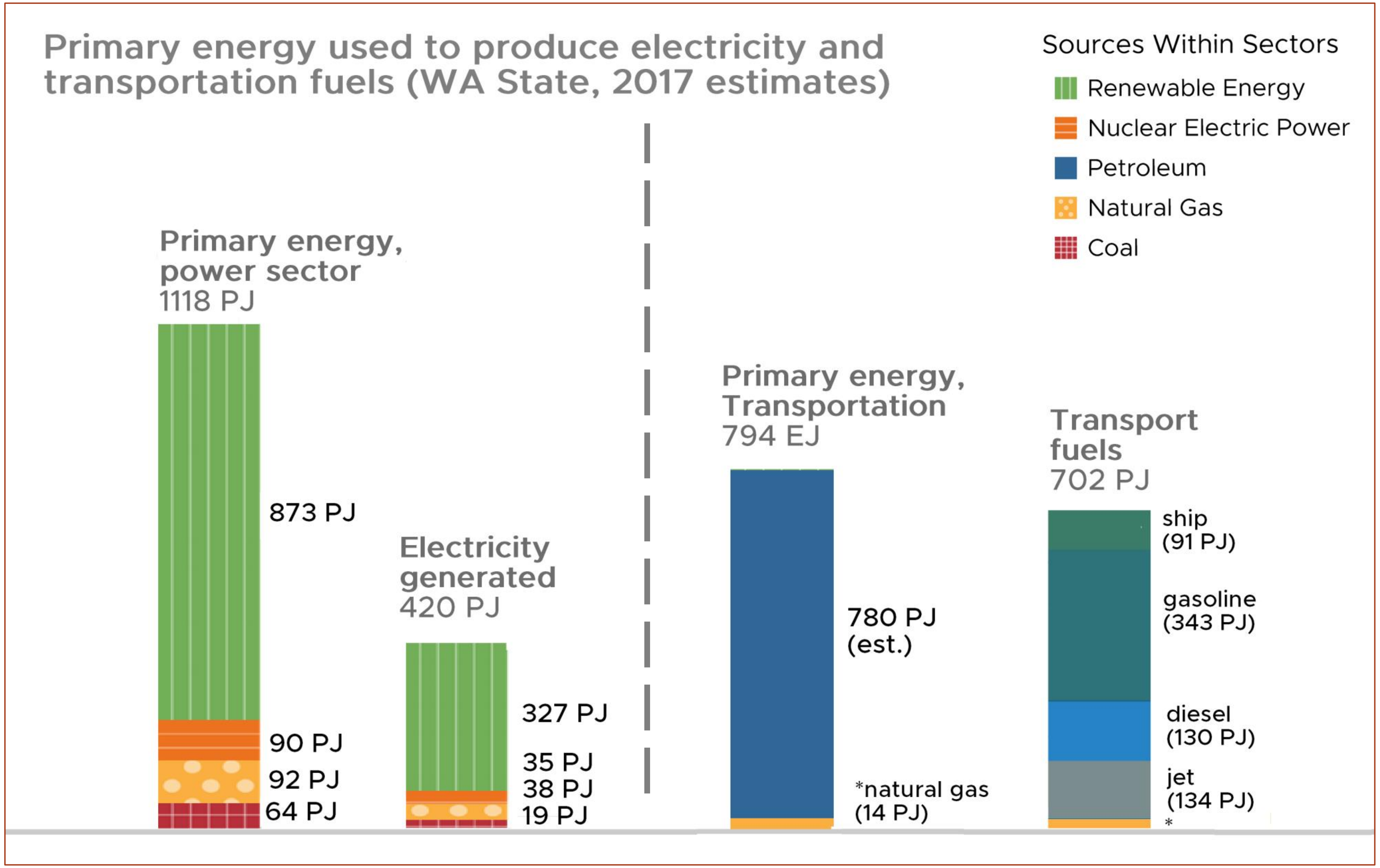
Pacific Northwest NATIONAL LABORATORY

Both the light duty fleet and the heavy duty fleet have room to improve fuel economy

Light duty vehicles in the U.S. travel 2.9 trillion miles (2017, DOT)	2° energy required
1. Today, average fuel economy is 22 mpg	15.8 EJ
2. Improve fuel economy to 50 mpg	7.0 EJ
3. Electrify light duty vehicles (130 mpg)	2.7 EJ

