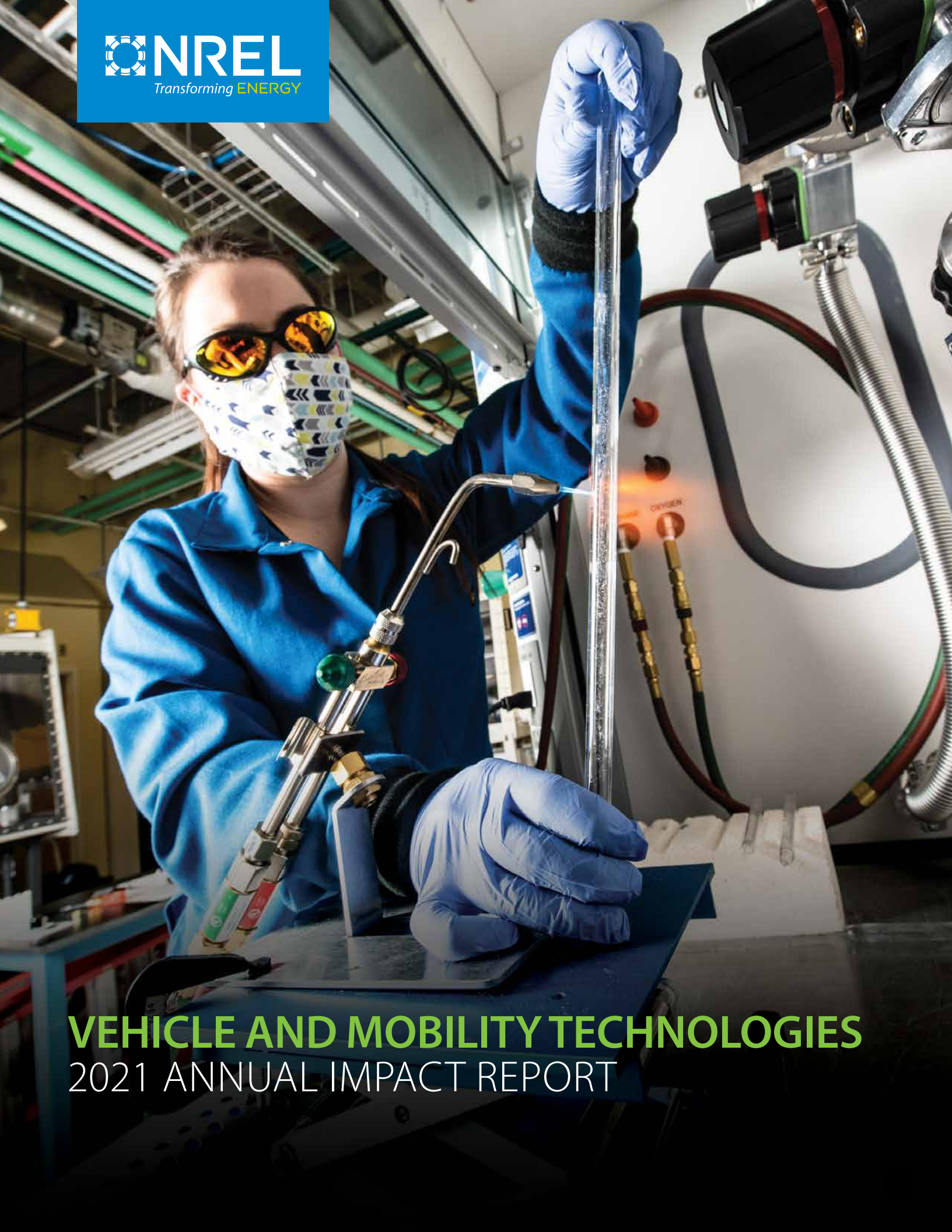
NREL
Transforming ENERGY



VEHICLE AND MOBILITY TECHNOLOGIES
2021 ANNUAL IMPACT REPORT

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EXECUTIVE SUMMARY

Executive Summary

Winning the Cold War. Putting a man on the moon. Connecting millions of people via the internet. Combatting a worldwide pandemic with revolutionary mRNA-based vaccines. Some of the most extraordinary American technological innovations of the last century to produce the greatest societal impacts have been built on the back of scientific research and development (R&D) efforts.

Today, the urgency of the global climate change crisis has awakened America once again, with its pioneering spirit and innovative national labs, to take the reins in leading the global clean-energy revolution—reaping the economic, environmental, and humanitarian benefits that go with it. Decarbonizing the transportation sector, the top contributor to U.S. greenhouse gas emissions, stands as a critical first task to limit global warming and preserve a safe climate future.

As the only national laboratory solely dedicated to energy efficiency and renewable energy, the National Renewable Energy Laboratory (NREL) released a **comprehensive vision for deeply decarbonizing transportation** (*nrel.gov/transportation/transportation-decarbonization.html*) in fiscal year (FY) 2021, rooted in crosscutting research and engineering. With a nod toward the realities that **human behavior is at the core of individual mobility decisions** (*nrel.gov/transportation/urban-mobility-and-equity-research.html*), this vision will help catalyze deep decarbonization of the entire transportation sector and support sustainable, equitable, and resilient energy transitions.

Similarly realizing the importance of understanding how the COVID-19 pandemic will result in future mobility impacts to travel, NREL answered the call to conduct a multipronged, data-informed mobility modeling and analysis effort on behalf of the U.S. Department of Energy's (DOE) Vehicle Technologies Office (VTO). The results are helping U.S. government agencies identify short- and long-term behavioral changes in travel patterns on the road and in the air.

NREL's deep expertise has also drawn recent requests from the Biden-Harris administration to advise on how to equitably deploy a national charging network, provide an extensive review of gaps in battery supply chains, as well as lead multiple initiatives to improve energy justice across government agencies and in communities across the nation.

These efforts have solidified NREL as an important resource for advancing clean vehicle technologies and sustainable mobility at a broader scale.

John Farrell
NREL Laboratory Program Manager, Vehicle Technologies

OTHER ACCOMPLISHMENTS

NREL continued to push the boundaries of science through its inventions, partnerships, publications, and news coverage.

PATENTS & RECORDS OF INVENTION

Innovations resulted in eight records of invention, three provisional application filings, three patent application filings, and one patent award, as described in the Success Metrics section of this report.

VALUE-ADDED PARTNERSHIPS

Industry and research partnerships leveraged DOE funds to establish a significant number of new agreements. For partnership agreements, there are currently 97 active agreements with 77 unique organizations (Cooperative Research and Development Agreements, Strategic Partnership Project Agreements, and Agreements to Commercialize Technology). For licensing agreements, there are currently 54 active license and option agreements with 43 unique organizations.

PUBLICATIONS & OUTREACH

NREL researchers published 199 technical reports, conference papers, journal articles, presentations, posters, fact sheets, brochures, and management reports and conducted outreach via the website *www.nrel.gov/transportation*, online feature stories, press releases, an e-newsletter, and social media campaigns.

KEY ACTIVITIES
SPOTLIGHT

Modeling and Analysis Inform COVID-19 Mobility Impacts and Vaccination Planning

A multipronged, data-informed mobility modeling and analysis effort led by a crosscutting team of researchers identified pandemic-related travel changes—on the road and in the air—and informed regional vaccine administration site planning. This work builds on research that began in 2020 when NREL's data analysis shed light on **transportation patterns during the COVID-19 pandemic** (*nrel.gov/news/program/2020/nrel-examines-us-transportation-patterns-during-covid-19-pandemic.html*) and helped inform epidemiological modelers about the spread of the virus.

Travel Changes: On the Road and in the Air

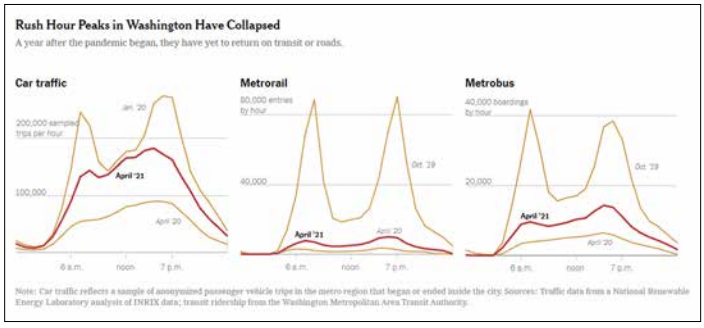
Changes in When and Where People Are Spending Time

Traditional methods for analyzing driver behavior are ill-suited for incorporating significant, abrupt environmental disruptions such as those that resulted from the COVID-19 pandemic. To address this, NREL developed metrics for analyzing granular travel data to quantify behavioral shifts in driving as a function of time, enabling comparisons before and after the pandemic began.

As detailed in the related technical paper—***Changes in When and Where People are Spending Time in Response to COVID-19*** (*nrel.gov/docs/fy21osti/78473.pdf*)—researchers looked at three metropolitan areas with significantly different labor markets: Denver, Colorado; Louisville, Kentucky; and Des Moines, Iowa. Although certain unique behavioral shifts emerged, common trends surfaced in the three seemingly distinct areas. For instance, drivers in all three areas spent more time at residential locations and less time in workplaces after the pandemic started. In addition, employees at workplaces that may be incompatible with remote working, such as hospitals and certain retail locations, generally retained much of their pre-pandemic travel activity.

The New York Times Taps NREL's Data Science Expertise

The New York Times leveraged NREL's data science expertise to identify changes in rush-hour patterns across the nation. Researchers drew on INRIX data to inform analysis referenced in the resulting article—"**A Little More Remote Work Could Change Rush Hour a Lot**" (*nytimes.com/2021/06/11/upshot/rush-hour-remote-work.html*)—



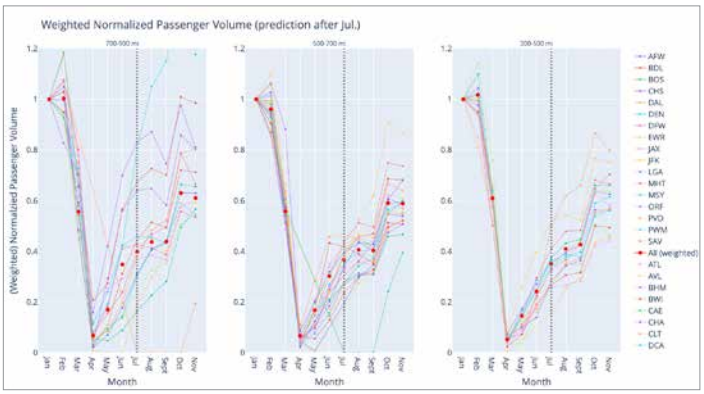
The article featured rush-hour traffic charts representing car traffic for several major U.S. cities, including the chart shown above on the left, based on NREL's analysis of INRIX data.

which covers the impacts of working from home on traffic during the pandemic.

Predicting Long-Distance Air Travel

NREL developed the Point-in-Time Air Travel Model, or PITA, to enable timely and accurate predictions of inbound traffic volumes from any domestic airport. PITA analysis results can inform national responses to critical events such as the COVID-19 pandemic.

Because of the lack of publicly accessible, real-time data on the number of passengers traveling from city to city, researchers tapped into two national data sets to estimate current airline passenger volumes between any two domestic airports. Using a combination of historical passenger count data and near-real-time passenger departure data, researchers can now estimate current air travel passenger counts for a given city or metro area.



To demonstrate the feasibility of using PITA to understand current air travel behavior, NREL used Chicago O'Hare International Airport as an example destination, providing estimated inbound traffic volumes from domestic airports for a 3-month period. *Figure courtesy Stan Young, NREL*

Spotlight on Mobility in Denver

NREL consulted on Denver's COVID-19 Mobility Task Force, providing national and regional insight into pandemic-related mobility changes along with information about emerging mobility technologies and practices that could benefit Denver. Findings were captured in a report highlighting regional mobility changes that may become longer term or permanent, highlighting the need for resiliency and flexibility.

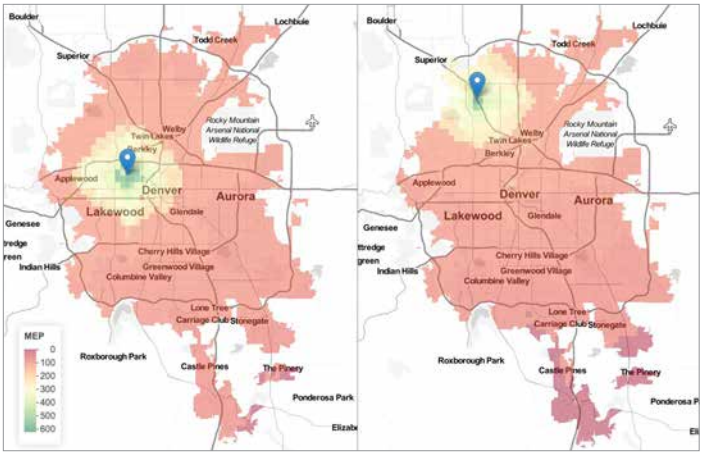
In a related effort, an NREL transportation behavioral analyst joined the advisory committee for the recently launched **Denver Moves Everyone 2050** (*denvergov.org/Government/Departments/Department-of-Transportation-and-Infrastructure/Programs-Services/Everyone*) initiative for the City of Denver, providing insight on mobility trends while also offering strategic guidance and analysis for regional mobility projects emanating from the initiative.

Vaccination Site Planning

Analyzing the Relative Ease of Accessing a Vaccination Site

To inform regional vaccine efforts, researchers used a modified version of the **Mobility Energy Productivity metric** (*nrel.gov/transportation/mobility-energy-productivity-metric.html*), or MEP, to quantify the relative ease of accessing certain vaccine administration sites via a variety of travel modes from any given location in the Denver metro area.

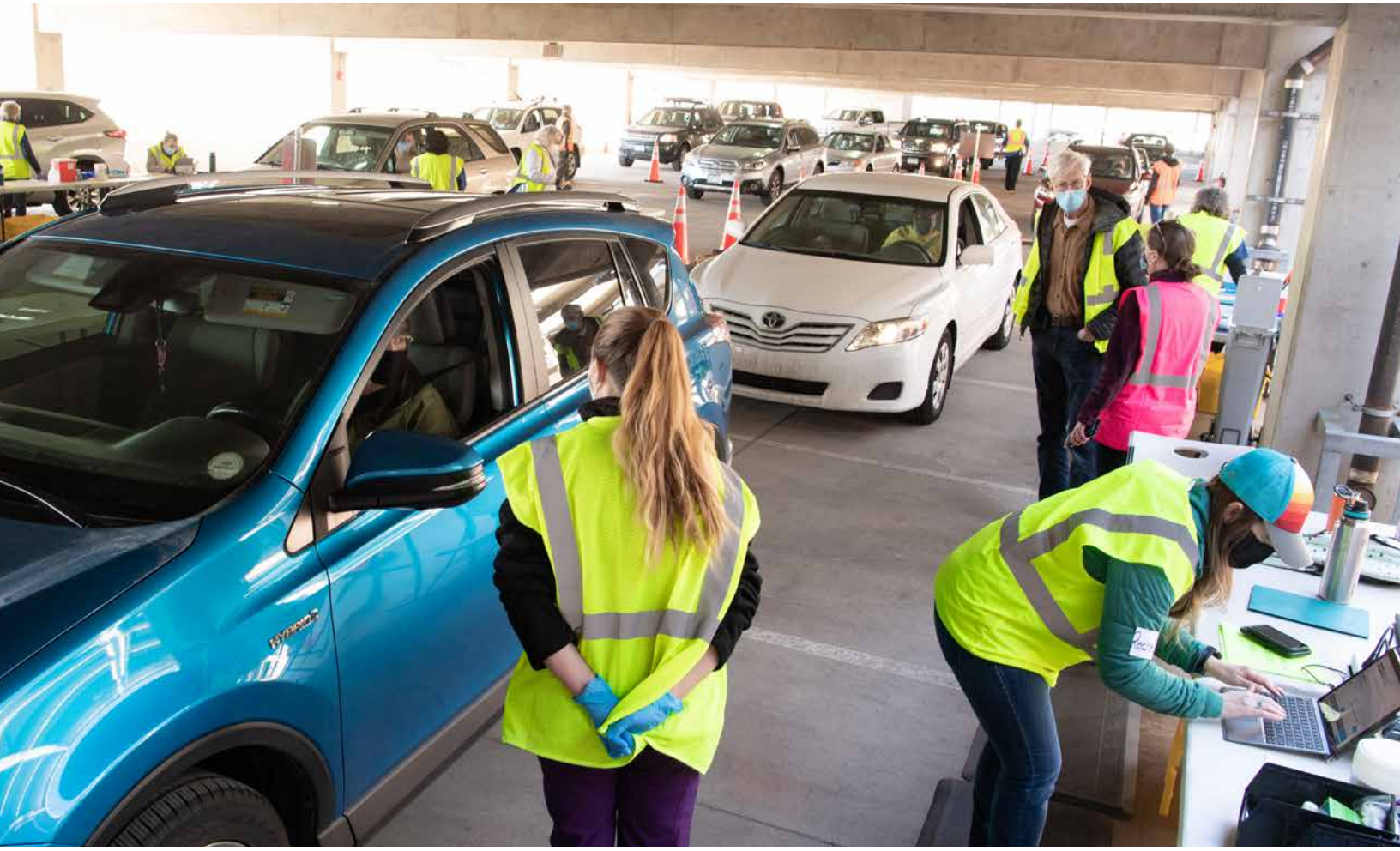
A logical extension of NREL's analysis would be to quantify how MEP scores vary across sociodemographic segments for each of the vaccine administration sites. For example, further analyses could inform if there are disparities in access to vaccine administration sites for low-income or mobility-constrained populations.



Site-specific MEP scores for the Senior Resource Center in Denver (left) and the Fat Cats Fun Center in Westminster (right); a higher score indicates greater accessibility. Analysis results show that the Denver site can be reached from a broader range of locations and via a greater variety of modes compared to the site in Westminster. *Figure courtesy Venu Garikapati, NREL*

Optimizing the Vaccination Administration Process in NREL's Parking Garage

Using a microscopic urban mobility simulation package, researchers explored various scenarios focusing on optimizing vehicle movements and determining efficient locations for administration and observation stations throughout NREL's parking garage. They also developed a queueing system to evaluate the performance of various volume scenarios and provide real-time estimates for wait times. The simulations revealed that scenarios with check-in times greater than 50 seconds could easily lead to large queue spillbacks. Although NREL never reached its full vaccine administration capacity, the analysis pinpointed the maximum number of vaccines—6,400—that NREL was capable of hosting per day.



Impactful Mobility Research Provides a Glimpse of a Decarbonized, Energy-Efficient Future

As the nation races to accomplish an ambitious suite of new energy goals, including net-zero-carbon emissions by 2050, research output in FY21 is keeping pace. With 82 peer-reviewed articles in prominent journals like *Nature Energy*, *Joule*, and *Advanced Energy Materials*—representing over an 18% increase from FY20—the future of mobility research has never looked brighter.

