NREL at a Glance

**Employees,**
postdoc researchers, interns, visiting professionals, and subcontractors

**World-class**
facilities, renowned technology experts

**Partnerships**
with industry, academia, and government

**Campus**
operates as a living laboratory

- 2,685
- 871
Transportation in the energy context

U.S. Primary Energy By Fuel (2019)

- Coal: 11%
- Natural Gas: 32%
- Petroleum: 37%
- Renewables: 10%
- Nuclear: 9%


- Transportation (28%) – 70% of total petroleum consumption
  - Coal: 3%
  - Natural Gas: 91%
  - Petroleum: 5%

- Industry (33%)
  - Coal: 4%
  - Natural Gas: 33%
  - Petroleum: 27%
  - Renewables: 8%
  - Nuclear: 29%

- Residential and Commercial Buildings (39%)
  - Coal: 22%
  - Natural Gas: 5%
  - Petroleum: 3%

Over 90% of transportation energy use from petroleum: least-diversified energy sector

Source: NREL. Data from U.S. Energy Information Administration Annual Energy Review

Electricity Generation by Fuel

- Coal: 28%
- Natural Gas: 31%
- Petroleum: 1%
- Renewables: 17%
- Nuclear: 23%
Today, transportation relies heavily on petroleum and it is the largest source of energy-related CO\textsubscript{2} emissions in the US. And mobility needs for passenger and freight are growing rapidly.
… but the landscape is changing rapidly

**Battery cost** declined by 90% since 2010 and pack prices expected below $100/kWh by 2024.  
– BloombergNEF

Cheaper to save the climate than to destroy it: **renewable energy prices** are now significantly below those for coal and gas generation, less than half the cost of nuclear.  
– Forbes (LAZARD)

California **bans new combustion engine** cars starting in 2035  
– State of California

**Sales of electric cars** topped 2.1 million globally in 2019 – 2.6% of sales – to boost the stock to 7.2 million EVs.  
– International Energy Agency

2019 EV sales reached 56% in Norway and **8% in California**  
– International Energy Agency

The **future of cars is electric** – but how soon is this future? By 2025, 10% of global car sales, rising to 58% in 2040.  
– Electric Vehicle Outlook 2020, BloombergNEF

**Amazon** has placed an order for **100,000 electric delivery vans** to be on the road by 2024.  
– USA Today

Average length-of-haul for heavy trucks has declined from **800 to 500 miles** between 2000 and 2018.  
– ATRI

DHL: Tesla semi trucks pay for themselves in **1.5 year**  
– CleanTechnica

California **bans new combustion engine** cars starting in 2035  
– State of California

**California bans new combustion engine** cars starting in 2035  
– State of California
Transportation is at a turning point

• On the horizon lies a future where affordable and abundant renewable electricity can be used to power cost-competitive battery electric vehicles (EVs) and produce energy-dense low-carbon fuels enabling to fully decarbonize transportation systems across all modes.

• The grid integration of EVs presents unique opportunities for synergistic improvement of the efficiency and economics of e-mobility and the power grid.

• At NREL, we're laying the scientific groundwork to get there. Among many other things, our research is finding ways for EVs to support grid planning and operations across several timescales and to fully exploit the synergies between EVs and renewables to provide transformative sustainable solutions for the integrated energy systems of the future.
ELECTRIC VEHICLE ADOPTION & ELECTRICITY DEMAND
Global LDV EV market expanding rapidly

The worldwide market share of electric cars reached a record high of 2.6% in 2019, expanding in all major markets except Japan, Korea and United States. Norway: 56% of 2019 sales. California: 8% of 2019 sales.

