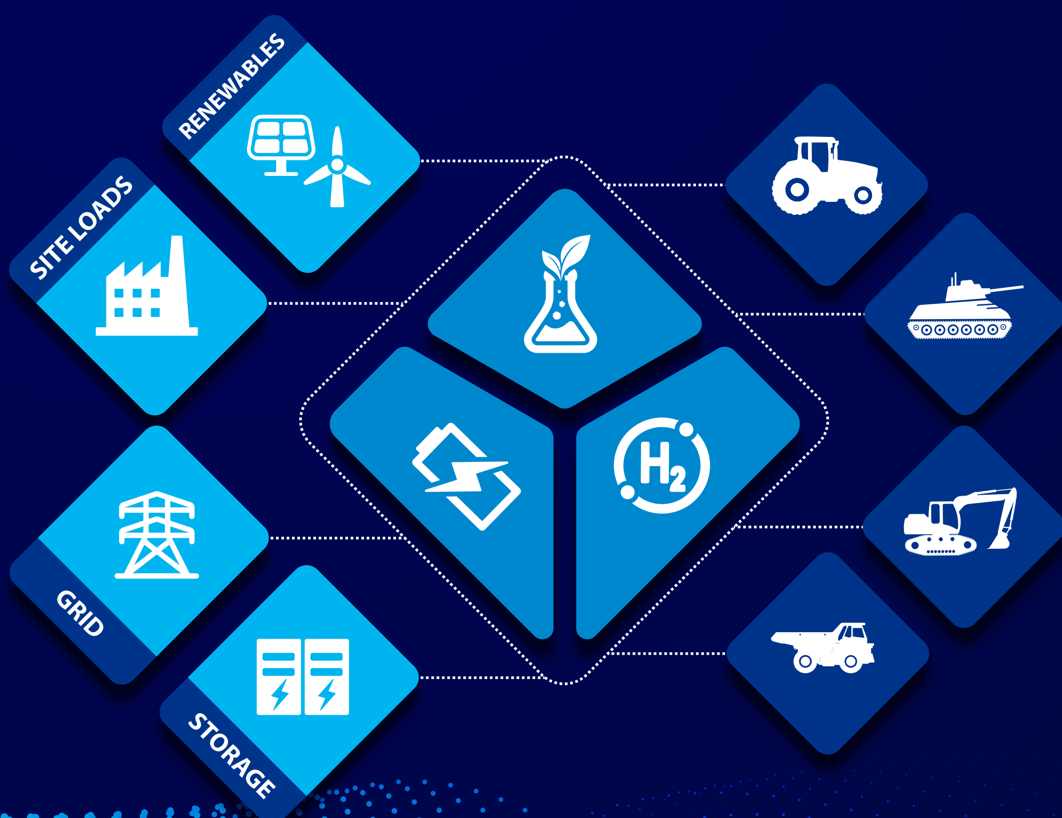
Off-Road Vehicle Decarbonization and Energy Systems Integration:

R&D Gaps and Opportunities



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Off-Road Vehicle Decarbonization and Energy Systems Integration: R&D Gaps and Opportunities

Insights from the NREL Off-Road Decarbonization and Energy Systems Integration Workshop

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Preface

This report summarizes findings from the Off-Road Decarbonization and Energy Systems Integration workshop, hosted by the National Renewable Energy Laboratory (NREL) from March 22–24, 2022. The workshop focused on the importance of collaboration among the off-road vehicle industry and government to address barriers and opportunities for decarbonization.

The workshop aligns with priorities of the U.S. Department of Energy (DOE) Vehicle Technologies Office and Hydrogen and Fuel Cell Technologies Office to decarbonize transportation in the agriculture, mining, construction, and military industries. This decarbonization effort is also intended to support original equipment manufacturers, industry associations, technology developers, utilities, and other stakeholders.

The sections within this report correspond to the three topic areas covered in the 3-day workshop: a high-level perspective of needs and challenges, vehicle and equipment decarbonization strategies, and energy systems integration opportunities.