Read on to learn more about some of this year's most forward-looking publications:

"Heavy-Duty Truck Electrification and the Impacts of Depot Charging on Electricity Distribution Systems"

(*doi.org/10.1038/s41560-021-00855-0*)

Nature Energy | NREL authors: **Brennan Borlaug, Matteo Muratori, and Madeline Gilleran**

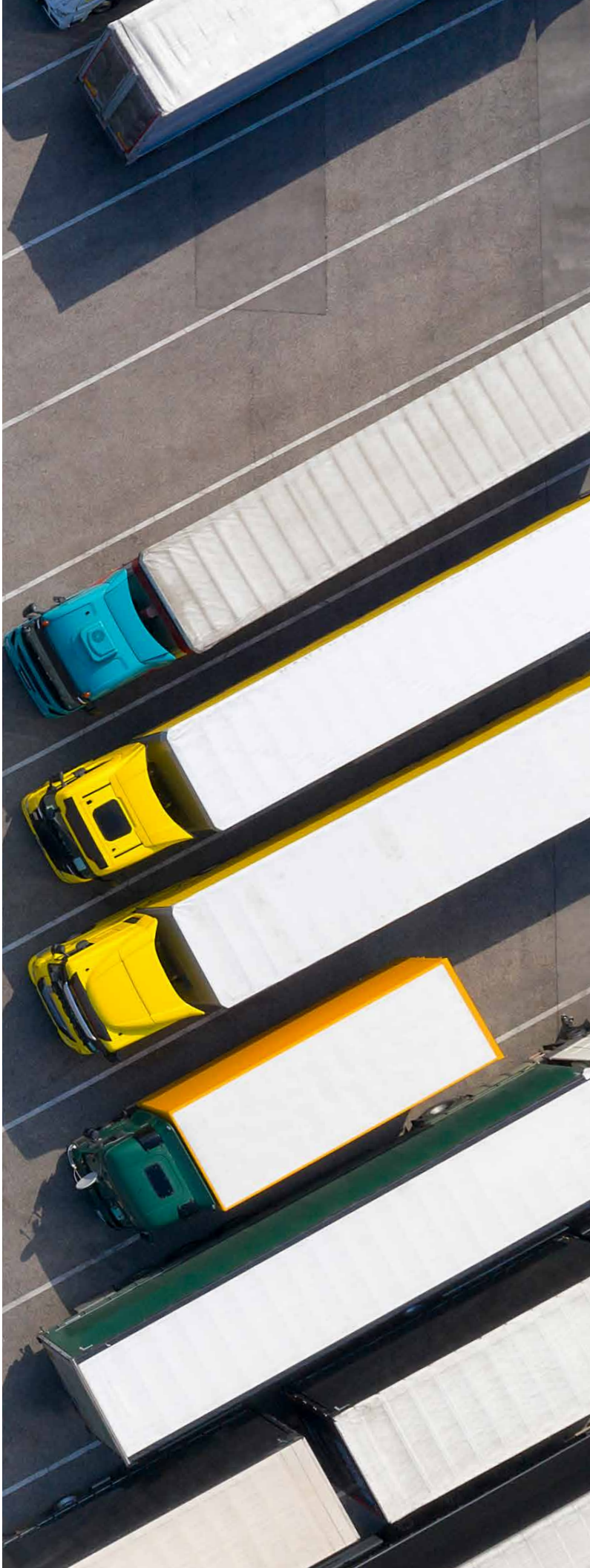
Heavy-duty trucking is responsible for a significant amount of greenhouse gas emissions, but efforts to curb their emissions through electrification have encountered concerns about range, charging requirements, and battery densities. The majority of these same trucks, however, operate within a short range, often with predictable routes and overnight periods in depots. In partnership with electric utilities Oncor and Southern Company, NREL's **in-depth analysis of current charging technologies** (*nrel.gov/news/program/2021/researchers-identify-near-term-opportunities-for-heavy-duty-trucks.html*) reveals that approximately 80% of the chosen depots could support charging a fleet of 100 heavy-duty vehicles without any upgrades—rising to nearly 90% when employing smart charging. The results, published in *Nature Energy*, offer promising evidence of a quicker transition as fleets and grids pivot toward full electrification. With this in mind, future efforts can examine other segments like last-mile delivery and long-haul trucking, and how they can be incorporated into the changing grid as well.

"Understanding How Chemical Structure Affects Ignition-Delay-Time φ-Sensitivity"

(*doi.org/10.1016/j.combustflame.2020.11.004*)

Combustion and Flame | NREL authors: **Richard Messerly, Jon Luecke, Peter St. John, Brian Etz, Yeonjoon Kim, Bradley Zigler, Robert McCormick, and Seonah Kim**

Part of the Co-Optimization of Fuels & Engines (Co-Optima) initiative is focused on identifying promising biofuels for advanced compression-ignition and multimode engines. With the overwhelming number of potential fuel candidates, however, evaluating individual fuels can be time-consuming and expensive. Using experimental measurement, numerical simulations of existing mechanisms, and quantum mechanical theory, the NREL team's findings demonstrate how certain chemical structures increase a fuel's sensitivity to the fuel-to-air equivalence ratio (φ-sensitivity)—a highly desirable property. The insights published in *Combustion and Flame* predict that



isopropyl propyl ether is just one of many possible biofuels with a high φ-sensitivity, a prediction that future experimentation will explore in depth.

"A Data-Driven Operational Model for Traffic at the Dallas Fort Worth International Airport"

(*doi.org/10.1016/j.jairtraman.2021.102061*)

Journal of Air Transport Management | NREL authors: **Monte Lunacek, Lindy Williams, Joseph Severino, Karen Ficenec, Juliette Ugirumurera, Matthew Eash, Yanbo Ge, and Caleb Phillips**

"Route Optimization for Energy Efficient Airport Shuttle Operations – A Case Study From Dallas Fort Worth International Airport"

(*doi.org/10.1016/j.jairtraman.2021.102077*)

Journal of Air Transport Management | NREL authors: **Devon Sigler, Qichao Wang, Zhaocai Liu, Venu Garikapati, Andrew Kotz, Kenneth Kelly, Monte Lunacek, and Caleb Phillips**

As demand for air travel steadily increases, so too does passenger vehicle travel at airports and its resulting energy use, emissions, and congestion. In an effort to **cope with these changing energy and transportation system demands** (*nrel.gov/news/program/2021/long-term-investments-at-major-transportation-hubs.html*), major U.S. airports like Dallas-Fort Worth (DFW) are turning to NREL for help.

As part of the multiyear Athena project, which provides decision support and insights to transportation hubs like DFW, NREL published two articles in the *Journal of Air Transport Management* outlining significant progress. In the first, years of detailed data from DFW on factors like individual vehicle arrivals and departures, aircraft movements, and weather provide context to evaluate different traffic prediction and simulation models. Combining demand forecast with a traffic microsimulation framework, the resulting "digital twin" simulates different scenarios, exploring the impacts of future policy changes, infrastructure expansion, and adoption of emerging technologies like autonomous vehicles. This first-of-its kind model gives DFW a new lens with which to examine their day-to-day operations and consider new directions for growth.

The second article details how the NREL team employed their newly developed tools to model how passenger shuttles at DFW can optimize their routes and schedules to reduce energy consumption and emissions—all without sacrificing passenger wait times. These results and others emerging from the Athena group point toward a changing transportation landscape, and how data-driven insights can be harnessed to make the most of how we invest in and plan for the future. With models like DFW at the forefront, other hubs can learn from their success and plan for their own improvements, too.

Strategic Research Partnerships Enhance Innovation and Generate Real-World Impacts

NREL's expertise and research capabilities make the laboratory a sought-after partner for solving complex mobility challenges. In FY21, NREL continued or initiated 26 unique strategic partnerships concentrated on cutting-edge vehicle technologies research. These collaborations with industry, government agencies, and research organizations drive real-world impact through early-stage research, targeted analyses, and scaling up new processes for market adoption.

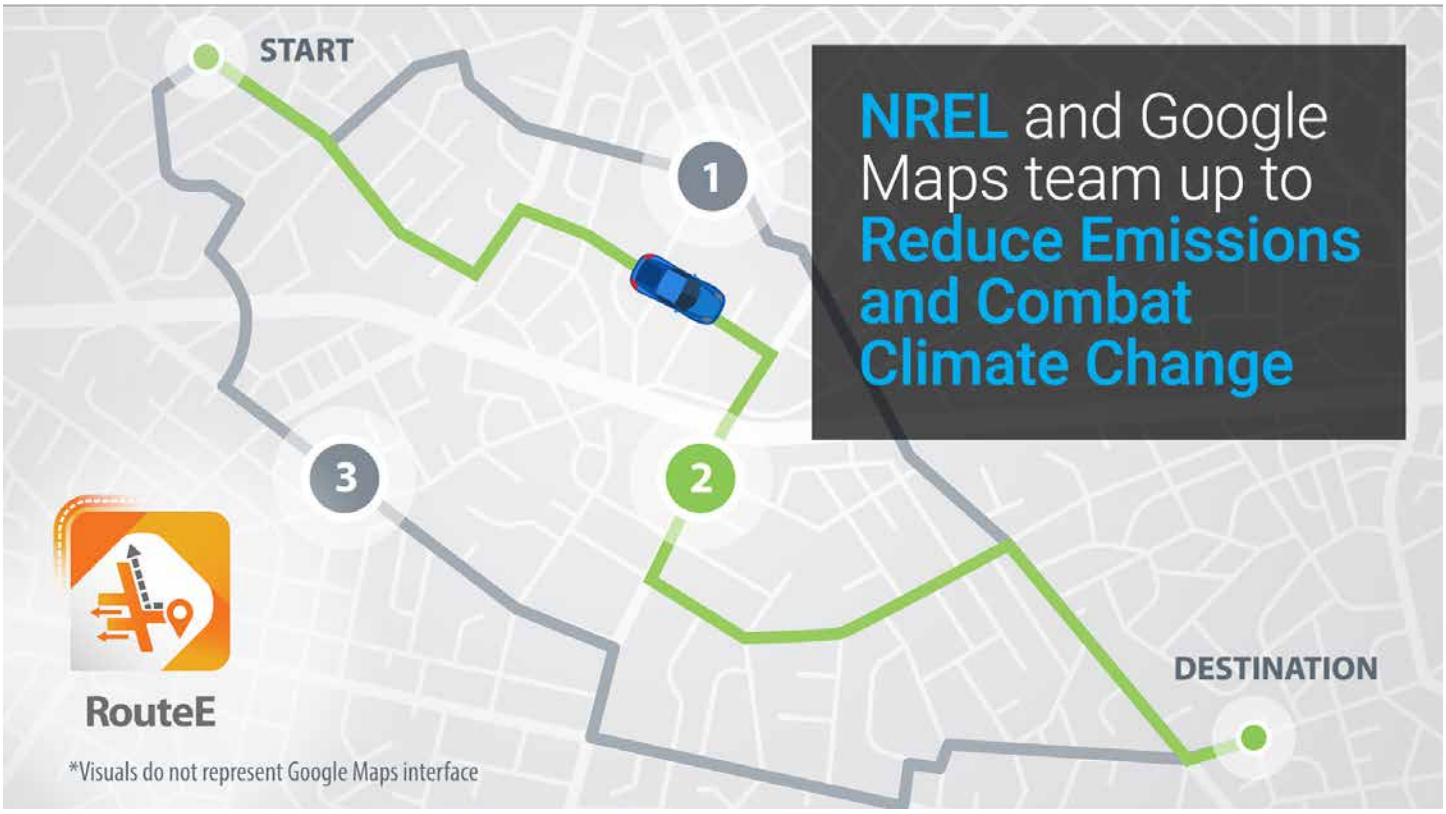
Featured Partnerships

Google Maps

NREL researchers are **partnering with Google Maps** (*nrel.gov/news/program/2021/google-taps-nrel-expertise-to-incorporate-energy-optimization-into-google-maps-route-guidance.html*) to incorporate energy consumption predictions into the route choices generated by the app. The RouteE Integration Project uses **predictive modeling** (*nrel.gov/transportation/route-energy-prediction-model.html*) based on real-world driving data to provide drivers with information about energy-efficient routes that generate significant energy savings with minimal impacts on travel time. An initial analysis in 2017 looked at travel data to evaluate how often drivers could have chosen a different route that would have consumed less energy. This study determined that approximately one-third of all trips had an alternative route that was more energy-efficient. Increasing awareness of more efficient routes could substantially reduce transportation energy consumption, given the large user base for Google Maps. The RouteE project also represents a successful transition of DOE-funded technology development being applied in industry with the greatest possible impact. The next phase of the project will involve supporting the initial release of the eco-routing Google Maps product while refining the accuracy and robustness of the RouteE models.

Australian Department of Defense

A project in partnership with the Australian Department of Defense will improve the speed and accuracy of predicting battery lifetimes, while relying on less test data. Battery lifetime models forecast how long a battery will last based on accelerated aging data and considering multiple degradation mechanisms that depend on the battery design and how it is used. Through this project, NREL is enhancing its **Battery Lifetime Analysis and Simulation Tool (BLAST) models** (*nrel.gov/transportation/blast.html*) to capture the full complexity of issues associated with scaling a single cell's aging to a large megawatt-class energy storage system with thousands of cells. Exposing this physics-based, machine-learning tool to more users and data sets allows NREL and DOE to learn more about the physics of battery degradation and enhance predictive capabilities. The next phase of this project will involve expanding single-cell life models to multi-cell systems and provide guidance to the project partner on how to use the BLAST toolset and incorporate findings into future projects involving megawatt-class energy storage systems to support high-power vehicle charging and the grid.



Video produced by Brittany Conrad, NREL. youtu.be/zjGEJbFf_rM?list=PL3GM1pjrYAcgSUBcidggn1MRVcogxwEZP

U.S. Department of Transportation Federal Highway Administration

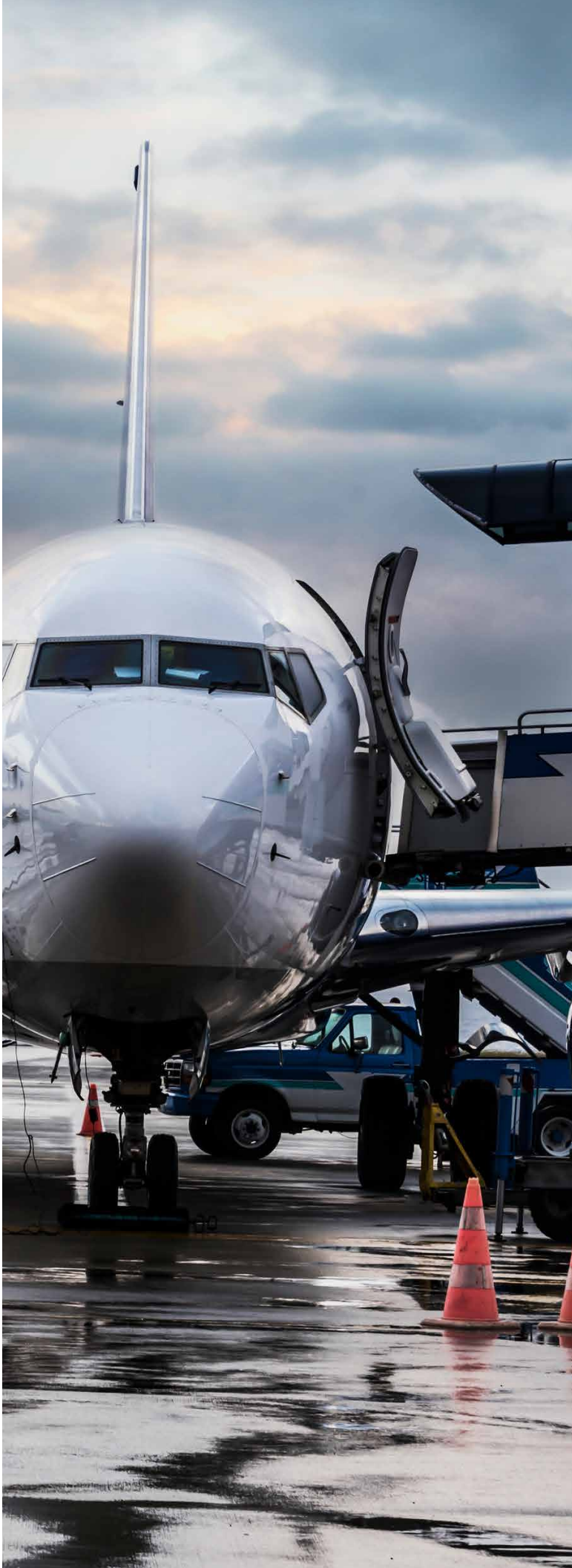
The U.S. Department of Transportation Federal Highway Administration (FHWA) Alternative Fuel Corridor program provides drivers with confidence that alternative fuels are available in their communities and along their drives. NREL researchers support this program by providing the data, tools, and analysis necessary to identify potential fuel corridors for compressed natural gas, liquified natural gas, propane, hydrogen, and electricity. This work resulted in 125 fuel corridor nominations from state and local officials in 49 states plus Washington, D.C., covering approximately 165,722 miles of the national highway system. NREL is poised to support FHWA and DOE with achieving the administration's goal of expanding electric vehicle (EV) charging and alternative fuel corridors across the nation. The lab is well positioned to play a key role in supporting the deployment of fueling stations along pending corridors and addressing fueling gaps to shape the nation's future alternative fueling system.

GE Aviation Systems

In partnership with GE Aviation Systems, NREL researchers are working to develop high-performance and efficient wide-bandgap power electronics for aviation and defense applications. Funded by the U.S. Army Research Lab, this work will provide increased performance, efficiency, and range for next-generation vehicles. Researchers designed and developed a converter that will be more efficient and compact compared to state-of-the-art commercial systems. This will allow for increased range and reduced fuel consumption in aviation and other mobility applications. In the next phase, the converter will be fabricated and evaluated for efficiency and power density.

Other Notable Strategic Partnership Projects

- Toyota Motor Engineering and Manufacturing North America—Toyota S Flow Evaluation
- Hyundai American Technical Center—Dual Layer Climate Control National Analysis
- U.S. Federal Transit Administration—Transit Survey Archiving and Analysis with the TSDC
- National Biodiesel Board— Modification to Existing Agreement: Addressing Market Barriers for Biodiesel
- City of Dallas—Techno-Economic Analysis of Zero Emissions Vehicles
- Robert Bosch—Thermal Dynamics Analysis Using Real-World Driving Data
- Rogers Corporation—A Fire-Retardant Material to Enhance Battery Module Safety
- Delaware Department of Transportation—Integrating MEP Metric into the DelDOT Travel Demand Model

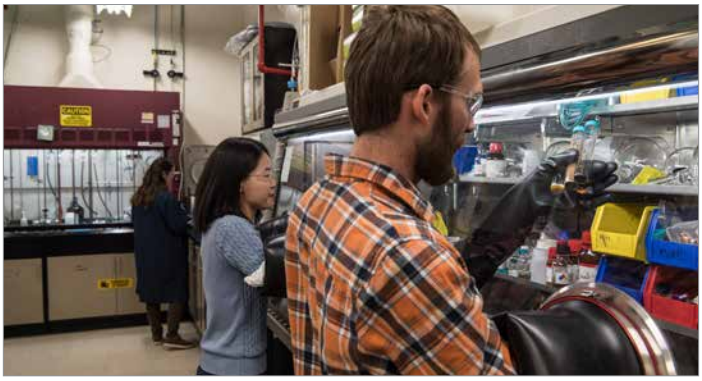


Consortia Leadership and Collaboration Signals Commitment to Furthering Battery Material, Low-Carbon Fuel, and Energy Storage Solutions

Silicon Anode Consortium Emphasizes Forward-Thinking Vision for Alternative Battery Chemistries

The NREL-led multi-lab **Silicon Consortium Project (SCP)** (*nrel.gov/transportation/silicon-anode-consortium.html*) addresses critical barriers to developing smaller, cheaper, and better-performing lithium-ion batteries for EVs by investigating the use of silicon as an alternative to graphitic carbon anode material.

The multidisciplinary team employs advanced characterization techniques, coupled with state-of-the-art research facilities, to study the electrode and cell chemistry of silicon-based batteries. Recent studies focus on the time-dependent degradation of this unique battery chemistry, highlighting the importance of continued calendar-life research to improve the long-term stability of silicon anodes.



Yeyoung Ha and Max Schulze study vials containing silicon nanoparticles in support of Silicon Consortium Project work to eliminate barriers to implementing silicon-based anodes in lithium-ion cells. *Photo by Dennis Schroeder, NREL 61175*

To further our understanding of the **calendar aging of silicon in batteries** (*nrel.gov/news/program/2021/calendar-aging-critical-to-future-silicon-based-batteries.html*), the SCP collaboration led development of a preliminary assessment method to measure the calendar lifetime of cells in under 2 weeks by holding the voltage of silicon cells at the top of their charge. The new test protocols allow the SCP to assess the progress of silicon modifications, cell designs, electrolytes, or additives faster and more efficiently than traditional methods. The current protocols do not yet provide absolute calendar lifetime predictions; however, researchers can use these data to identify the most promising strategies for mitigating calendar aging in silicon electrodes.

NREL Co-Optima Research Reduces Engine Experiment Costs, Identifies Blendstocks With Potential for Deep Decarbonization

Research by the NREL team continues to make vital contributions to DOE's **Co-Optimization of Fuels & Engines (Co-Optima) initiative** (*energy.gov/eere/bioenergy/co-optimization-fuels-engines*), a collaboration of nine national laboratories accelerating development of low-carbon co-optimized biofuels and engines for long-term sustainable transportation. The lab conducted experiments examining a range of biofuel compositions using a single-cylinder research engine, combined with full-scale engine simulations and advanced machine-learning techniques, to optimize advanced compression-ignition (ACI) combustion strategies. NREL also worked with Co-Optima partners on **research related to mixing-controlled compression-ignition (MCCI) truck engines** (*nrel.gov/news/program/2021/big-emissions-cuts-and-efficiency-gains-for-big-rigs.html*), pinpointing diesel blendstocks with the potential to dramatically slash the carbon content of fuels and reduce greenhouse gas emissions, as well as be produced at a competitive cost and decrease vehicle operating expenses.

NREL's ACI research has made it possible to explore key reacting flow phenomena and develop an optimal operating map for experimental study. In addition, the close correlation of engine experiments and simulations is anticipated to ultimately reduce research costs and allow for higher throughput.

In addition to assessing the impact of all identified MCCI blendstocks on nitrogen oxides (NO_x) and particulate matter emissions, NREL researchers played a leading role in identifying top blendstock candidates in three chemical families. These included isoalkanes from food waste, which were among the most promising candidates studied.