Heavy duty vehicles in the U.S. travel 0.31 trillion miles (2017, DOT)	2° energy required
1. Today, average fuel economy is 6.4 mpg	6.7 EJ
2. Improve fuel economy to 11 mpg	3.9 EJ
3. Electrify heavy duty vehicles (17 mpg)	2.6 EJ

Petroleum refining is highly efficient compared to electricity production



A 737 on a 4 hour flight uses around 430 GJ (10 t); battery technology will need to improve >60 fold to match jet fuel

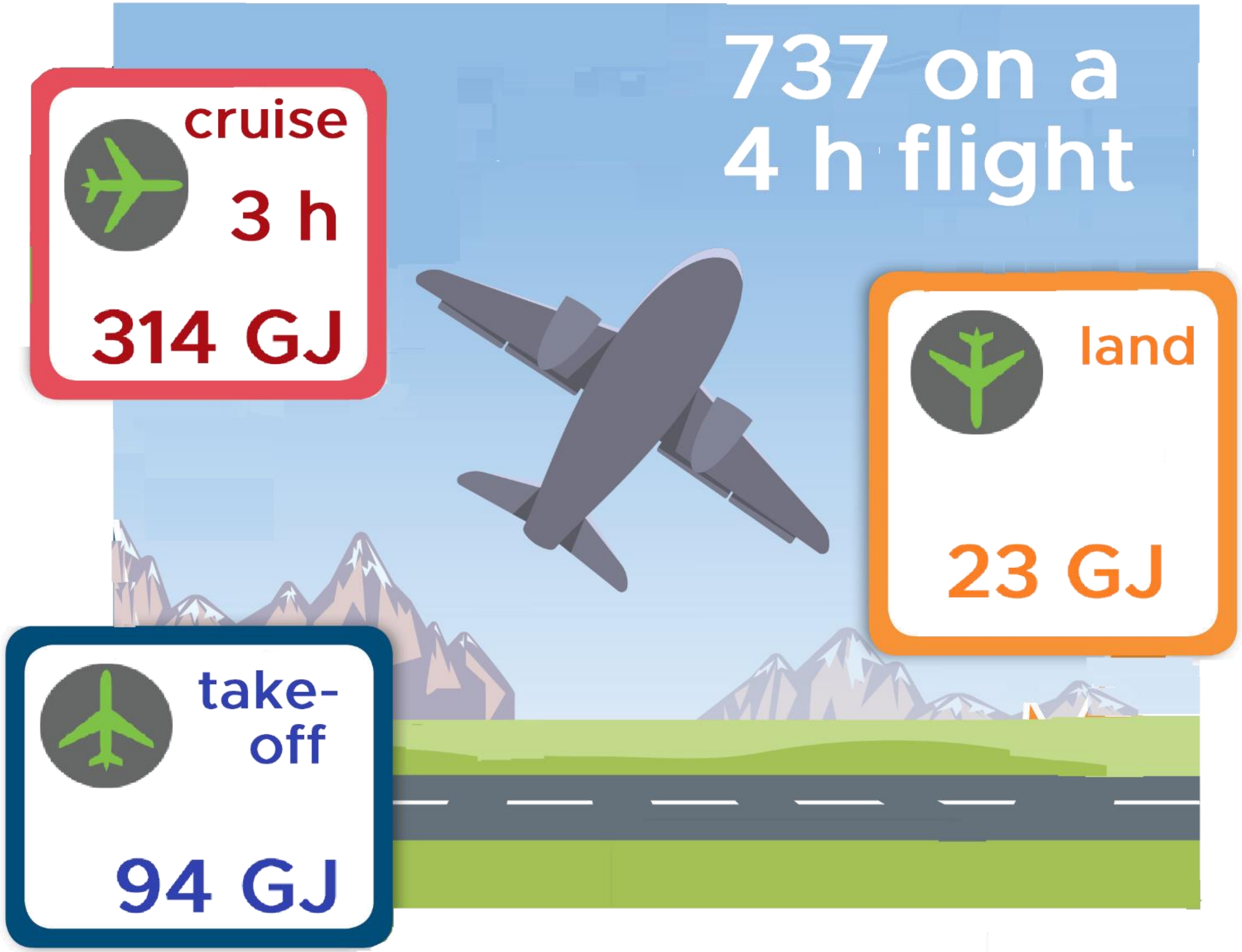
Energy density
Jet fuel density = 43 MJ/kg
Battery density = 0.72 MJ/kg (200 Wh/kg)