Source: 2020 IEA Global EV Outlook
Technology adoption and energy transitions generally follow S-curve shape and are generally underestimated.

invention → innovation → niche market → pervasive diffusion → saturation → senescence

Source: https://www.nrel.gov/analysis/electrification-futures.html
Future expectations: consistently adjusting US LDV EV sales projections upward

What are the main drivers of the rise in EV adoption

1. Technology: batteries and electric drive systems
2. Markets: industry support and make/model availability
3. Charging infrastructure
4. Consumers: maintenance and fuel costs
5. Decarbonization pathway and policy support
EVs have **zero exhaust emissions** and cost less to fuel and maintain.

Recent policy momentum for heavy-duty truck electrification:

- In June 2020, **CARB approves M/HDV sales mandate** starting in 2024 and requiring all new sales be ZEVs by 2045\(^1\).
- In July 2020, Governors from 15 states (+ Washington, D.C.) signed **joint MOU committing to 100% of M/HDV sales be ZEVs by 2050** with an interim target of **30% ZEV sales by 2030**\(^2\).

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EFS scenarios project **great degree of future electrification**, especially for transportation, in line with several energy system transformation scenarios.

**EFS High scenario, 2050:**
- Transportation share of electricity use increases **from 0.2% in 2018 to 23% of electricity consumption in 2050.**
- 1,424 TWh increase in transportation-related electricity consumption relative to the 2050 Reference scenario.

Source: [https://www.nrel.gov/analysis/electrification-futures.html](https://www.nrel.gov/analysis/electrification-futures.html)
EFS transportation sector details

- 2050 U.S. transportation fleet (High scenario):
  - **240 million** light-duty plug-in electric vehicles
  - **7 million** medium- and heavy-duty plug-in electric trucks
  - **80 thousand** battery electric transit buses
- Together these deliver up to **76%** of miles traveled from electricity in 2050
- 138,000 DCFC stations (447,000 plugs) and 10 million non-residential L2 plugs for light-duty vehicles

Vehicle stock

Source: [https://www.nrel.gov/analysis/electrification-futures.html](https://www.nrel.gov/analysis/electrification-futures.html)
EV-GRID INTEGRATION

Backward looking – lessons learned
Traditional electricity system: large-scale generation; centralized, one-way control; and passive loads

➢ Breakdown of **US average retail electricity prices** (data from EIA):

Generation: 58%       Transmission: 13%       Distribution: 29%

Source: DOE 2015 QTR
The grid has evolved over time to accommodate greater annual load additions than 100% light-duty EV sales.

~17M vehicles sold each year in the US: greatest opportunity for electricity demand growth

Based on historical growth rates, sufficient energy generation and generation capacity is expected to be available to support EVs, even for 100% EV sales.
What about local distribution systems?

Residential EV charging represents a significant increase in household electricity consumption that can require upgrades of the household electrical system and unless properly managed it may lead to exceeding the maximum power that can be supported by distribution systems, especially for legacy infrastructure and during high demand times.

- **Clustering effects** in EV adoption and higher power charging exacerbates these issues.
- Effective planning, smart EV charging, and distributed energy storage systems can help to cope with these potential issues.
- Key to consider EVs in system upgrades

EV-GRID INTEGRATION

Forward looking – modeling and analysis
The electric power system is undergoing profound changes.

The traditional system based on the predicament that generation is dispatched to match demand is evolving into a more integrated supply/demand system in which demand-side distributed resources (generation, energy storage, and demand response) respond to supply-side requirements, mainly driven by variable renewable generation.
And EVs are not just a ”burden”, flexible EV charging can satisfy mobility needs while also supporting the grid

- **Vehicles are underutilized assets**: parked ~95% of the time. EV charging profiles can look significantly different if vehicles are charged at different locations or times.
- **Flexibility is secondary to mobility needs and is enabled by charging infrastructure**

**Home-Dominant Charging**

**No Home Charging**

Source: NREL (EVI-Pro Model)
EVs can support the grid in multiple ways providing values for different stakeholders, including non-EV owners

Smart electric vehicle-grid integration can provide flexibility – the ability of a power system to respond to change in demand and supply – by charging and discharging vehicle batteries to support grid planning and operations over multiple time-scales.