Integrating Energy Technologies With Behind-the-Meter Storage Solutions

(Left to right) Researchers Darice Guittet, Maddy Gilleran, Margaret Mann, and Eric Bonnema are part of the BTMS Analysis team that developed the EVI-EDGES model, which evaluates how integrated systems can unlock additional value for building owners, utilities, and EV drivers—at the same time, across the United States. *Photo by Werner Slocum, NREL 65865*

As lead of the Behind-the-Meter Storage (BTMS) Consortium, NREL is working with four other national laboratories to develop energy storage technologies that minimize costs and grid impacts of increased EV usage. BTMS research aims to integrate EV charging, solar photovoltaic generation, and energy-efficient buildings using

controllable loads to support widespread access to EVs at reasonable costs without major grid impacts or upgrades. The BTMS Consortium focuses on research at a low technology readiness level guided by system-level thinking.

To evaluate the next-generation technologies developed as part of consortium efforts, NREL developed a new energy storage simulation model called **Electric Vehicle Infrastructure - Enabling Distributed Generation Energy Storage (EVI-EDGES)** (*nrel.gov/transportation/evi-edges.html*). EVI-Edges identifies optimal system design and energy flows for thermal and electrochemical BTMS systems based on climate, building type, electric vehicle charging station characteristics, and utility rate structure. Recent analysis explored the economic feasibility of BTMS with cobalt-free chemistries, such as LMO/LTO ($LiMn_2O_4$ for the cathode and $Li_4Ti_5O_{12}$ for the anode), taking the effects of battery degradation into account. The model allows researchers to maintain a forward-thinking vision for storage system design and optimization.

NREL Moves the Needle on Transportation & Mobility Priorities

From enacting leading-edge transportation decarbonization efforts to combat climate change to executing numerous assignments that bolster new White House administration priorities in vehicle electrification and energy justice, NREL delivered considerable achievements throughout 2021, in collaboration with its government and industry partners.

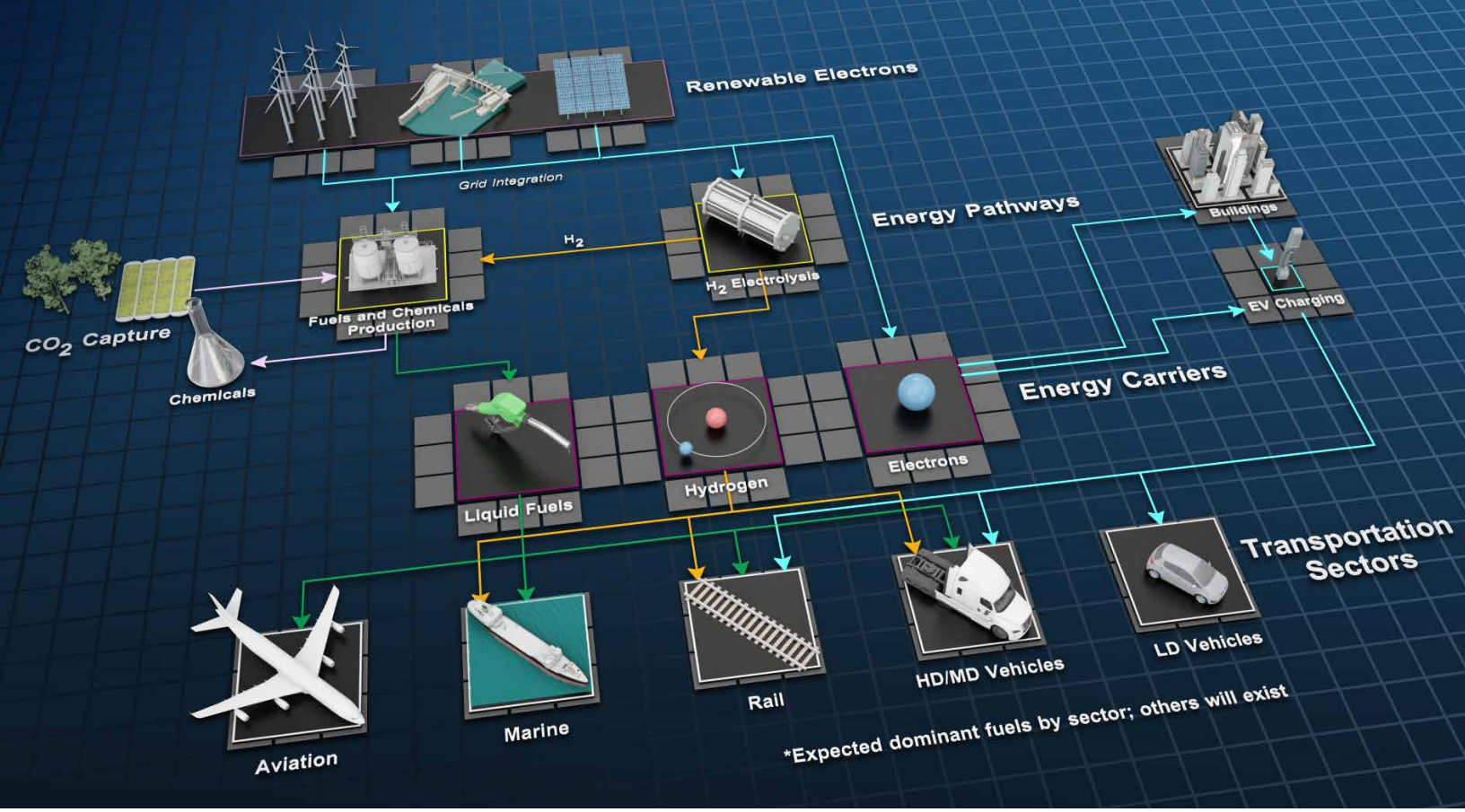
Transportation Decarbonization

The transportation sector is the largest source of greenhouse gas emissions in the United States, accounting for about 28% of total carbon emissions. Turning that metric to zero stands as a critical task in the global push to drive down emissions to avoid the worst impacts of climate change.

In response to this urgent need, NREL has **reignited its science-driven approach to decarbonizing transportation** (*nrel.gov/news/program/2021/lighting-the-path-to-net-zero-nrels-research-strategy-drives-deep-transportation-decarbonization.html*), leveraging decades of the laboratory's clean energy research, with an aim to reshape existing mobility systems for a more sustainable, resilient, and equitable climate future.

As an initial venture to identify the most impactful research, development, and deployment needs to realize a net-zero-emission transportation system by 2050, NREL teamed with the Institute of Transportation Studies at UC Davis (ITS-Davis) to host an invitation-only virtual workshop in April. The inaugural event spurred dialogue between transportation policy and technical thought leaders around opportunities for electrification and low- or net-negative-carbon fuels across major sources of transportation greenhouse gas emissions, including light-, medium-, and heavy-duty vehicles; aviation; rail; marine; and electric, hydrogen, and liquid fuel-powered energy systems.

This workshop illuminated the need for common understanding and integration among different transportation sectors, solidified NREL's leadership in this research space, and strengthened ties across academia, industry, government, utilities, and R&D.

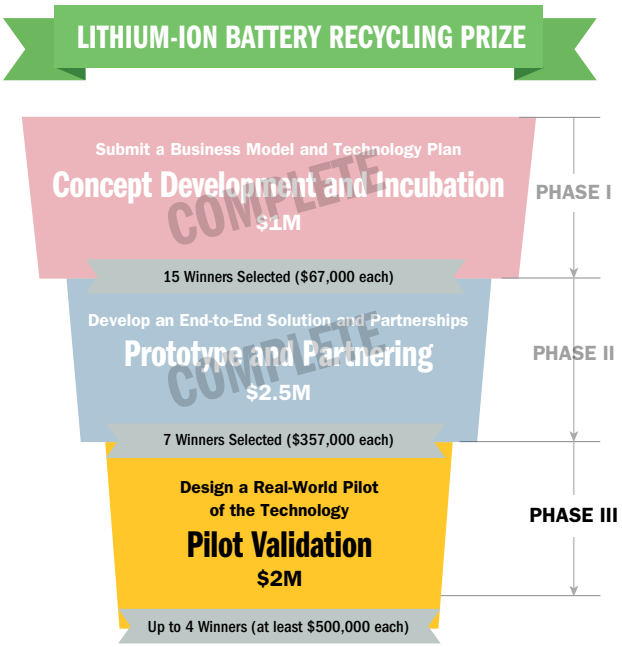


A Whole-System Approach—NREL's research strategy for deep decarbonization considers transportation sectors as part of a larger energy ecosystem powered by renewable electrons and linked by low-carbon energy carriers.

Lithium-Ion Battery Recycling Prize

The NREL-administered $5.5-million Lithium-Ion Battery Recycling Prize is nearing its conclusion, as seven teams participate in the third and final phase of the competition. The Prize aims to develop and demonstrate processes that, when scaled, have the potential to capture 90% of all discarded or spent lithium-ion (Li-ion) batteries in the United States for the eventual recovery of key materials for reintroduction into the U.S. supply chain. Winning teams must incorporate collecting, sorting, storing, and transporting spent Li-ion batteries from consumer electronics, electric vehicles, and stationary storage applications.

Phase III of the Prize focuses on pilot validation of the end-to-end concept. The seven participating teams are building a pilot-scale demonstration of their battery recycling model to demonstrate the feasibility of their solution. Throughout this final phase, teams are participating in networking events with industry experts to inform their business plan for real-world implementation. At the conclusion of the Prize, a panel of experts from DOE will identify up to four winners to receive cash awards of at least $500,000 to encourage the deployment of their recycling model. The deadline for Phase III submissions is April 8, 2022.



New Administration Support

Upon entering office, the Biden-Harris administration announced bold initiatives to tackle converging crises, with sweeping actions to address climate change and advance equity within underserved, minority, and rural populations chief among those. NREL has been tapped on numerous occasions to support these new administration priorities through a series of analyses, consultations, and high-profile appointments to support both the White House's Council on Environmental Quality and Justice40 Initiative.

Researchers Advise White House on National Charging Infrastructure Network

To support rapid passenger EV adoption across the United States, the Biden-Harris administration is advocating investment in a national charging network of 500,000 new EV charging stations. Tasked by DOE and the U.S. Department of Transportation, NREL provided a preliminary analysis that found the market will need to expand quickly to reach 100% light-duty EV sales by 2035—reaching approximately 4 million EVs on the road by 2025 and about 55–85 million or more by 2035, according to Transportation Energy & Mobility Pathway Options (TEMPO) model simulations. Using NREL's Electric Vehicle Infrastructure Projection Tool, better known as EVI-Pro, the team also projected that targeted deployment of 500,000 EV chargers can provide charging along corridors for more than 60 million vehicles and local charging for several million vehicles, ideally within disadvantaged communities.

Supply Chain Analysis Identifies Growth Areas for Future Lithium-Ion Battery Use

A vital component of President Biden's strategy for decarbonization and supply chain resilience is to boost domestic recycling of batteries such that recovered cobalt, nickel, and lithium can be made available for U.S. battery manufacturing. As part of an extensive review of gaps in supply chains, NREL was asked to perform analysis on global suppliers and future demands for lithium-ion batteries. From the acquisition of raw materials, to the manufacturing of battery components such as cathodes, and the production of batteries and recycling, a strong supply chain is critical for the successful growth of batteries in transportation applications. NREL researchers used the **Lithium-Ion Battery Resource Assessment (LIBRA) model** (*nrel.gov/transportation/libra.html*) to evaluate the manufacturing, use, and recycling industries, highlighting global and regional impacts across interlinking supply chains. This analysis contributed to DOE's input to The White House's report, ***Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews Under Executive Order 14017*** (*whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf*).

Experts Guide Administration Efforts To Electrify Federal Fleet, Promote Equitable Distribution of Climate Investments

Ted Sears. *Photo courtesy Ted Sears, NREL 63546*

NREL fuel and vehicle regulations expert Ted Sears has been tasked by the White House's Council on Environmental Quality **to guide the effort to convert the federal fleet to zero-emission vehicles**. Sears' selection follows a Biden administration executive order on transitioning the entire fleet—over 600,000 cars, trucks, and SUVs—to EV models manufactured in the United States. Working through the U.S. Department of Energy, Sears will help sculpt policies to advance the White House's fleet electrification goals, including milestones and directives to enable federal fleet managers to craft EV action plans.

Similarly, NREL Behavioral Scientist Paty Romero-Lankao was invited to join the Justice40 Initiative Metrics Working Group chaired by Deputy Director for Energy Justice at DOE Shalanda Baker, signifying the lab's position as an energy justice thought leader. Comprising approximately 20 select members from across NREL, DOE, and the national laboratory complex, the working group advises the implementation of Biden's Justice40 Initiative —a plan to deliver 40% of the overall benefits of climate investments to disadvantaged communities and inform equitable research, development, and deployment within DOE.

Energy Justice Efforts

Paty Romero-Lankao. *Photo by Dennis Schroeder, NREL 53239*

Alongside the Justice40 Initiative, Romero-Lankao and her team have initiated a Los Angeles 100% Renewable Energy Study (LA100) Equity Strategies study to expand on the success of NREL's **initial LA100 study** (*nrel.gov/news/features/2021/la100.html*) completed earlier this year. Results from LA100 indicated that all communities could benefit from the modeled clean energy scenarios; however, the new study focuses on energy inequity by developing cutting-edge science to increase access to the clean energy scenarios modeled in LA100. These intentionally designed strategies, such as alternative tariff structures and rate designs, transportation electrification investment prioritization, and targeted standards and subsidies, are integral to improving equity in the transition to clean energy. The study, which kicked off at the end of FY21, aims to improve energy justice, with impacts such as reduced energy burdens, increased access to energy services like cooling, and improved quality of life.

Capability Investments in Support of Clean Transportation

Infrastructure Research Capabilities Charge Forward To Meet Growing Demand

The number of EVs on the road is expected to reach 7 million by 2025. Major manufacturers have announced plans for EVs to comprise 50% of all new vehicle sales by 2030. Hand in hand with the upward trajectory of EV sales is the growing demand for faster, higher-power charging.

NREL is enhancing its world-class facilities through a combination of investments from the bench scale to the utility scale, providing a continuum of critical capabilities to enable EVs at scale.

EV Research Infrastructure Evaluation Platform Evolves To Address Critical Needs

The unique Electric Vehicle Research Infrastructure (EVRI) evaluation platform at NREL's ESIF enables researchers and industry stakeholders to study and develop a new generation of electrified transportation technologies within the context of the larger energy ecosystem.

New Vehicle Emulation System and Chargers Enable Enhanced Studies

New this year is a vehicle emulation system that interfaces with a 350-kW charger from BTC Power. The NREL-developed system enables enhanced power-hardware-in-the-loop studies as well as the emulation of EV batteries and battery management systems. The emulation system allows researchers to perform dynamic battery voltage evaluations of charging systems for any battery chemistry and charging protocol. NREL plans to bring more vehicle emulators online to support concurrent evaluations of multiple chargers.

NREL also installed a 350-kW charger from Efacec, bringing EVRI's total number of 350-kW extreme fast-charging units to three to allow for broader system performance and control studies.

Industry Collaboration Informs Development of Charging Standard for Commercial EVs

Leveraging EVRI's world-class capabilities, researchers are collaborating with industry experts—including EV and charging equipment manufacturers and component suppliers—on a new high-power charging standard dubbed the Megawatt Charging System (MCS). The standard will provide commercial fleets with stability and certainty in accessing infrastructure globally while facilitating charging capacity up to 3.75 MW. Transferring this much energy within a short time frame also requires uniquely designed cabling, connectors, and charging inlets.

Researcher captures a thermal image of an MCS charging system. *Photo by Dennis Schroeder, NREL 65254*

Events Leverage EVRI Capabilities To Support Interoperability of High-Power Charging Components

Following its first high-power EV **charging connector evaluation event in September 2020, NREL co-hosted a second round of evaluations** (*nrel.gov/news/program/2021/industry-experts-researchers-put-charging-systems-for-electric-trucks-to-test.html*) at EVRI in July and August 2021 in collaboration with the Charging Interface Initiative. This year's event featured expanded studies to consider more real-world cases for safety and durability within the MCS standard.

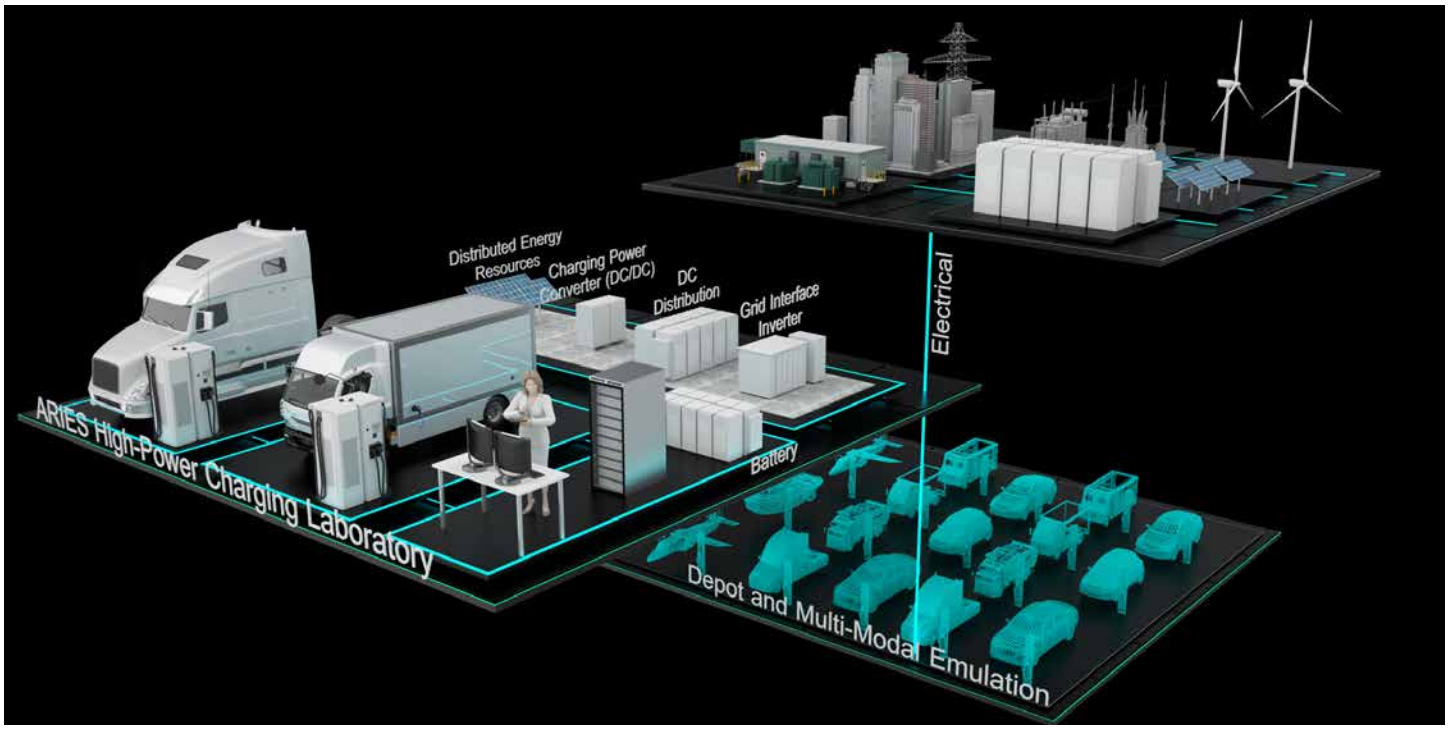
This work leveraged EVRI's newly developed thermal evaluation benches for characterizing air- and liquid-cooled charging connectors for 350–3,000 A, along with a fit and ergonomics apparatus enabling the suspension of cables up to 11 feet in the air to simulate the dispenser-to-vehicle connection process.

Manufacturers evaluated interoperable designs for vehicle inlets and charger connectors. They brought refined, molded prototype connectors based on 3D-printed proofs of concept that were evaluated last year. This evaluation series provided the opportunity for researchers and industry participants to discuss the technical merit of different equipment parameters pertaining to the MCS standard and come to consensus.

Expanded Research Efforts Focus on Enabling High-Power Charging at Scale

These evaluation events are part of NREL's broader effort to enable affordable, convenient, high-power charging that is well integrated with buildings and the grid. Researchers are conducting ongoing analyses to determine how higher-power charging stations and electricity demand from trucks will affect the electric grid, as well as how technologies such as smart charge management and behind-the-meter storage can mitigate impacts.

Significantly enhancing EVRI capabilities, NREL's **Advanced Research on Integrated Energy Systems (ARIES)** (*nrel.gov/aries*) research platform will dramatically push the envelope for enabling decarbonized, high-power charging at utility scale. ARIES represents a substantial scale-up in experimentation capability, allowing for research at the 20-MW level, a tenfold increase from the 2-MW capacity at ESIF. Connecting these capabilities allows for the pairing of EVs



The megawatt charging capabilities under development at ARIES will provide a platform for fully integrating vehicles and charging components with the broader ecosystem via hardware-in-the-loop experimentation, on-site emulation, and national-scale simulation. *Illustration by Josh Bauer, NREL*

with megawatt-scale charging equipment, emulators, and distributed energy resources. Researchers can measure how varying loads and control systems affect the health of the broader system.