Today (Tesla Model 3 battery)[1]
- battery weight = 600 t
- Volume = 154 m^3

737-900 (passenger)[2]
- MTOW = 85 t, 51.3 m^3 of cargo

737-400 BCF cargo plane[3]
- 21 t of cargo, 141 m^3

Batteries will need to improve 25 fold to even fly the plane (if no other cargo or passengers were on board)



Energy calculated by Holladay and compared to GA Tech models

1 https://evannex.com/blogs/news/tesla-s-battery-pack-is-both-mysterious-and-alluring-work-in-progress
2 http://www.b737.org.uk/737ng.htm#737-900 3 https://www.volga-dnepr.com/en/fleet/B737/

A 777 on a 10 hour flight uses 3 TJ of fuel having a mass of 70t; today's battery would have a mass of 4,200 t

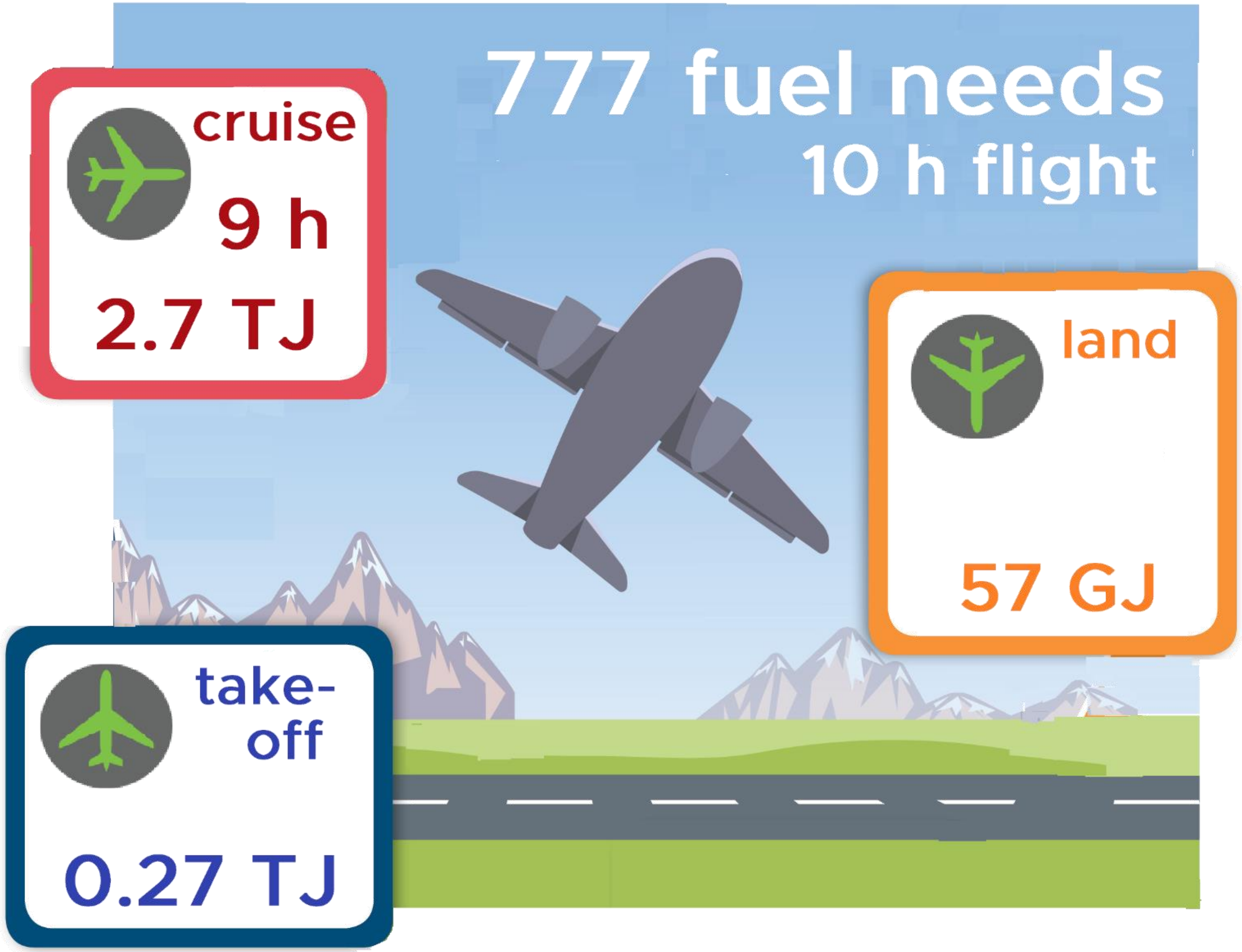
Jet fuel density = 430 MJ/kg
Battery density = 0.72 MJ/kg (today)