Acknowledgments

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List of Acronyms

ARIES	Advanced Research on Integrated Energy Systems
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
GHG	greenhouse gas
NREL	National Renewable Energy Laboratory
RD&D	research, development, and deployment

Executive Summary

The goal of the NREL Off-Road Decarbonization and Energy Systems Integration workshop was to gather thought leaders from industry, regulatory bodies, and government to identify the challenges and opportunities of off-road decarbonization and inform the U.S. Department of Energy on precompetitive research, development, and deployment (RD&D) that can achieve rapid and deep emissions reductions. As a result, DOE, industry, and other government agencies are better prepared to accelerate the development and deployment of future energy systems that integrate the off-road transportation sector with larger, renewable-energy-based systems and a range of sustainable mobility options.

The workshop included 78 participants and featured presentations from:

- Equipment manufacturers: John Deere, Volvo, Cummins, Komatsu, Eaton, Caterpillar, FPT Industrial
- Renewable power system integrators: juwi AG
- Fuel providers: Air Liquide Hydrogen Energy
- Industry trade associations: Association of Equipment Manufacturers, Truck and Engine Manufacturers Association
- Utilities: Xcel Energy
- National laboratories: NREL, Oak Ridge National Laboratory
- Government: DOE, U.S. Department of Defense (DOD), U.S. Army, California Air Resources Board, U.S. Environmental Protection Agency.

The workshop focused on the role the off-road sector can play in helping achieve the U.S. goals of carbon-pollution-free electricity by 2035 and a net-zero-emissions economy by no later than 2050. Participants discussed stakeholder and sector-wide energy and equity goals, as well as strengthening U.S. working communities, protecting public health, and advancing environmental justice. The workshop also addressed programmatic priorities of the Office of Energy Efficiency and Renewable Energy to decarbonize the grid, transportation, and industrial and building sectors as an integrated system with off-road sectors including agriculture, mining, and construction. DOD priorities related to energy and operational security and resilience were also addressed.

Over 3 days of discussion and presentations, several key findings emerged:

- Rapid progress toward decarbonizing the off-road sector will require a collaborative framework, including coordinated participation from industry, government agencies, national laboratories, and the broader research community to help develop technologies, demonstrate pathways for integration, and support precompetitive RD&D.
- Infrastructure and energy storage are critical pieces of the puzzle, as there are numerous challenges for bringing decarbonized fuel and power to remote sites, depending on the application. Construction, agriculture, mining, and military all have different duty cycles, energy requirements, and environmental demands.
- Industry will need a predictable regulatory framework, including harmonized regulations between nations, where possible, and supportive regulations that generate market pull.
- The off-road sector has very specific, extreme performance requirements that are not common in light- and medium-duty vehicle applications. Decarbonization technologies will have to tolerate high temperatures, confined and dusty spaces, rugged operating conditions, and demanding duty cycles.
- The off-road sector must advance multiple technical pathways while finding the best fit for specific applications while meeting regulatory requirements. Between different options for fuel, energy sources, generators, vehicles, and customer needs, there are many technology options and deployment strategies.

- To determine best-fit technologies, it is critical to understand diverse duty cycles and refueling/powering strategies. It will also be critical to discover the optimal fuel and powertrain combinations.
- Decarbonization will require technology solutions for the millions of fossil-fuel-powered machines that are currently in the field. An important focus is the development and production of net-zero-carbon fuels. Biofuel is the primary alternative fuel across the sector, but there is insufficient biomass supply to achieve decarbonization across all transportation modes. Identifying the best uses for future biofuels will require attention around market sector economics and decarbonization priorities (e.g., using biofuel for aviation vs. heavy-duty on-road vehicles or off-road transportation), new feedstocks and processes for biofuels, and the role of e-fuels.
- Total cost of ownership is an important metric that integrates both capital and operational costs for technology, energy, and vehicle performance (i.e., the efficiency of various powertrain alternatives) with each application's duty cycles.
- There is a need to develop solutions and approaches that are inclusive, improve air quality in underserved communities, and tap into the diversity of the nation by creating new jobs and opportunities.