As electrification prospects improve for other modes such as aviation and rail, NREL expects ARIES' world-class capabilities to provide key insights along the path toward decarbonization.

New Charging Power Electronics Lab on the Way

Rounding out NREL's capabilities at the bench scale, NREL has launched the design process for the Charging Power Electronics Lab. The new lab will facilitate development, prototyping, and evaluation of power devices and components as well as characterization of bench-level EV charging hardware. It will also enable the development and evaluation of primary controls for these devices supporting research and development activities at higher power levels (>50 kW) within ARIES. NREL anticipates the new lab will be in full operation by the beginning of FY22.

Future Plans

The multi-year, multi-investment ARIES research platform will continue to ramp up in the coming years, establishing world-class megawatt charging and grid integration capabilities for enabling the electrification of over-the-road commercial vehicles and beyond. Leveraging Vehicle Technologies Office investments, NREL has initiated a series of targeted investments such as a sophisticated megawatt-scale behind-the-meter storage system, megawatt-scale battery emulator, DC-as-a-service microgrid and fast chargers, extension of the 1,600-A electrical bus (AC and DC) to EVRI, and, critically, the establishment of megawatt-level charging capabilities.

Ultramodern Approaches to Battery Research Yield Breakthroughs in Modeling and Analysis

Continued decarbonization of transportation relies on cutting-edge energy storage technologies to meet clean energy demand. At the forefront of this effort, NREL's electrochemical energy storage researchers are exploring new ways to optimize batteries for safe, reliable, and fast-charging electric vehicles. In FY21, this team implemented several notable advancements in battery research that transform NREL's characterization of battery technologies.

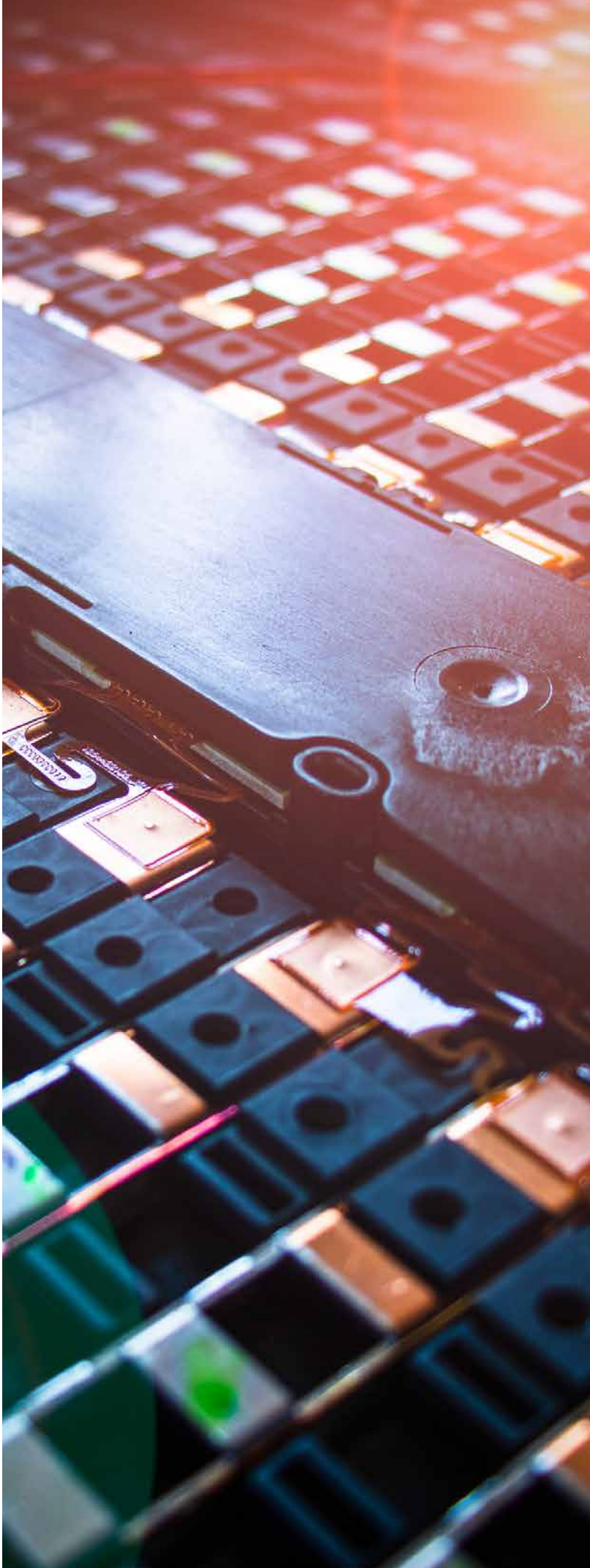
Machine-Learning Techniques Reimagine Modeling Capabilities

NREL researchers are turning to sophisticated machine-learning and artificial intelligence techniques to evaluate manufacturing quality, lifetime and performance, materials research, and safety protocols for energy storage applications. In one project, scientists used electron backscatter diffraction, machine learning, and multiphysics modeling to simulate the pathways lithium ions take when intercalating into cathode particles. The integrated approach allowed researchers to view a realistic electrode architecture in a virtual environment to inform the design of next-generation cell chemistries.

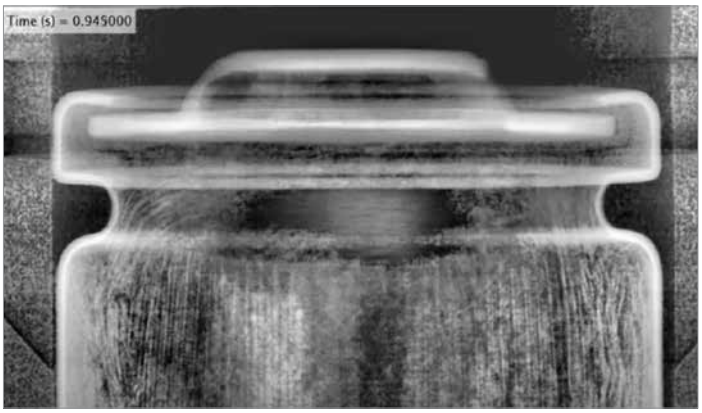
Physics-based machine learning added a fresh perspective to NREL's battery lifetime, performance, and safety modeling by analyzing existing models and identifying the most effective methods for accurate predictions. NREL researchers use machine learning to evaluate electrical, thermal, acoustic, and mechanical data and enhance existing battery failure prediction models to pinpoint safe cell designs and operating conditions. More opportunities exist, and the NREL-hosted **Machine Learning and Batteries workshop** (*nrel.gov/news/program/2021/images/02182021-ml-workshop.pdf*) in March 2021 emphasized a commitment to forward-thinking machine-learning applications for advanced battery research.

Collaborations Inspire Community-Supported Data Sharing

Several notable collaborations highlight the need for shared data across industry to realize the full potential benefits of machine learning for batteries. Modern data science methods such as machine learning rely on access to large uniform data sets across numerous institutions and experimental facilities. In support of Federal Consortium for Advanced Batteries objectives, NREL and Idaho National Laboratory initiated the development of a shared battery data hub, ElectroBatt, as a resource for physics-based machine learning for life prediction and design of advanced batteries. This repository, funded by VTO's Physics-Based Machine Learning of Lithium-Ion Batteries project, underscores the ongoing efforts to address data gaps through community-supported hubs of information.



In addition, NREL released the open-access **Battery Failure Databank** (*nrel.gov/transportation/battery-failure.html*) after years of data collection alongside NASA and University College London. The databank includes extensive safety data and high-speed X-ray radiography videos from several hundred abuse tests conducted on lithium-ion batteries. These experiments provide insight into the rapid structural dynamics that occur within the cell during thermal runaway, facilitating linking internal events to the thermal response of cells. Alongside the existing **Battery Microstructures Library** (*nrel.gov/transportation/microstructure.html*), a compilation of X-ray nano-computed tomography data of lithium-ion electrodes, this database plays a pivotal role in furthering complex battery physics research.



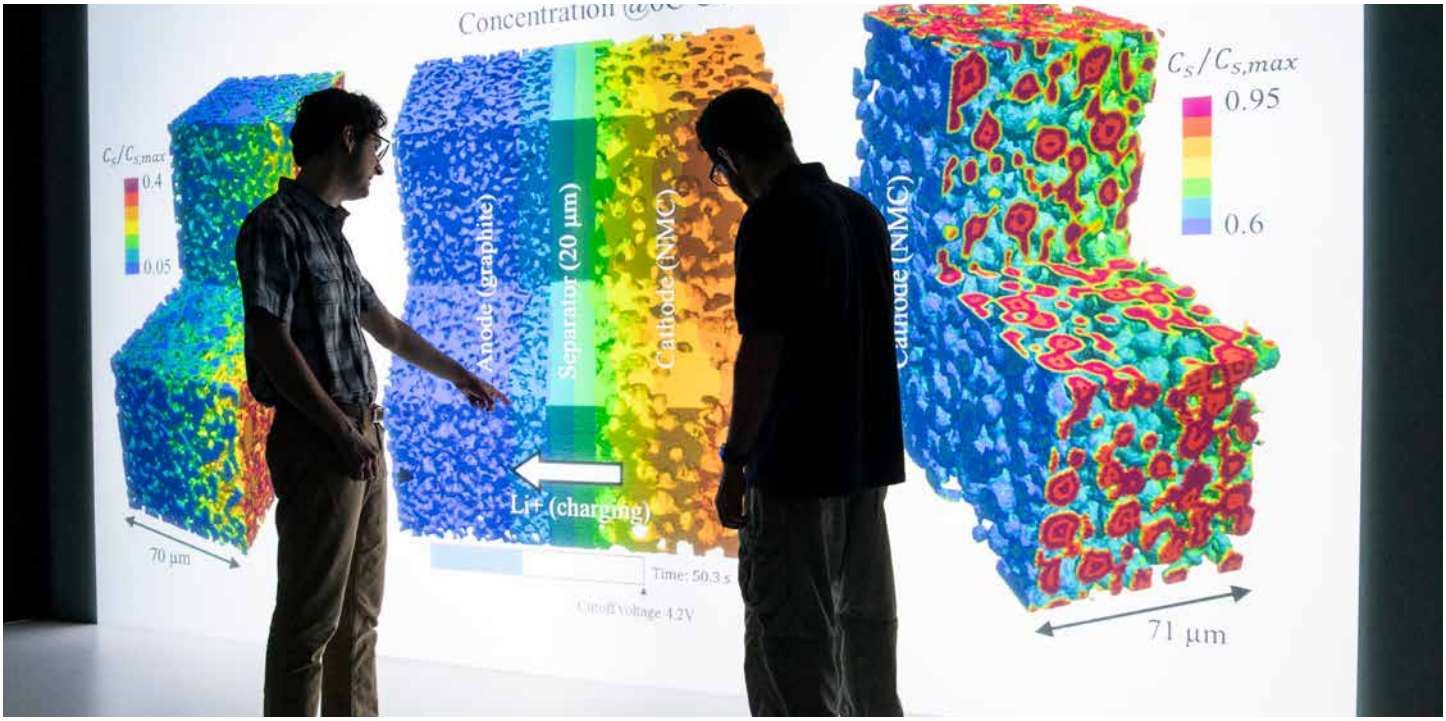
Screenshot from a Battery Failure Databank radiography video of a Soteria Li-ion 18650 cell at 100% state of charge undergoing thermal abuse inside a fractional thermal runaway calorimeter.

Advances in Microstructure Modeling Guides Battery Developments

Researchers rely on advanced microstructure and particle-scale analysis capabilities to provide an in-depth look at battery electrodes. This allows for more accurate predictions about battery performance to be made, and for researchers to identify optimal microstructure and particle architecture to guide the development of next-generation lithium-ion batteries.

Recently, NREL researchers used focused-ion beam electron backscatter diffraction and X-ray nano-computed tomography to generate a representative particle of a lithium-ion cathode electrode with its polycrystalline nanoscale architecture. This multiscale imaging approach provided a full-detail model to inform synthesis approaches of particle architectures with enhanced performance.

Ongoing microstructure-scale electrochemical modeling at NREL also led to the development of a newly released, open-source **Microstructure Analysis ToolBox (MATBOX)** (*github.com/NREL/MATBOX_Microstructure_analysis_toolbox*). MATBOX automates the complex and time-consuming analysis process, providing microstructure parameters and three-dimensional meshes necessary for electrode modeling at macro and microstructure scale, and enables design space analysis at the microstructure scale to identify promising electrode architectures. MATBOX has already become a critical step in the modeling workflow for DOE's eXtreme Fast Charge Cell Evaluation of Lithium-Ion Batteries (XCEL) program, and this tool will help advance the field of heterogenous materials analysis.



Meshes generated with MATBOX are used in other NREL electrochemical microstructure scale models. Simulations reveal nonuniform utilization of the anode material (left), significant gradient within the electrolyte (center), and in-plane heterogeneities (all images) that baseline one-dimensional macroscale models would otherwise neglect. *Photo by Dennis Schroeder, NREL 64757*

LABORATORY DIRECTED RESEARCH AND DEVELOPMENT (LDRD) PROGRAMS

Novel Lithium-Sulfur Polymer Demonstrates Very High Ionic Conductivity

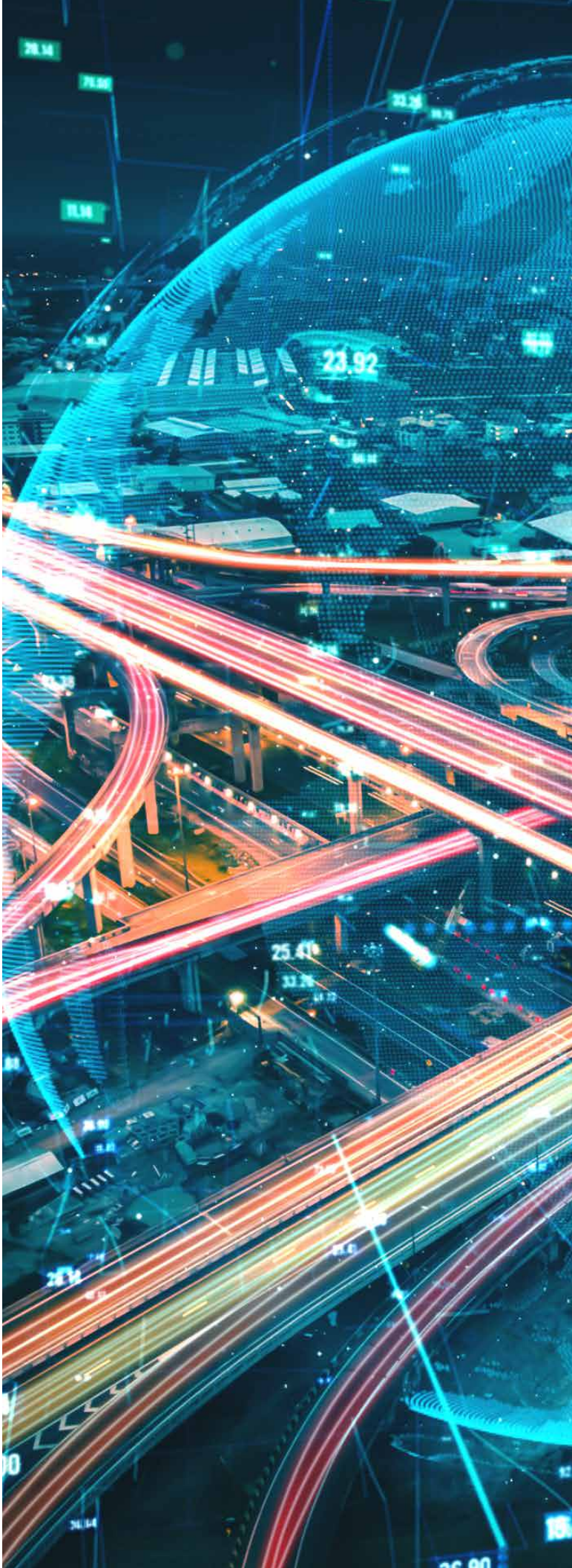
Solid-state batteries have the potential to enable significant increases in the energy density of batteries and result in major cost reductions. However, researchers have not yet identified stable solid-ion conductors that meet the performance metrics required in a functioning cell. New materials capable of functioning at voltages as low as lithium metal and conducting lithium ions at rates sufficient for battery applications are needed to develop solid-state batteries. NREL's Next-Generation Ion Batteries LDRD project recently invented new lithium-sulfur polymer structures and synthetic methods that demonstrate room-temperature ionic conductivities comparable to current state-of-the-art materials. This new class of ion conductor materials provides another route to stabilizing the solid electrolyte cathode and anode interfaces in solid-state batteries. In the next phase of this work, researchers will use chemical modification of the polymer to stabilize the cathode-electrolyte interface and produce fully functional solid-state batteries.

Research Demonstrates Performance and Studies Reliability of Ga_2O_3 Devices at High Operating Temperatures

Increased electrification of transportation and other sectors of the economy requires electronic devices that can operate at high power and withstand high temperatures. Beta-gallium oxide (β-Ga_2O_3) is an ultrawide bandgap semiconductor that shows promise for these applications because of its 4.9-eV bandgap, facile electron doping, and ability to manufacture wafers from melt. New NREL research demonstrates the successful fabrication and characterization of Ga_2O_3/Pt Schottky barrier diodes with up to 400°C operating temperature, higher than for conventional Si-based devices, but lower than the theoretical limit of this material. However, the degradation of ohmic contacts over multiple thermal cycles is observed due to titanium diffusion, resulting in a significant increase in series resistance of the diodes at ambient temperature. These results highlight the need for further development of high-performing rectifying contacts and more stable ohmic contacts to Ga_2O_3 for high-power and high-temperature applications. A publication describing this research was highlighted as "Editor Pick" in the Special Topic Collection on Gallium Oxide Materials and Devices in the *Journal of Vacuum Science & Technology A*.

Infrastructure Perception and Control Project Allows Intersections To Orchestrate Intelligent Roadway Management

The Infrastructure Perception and Control (IPC) project, part of the larger initiative called Autonomous Urbanization for Mobility and Communities, is conducting foundational R&D to enable intelligent roadway infrastructure (IRI) management. IRI is a system of sensors, processing, and communications that leverages the advancements in automated vehicles (AVs) to include management of our roadways and intersections. This is critical not only for AVs to see beyond the limits of their own



sensors, but to ensure safe passage of automated public mobility and protect and service vulnerable road users, such as pedestrians and cyclists, which may never have 'AV technology' otherwise. IPC applies advanced computing techniques to fuse data from modern spatial sensing technologies such as lidar, radar, and video imaging into an ultra-precise digital picture of all moving objects, enabling safety, energy, and mobility benefits for all road users. Most recently, in partnership with the City of Colorado Springs, an end-to-end concept of operations (CONOPS) was defined that integrates the IPC processing engine with sensor installation at a demonstration site. The CONOPS defines the messaging in and among the elements of the system, including the traffic signal controller leveraging the digital state-space image, optimizing throughput and safety while minimizing delay and energy. This work is critical because intelligent roadway infrastructure is needed to accelerate benefits of increased automation in the U.S. transportation sector. The IPC provides an infrastructure-based cooperative perception approach that enables cooperative driving automation functions that can both accelerate automated vehicle deployment and equitably distribute benefits to all roadway users. Later this year and in 2022, the simulation-based development environment will be integrated and validated in real-world demonstrations.

New Methodology Simulates Energy Use by Socioeconomic Group, Addresses Energy Equity Issues

With a focus on addressing energy equity in sustainable energy deployment, NREL developed an agent-based model (ABM) methodology to simulate energy use by different socioeconomic status groups. This LDRD project embedded buildings- and transportation-focused ABMs in the context of behavioral science, thereby improving understanding of how societal factors and human behavior affect residential electricity loads. Researchers compared five scenarios—Baseline, Baseline Plus, Travel, EV Penetration, and COVID-19—to evaluate the significance of the approach for estimating electricity consumption. Results indicate that (1) daily average electricity uses vary over the day, between summer and winter, and across socioeconomic status groups; (2) only one of the two wealthy clusters exhibited the highest increase in energy consumption under the electric vehicle penetration scenario; and (3) only the lowest income cluster did not increase its electricity consumption at home under the COVID-19 scenario, in line with the hypothesis that most essential workers who cannot work from home have low levels of income. Such insightful simulations can inform the use of load profiles to integrate clean energy into a reliable, resilient, and efficient electricity grid; improve energy-demand predictions to inform renewable energy development; and accelerate the development and adoption of controls supporting sustainable building, charging, and transport. Next steps involve integrating this methodology into the Equity-in-the-Loop LDRD project as well as integrating behavioral and equity analytics into the Autonomous Urbanization for Mobility and Communities LDRD project.