<table>
<thead>
<tr>
<th>Power System Application</th>
<th>Time Scale</th>
<th>Vehicle-Grid Integration Value</th>
<th>Generation Capacity and Transmission/Distribution Planning</th>
<th>Resilience To Extreme Events</th>
<th>Seasonal Planning (Hydro/Long-Term Storage Dispatch)</th>
<th>Commitment and Dispatch Decisions</th>
<th>Balancing and Power Quality</th>
<th>Support End Consumers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Multi-year</td>
<td>Ability to reduce peak load and capacity requirements and defer distribution systems upgrades if reliable EV charging flexibility is available</td>
<td>Years (planning), hours (real-time response)</td>
<td>Load response to natural events (heat waves, tornados) or human-driven disasters, load postponement over days, and support microgrid management and grid restoration (V2G)</td>
<td>No role for EVs</td>
<td>Leverage EV charging flexibility to support supply dispatch and load-supply alignment (tariff management), variable renewables integration, operating reserves, energy arbitrage (V2G)</td>
<td>Provide voltage/frequency regulation and support distribution system operations</td>
<td>Years (planning), hours (real-time response)</td>
</tr>
</tbody>
</table>

EFS: flexible load is “dispatched” by shifting electricity demand to minimize total bulk electric system costs

The flexible portion of the load (2/3 of the total from EVs) is dispatched in ReEDS considering the constraints on flexibility and factors related to the generation mix (e.g., amount and profile of VRE generation)

Source: https://www.nrel.gov/analysis/electrification-futures.html
EFS: flexible loads provide value to the bulk power system

Demand-side flexibility provides value by:

- **Reducing total bulk electric system costs** in all scenarios
- **Mitigating** some of the electrification-induced investments needed
- **Reduce operational costs by up to 10%** (lower electricity cost for all)
- Complement renewable and enhance the ability of electrification to decarbonize the energy sector by **reducing VRE curtailment**

Caveat: no incremental cost to implement load shifting considered

Source: [https://www.nrel.gov/analysis/electrification-futures.html](https://www.nrel.gov/analysis/electrification-futures.html)
Value of managed EV charging, more examples

Missing a holistic assessment of the value of smart charging across multiple value streams

**SYSTEM-LEVEL (GRID)**

Smart charging of **3M EVs in California in 2030:**
- 3%–8% reduction in **electricity production costs** ($210–$660M)
- Reduce **peak demand** by 2.8% (avoided capacity)
- Reduce **renewable curtailment** by up to 13%
- Reduce grid **CO₂ emissions** by 3%–5%

**RETAIL-LEVEL (CONSUMER)**

Shifting residential charging to off-peak time-of-use (TOU) periods **reduces charging costs by 26%**

Source: Zhang et al. 2018

Source: Borlaug et al. 2020
We envision a future transportation system that will be optimally integrated with smart buildings, the electric grid, renewables, and other infrastructure to maximize energy productivity and achieve an economically competitive, secure, and sustainable future.
Emerging topic: electric vehicles are rapidly changing the transportation demand landscape

- Electric vehicles provide a pathway to decarbonize the transportation system, eliminate tailpipe emissions, solve petroleum dependency, and improve system efficiency.

- EV success is dependent on cheap and abundant clean electricity, but EV flexibility enables for synergistic improvement of the efficiency & economics of mobility and electricity systems:
  - Optimize the design and operation of future integrated systems
  - Reduce mobility and energy costs for all consumers
  - Smart charging unlocks the synergies between EVs and VRE as both promise large-scale deployment

- System-level integrated demand/supply thinking is required

Two large and complex industries are on a “collision path”: how to enable effective integration?

- What technologies and infrastructure are required to enable smart charging?
- What are the tradeoffs across different VGI value streams, and how to address the seams between bulk power and distribution systems?
- How to engage and properly compensate EV users for providing flexibility?
References

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Thank you!