The workshop ended with a recognition that the off-road sector is broadly committed to decarbonization, resilience, energy efficiency, and equity initiatives, and that across the sector, companies share many of the same challenges. Next steps will center around creating common resources and collaborative demonstrations that aid the entire sector.

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1 Introduction

Anthropogenic greenhouse gas (GHG) emissions are causing global climate change, with many undesirable impacts such as increased storm intensity and elevated average temperatures. Transportation is the largest source of GHG emissions in the United States at 33%, with the off-road sector contributing 9% of total transportation emissions, making it an important target on the path to decarbonized energy systems. Significant technological developments, in addition to overcoming unique operational changes, will be necessary to reduce GHG emissions in this sector, as will close collaboration of public and private entities.

The National Renewable Energy Laboratory's (NREL's) Off-Road Decarbonization and Energy Systems Integration workshop provided an inclusive venue for public and private entities to express their perspective on challenges and opportunities in decarbonizing the off-road sector. The 3 days focused on high-level perspectives (Day 1), off-road vehicle and equipment decarbonization strategies (Day 2), and energy systems integration (Day 3). Each day raised suggestions, solutions, and challenges through presentations from national thought leaders and discussions among panel members and the audience. A key objective of the workshop was to identify precompetitive research, development, and deployment (RD&D) that can accelerate decarbonization while leveraging economies of scale across the diverse off-road technology space. An additional objective was to inform the U.S. Department of Energy (DOE) on opportunities to promote collaboration across original equipment manufacturers, suppliers, utilities, fuel providers, and other stakeholders. Those findings are described herein.

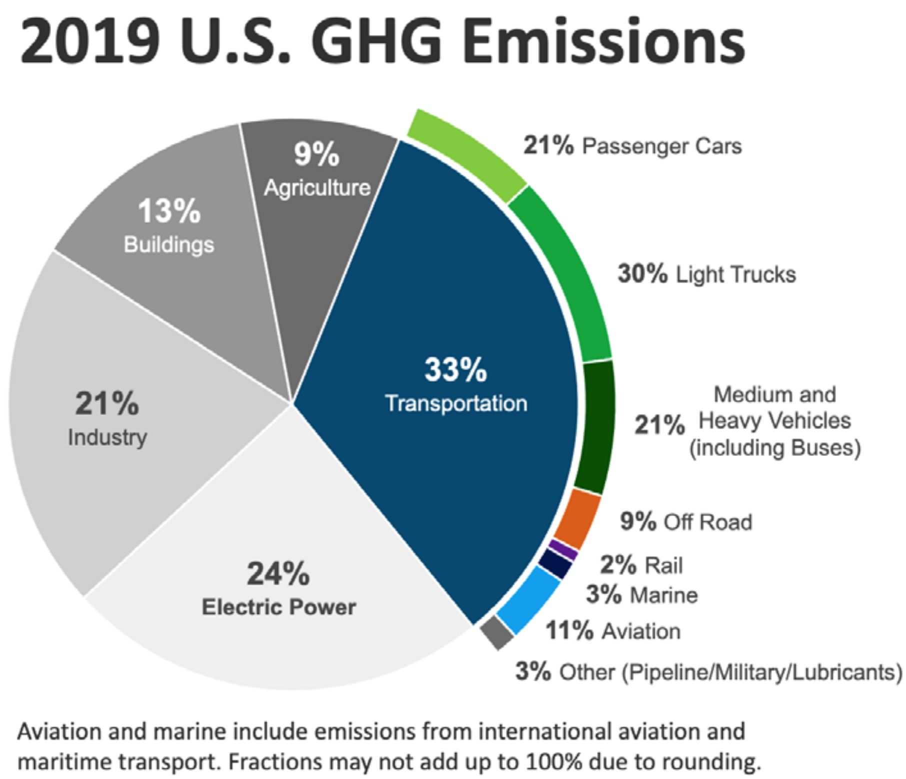

Figure 1. Transportation is the largest source of GHG emissions in the United States.
Image from the U.S. Department of Energy.