Equipment Investments Provide Platform for New Capabilities

NREL's groundbreaking transportation research, engineering, and analysis relies on state-of-the-art equipment and platforms to expand what is possible in the lab. In FY21, NREL invested in specialized equipment and systems to give researchers the experimental capabilities they need to pose targeted research questions and provide innovative solutions to complex scientific challenges. These capabilities provide the steppingstones necessary to expand NREL's global leadership in the development of sustainable, resilient, and equitable mobility systems to accelerate deep decarbonization transportation research.

Internally Funded Science of Safety Upgrades Enhance Battery Safety Investigation Abilities

Recent investments in the Science of Safety facility will enhance NREL's capabilities to directly investigate battery safety questions as a function of synthesis or operating conditions. NREL's Energy Storage team purchased an X-ray diffraction (XRD) unit to accommodate measurements across a wide range of operating pressures and temperatures within the facility. Combined with the existing ability to use models to quantitatively track gas generation from batteries as they age or experience damage, the new setup featuring the XRD unit allows researchers to track changes to material composition as a function of synthesis conditions in real time. NREL also added a Bitrode cycler that is integrated into the high-pressure test bay to address multiple current ranges representative of the test articles characterized in the lab space. This will add 16 channels to the high-pressure test bay, with a wider range of current and voltage capabilities. Both pieces of equipment will be fully operational by the end of the 2021 calendar year and will be used to support VTO- and industry-funded projects.

Investments Advance Power Device Analysis and Thermal Characterization Capacity

NREL's power electronics and electric machines research expanded its capabilities through the addition of a power device analyzer and transient thermal tester. These capabilities will support critical research aimed at characterizing and evaluating advanced power electronics modules and packages for a wide range of energy efficiency and renewable energy applications. Advanced power electronics modules increase performance and efficiency for electrification applications, ultimately helping reduce energy consumption and greenhouse gas emissions. The Keysight B1505A is a high-power device analyzer and curve tracer that significantly enhances the lab's capacity for advanced power device and power electronics module characterization. The analyzer can characterize high-power devices up to 10 kV of reverse voltage and up to 1,500 A of on-state current with a resolution of sub-pico amps. It enables researchers to efficiently perform multiple types of current-voltage (IV), capacitance-voltage, pulsed IV, and transient characterization of power devices.

The Siemens Power Tester 2400A will enable thermal and reliability characterization of the next generation of silicon carbide wide-bandgap power modules. Researchers will use the unit to develop novel thermal management technologies in various applications, such as automotive and aviation. The Power Tester can provide up to 2,400 amps of current and allows for device temperature measurements for module junction-to-fluid thermal resistance calculations. Power cycling stress (AQG 324 power cycling standard) loads can also be applied to evaluate reliability. *(left) Photo courtesy Sreekant Narumanchi, NREL and (right) Siemens*

Director's Fellows Offer Innovative Solutions to Long-Standing Transportation Challenges

The urgent need to find transformative decarbonization solutions to inherent transportation challenges has taken center stage in the fight against climate change, with scientific advances like NREL's sustainable mobility research leading the way. In 2021, two director's fellows added to the laboratory's deep bench of research teams have made outstanding contributions thanks to their unique visions and passion for driving energy-efficient transportation solutions. The NREL Director's Fellowship is awarded to a highly select number of exceptionally qualified up-and-coming scientists and engineers with outstanding talent and credentials in renewable energy research and related disciplines.

Director's Fellow Leans on Materials Science To Build Societal Advancements

Dr. Annalise Maughan. *Photo courtesy of Annalise Maughan*

NREL vehicle electrification research covers everything from charging infrastructure to powertrain technology. With the Biden-Harris administration's ambitious focus on decarbonizing all modes of transportation, this research has become even more important. Achieving these aggressive goals, however, will require significant advancements in battery technology to power the rapid rise of electric vehicle adoption safely, affordably, and sustainably.

Dr. Annalise Maughan has been an integral part of NREL's work on batteries for vehicle electrification as an NREL Director's Fellow. Current electric vehicles utilize lithium-ion batteries, which can overheat under some abuse conditions, and depending on the chemistry employed, can be highly flammable. But these limitations have guided the questions she is addressing with her research. Typical lithium-ion batteries have two solid electrodes with a flammable liquid electrolyte between to facilitate rapid lithium-ion transport. Maughan identified a way to improve safety and efficiency of batteries by using solid rather than liquid electrolytes. All-solid-state batteries could be a safer and more energy-dense alternative to current batteries, but in order for these alternatives to be competitive, Maughan recognized the need to design a solid electrolyte with high ionic conductivity.

In collaboration with NREL's Yeyoung Ha, Ryan Pekarek, and Max Schulze, Maughan discovered a new solid electrolyte with high ionic conductivity for all-solid-state batteries, cyanide argyrodite (Li_6PS_5CN), which can exhibit high ionic conductivities that could be beneficial for all-solid-state batteries. While complete understanding of the effects of the cyanide ion on the ionic conductivity of Li_6PS_5CN is still in the works, Maughan's discovery of a new solid electrolyte material that can compete with some of the existing highest-performing solid electrolytes could alter vehicle electrification as we know it by creating more options for batteries for vehicle electrification.

Maughan says her love of materials sciences is at the center of her work as an NREL Director's Fellow. She traces societal advancements including renewable energy back to materials science.

"In my perspective, discovering and eventually designing new materials with desirable properties predicate growth in renewable energy. Understanding materials at a fundamental level is one of the first steps to realizing renewable energy technology," she said.

Agile Urban Planning Provides Director's Fellow Pathway to Decarbonizing Transportation

Dr. K. Shankari. *Photo courtesy of K. Shankari*

To succeed in creating sustainable and viable transportation systems, cities across the country are rethinking how to address systematic issues such as improving mobility access, decreasing traffic congestion, and slashing air pollution.

NREL has established itself as a go-to resource for energy-efficient and equitable mobility solutions, supported by impactful work like that being conducted by Director's Fellow Dr. K. Shankari. Shankari is making strides in advancing mobility efforts through use-inspired research and transportation data that can support communities in conscientiously meeting their sustainable transportation goals and empower public agency programs to incentivize clean transportation.

Shankari's work provides tools for communities to collect their own data and use it to develop locally sensitive policies. These tools are structured around personal travel data and analyzing that data to maximize the societal impact of mobility efforts by influencing human behavior. In collaboration with NREL team members, nonprofits like **FabMob** (*lafabriquedesmobilites.fr*), and research groups at organizations like the University of New South Wales, Shankari manages OpenPATH, an open-source, extensible platform she developed for measuring and analyzing human mobility. OpenPATH consists of an app, server, and analysis pipeline for generating linked, end-to-end, multimode travel diaries that are then displayed to the user and aggregated into statistics that are stored similarly to information from travel surveys.

Currently, the tool is being used by the Colorado Energy Office to evaluate the impact of a **pilot program to provide e-bikes to low-income households** (*nrel.gov/news/program/2021/pilot-program-sheds-light-on-e-bike-use-patterns-energy-efficiency-benefits.html*) in six locations across Colorado. A pre-pilot program in the Denver area during fall 2020 showed that e-bike trips primarily replaced individual driving trips, mechanical bike trips, and walking. Replacing individual driving trips improved transportation energy efficiency and had a positive energy impact because it decreased the amount of fuel used, and replacing walking and mechanical bike trips had a negative energy impact due to the e-bike's use of energy but improved participant productivity. The preliminary study shows an overall positive impact on mobility and access to clean transportation in low-income households, providing preliminary evidence that such programs can simultaneously meet equity and sustainability goals.

"I see a future where this project provides a win-win-win solution in which stakeholders can access OpenPATH in exchange for data sharing," Shankari said. "The value in a project like this is that data collection from the tool can be integrated with existing projects to provide automated, locally relevant metrics and decision support, as well as long-term research access to data with strong privacy guarantees."

Shankari's work in this field, as well as her depth of experience in computational mobility, positions her well to further empower communities to equip and improve their mobility options as a pathway to combat climate change and further contribute to NREL's equitable and energy-efficient transportation research portfolio.

Award Recognition

NRELians Recognized for Outstanding Technical Leadership

Transportation Infrastructure team lead Maggie Mann and VTO laboratory program manager John Farrell were named Distinguished Members of NREL Research Staff (DMRS) for outstanding technical leadership in their different roles. The DMRS designation is bestowed on individuals who have a demonstrated record of sustained contributions and leadership and who have made contributions that advance the frontiers of science, analysis, and engineering to enable NREL's mission objectives. Mann was recognized for her development of analysis methodologies and sustained NREL capabilities in fields including modeling approaches for behind-the-meter energy storage, supply chain analysis methodologies for battery critical materials, development and implementation of standard methodology for manufacturing cost analysis, and more. Farrell was recognized for his leadership prowess and guidance of NREL's Vehicle Technologies Program, which has contributed to a national vision for high-performance, efficient transportation options that leverage sustainable domestic resources and minimize emissions.

Maggie Mann. *Photo by Dennis Schroeder, NREL 42824*

John Farrell. *Photo by Dennis Schroeder, NREL 49367*

Sears Tapped To Advise Federal Fleet EV Conversion

Following a Biden administration executive order on transitioning the entire federal fleet to EV models manufactured in the United States, NREL Senior Project Lead Ted Sears is directing the development and implementation of activities to build policies that combat climate change by putting more EVs on the road. Sears' technical knowledge in executing federal fleet policy and strong relationships with federal fleet managers, General Services Administration, and national lab technical experts positions him to develop and draft policy that advances fleet electrification goals of the White House and fast-tracks the move to climate-friendly mobility. Also notable in his sustained contributions are Sears' oversight of the State and Alternative Fuel Provider Fleet Program, an offshoot of the Federal Energy Policy Act known for seeding new markets for alternative fuel vehicles and technologies, and his service as the task lead for the Sustainable Federal Fleets Program, part of the U.S. Department of Energy's Federal Energy Management Program (FEMP). Converting the entire federal fleet to electric vehicles would reduce carbon dioxide emissions by roughly 3.6 million tons per year and ignite broader production and deployment of EVs and associated technologies across the vehicle transportation sector.

Ted Sears. *Photo courtesy of Ted Sears.*

Behavioral Scientist Spearheads the Pursuit of Environmental Justice Research

NREL Mobility Behavioral Scientist Paty Romero-Lankao is representing NREL in the Justice40 working group and the **National Academies' Committee on Accelerating Decarbonization in the United States** (*nationalacademies.org/our-work/accelerating-decarbonization-in-the-united-states-technology-policy-and-societal-dimensions*), two initiatives driving environmental justice efforts. The Justice40 working group is creating guidance on how federal investments should be made so that 40% of the overall benefits flow to disadvantaged communities. The Justice40 Initiative is a critical part of the administration's whole-of-government approach to advancing environmental justice. The National Academies' Committee on Accelerating Decarbonization in the United States is crafting the study's second report that will assess a wider spectrum of technological, policy, social, and behavioral dimensions of deep decarbonization and their interactions.

Paty Romero-Lankao. *Photo by Dennis Schroeder, NREL 51637*

Narumanchi Honored with Appointments to Numerous Editorial and Advisory Boards

Senior engineer Sreekant Narumanchi is notable in his supervision of NREL's advanced power electronics and electric machines research focusing on thermal management and reliability. His broad expertise recently earned him an appointment as External Advisory Board Member of the School of Mechanical and Materials Engineering at the Washington State University (2021–2023), Scientific Advisory Board Member of the POETS NSF Engineering Research Center (renewed 2021–2023), Member of the Executive Committee of the ASME Electronic and Photonic Packaging Division (2020–2025), Guest Editor of the *IEEE Transactions on Components, Packaging, and Manufacturing Technology* journal (2020–2022), and Associate Editor of the *ASME Journal of Electronic Packaging* (renewed from 2021–2024). Narumanchi's contributions toward the development and characterization of various thermal management technologies and interface materials, as well as reliability characterization of interfaces for power electronics packaging applications, make him distinguished in his fields.

Sreekant Narumanchi. *Photo by Dennis Schroeder, NREL 61664*

McCormick Earns Editorial Board Distinguishment for Engine and Automotive Engineering Publishing Platform

NREL platform lead and research fellow Robert McCormick was granted membership of the Editorial Board of *Frontiers in Mechanical Engineering – Engine and Automotive Engineering*. *Frontiers* is an award-winning open-science platform and leading open-access scholarly publisher whose mission is to make high-quality research results openly available to the world and accelerating scientific and technological innovation, societal progress, and economic growth. McCormick's previous receipt of the MRI/Battelle Chairman's Award for Exceptional Performance (2005), the National Biodiesel Board's Eye on Biodiesel Innovation Award (2006), and the MRI/Battelle H. M. Hubbard Award (2007), as well as his long tenure of work in fuel processing, catalysts, and fuel-utilization research and development make him a valuable member of the editorial board. He also serves on the editorial board of *Progress in Energy and Combustion Science*, as an associate editor of the *SAE International Journal of Fuels and Lubricants*, and as a peer reviewer for multiple journals.

Bob McCormick. *Photo by Dennis Schroeder, NREL 57129*

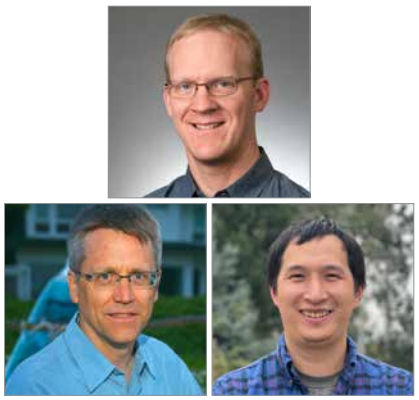
Senior Systems Engineer Selected for Prestigious Membership to Transportation Research Boards

Senior Systems Engineer Matteo Muratori was appointed as Member of the Editorial Board of *Transportation Research Part D*, which publishes original research and review articles covering all localized and global aspects of the interaction between transportation and the environment, including the environmental impacts of transportation, policy responses to those impacts, and their implications for the design, planning, and management of transportation systems. Muratori was also appointed to the Standing Committee on Alternative Transportation Fuels and Technologies of the Transportation Research board (TRB), part of the U.S. National Academy of Sciences, which provides leadership in transportation improvements and innovation through information exchange, research, and advice regarding all modes of transportation. Muratori brings 10 years of experience in conceiving and performing technical analysis, providing engineering recommendations based on physical and economic modeling, and evaluating decisions involving conflicting objectives and uncertainty to these two boards.

Matteo Muratori. *Photo by Dennis Schroeder, NREL 51637*

NREL Coauthored Platooning Paper Recognized as One of the Best at SAE World Congress

A platooning paper authored by NREL transportation researchers Michael Lammert, Kenneth Kelly, and Chen Zhang—along with several partners from Cummins Inc.—received top honors at the SAE World Congress Experience Digital Summit. Their **"Advancing Platooning with ADAS Control Integration and Assessment Test Results"** paper (*saemobilus.sae.org/content/2021-01-0429*) will be included in the *SAE International Journal of Advances and Current Practices in Mobility*, which showcases the best papers from SAE events. Building on NREL's extensive **platooning research** (*nrel.gov/transpor tation/fleettest-platooning.html*), the study detailed in the paper focuses on the real-world fuel economy impact of using cooperative adaptive cruise control with and without advanced driver-assistance systems in heavy-duty trucks.



Michael Lammert, Ken Kelly, and Chen Zhang. *(Top) Photo by Dennis Schroeder, NREL 25753; (Bottom, left to right) Photos courtesy of Ken Kelly and Chen Zhang*

Two Publications Tap Ahmed Mohamed's Electric Vehicle Grid Integration Expertise

NREL transportation researcher Ahmed Mohamed was recently appointed as an associate editor for the Institute of Electrical and Electronics Engineers' Transportation Electrification Community newsletter, a quarterly publication focusing on transportation electrification for land, marine, and aerospace applications. Additionally, he was appointed as a topic editor for the journal *Energies* and is serving as a guest editor for a special edition on electric vehicles in a smart grid environment.

Ahmed Mohamed. *Photo courtesy of Ahmed Mohamed*

R&D HIGHLIGHTS

Battery Technology R&D

Battery Recycling Prize Participants Demonstrate End-to-End Solution Pilot Validation Progress

All seven teams participating in Phase III of the Lithium-Ion Battery Recycling Prize are reporting promising developments in the validation of their end-to-end solutions for successfully recovering lithium-ion batteries. The teams submitted progress updates for review by the prize administrators, and a panel of four reviewers (representing VTO, the Advanced Manufacturing Office, and NREL) reviewed the updates and provided feedback to inform the teams' pilot validation development as they work toward the Phase III final submission requirements. The prize administrators worked closely with the review panel to compile and edit feedback for the participating teams. Phase III participating teams have until April 8, 2022, to finalize and submit their Phase III requirements.

Model Cathode Materials Exhibit Similar Behavior to Commercial Cathode Materials

To simplify the study of the cathode material degradation process in lithium-ion batteries, model materials are needed that can be studied separately from commercial composite cathode materials. Model material systems enable researchers to isolate the contributions of individual cathode components to the overall degradation process. However, these model systems may not accurately represent real-world battery functionality. In a new study, NREL researchers show that an existing model cathode for the $LiMn_2O_4$ system (also developed at NREL) does, in fact, accurately represent the degradation products of real-world commercial cathode materials. This means that the knowledge gained from earlier model systems studies can be leveraged to prevent performance degradation in commercial lithium-ion batteries. In future work, researchers will explore the degradation processes of additional model cathode materials, including $LiNi_{0.5}Mn_{1.5}O_4$ and lithium nickel manganese cobalt oxide materials, using similar simplified model systems. In addition, researchers will explore how cathode degradation products interact with the anode's solid electrolyte interphase layers.

New Silicon Materials Demonstrate Excellent Cycling Capabilities in NMC 811 Cells

One of the primary barriers to deploying silicon-based batteries is the limited calendar life of silicon anodes. However, new research on small silicon particles prepared and coated with polyethylene oxide components (Si@PEO) shows improvement over previous silicon electrodes. Thermal treatment of Si@PEO results in silicon composites with excellent cycling performance. The electrode prepared using these new silicon materials demonstrates long cycle life and shows promising calendar life improvements. These materials, along with others under development within the Silicon Consortium Project, provide new methods for protecting the silicon particles from degradation, potentially allowing for greater lifetimes and high-capacity cells. Future research to scale Si@PEO for active full-cell deployment will offer further insight into the potential failure mechanisms within the silicon electrode.

Cobalt-Free Lithium-Ion Cells Show Promising Cycle and Lifetime Potential

NREL's Behind-the-Meter Storage (BTMS) team is developing high-energy lithium-ion cells that can achieve more than 8,000 cycles over 20-year lifetimes for stationary applications that minimize costs and grid impacts. The (cobalt-free) LTO/LMO cells developed by the BTMS team demonstrate promising performance in recent rate and cycle evaluations. The Argonne National Laboratory Cell Analysis, Modeling, and Prototyping facility coated these materials, and Sandia National Laboratories developed 2-Ah 18650 cells for evaluation at NREL. These new coin cells have thick electrodes coupled with low-flammability electrolytes for improved energy density. Over the next year, the team will use these cells to develop a prototype rack while concurrently increasing the energy density at the cathode for second-generation BTMS cells.

Presence of $Li_xF_yPO_z$ Reveals Linkage With Improved Cell Performance in Nickel-Rich Cathodes Cycled With Dual Salt Electrolytes

The standard salt used in lithium-ion battery electrolytes, $LiPF_6$, results in an unstable cathode electrolyte interphase made up of varying components (organic species, LiF, $Li_xF_yPO_z$, etc.), leading to significant performance losses. NREL and Argonne National Laboratory researchers are spearheading the investigation of a potential dual salt formulation that includes relatively small concentrations of $LiPF_2O_2$. Interest in this new salt arises from the fact that that $LiPF_2O_2$ can form a denser, more uniform cathode electrolyte interphase rich in $Li_xF_yPO_z$ species. Surface analysis with time-of-flight secondary ion mass spectroscopy and X-ray photoelectron spectroscopy reveals that using $LiPF_2O_2$ concentrations as low as 0.05 M leads to a significant increase of $Li_xF_yPO_z$, concurrent with improved cell performance. Understanding the effect that electrolyte components have on the composition of the cathode electrolyte interphase, particularly in relation to electrochemical data on cell performance, is vital to the development of successful new electrolyte formulations. Future work will involve evaluating the interplay of the new salt versus different concentrations of ethylene carbonate solvent to see which avenue leads to a more robust increase in cell performance.