Today (200 Wh/kg):
- battery weight = 4,200 t
- Volume = 2,100 m^3

777-300 (passenger)
- MTOW = 340 t, 214 m^3 of cargo

777F cargo plane
- 104 t of cargo, 636 m^3

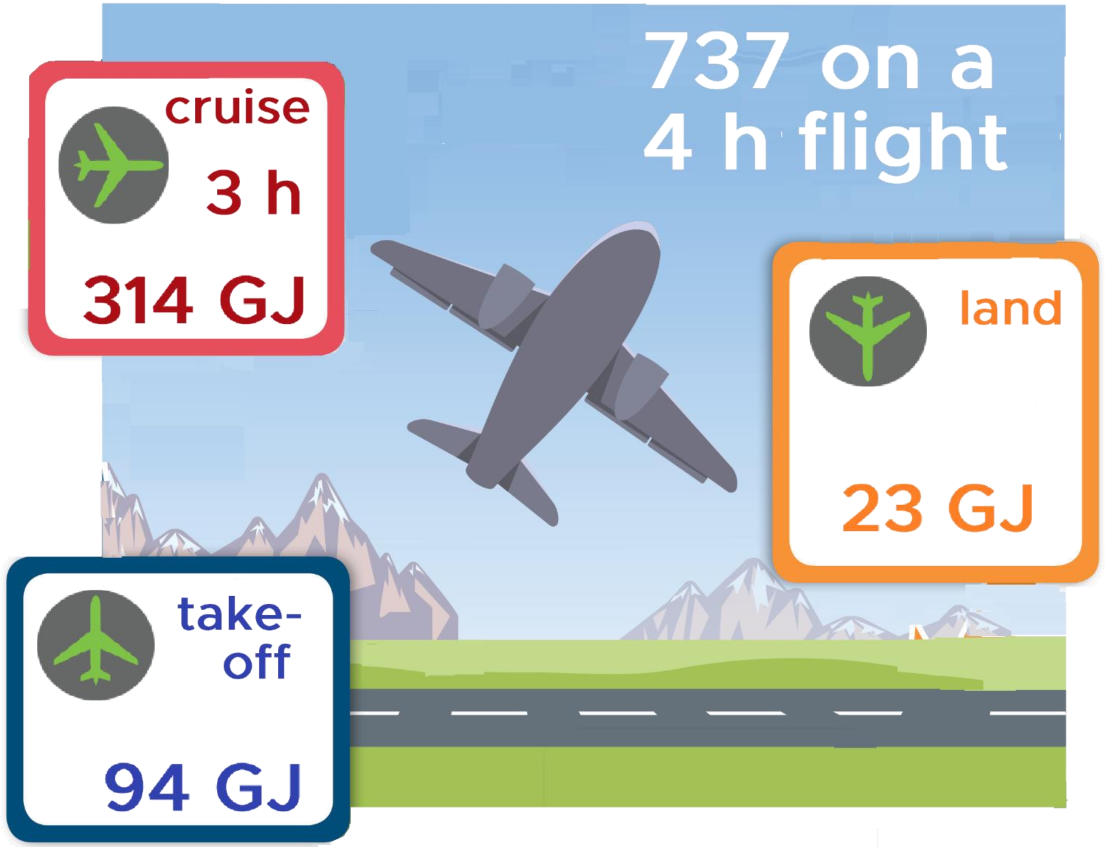
Batteries will need to improve 40 fold to simply fly the plane with no passengers or cargo