2 High-Level Perspective of Needs and Challenges

In Day 1 of the workshop, participants heard from government agencies, regulators, and industry trade associations about the overall challenges facing the off-road transportation sector, along with regulatory and industry approaches to addressing the problem. Speakers came from the Office of Energy Efficiency and Renewable Energy, Office of the Secretary of Defense at the U.S. Department of Defense (DOD), California Air Resources Board, Office of Transportation and Air Quality at the U.S. Environmental Protection Agency, Association of Equipment Manufacturers, and Truck and Engine Manufacturers Association.

Following the keynote presentations, participants shared thoughts during a panel discussion. Key takeaways from Day 1 were:

- RD&D should focus on solutions that have broad utility, cut across applications, and have attractive economics as reflected in total cost of ownership. Early wins are important for catalyzing technology deployment and should be targeted (e.g., early adopters, off-road technology demonstrations).
- Although the off-road sector has unique performance requirements, much of the decarbonization technology related to powertrain electrification is leveraging advances from on-highway vehicle innovations. The off-road sector should capitalize on that technological momentum to prioritize areas of research that transfer on-highway R&D to off-road applications.
- Decarbonization will need to address GHG emissions from millions of fossil-fuel-powered machines that are currently in the field (often with long service lifetimes). This will require the development and production of net-zero-carbon fuels.

2.1 Department of Defense Keynote

DOD has specific needs and challenges that inform its decarbonization approach. For one, decarbonization is a "mission-critical" strategy—a more sustainable force is more agile and survivable, serving national defense in the field.

For DOD, decarbonization can pertain to innovations that streamline operations and create new efficiencies in the field. These include improvements to scheduling for refueling and airlifting, ship routing, and optimizing cargo (e.g., not flying an empty aircraft). This can also include technology innovations like reduced drag for ships and aircraft, new propulsion for fixed- and rotary-wing aircraft, vehicle hybridization, and new low-carbon fuels. DOD is also interested in building resilient supply chains for fuels and batteries.

2.2 A Collaborative Framework for Industry–Government Dialogue

A major opportunity for government–industry collaboration is to facilitate precompetitive research, helping to close knowledge gaps and provide invaluable information and data. Some areas where such research would be especially useful include:

- Vehicle electrification, powertrain designs, and fuel cell technologies.
- Data on environmental and societal costs of decarbonizing the off-road sector.
- Collaborative projects with willing customers that iteratively test and improve a technology based on rapid feedback.
- Quick in-lab stress tests of possible integration and component solutions.
- Analysis of impact of decarbonization on 5-year planning for companies.

DOE is undertaking collaborative initiatives to facilitate decarbonization RD&D in the trucking sector, including the 21st Century Truck Partnership (VTO 2021) and the SuperTruck initiative (DOE 2021), among others. These partnerships bring industry partners together with multiple federal agencies and national laboratory researchers to identify research priorities. Considering the usefulness of such initiatives, industry participants voiced that they need better awareness about similar research programs at national laboratories, which will help set cross-sector priorities and identify inroads for further collaboration.

Apart from in-lab demonstrations, national laboratories and DOE can also facilitate industry-supportive efforts to develop standards, designs, and codes for technology hardware, interconnection, and interoperability. Lastly, DOE's awareness of supply chain and technology availability will be helpful for framing industry pathways.

2.3 Infrastructure for Decarbonized Fuel and Power at Remote Sites

Decarbonizing the off-road sector faces a major challenge with providing zero-carbon energy infrastructure, which varies by application (e.g., mining infrastructure may be larger in scale and exist for decades, whereas construction infrastructure may have high initial demand and last for only months or a few years) and may require megawatts of power, sometimes in areas with no grid connection. In some applications, a high-power grid interconnection could be necessary, which opens further questions around how to provide grid support and stability with such interconnections.

For grid-tied applications, it will be important to keep installation and commissioning time and costs low. In construction, for example, a high electrical demand early in the construction project timeline will affect system planning and costs. These could be reduced, in part, by scalable and/or modular charging designs. Such installations should consider the requirements of the utility, which will potentially need to install temporary primary or secondary circuits, and must accommodate the particular load of the off-road application. This opens opportunities for co-locating renewable power production near or on-site, and for operations to explore optimal charge strategies that are grid-supportive.