New Techniques Demonstrate Methods To Mitigate Degradation in High-Nickel Cathodes Due to Particle Cracking

When charged to high voltages, high-nickel cathodes are prone to a buildup of mechanical stress along the grain boundaries, which can lead to loss of capacity with cycling due to cracking of the particles. NREL researchers are studying techniques to mitigate degradation from particle cracking and to control capacity fade to enable high-nickel cathodes for vehicle applications that require thousands of cycles. Results show that reducing the cathode particle size relieves the accumulation of stress within the cathode during cycling. However, smaller particle sizes result in larger surface areas and higher side-reaction rates for a given loading. To improve cycling performance, techniques must address both problems simultaneously. One such strategy uses ball milling of cobalt-free cathodes synthesized at The University of Texas at Austin, followed by surface stabilization using a phosphate-based coating. This technique results in less than 6% fade in capacity across 500 cycles, even at an end-of-charge voltage of 4.4V in a full-cell configuration. In future work, researchers will perform cell teardowns after cycling to develop a mechanistic understanding of how the coatings passivate the surface of the ball-milled cathodes, preventing subsequent pulverization.

Mitigation Strategies Suppress Lithium Plating and Temperature Heterogeneity of Large-Format Lithium-Ion Cells, Decrease Thermal Impacts of Fast Charging

NREL researchers are continuously striving to minimize the impact of extreme fast charging on the large lithium-ion battery cells used in electric vehicles (EVs). To better understand the temperature and charge differences between small test cells and large EV cells, NREL uses 3D imaging coupled with electrochemical-thermal models. During fast charging, small cells experience nearly constant temperatures due to efficient heat dissipation to the testing accessories. By comparison, large cells exhibit significant self-heating, resulting in higher charge acceptance and acceptable heterogeneities in temperature and state of charge. This suggests that self-heating is beneficial for large cells in early stages of fast charging. In the next stage of charging, novel thermal management techniques, including multiple-sided cooling and immersion cooling, can be incorporated to mitigate aging heterogeneity and control the ideal temperature for fast charging. In future work, researchers will evaluate the alleviation of these mitigation requirements with fast charge cell design improvements.

Solid Electrolyte Interface Model Illuminates New Insights for Optimizing Electrode Performance

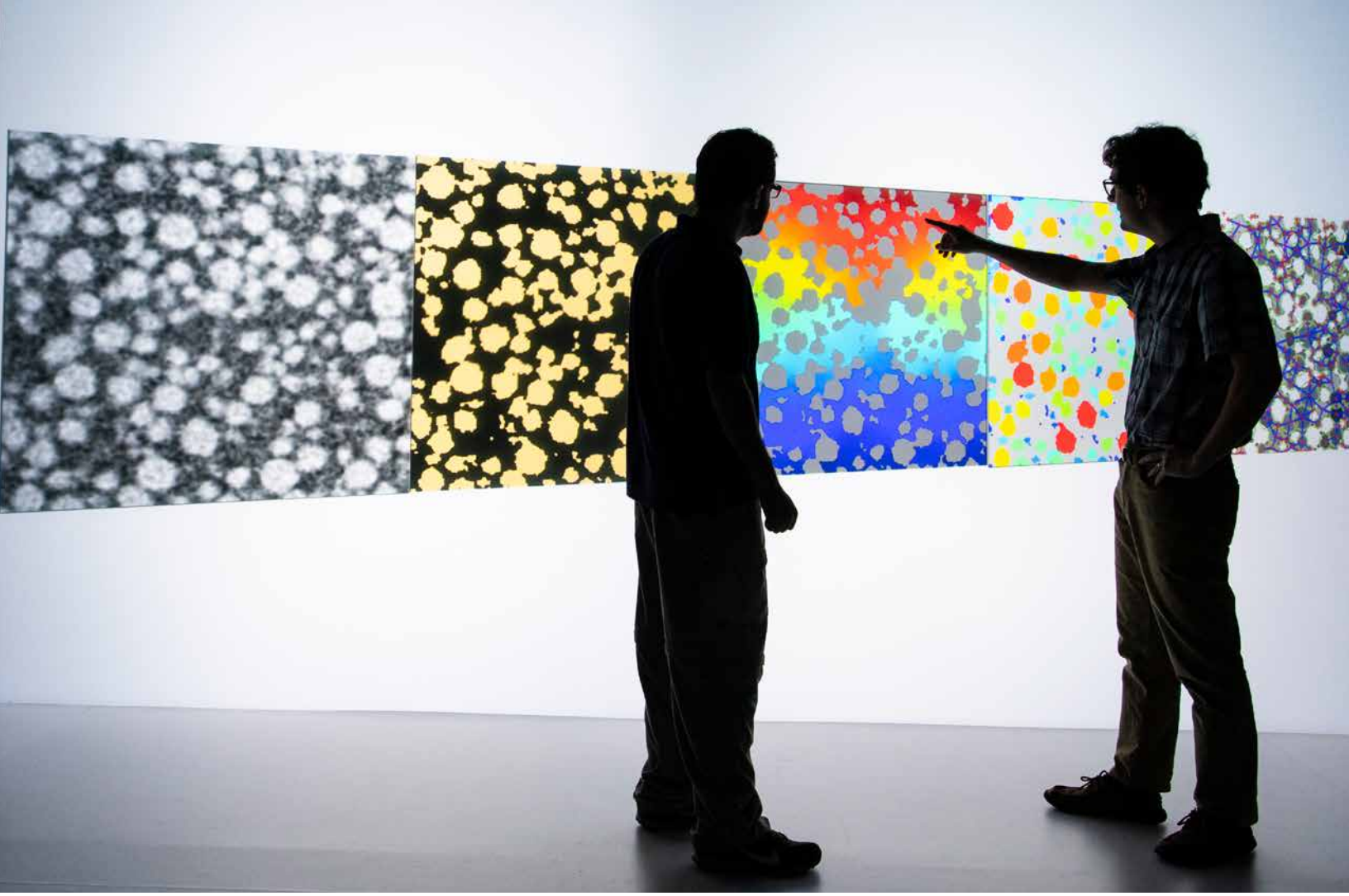
Understanding how solid electrolyte interface (SEI) growth affects complex composite electrodes is critical to designing silicon-based cells with high energy densities, long lifetimes, and good rate capabilities. NREL researchers modified an existing standalone SEI model, which was developed to measure growth on a simple, planar surface, and added it to a composite electrode scale model. The electrode scale model considers the large deformation mechanics that occur in silicon electrodes due to swelling and contraction during rate cycling. Thus, the model provides new insight into how these mechanics affect SEI growth and how SEI growth affects lithium-ion transport in the electrolyte phase. Often, researchers try to develop high-performance silicon electrodes using trial and error discovery. This model offers new physical insight into optimizing electrode performance, accounting for silicon mechanics and SEI growth to explore the effect of varying initial electrode properties, such as composition and porosity, on performance and lifetime.

Machine Learning Research Doubles the Accuracy of Lithium-Ion Battery Lifetime Models

NREL researchers are using machine learning to identify degradation models for lithium-ion batteries from accelerated aging data for implementation into techno-economic models, incorporating predictive uncertainty to evaluate model accuracy and convergence. Accelerated aging studies of lithium-ion batteries are time-consuming and expensive and present complex degradation trends that are challenging to model accurately. Additionally, as batteries become more durable, it is becoming cost-prohibitive to age batteries to end-of-life even under accelerated conditions. A machine-learning-empowered procedure developed at NREL identifies accurate degradation models from accelerated aging data while also quantifying uncertainty versus test duration (time, cycle throughput) and experimental conditions (aging temperature, cycling parameters). This methodology enables model-informed experimental design, such as using predictive uncertainty to suggest new test conditions or quantify a test duration's impact on predictive uncertainty. Degradation models are incorporated into systems-level analysis software at NREL (BTMS EVI-EDGES) and externally (SimSES by Tech. Univ. of Munich). Future work will extend this methodology to predict degradation trends for battery performance models, such as equivalent-circuit or physics-based numerical models. Connecting machine learning with physical models will enable transfer learning across chemistries and designs.

Advances in Lithium Plating, Charge Protocols, and Cathode Aging for Extreme Fast Charging

High-energy-density batteries for electric vehicles (EVs) are limited to charge rates of 1C–2C (1 hour to 30 minutes for full charge) due to lithium plating, cathode cracking, and excessive heat generation. To increase widespread adoption of EVs, charge rates must reach 4C–6C (15 to 10 minutes) to be competitive with refuel times for internal combustion engines. Using a suite of electrochemical models, NREL contributed significant research to accelerate the development of fast-charging EVs. Three peer-reviewed articles (one published and two in progress) detail these findings. In a lithium-plating review article published in *Advanced Energy Materials*, NREL details how jointly developed lithium-plating models and detection/quantification techniques are necessary to help accelerate the development of fast charging. In an upcoming article about cathode aging, NREL modeling is improving the understanding of how lithiation heterogeneity changes with loading and NMC-type batteries. The third article discusses how modeling helps develop protocols to minimize lithium plating and may contribute to protocols for all degradation modes.



3D Model Predicts Performance, Damage of Anisotropic Polycrystalline Cathode Materials

The polycrystalline architecture of nickel-manganese-cobalt (NMC) cathodes greatly impacts performance. While grain size and orientation impact diffusivity, the architecture, voltage window, and C-rate impact mechanical fracture, capacity fade, and active surface area growth. Researchers at NREL are seeking to provide clear design guidance and solutions to improve cathode materials. In FY20, NREL developed and published an electron-backscattering technique to image the 3D particle architecture. Subsequently, NREL and the University of Ulm published two journal articles using neural networks to segment the images and generate both measured and virtual geometries. Using these geometries and NMC532 and NMC811 material properties as inputs, in FY21 NREL published a 3D electrochemical/mechanical continuum damage model that explores the cathode design space and elucidates the most promising architectures. The work has helped explain the wide performance differences for several NMC532 and NM811 materials in DOE's XCEL program. Despite higher particle fracture, the XCEL NMC811 material outperforms NMC532 thanks to its damage-tolerant, radially oriented grains and higher bulk diffusivity. Further research will enhance the model with electrolyte infiltration and structural disordering physics to fully link cathode material properties and geometry with performance and lifetime predictions. The model will clarify the benefits of strategies such as single-crystal particles with varying size and edge-plane arrangements.

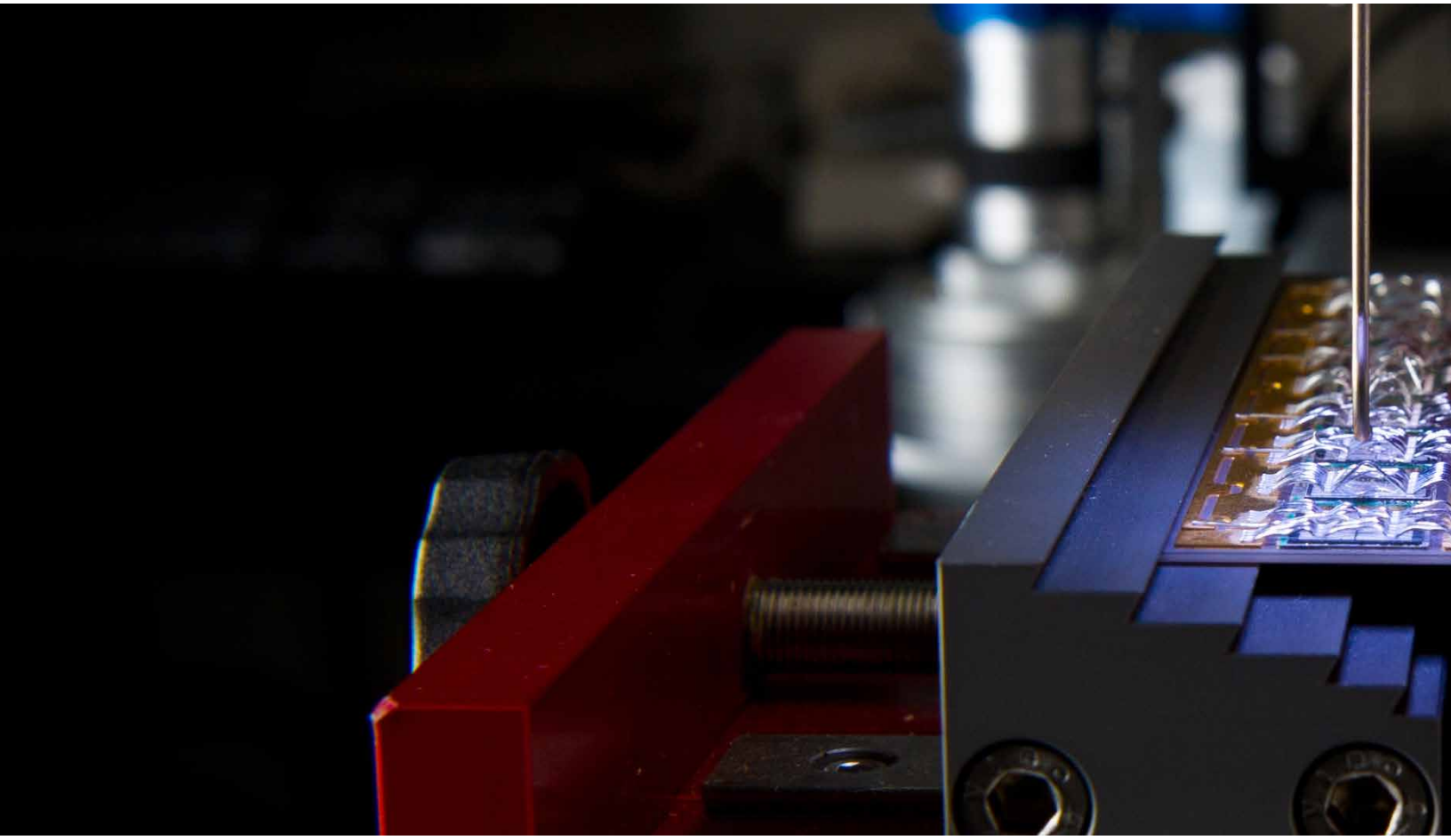
Electric Drive System Technology R&D

Organic Direct Bond Copper Substrates Enable Power-Dense, Reliable, and Cost-Effective Power Electronics Packages

When increasing power density and maximizing performance of wide-bandgap devices, a primary objective is to decrease the thermal resistance pathway in power electronics packages. Researchers can do this by either replacing package layers with new materials that enable greater thermal, electrical, and reliability performance, or eliminating layers and components through new packaging designs. Researchers at NREL, in partnership with collaborators at Oak Ridge National Laboratory and DuPont, developed a new packaging process to fabricate prototype substrates utilizing organic electrically insulating materials. The ability to bond thick (1–1.5 mm) copper metallization layers using the new process improves heat spreading directly below devices and lowers their junction temperatures. In future work, researchers will package these copper substrates into half-bridge power module subassemblies with more complex design features (additional insulation layers, integrated heat sinks) that will be evaluated via experimental electrical, thermal, and thermomechanical characterization.

Expanded Power Electronics and Electric Machine Research Aim To Reduce Energy Consumption Across Applications

NREL researchers are working on four ARPA-E projects, totaling more than $2 million of funding to the lab, focused on advanced power electronics and motors. These projects aim to develop components across applications for improved performance, efficiency, power density, and reliability, while keeping costs low. Two efforts stem from the 2018 ARPA-E Open Call. The first focuses on developing 10-kV silicon carbide and gallium nitride packaging technologies for high-efficiency, medium-voltage applications alongside Virginia Tech. In collaboration with Stanford University, an additional project is developing novel solutions for cooling data centers and other power electronics applications with extreme heat fluxes. This year, two additional projects started. The first project aims to develop high power density electric motors, power electronics, and electric drives for electric aviation applications with Marquette University and General Electric. The second effort focuses on wide-bandgap semiconductor amplifiers for plasma heating and control in collaboration with Princeton Fusion System. NREL's experience in thermal-fluids, mechanical, and reliability aspects directly contributes to the design, development, and evaluation of these advanced components, with applications across aviation, fusion energy, data centers, mobility, and grid integration.



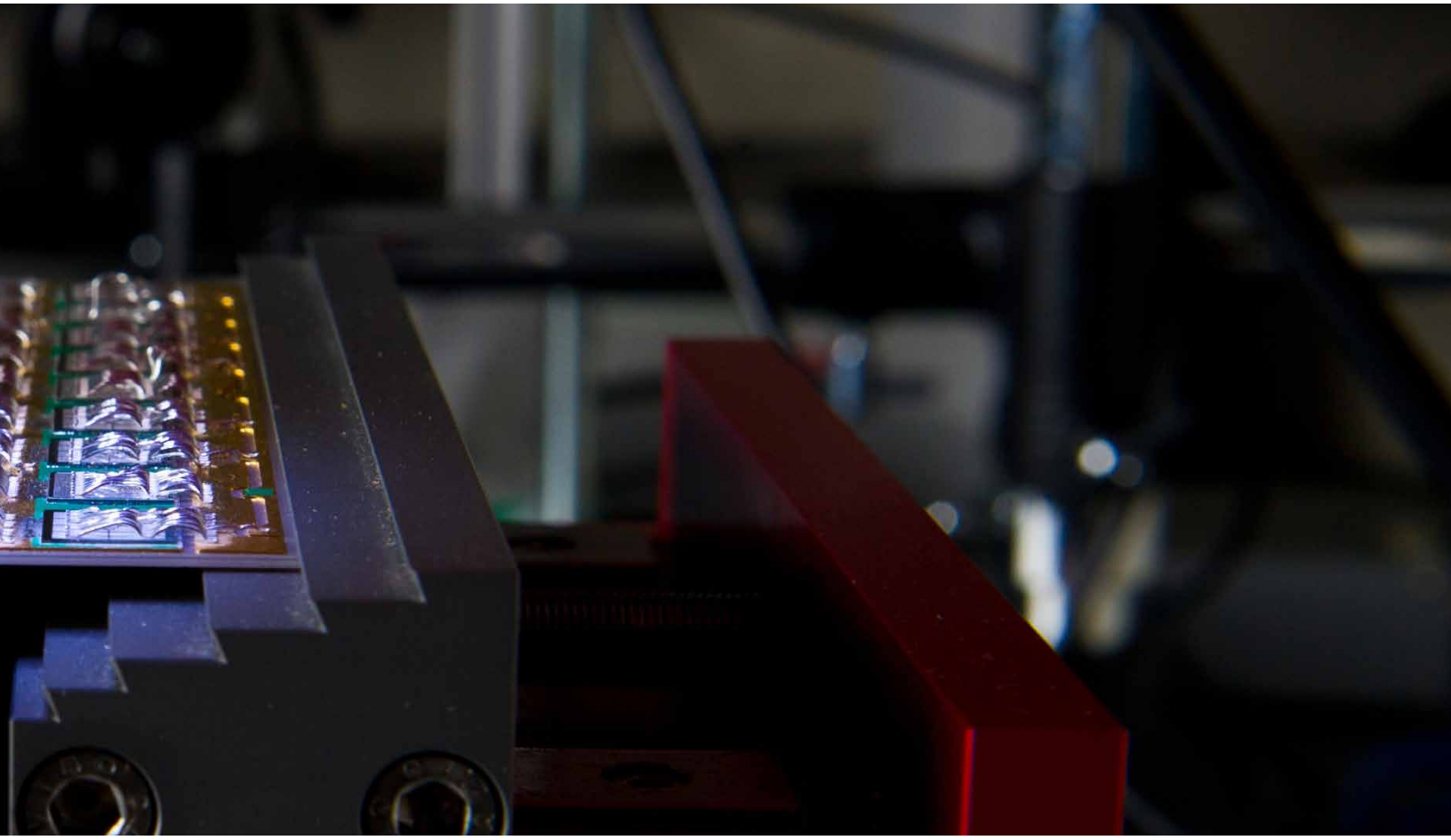
Grid and Infrastructure

Controller Hardware-in-the-Loop Evaluations Inform Development of Multi-Port 1+ Megawatt Charging System for Commercial Vehicles

To facilitate coordinated charging at megawatt-scale charging stations, new research at NREL focuses on developing, validating, and assessing a site controller and battery management system (BMS) through controller hardware-in-the-loop (CHIL) evaluations. Such CHIL assessments bridge the gap between software simulations and hardware evaluations to accelerate deployment while facilitating real-world application with less in-field troubleshooting. CHIL evaluations are critical because issues that might occur in real-world implementation but not in software simulations—such as communication delays and noise among components—can be investigated and resolved before power hardware evaluation. For the CHIL experiments, the site controller and BMS were implemented on an embedded hardware system (Raspberry Pi single board computer) and integrated into a real-time simulation system (OPAL-RT) that runs an NREL-developed direct-current (DC) bus model, distribution feeder model, and EV model. Next, NREL will run additional real-world scenarios in the CHIL environment, evaluate NREL-developed controller hardware with detailed power electronics models developed by Oak Ridge National Laboratory, and make revisions based on evaluation results.