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Abstract

Transportation is already the largest source of CO2 emissions in the U.S. and mobility needs for passenger and freight are growing rapidly. However, after over a century of petroleum dominance, new disruptive technologies and business models offer a pathway to decarbonize the sector. Transportation is at a turning point. On the horizon lies a future where affordable and abundant renewable electricity can be used to power cost-competitive battery electric vehicles (EVs) and produce energy-dense low-carbon fuels enabling to fully decarbonize transportation systems across all modes. And the integration of EVs into power systems presents unique opportunities for synergistic improvement of the efficiency and economics of mobility and the power grid. At NREL, we’re laying the scientific groundwork to get there. Among many other things, our research is finding ways for EVs to support grid planning and operations across several timescales and to fully exploit the synergies between EVs and renewables to provide transformative sustainable solutions for the integrated energy systems of the future.
Transportation systems have relied on petroleum for over a century…

Today, transportation is the **largest source of energy-related CO₂ emissions** in the U.S. and it is responsible for ~70% of total petroleum use.

Source: NREL. Data from EIA Annual Energy Review

**Least-diversified energy sector**

- Over 90% of transportation energy use from petroleum
- 5% from bioenergy
- Electricity accounts of 0.1% of transportation energy use and transportation consumes 0.2% of electricity
When and where EV charging occurs will be as critical as how much electricity is needed.

a) ASSUMPTION: EV charging is often assumed to simply scale up electricity demand.

b) COMPLEXITY: Future EV charging could change the shape of demand, depending on when and where charging occurs.

c) INTEGRATION: EV charging can impact power system planning and operations, particularly with high shares of variable renewable energy.

d) FLEXIBILITY: Optimizing EV charging timing and location could add flexibility to help balance generation and demand.

Source: Muratori and Mai, The Shape of Electrified Transportation

More nuanced demand-side modeling needed to assess the integration opportunities of EVs on the power system.
Projecting disruptive pathways is complex, and requires new “thinking” (modeling)

**TEMPO** (Transportation Energy & Mobility Pathway Options) is intended to generate future pathways to achieve system-level goals, explore the impacts of technological breakthroughs and behavioral changes, estimate energy/emissions implications of different scenarios and decisions, affordability and infrastructure use impacts, and assess multi-sectoral integration opportunities.

**TEMPO finds pathways to achieve energy/emissions goals and estimates implications of different scenarios and decisions**

- Travel behavior (trips)
- Mobility impacts (traffic, e-commerce)
- Sociodemographics
- Consumer preference
- Charging/refueling availability
- Fuel costs
- Vehicle cost and performance
- Transportation/mobility demand evolution
- Travel mode choice
- Technology adoption
- Vehicle ownership models
- Stock turnover (passenger and freight)
- System evolution (infrastructure)
- Pathway to energy and emissions objectives (assess and inform policies)
- Energy demand (hourly) and charging flexibility
- GHG and pollutants emissions
- Market segmentation (technology penetration)
- Mobility costs and infrastructure use
- Required policy levers

**Coupling to other tools** enables exploring feedbacks and synergies across sectors
- Bottom-up technology models
- Higher-fidelity models
- Macro-economic/integrated assessment models
- Power system models
• **Battery pack cost** dropped by 85% since 2010, reaching ~$150/kWh today

• EVs **already cost-competitive** for some users, over the vehicle life

• Consensus that **$80-100/kWh needed for MSRP-parity** (~$60 cell level)

• **Multiple pathways** to achieve that cost

• Three major **challenges/goals:**
  – Continue reducing battery costs
  – Eliminate dependance on critical materials
  – Develop safe batteries that charge in <15 minutes

![Reducing Costs for Batteries](image-url)
• 2020: 200+ EV models available globally (40+ in the US)
• Number of models will grow dramatically: over 500 different EV models by 2022 globally
• Largest growth in bigger vehicles and less premium models will expand market
• Growth is primarily in BEVs but still a lot of PHEV during transition