For applications without suitable grid connection, low-carbon fuels are a potential path in the short term, though availability of such fuels is a significant constraint. Microgrids using batteries, wind, and solar are another option, which have been shown to be successful in systems for mining (Siemens AG and juwi AG 2022). Such microgrids require attention to the local variable energy supply and system cycling, as well as the ability to step up and step down loads as needed.

Hydrogen is another alternative for areas without grid connection. With pilot projects just beginning around the world, issues that need to be addressed include how best to produce, store, distribute, and dispense low-cost hydrogen generated from renewable energy. Answers to these will largely be site-specific and will require further RD&D and pilots to develop and demonstrate what works best. Meanwhile, renewably produced hydrogen will need to come down in cost and grow in scale.

A variety of upcoming technologies and solutions could make off-road infrastructure more manageable. Solid-state transformers are lighter, more compact, and more versatile than traditional grid transformers and provide two-way power flow, which could facilitate more flexible system architectures. Other state-of-the-art concepts include high-power non-contact charging and mobile refueling, which could add flexibility to operations.

2.4 Predictable Regulatory Frameworks

The entire off-road sector has a need for a clear regulatory framework to guide the decades-long path to decarbonization. Importantly, this regulatory framework should generate market pull for clean energy technologies. DOE, in coordination with federal and state agencies, can be an enabler in this regard by developing technology, tools, data, and knowledge to inform policy. These efforts should include holistic analyses of equipment types, tools and data for quantitative comparisons, and information gathering from diverse sources.

Areas where consistent and predictable policy is needed include:

- Waste and recycling requirements for batteries and water.
- Direct (tailpipe) and indirect emissions regulations.
- Local-scale air quality effects.
- International consistency around emissions and credits.

2.5 Inclusivity and Value to Community

Industry participants recognized the importance of inclusivity and community involvement from a variety of perspectives:

- There is a need to engage communities where the products are produced and have closer relations with communities along the supply chain.
- There is significant value derived from a diverse workforce, and the off-road sector will benefit by capitalizing on the skills afforded by increased diversity.
- Projects should incorporate input from communities in which the off-road industries operate.

- There is a need for broad societal education and preparation of workforce for the energy transition underway.
- Off-road projects tend to be situated more often near small and rural communities, especially mining and agricultural projects. Project stakeholders should assess impacts to these communities and seek their input.

2.6 Strategies for Diverse Technology Pathways

The off-road sector is distinguished by an enormous variety of equipment, generally manufactured at relatively low volumes. Moreover, some of the vehicles are among the largest and heaviest on Earth. Because the sector services such diverse and demanding applications, there is a need to consider vehicle and component designs from a whole-system perspective—i.e., to understand the uses, durability requirements, and supply chain for different components and parts. DOE and DOD, in collaboration with their industry partners, can help build knowledge and capabilities in this area by identifying the best manufacturing and technology pathways available.

2.6.1 Diverse Duty Cycles

Across agriculture, mining, construction, and military applications, vehicles have widely different duty cycles. This introduces the challenge of optimizing charge/refuel schedules, but also creates flexibility in designing such schedules; system operators can be creative while balancing trade-offs like charging and equipment downtime.

Duty cycle considerations also play into wider decisions about infrastructure, technologies, and operations. A path forward and a challenge for DOE and industry is to understand the work function of each class or type of equipment and then match it to the most suitable decarbonization technology.

2.6.2 Diverse Fuel and Powertrain Optimality

Improving powertrain efficiency is a major area of opportunity for implementing low- or zero-carbon fuels. By optimizing powertrains with fuel types, fuel use, vehicle efficiency, and lifetime could improve significantly. Fuel and powertrain decisions should be considered from a larger integration perspective as well, including consideration of the current active vehicle fleet already in the field. Zero- or low-carbon fuels are an immediate way to help decarbonize the sector with current vehicle technology.