New Infrastructure Siting Methodology for Electric Vehicle Supply Equipment Improves Resolution of Grid Impacts

Future charging infrastructure must be convenient and affordable, which requires an understanding of where charging will be needed and what the corresponding impact on the distribution system may be. To achieve highly accurate siting (down to the parcel level) of electric vehicle supply equipment (EVSE), NREL has developed a new vectorized methodology that relies on real-world and imputed knowledge of parking spaces, business types, and residential styles. This ensures that charging infrastructure is not over-allocated in areas of high adoption. Furthermore, the new method provides a verification for travel data, ensuring that any trips taken for a specified purpose, such as shopping or schooling, indeed have that purpose available in the destination provided. Such granular knowledge and high-fidelity siting were implemented for the city of Alameda, California. Having this level of geographic fidelity allows NREL to assess the grid impacts of future EVSE siting scenarios. The next steps are to conduct further scenario analysis for California's Bay Area using travel data from the Behavior, Energy, Autonomy, and Mobility (BEAM) modeling framework.



EVI-X Modeling Suite Powers World-Class Charging Infrastructure Analyses

NREL conducts studies at multiple scales—from the regional, state, and national levels to site and facility operations—to inform the development of large-scale charging infrastructure deployments. In addition to identifying the number and type of chargers needed to meet a given demand, researchers pinpoint efficient charging station locations.

A key aspect of NREL's work involves developing grid-integrated, smart-charging strategies that can mitigate the need for costly grid upgrades while offering benefits beyond EV charging. Such potential benefits and opportunities include improving grid flexibility by more effectively utilizing renewable energy; shaving peak electricity demand and filling demand valleys; lowering costs via demand-charge mitigation; and providing voltage support, frequency regulation, and demand response.

NREL's **EVI-X modeling suite** provides researchers with the integrated resources needed to conduct multifaceted analyses that provide insights critical to the development of successful charging networks that meet the needs of users while supporting the grid.

Network Planning

EVI-Pro Charging infrastructure projection based on typical daily travel

EVI-Pro Lite Simplified version of EVI-Pro (free to use)

EVI-Equity
Charging infrastructure accessibility from environmental-justice perspective

EVI-OnDemand
Charging infrastructure demand modeling for ride-hailing services

EVI-RoadTrip
Charging infrastructure analysis for long-distance travel

EVI-Pro HD
Depot and corridor charging infrastructure projection for commercial vehicles

Tools are applicable to:

- Light-duty vehicles
- Medium- and heavy-duty vehicles

Site Design

EVI-Fleet

Operational and economic analysis for fleet electrification

EVI-EnSite

Charging infrastructure energy estimation and site optimization

EVI-EDGES

Techno-economic evaluation of behind-the-meter storage

EVI-InMotion

Dynamic and quasi-dynamic charging infrastructure design

HEVII

Multi-fidelity telematics-enabled vehicle and infrastructure design

Financial Analysis

EVI-FAST

Charging infrastructure financial analysis

Next-Generation Engines and Fuels

Phi-Sensitive Renewable Oxygenate Fuels Offer Enhanced Combustion Control and Improvement of Advanced Compression-Ignition Engine Operability

Advanced compression-ignition (ACI) engines operating on gasoline offer efficiencies comparable to conventional diesel engines, while emitting very low levels of nitrogen oxides (NO_x) and soot. However, their operating range can be limited by knocking combustion, which arises from rapid heat release rates during autoignition. A fast method to control the heat release rate (and timing) is stratification of local equivalence ratios. This control strategy is enabled by highly phi-sensitive fuels for which the time-delay to autoignition strongly depends on the local equivalence ratio. NREL researchers investigated the phi-sensitivity of pentyl alcohols and esters as renewable blendstocks for gasoline, aiming to improve ACI engine operability. A blend of 30% 1-pentanol was shown to be significantly more phi-sensitive than a baseline E10 gasoline, thus increasing combustion control through late injection timing. In contrast, a 35% blend of methyl-pentanoate was significantly less phi-sensitive than the baseline gasoline, demonstrating a wide range of fuel chemistry impacts on fuel phi-sensitivity. Additional experiments will be performed with a 30% 2-pentanol blend, and the results will be used to validate a computational fluid dynamics (CFD) model of ACI combustion. CFD simulation results can in turn be used to guide future experiments extending into other speed–load regions and other renewable blendstocks.

Study Quantifies Effects of Exhaust Gas Recirculation Dilution on Phi-Sensitivity

Phi-sensitivity in fuels may be leveraged to control combustion phasing in advanced compression ignition engines, thereby managing engine load with increased efficiency and low engine-out emissions. Exhaust gas recirculation (EGR) dilution may also be used to manipulate autoignition timing and engine load, but the combined interactive effect of EGR with phi-sensitivity is not accurately predicted in current kinetic mechanisms. Further in-depth study of why current kinetic mechanisms do not fully account for the effects of EGR sensitivity on phi-sensitivity will enable more predictive engine simulations. Upgrades to NREL's Advanced Fuel Ignition Delay Analyzer now allow researchers to incorporate EGR species in gas blends for detailed studies of both phi-sensitivity and EGR dilution across various fuel types, including iso-octane, 1-pentanol, prenol, diisopropyl ether, and PRF80. In collaboration with Colorado State University and Argonne National Laboratory, NREL compared experimental data with kinetic simulations for phi-sensitivity and EGR dilution sensitivity to examine the underlying chemical kinetics responsible for these properties. The research completed on this topic under DOE's Co-Optimization of Fuels & Engines (Co-Optima) initiative will be submitted for journal publication and will help guide further research on EGR and phi-sensitivity interactions.

Natural Gas Research and Development Consortium Demonstrates New Advancements in Fuel Injection and Combustion Strategies

An NREL-led consortium with DOE, the California Energy Commission, and the South Coast Air Quality Management District aims to develop breakthrough technologies for natural gas vehicles (NGVs). The consortium funds projects that target barriers to more widespread adoption of NGVs, including cost of ownership, limited product offerings, combustion stability, emissions, and fueling infrastructure. Recent achievements by Michigan Tech University (MTU) demonstrate new advancements in natural gas fuel

injection and combustion strategies, ultimately leading to the integration of commercially scalable components for medium- and heavy-duty applications. MTU, in consultation with Westport Fuel Systems Inc., is working to develop a high-efficiency, high-output mono-fueled natural gas compression ignition engine for medium- and heavy-duty applications. The research objective is to attain an improvement in combustion efficiency comparable to that of conventionally fueled vehicles and to reduce emissions to near-zero levels by demonstrating the feasibility of directly injecting natural gas in a compression ignition engine. Most recently, MTU has achieved robust compressed natural gas combustion without the use of cetane booster through heavy-duty single cylinder research engine experimentation. Additionally, MTU has performed fuel injection component evaluation to characterize direct natural gas injection and ignition under representative engine conditions, guiding injector and engine development. MTU will continue to expand the boundary conditions and extended injection pressure ranges with the constant volume combustion chamber (CVCC) device. Simulation and modeling will continue to expand on the CVCC data for further validation of the 1D and computational fluid dynamics models they have developed.

Medium- and Heavy-Duty Vehicle R&D

Advanced Fluid Power System Uses Machine-Learning-Based Control To Increase Efficiency of Agricultural Tractors by 50%

In the United States, agricultural tractors spend 30%–40% of their time using high-power-demand implements, such as planters and sprayers. The overall efficiency of the combined hydraulic systems can be as low as 25%, mainly due to conflicts in the hydraulic controls of the tractor and the implements. A research team including NREL, Purdue University, Case New Holland Global, and Bosch Rexroth has launched the development of a novel multi-pressure rail (MPR) hydraulic system. An MPR-equipped tractor/planter combination is expected to reach 50% overall efficiency of the hydraulic system, doubling the efficiency of current state-of-the-art technology. During the first year of the project, NREL has identified key system metrics for characterizing tractor performance and has developed the initial supervisory control architecture that will use representative duty cycles and machine-learning-based controls to optimize tractor performance. Next steps are to develop the off-road duty cycles, complete the machine-learning-based control strategy development, and implement the optimized controls on a prototype MPR-equipped tractor to demonstrate its effectiveness. Fuel economy and performance of the system will be evaluated on an agricultural tractor on Purdue-owned farmland.

Lightweight Materials

Epoxy-Anhydride Resin Enables Consistent Carbon Fiber Reuse, Demonstrates Pathway to Lower Material Costs and Greenhouse Gas Emissions

Demonstrating that recyclable-by-design resins can enable the reuse of carbon fibers across multiple lives is critical to enabling greater use of carbon fiber in vehicles. By leveraging their bio-based recyclable-by-design resin alongside woven carbon fiber, NREL researchers demonstrated that carbon fibers can be used in three material lives with no degradation to performance. To accomplish this, researchers implemented a room-temperature, catalytic depolymerization technique that maintains fiber quality and alignment, which is paramount in assuring consistent performance of carbon fiber reinforced composites (CFRC) in subsequent lives. This represents a significant improvement over current state-of-the-art non-recyclable epoxy amine chemistries, which can only be used in one material life. By demonstrating reuse across multiple material lives, NREL is creating additional value propositions for the use of recyclable-by-design resins alongside carbon fiber. Specifically, these resins can lead to a lower cost and lower greenhouse gas impact of carbon fiber across multiple lives. In future work, researchers will explore methods to increase the thermomechanical performance of CFRCs, as well as thermoforming of CFRCs. Additionally, researchers will conduct analysis to demonstrate the techno-economic and life cycle assessment benefits of reusing carbon fiber across multiple lives.

Data and Systems Research

Enhanced Search Tool Connects Transportation Stakeholders with Relevant Laws and Incentives

NREL's enhancement of the Laws and Incentives Database on the Alternative Fuels Data Center website provides more ways for transportation stakeholders to search for incentives, laws, and regulations in their state. The improved tool now offers a filter to narrow search results by utility. For California, which has more than 150 laws and incentives on alternative fuels and advanced vehicles, the search tool also now includes an option to filter by county. Together, these new filters make it easier for website users to find laws and incentives, which helps support the market for alternative and renewable fuels, advanced vehicles, and emerging transportation technologies. In addition, NREL's recently published **examples of utility-related laws and incentives** (*afdc.energy.gov/laws/utility-examples*) shed light on the development process for utility programs. In FY22, NREL plans to add a feature that lets users filter search results by date as well as new topics like renewable diesel and fees for plug-in electric vehicles.

Clean Cities Podcast Ties Energy Efficient Mobility Systems Research to Action

A new NREL-produced podcast is helping Clean Cities coalitions apply Energy Efficient Mobility Systems (EEMS) research to their work in deploying alternative fuels and advanced mobility technologies. The podcast, "On the Go: An On-Road Transportation Podcast with Clean Cities," provides a platform for experts to share their knowledge in an engaging, discussion-based format. Three episodes demonstrate how coalition activities can benefit from EEMS insights and how the research can enhance mobility at the local level. Two of these episodes showcase how two coalitions learned from each other through a peer exchange on best practices for implementing transportation demand management to address growth-related congestion. A third episode highlights how innovative mobility technologies and services can benefit rural communities. These episodes can be used by Clean Cities coalitions and their stakeholders to understand how transportation demand management and other systems-based approaches can be applied to transportation challenges in their local communities.

Environmental Justice Metrics Quantify and Expand Federal Benefits to Underserved Communities

NREL researchers are developing guidance and best practices for evaluating the environmental justice (EJ) benefits of DOE programs and maximizing benefits to underserved communities. This work is in response to the Biden administration's Justice40 Initiative (J40), which set a goal that historically marginalized and overburdened communities should receive 40% of the overall benefits of federal investments. The Office of Management and Budget selected 21 federal programs, including four EERE programs, to serve as pilots for initial implementation of the J40 goal. NREL researchers drafted guidance for the selected technology integration programs, including an implementation plan, a stakeholder engagement plan, metrics that represent EJ benefits, and methods for calculating those metrics. The metrics include the amount of federal spending allocated to disadvantaged communities, stakeholder engagement, household energy expenditures, emissions, fuel savings, and jobs created. Substantial stakeholder engagement was incorporated into the process to accurately reflect the real-world needs of the programs and communities being served. Next steps will involve applying the guidance and metrics to each program, determining how to gather the necessary data without imposing additional burdens on

communities, and applying an equity lens to identify broader-scale programmatic changes.

Athena Annual Stakeholder Meeting Provides Platform for Discussion on Major Ports' Challenges, Opportunities for Broader Applicability of Research Findings

DOE's Athena project brings together stakeholders from across the United States, including some of the nation's largest airports and seaports. These stakeholders help inform and direct research to ensure that the results are generalizable to other major transportation hubs. The Athena team held its third annual stakeholder meeting virtually in September 2021 and welcomed participation from major airports (LAX, ATL, DEN, SEA, DFW, SLC, JFK, EGR, and LGA), as well as seaports (Port of Seattle, Port of Long Beach, Port Authority of New York and New Jersey), technology companies (INRIX, Toyota, UBER), transportation companies (American Airlines, UPS), universities (University of Michigan, Texas State) and governmental entities (FAA, NASA). The Athena project applies advanced data analysis and computing to operations and planning challenges faced by the nation's major ports. Projects advisors and stakeholders are a critical part of the project, ensuring ongoing relevance, generalizability, and opportunity for immediate impact of results. Members of the Athena team were recently awarded a DOE I-Corps project focused on developing commercialization strategies for the Athena digital twin. Through this investigation and ongoing discussions with the stakeholder network, the team hopes to plot the course for broad application of Athena's outcomes and help address important problems that U.S. transportation hubs are facing.

NREL Paves the Way to Safe Operations at Roadway Junctions for Automated and Traditional Vehicles

Chosen as one of the best papers at the Business of Automated Mobility Forum, NREL's "Safe Operations at Roadway Junctions - Design Principles from Automated Guideway Transit" paper, which was selected for inclusion in the *SAE International Journal of Advances and Current Practices in Mobility*, is part of a larger initiative to examine system-level issues related to harnessing vehicle automation for public mobility. While manufacturers are pursuing autonomy for individual vehicles, cities are looking for viable solutions to reduce automobile dependence (and parking requirements) in core districts, increase safety, and provide more equitable, high-quality transportation. Intelligent roadway infrastructure offers a roadmap for fleets providing mobility services, incorporating traditional vehicles and emerging automated platforms. The paper lays out a framework to ensure safe operations through each roadway junction—the most dangerous area of the network for automated or manual vehicles. It also describes the functionality of next-generation traffic management, drawing on lessons from automated train control, automated people movers (such as those at airports), and decades of traffic signal control on roadways. Next steps will involve interfacing this architecture with a number of automated shuttle and mobility industry initiatives along with jurisdictional entities seeking a clear pathway to safely deploy automated vehicle mobility services.

School Bus Technical Assistance Program Sets K-12 Fleets Up for Success With Electrification

NREL is working to create a technical assistance (TA) program that provides expertise and resources to K–12 schools interested in deploying electric school buses (ESBs). Interest in adopting ESBs is increasing, in part due to the Biden administration's robust clean transportation goals. This TA program will help meet the growing need to educate and assist fleets across the country that are in various stages of ESB adoption—from districts just starting initial discussions to others who have already ordered ESBs. NREL is creating a 7- to 10-part series of ESB TA topics, each of which will include two to four prerecorded short discussion modules and an accompanying handout with links to the external resources discussed (i.e., Alternative Fuels Data Center content, case studies, reports, and websites). Content created from a seven-part webinar series for the National Association for Pupil Transportation (NAPT) will be leveraged for this effort. Lessons learned from the NAPT series, as well as new information gathered from fleets and industry, will also be incorporated. NREL has completed a draft of part one in the series, which is focused on an introduction to ESBs. The team will record the segment in FY22, along with the rest of the series.

Improvements to Natural Gas Codes and Standards Could Reduce Cost of Building New Facilities and Expand Adoption

NREL is proposing revisions to natural gas codes and standards to help streamline the processes required for constructing new natural gas facilities while maintaining a strong commitment to safety. Currently, the code that governs natural gas vehicles and stations—NFPA 52—contains extensive duplication, making it difficult and time consuming for the Authority Having Jurisdiction to interpret and apply the relevant standards. Complicated, confusing code can increase the time and cost of a project, as well as contributing to uncertainty when the code is interpreted differently in different jurisdictions. Marathon Technical Services, an NREL subcontractor, has extensive expertise in natural gas facilities and is co-chairing a task force to identify opportunities for consolidating and re-organizing the code. Removing duplication and organizing the code in a more intuitive manner can help generate more consistent interpretation and application of the code. These improvements should help increase deployment of new natural gas facilities by reducing unnecessary costs. Recommendations will be presented to the code committee working to revise NFPA 52 for the new version scheduled for release in 2023.

Experts Deliver Unbiased Viewpoint on Propane Codes and Standards, Support Development of Incident Report Tracking

NREL researchers are providing critical assistance to the CSA Group's Propane Autogas Advisory Council by reviewing propane codes and standards and evaluating needs for incident tracking, updates, revisions, recommendations, and other changes. As the population of propane fueled vehicles continues to increase, the council supports this growth by providing relevant codes and standards to the industry and key stakeholders, as well as improving the understanding of design or safety concerns. NREL brings an unbiased, third-party point of view to the council, as well as years of subject matter expertise. NREL's contributions to the Council include recommendations for the U.S. Department of Transportation's National Highway Traffic Safety Administration to include propane fuel system and propane fuel tank integrity requirements in federal motor vehicle safety standards. NREL is also supporting the development of propane incident report tracking within the industry. In addition, NREL assists the council with connecting industry stakeholders to improve collaboration. Integration and collaboration across the landscape is essential for harmonization and addressing safety concerns.

Collaboration Provides States With Tools for Successful Transportation Electrification

NREL is partnering with the National Association of State Energy Officials (NASEO) to address pressing needs of states throughout the country for resources on electric vehicle (EV) infrastructure planning and investments. Nearly every state in the country is engaging in vehicle electrification, in part due to robust clean transportation goals set by the Biden administration. These states require technical assistance from peer experts with experience in EV infrastructure planning and buildouts. In particular, these states require station siting and installation guidance to ensure that EV chargers are convenient to consumers and located equitably. NREL and NASEO kicked off the project by planning a series of four workshops aimed at addressing key electrification questions. The answers to these questions will be used to assemble a thorough and robust suite of online tools and resources that will assist states in addressing barriers to transportation electrification and installing EV charging infrastructure. In the first quarter of FY22, NREL and NASEO will hold the workshops and begin compiling the suite of tools and resources with input from industry.

Clean Cities Training, Resources, and Network Key to Successful Model for Deploying Alternative Fuels and Advanced Vehicle Technologies

Well-established, extensive training provides Clean Cities coordinators with the knowledge and resources they need to successfully engage their local communities and deploy alternative fuels and advanced vehicle technologies. New coordinators attend a multi-day Coordinator 101 workshop that provides them with the foundational information they need to be successful. The most recent workshop was held virtually in July 2021 and was attended by 23 coordinators. It included an overview of Clean Cities and DOE priorities, a tour of tools and resources available in the Alternative Fuels Data Center, an introduction to alternative fuels, tips for building stakeholder relationships, and strategies for short- and long-term planning. In addition to these resources, coordinators gained connections to an active and knowledgeable network of experienced Clean Cities coordinators and program staff, including technical staff from DOE, the National Energy Technology Laboratory, NREL, and Argonne National Laboratory. The experiences and expertise of this network are

unparalleled, particularly when it comes to establishing the relationships and partnerships that are key to the success of the Clean Cities Coalition Network and VTO Technology Integration Program. Due to coordinators' abilities to foster local connections and relationships, this network expands beyond the coalitions and encompasses their stakeholders.

Clean Cities Coalitions Pursue Environmental Justice Projects To Provide Insights for Future Community Engagement Efforts

NREL is providing guidance to two Clean Cities coalitions that are working to better understand community-based decision making in underserved communities. Kansas City Regional Clean Cities and Clean Fuels Ohio are gaining real-world experience on how transportation projects can be approached and designed through an equity lens. The coalitions are building relationships with local community organizations, attending community meetings, and conducting listening sessions to understand priorities and needs. NREL researchers are providing the coalitions with strategies and best practices for engaging in equity-focused work, as well as technical support to analyze and better understand the results of their efforts. Clean Fuels Ohio is collaborating with government agencies and academic institutions that have established relationships with underrepresented communities, whereas Kansas City Regional Clean Cities is working alongside smaller nonprofits (Hispanic empowerment centers and an activist poetry group) and utilizing strategies specifically targeted to each group. Their experiences will inform NREL's broader efforts to reshape the approach to traditional transportation project planning by incorporating new environmental justice considerations.

Alternative Fuels Regulatory Program

EPAct Annual Reports, Submitted and Approved in Record Time, Bring Resource Savings

NREL's continued development of improved web tools, both for covered fleets and for database administration, brings a streamlined compliance review process and net resource savings for the EPAct Program and DOE. One hundred percent of the EPAct fleet Alternative Fuel Transportation Program Model Year (MY) 2020 annual reports due to DOE have been submitted, processed, reviewed, and approved, and all fleets are in compliance for MY20. The collection, review, and approval process was one of the most efficient annual report review periods in the program's history, largely due to continued upfront communication with reporting fleets and more seamless interaction among team members. The success of this process is also a testament to the DOE team's strong approach to compliance; all reports, delinquent reporting fleets, and fleets seeking exemptions have been addressed to completion. Next, the team will continue to implement the program to ensure compliance by covered fleets, and on the administrative side, will add user-side and admin-side functionality to the alternative compliance tools.