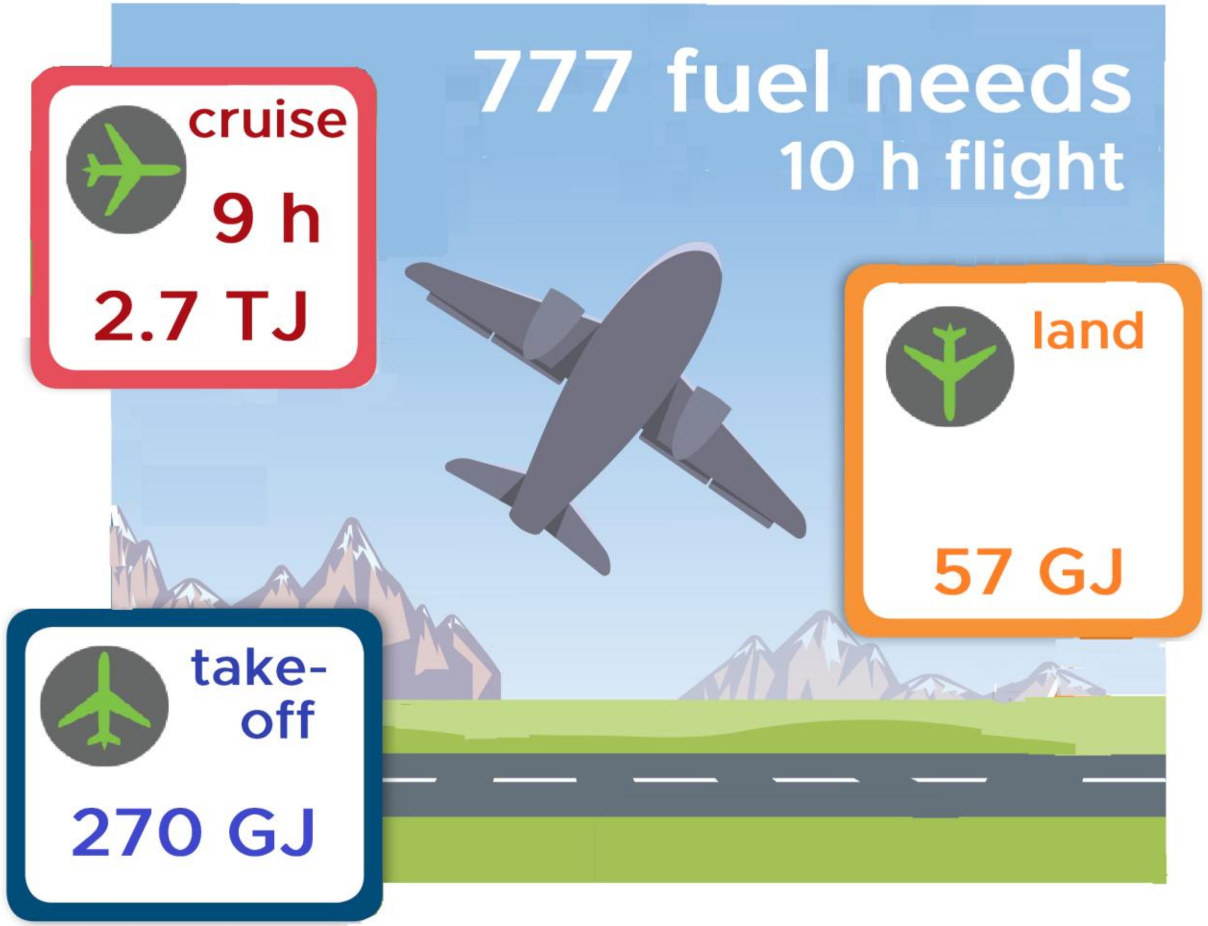


Energy calculated by Holladay and compared to GA Tech models

[1] https://evannex.com/blogs/news/tesla-s-battery-pack-is-both-mysterious-and-alluring-work-in-progress
[2]http://www.aerospaceweb.org/aircraft/jetliner/b777/

Aircraft use 100s and even 1000s of GJ of energy for single flights



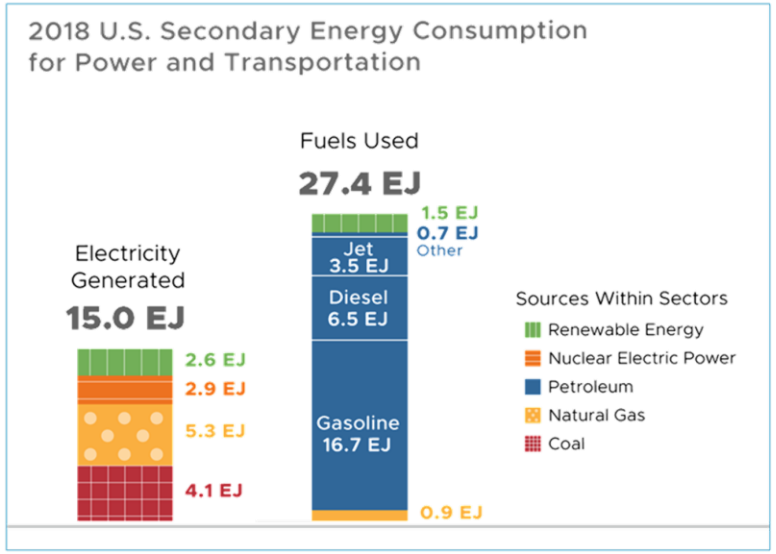


While even takeoff takes more energy than a typical car uses in a year, a lot more people are on the jet (737-900 seats 177 passengers, a 777seats 396 people)

G = giga = billion; T = tera = trillion

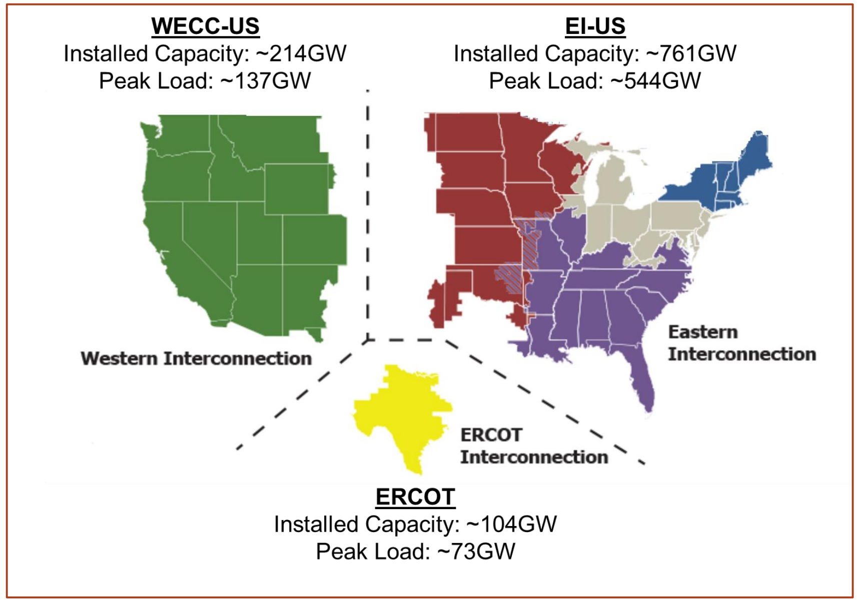
There are several disconnects that must be solved

1. Size



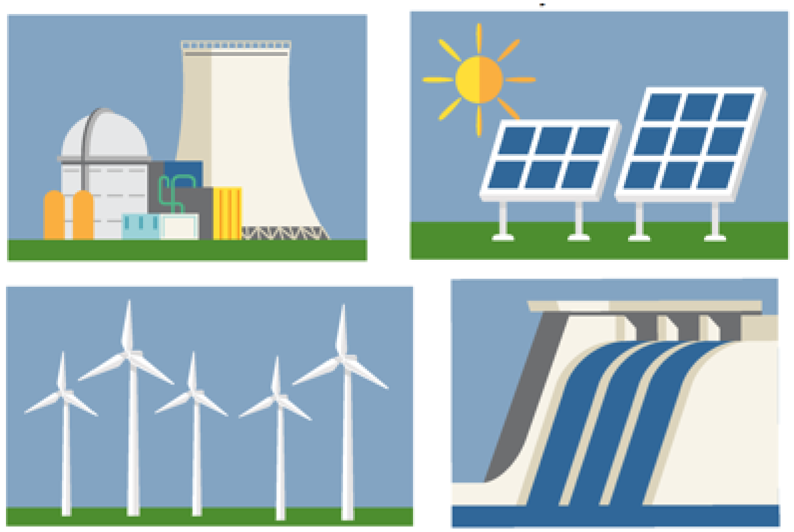
Energy used in transportation is nearly 2x generation

2. Logistics (co-location)



Sourcing of clean, concentrated CO_2 and clean electrons

3. Land use questions



Lack an understanding of implications on land use

S&T needs to support highly distributed collection and processing.
Even the relatively small scale of an ethanol plant would require massive wind or solar farms.