Modeling

Integration of Heavy-Duty Vehicle Market Analysis Tools Allow Rapid and Responsive Adoption and Impact Simulations

Emergent powertrain options, technological advances, and new policy goals are creating rapidly changing conditions in the heavy-duty vehicle market—the economic, energy, and environmental impacts of which can be unclear. NREL has enhanced the techno-economic analysis pipeline for commercial vehicles by integrating the Future Automotive Systems Technology Simulator (FASTSim™), Transportation Technology Total Cost of Ownership (T3CO) tool, TRUCK market adoption model, and Heavy-Duty Stock (HDStock) model. These tools enable seamless and robust handling of scenarios with automated processing of input assumptions. The integrated toolset also now incorporates additional powertrain and class variations via flexible nesting of technology configurations and composite options and an improved representation of consumer valuation of vehicle range and fuel availability. The integrated toolset addresses DOE's need for responsive and robust analysis of the dynamic and diverse heavy-duty vehicle market. In future work, the toolset will be used to assess transportation decarbonization goals and their potential impacts. These applied analyses will help DOE understand tradeoffs in research, development, demonstration, and deployment investments in the heavy-duty vehicle space.

New Tool Enables Researchers To Assess Electric Vehicle Charging Infrastructure From an Equity Standpoint

NREL's new Electric Vehicle Infrastructure for Equity (EVI-Equity) tool enables researchers to fill the knowledge and data gap about the equitability of existing EV charging infrastructure and how equity aspects will evolve in the future. NREL initiated the development of EVI-Equity based on literature reviews on energy justice, energy equity, EV adoption, and charging infrastructure. NREL has identified the data needs for EVI-Equity and has begun the collection process, which will continue into fiscal year 2022. Building on the literature review and data gathered to date, a journal article manuscript has been produced, showing preliminary national and state-by-state equity analyses of current EV adoption and charging infrastructure. Having a comprehensive, detailed understanding of the equitability of existing and future charging infrastructure will play a critical role in enabling more equitable infrastructure investment (in both the public and private realm), planning, and deployment. Next steps will involve collecting more diverse social, economic, demographic, and environmental data and incorporating these data into the analysis; accounting for various future infrastructure deployment scenarios at different spatial scales (national, state level, metropolitan area level, and census block group level); and identifying what equitable charging infrastructure might look like in the next few decades.

Measuring Mobility Quality and Opportunities

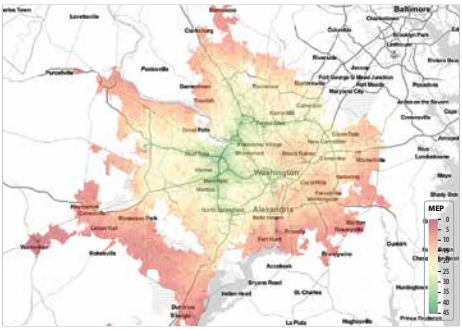
NREL developed the Mobility Energy Productivity (MEP) metric to quantify the ability of an area's transportation system to connect individuals to goods, services, employment opportunities, and other activities while accounting for time, cost, and energy.

Transportation Options:
More modes of transport within a location means higher MEP

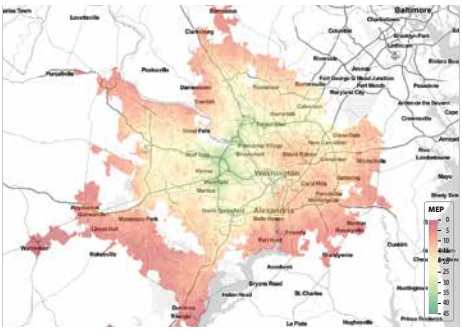
Making Efficient Travel Choices
MEP uses time, cost, and energy to measure the efficiency of travel options for people accessing opportunities.

Decision Factors:
Faster, cheaper, more energy-efficient travel options will lead to a higher MEP

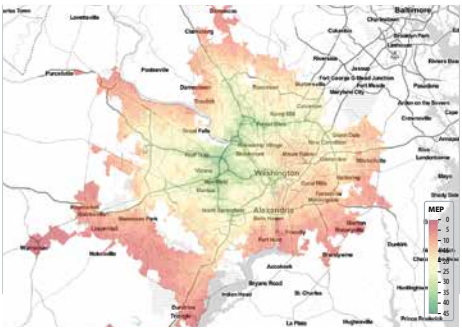
All Population: MEP Value 18.6



Low-Income Population: MEP Value 5.0



High-Income Population: MEP Value 7.6



MEP can also be used as a tool to **Quantify Equity in Accessibility**

The Problem

Need to evaluate how easily different population groups can utilize different modes of transportation to access goods, employment, and services

The Opportunity

MEP can objectively quantify multiple dimensions of equity in accessibility:

- Quality of access provided by any mode or combinations of modes
- Identify areas with poor access to health care, jobs, or any other opportunity
- Identify mobility inequality by calculating MEP for different sociodemographic cohorts

Application

This example application explores how MEP scores differ around access to job opportunities between low- and high-income populations in Washington, D.C.

Higher MEP scores indicate more efficient, affordable mobility options to access more and varied destinations.

Next Steps

Researchers will continue refining the methodology to generate MEP scores that better reflect the mobility opportunities while considering the constraints of specific population subgroups. This is the first step toward being able to utilize the MEP metric in analyses that apply an equity-based lens to evaluate mobility systems.

Computational Modeling and Simulation

Micromobility Scenarios Reflect Parameters of Current and Emerging Mode Options for Transportation Modeling

A research team from NREL, Lawrence Berkeley National Laboratory, and Argonne National Laboratory is working to characterize and integrate emerging micromobility modes that have not previously been included in transportation models. The goal of this work is to better reflect the current mobility landscape—encompassing shared, on-demand, and private human-powered and electric-assisted vehicle options—and improve the energy estimation of transportation models. Informed by data and input from industry and government partners, such as Washington, D.C. and San Francisco, the State of Colorado, and the North American Bikeshare and Scootershare Association, the team is identifying key behavioral levers and operational parameters in micromobility scenarios for workflow modeling. These include behavioral factors such as pricing, availability, and adoption rates, as well as operational factors such as management type and service characteristics of shared micromobility systems. Understanding micromobility is critical, as it has grown to be a key mobility resource across the nation and is among the least expensive and most accessible mobility options for low-income users. It also has the potential to reduce dependence on larger, less energy efficient vehicles for passenger and delivery uses. Next steps include coordinating with modeling teams to run micromobility scenarios to generate energy impact estimates, and refining scenario iterations as novel micromobility vehicles and practices are identified.

Online Mobility Energy Productivity Calculations Offer Faster Performance, New Intra-Lab Collaboration Opportunities

The mobility energy productivity (MEP) metric, which evaluates the ability to reach different activities in a given region via a variety of travel modes, is computationally intensive, necessitating many path searches for a single regional MEP score. Previously, this process used the R scripting language to send queries to a database that would perform the path searches, and the results would then be processed in R. Given that MEP calculations must be run for hundreds of scenarios for EEMS research, the research team recognized the need for improved computational efficiency. Consequently, NREL rewrote the MEP calculation procedure to run as an application on Amazon Web Services (AWS)—using AWS Lambda and Elastic Map Reduce—and to use the Apache Spark framework for distributed analytics. Initial experiments have shown a 50% speedup, reducing computing infrastructure costs. The refined version of the MEP code (V 2.0) not only runs faster, but also allows MEP jobs to be launched through a web application portal as a software-as-a-service integration for DOE lab partners and external collaborators. Next, NREL will conduct software engineering work to examine and debug the integration, employing AWS best practices before evaluating end-to-end MEP calculations in an automated pipeline.

Visualization Dashboard To Support Better Understanding and Planning For Future Transportation Scenarios

Visualizing and communicating the outputs of forward-looking transportation modeling scenarios make the results more actionable to stakeholders. Insights from a new, collaborative visualization dashboard will help practitioners prioritize strategies with the largest positive impact. NREL is partnering with Lawrence Berkeley National Laboratory on a transportation system modeling platform called BEAM CORE, and the complementary application and collaboration tool (BEAM CORE ACT) will distill results into easily digestible insights and allow users to experiment with different model assumptions to better understand the impacts of specific technologies or policies. While the dashboard is still in the early stages of development, the prototype version has demonstrated its overall framework and capabilities using data from previously completed analyses. Ultimately, the dashboard will provide a critical way of relaying the national laboratories' advanced analysis results to the practitioner community. The next step is to evolve the initial prototype, integrating results from the latest model scenarios, and to incorporate additional features.

Agent-Based Freight Transportation Modules Demonstrate Fully Functional Simulation and Deployable Capability

Because integrated freight transportation system models are typically defined as a set of mathematical formulas and relationships, researchers must ensure that they accurately represent travel behavior and patterns while also capturing the modeled dynamics with an acceptable degree of accuracy. NREL and Lawrence Berkeley National Laboratory researchers compared modeled outcomes to observed data in the San Francisco Bay Area and adjusted individual models. To calibrate e-commerce generation models, distributions of online shopping frequencies by demographic characteristic and geographic region were compared to modeled demands. For carrier operation, distributions of tour characteristics by truck type and truck volumes by geographic region and time of day were used. To validate the integrated modules, system-level outcomes such as truck traffic volumes, travel time, and speed were used. Such calibration and validation procedures are an essential step in the transport-demand model development and application process, as they help ensure accurate and consistent results. In future work, researchers will build on the short-term freight modules to develop advanced modeling capabilities. These advanced capabilities will allow researchers to simulate long-term life cycle events of business establishments coupled with supply-chain formations, while accounting for agents' behavioral dynamics in medium- and short-term decisions.

Livewire Implements Targeted Data on Electric Vehicle Supply Equipment Infrastructure

The Livewire team's incorporation of targeted data directly addresses a priority defined by the Livewire Data Working Group (DWG), namely, adding more electrified vehicle and charging infrastructure data to the platform. The new targeted data fulfills Livewire's commitment to implement new features and includes two datasets from the National Association of State Energy Officials and National Association of Clean Air Agencies (NASEO-NACAA) Volkswagen Environmental Mitigation Trust Working Group, pertaining to (1) vehicle data and (2) electric vehicle service equipment. Data and platform needs are driven by user input, and the Livewire team previously established five priorities by analyzing feedback from a survey and completing a series of conversations with Livewire DWG members representing five labs. The priorities include: (1) adding more automated and connected light-duty and medium-/heavy-duty vehicle data, (2) adding more electrified vehicle and charging infrastructure data, (3) standardizing data across projects, (4) enabling querying and filtering of data before downloading, and (5) adding the ability to download subsets of data. The Livewire team will continue to work with the DWG to define priorities and to target data and platform features that are in line with user needs.

Reinforcement Learning Provides a Competitive and Computationally Efficient Solution for Vehicle Trajectory Tracking

Control of connected and autonomous vehicles (CAVs) is a significant challenge, with tasks like low-level actuation of brakes, steering, and throttle that must be automated. Existing algorithms have shortcomings such as energy inefficiency, computational intractability, and lack of smoothness. To help solve these challenges, NREL used its 2D physics-based vehicle simulator, KRoad, in conjunction with the reinforcement learning (RL) algorithms implemented in the open-source RLlib package. NREL researchers submitted a paper, "Autonomous Vehicle Trajectory Tracking via Model-Free Deep Reinforcement Learning," to *IEEE Transactions on Intelligent Transportation Systems*, which explains the RL controllers in more detail. RL has the potential to significantly improve vehicle trajectory tracking and can be inserted piecemeal into the existing CAV control pipeline, serving as inspiration to continue exploring the integration of RL controllers across the multitude of CAV control activities. This research can be applied to several similar activities, and a next target is energy-efficient cruise control.

New Data Anomaly Detection Method Enhances the Accuracy of Traffic Volume Estimation Models

Anomalies in input data may weaken prediction and forecasting models built on observational datasets, including models for traffic volume prediction. However, identifying anomalies manually is onerous, if not impossible. Previous efforts using the Local Outlier Probability (LoOP) algorithm detected some of the most extreme outliers but failed to detect less extreme cases. Consequently, NREL evaluated a new method—isolation forests—for its potential to identify anomalies, as demonstrated in other research and literature. This method attempts to isolate anomalies (based on probe data patterns as well as patterns observed in ground-truth traffic volumes) using trees. The approach was found to be advantageous compared to the previous LoOP method, primarily because of its faster computation speed. However, the approach still skews toward extreme observations (e.g., very high-volume days or hours). Using an input variable describing the relative hourly volume change proved to be one of the most impactful methods for consistently detecting known extreme hourly volumes. Automated and computationally efficient methods for detecting anomalies in traffic data would further enhance ubiquitous volume estimation and enable stakeholders, such as state departments of transportation, to have reliable and accurate information on historical and expected traffic volumes.

Real-Time Traffic Signal Algorithm and Improved Simulation Models Demonstrate Positive Impacts on Energy Consumption and Delays

In collaboration with Oak Ridge National Laboratory, the Chattanooga Department of Transportation, and Siemens, NREL demonstrated the effectiveness of a model predictive control (MPC) algorithm using real-time data feeds. This demonstration has led to an increase in stakeholder confidence and investment, resulting in more extensive experiments and longer durations of expansion control. In addition, the team developed a workflow for the simulation models to mimic real-world historic data, which will be used to support development of reinforcement learning algorithms for future experiments. The results demonstrate up to a 4.7% decrease in energy consumption and up to a 32% decrease in delays for given days, aggregated over the entire corridor. These results will foster future collaboration and experimentation in Chattanooga, Tennessee. This evaluation of field experiments enables further analysis of traffic performance, providing incremental improvements to control strategies. Calibrated simulations provide initial baseline scenarios that can be assessed safely given new development of reinforcement learning models. At the end of September, two experiments will be conducted in Chattanooga, over a continuous 24-hour period. A reinforcement model is currently being developed and assessed for future experimentation. In addition, a comparative analysis model will be implemented in Chattanooga, which was developed by students at New York University in collaboration with Oak Ridge National Lab and NREL. Next quarter, a reinforcement learning model will be put into experimentation as a comparison to the existing MPC algorithm mentioned above.

SUCCESS METRICS

Patents & Records of Invention

Records of Invention

- Mitigate the Severity of Thermal Runaway in Li-Ion Battery Pack through Prompt Energy Release
- Group IV Alloyed Nanoparticle Electrodes for Li-Ion Batteries
- Boron-doped Silicon Nanoparticle Electrodes for Li-Ion Batteries
- Methods and Control for Multi-Port DC Fast Charging Site for Electric Vehicles with Distributed Energy Resources and Energy Storages
- A Charge Control and Predictive Unit (CCPU) for Optimal Battery Management with Predictive Capabilities
- Casing Design Enabling Simultaneous Direct Gas and SPME In Situ Sampling of Pouch Cell Batteries
- Distributed Batch Reachability Algorithm for Multimodal Transportation Networks
- Room Temperature Depolymerization of Epoxy-Anhydride Thermosets to Maintain Fiber Integrity

U.S. Provisional Patent Applications

- Ion Insertion for Cathodes
- Electrolyte Components for Charging of Batteries
- Casing for Pouch Cell Batteries

Patent Applications

- Jet Impingement Manifolds for Cooling Power Electronics Modules
- Cathode Recycling of End-of-Life Lithium Batteries
- Methods for Cathode Recycling of End-of-Life Lithium Batteries

Patent Awards

- Coated Semiconductor Particles and Methods of Making the Same

Publications & Communications

Vehicle Technologies Publication Metrics

Publication Type	Q1	Q2	Q3	Q4	**Total**
Journal Articles	31	21	14	16	**82**
Technical Reports, Conference Papers, Book Chapters, and Subcontractor Reports	22	12	28	12	**74**
Patents	1	0	0	0	**1**
Presentations and Posters	8	7	6	9	**30**
Brochures, Fact Sheets, and Other Outreach Materials	3	3	3	3	**12**
Management Reports	0	0	1	0	**1**
Total Publications	**65**	**43**	**52**	**40**	**200**

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3. 2021. *At a Glance: Electric Vehicles*. Office of Energy Efficiency and Renewable Energy. *https://www.nrel.gov/docs/fy21osti/80618.pdf*

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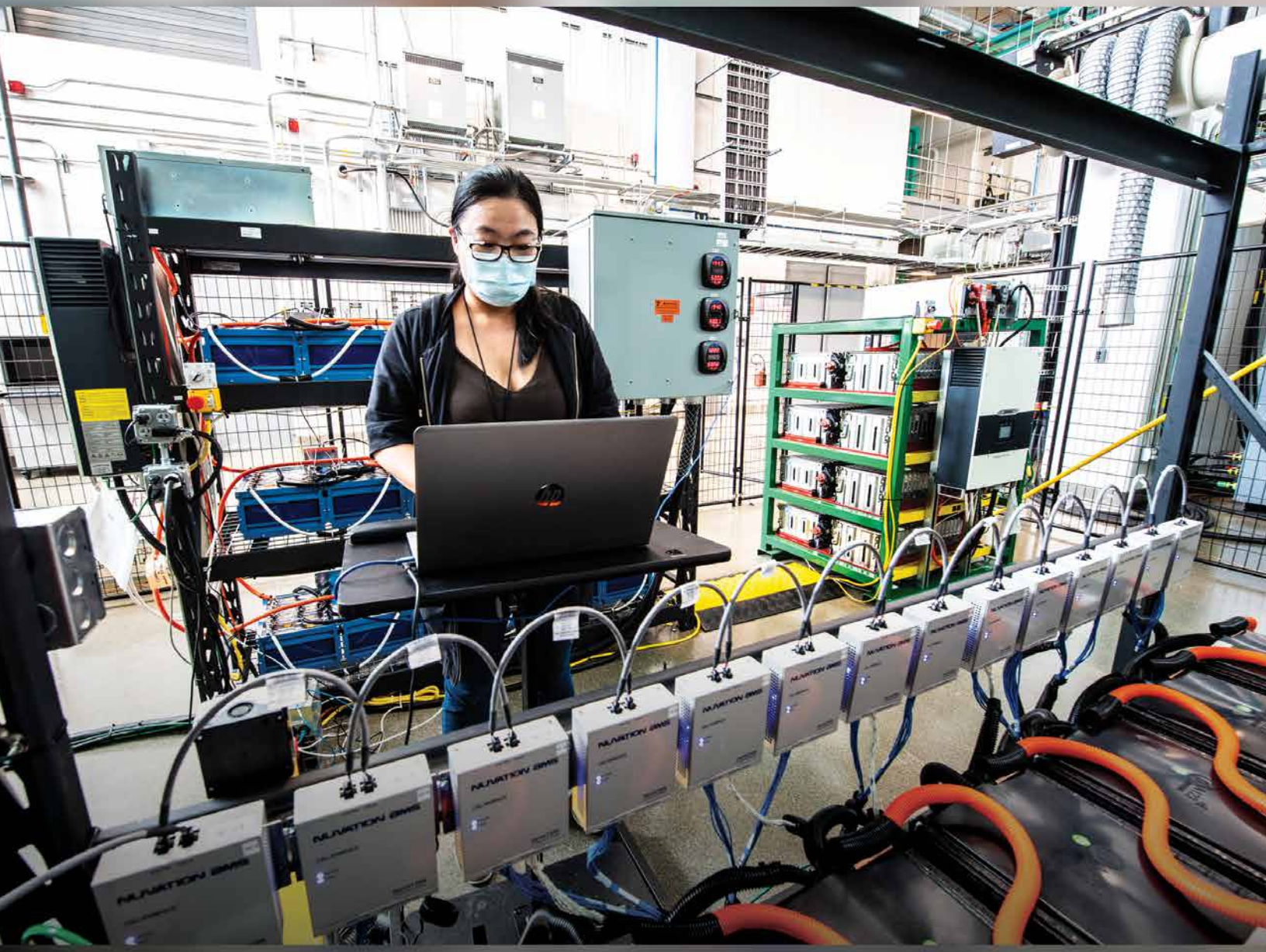

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Commercial Vehicle Technologies ..... **Jason Lustbader**
Data Sciences ..... **Caleb Phillips**
Electric Vehicle Grid Integration ..... **Andrew Meintz**
Energy Storage – Modeling ..... **Shriram Santhanagopalan and Kandler Smith**
Energy Storage – Materials ..... **Rob Tenent**
Legislative/Regulatory Support ..... **Ted Sears**
Mobility Systems ..... **Stan Young**
Power Electronics & Electric Machines ..... **Kevin Bennion**
ReFUEL Laboratory ..... **Jon Burton**
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Vehicle Modeling and Analysis ..... **Eric Wood**

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VEHICLE AND MOBILITY TECHNOLOGIES
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