2.6.3 Diverse Customer Needs

Even within specific industries, customers could have a range of priorities that shape project design. Such priorities could include regulatory requirements, costs, environmental protections, or being the industry leader of a new technology.

2.7 Ruggedness of Hardware

Off-road vehicles have substantial requirements related to ruggedness. Vehicles may operate more or less continuously for decades. They may operate in confined spaces and explosive atmospheres, very high or low temperatures, and dusty air. Decarbonization of the off-road sector raises new considerations and extremes related to harsh operating environments and the need for unique solutions that are not required for the on-road fleet.

New decarbonization technologies for the off-road sector will have to sustain relatively severe and short runs—a consideration that is not relevant in light-duty electrification. New technologies will also have to manage air filtration and cooling, which will require engineering a new variety of rugged fuel cell equipment components. Technologies that are degraded and no longer suitable for original applications could potentially also enter a secondary market.

Microgrid ruggedness is another challenge. The DC working electrical bus should be resistant to serious transient loads, which raises considerations about battery sizing and other hardware. The sector can look to recent technical progress in configuration and protection approaches for DC microgrids. For microgrids and technologies, the industry will need new standards, designs, and codes for safety.

2.8 Availability of Biofuels

Switching to biofuels appears to be a near-term and less disruptive pathway to decarbonization, as it mostly avoids redesigning the powertrains. However, the approximately 65 billion gallons of biofuels available by 2040 (Tan et al. 2021) are insufficient for all the hard-to-electrify sectors like aviation, rail, marine, off-road, and long-haul trucks (Reid, Ali, and Field 2020).

As a result, there is a need to optimally target biofuels applications, produce e-fuels to make up any liquid fuel shortfalls, and electrify (e.g., battery and fuel cell electric vehicles) where it makes sense. Electrified powertrains and hydrogen internal combustion engines or fuel cells may be more suitable long-term solutions for some applications because their energy supply is less constrained than biofuel.

For the biofuel supply that is available, industry would benefit from knowing what the best use cases are for the off-road sector. DOE could help inform in this area. Additionally, DOE research into new sources of biofuel, biofuel properties needed to optimize engines used in off-road applications, and their economic potential is crucial information for the sector. Novel sources and pathways to biofuels are currently being developed from wet waste, wood waste, and regenerative agriculture biomass, among other sources (NREL 2022). Progress in this area has the possibility to create new supplies of biomass and open novel integration scenarios that develop local resources for fuel.

2.9 Key Takeaways of Day 1

Achieving the U.S. goal of a net-zero-carbon energy system by 2050 will require success across all sectors of the economy, including off-road industries. DOE and the national laboratories are well positioned to integrate knowledge and supply necessary information to the off-road sector. Such support should come in the form of precompetitive RD&D supporting a broad range of sustainable transportation technologies, reliable and unbiased data from collaborative RD&D, as well as leadership in setting the priorities for the sector to follow. Industry will benefit from better awareness around DOE efforts.

The off-road sector is very diverse and has a wide variety of requirements, and as such, new technologies need to support this diversity. DOE could be helpful in addressing the technological space from a whole-systems perspective, including how to optimize systems given the diversity in parts, applications, and strategies, and determining the economic viability of technologies.

The whole-systems perspective is also important to guide development of energy infrastructure technologies. An even wider perspective brings communities and society into focus; the off-road sector would benefit from incorporating the input of communities in which they operate.

3 Vehicle and Equipment Decarbonization Strategies

Keynote presentations on Day 2 included speakers from NREL, DOE's Hydrogen and Fuel Cell Technologies Office, the U.S. Army Ground Vehicles Systems Center, and Oak Ridge National Laboratory. Representatives from Caterpillar, John Deere, Komatsu, Eaton, Cummins, and Volvo presented perspectives on the opportunities and challenges for each industry—military, agriculture, construction, and mining—and then convened for a panel discussion around industry-specific technologies and strategies.

Main takeaways from Day 2 are:

- Decarbonization of vehicles will follow three main routes: batteries, hydrogen fuel cells, and hybridized internal combustion engines that use low-carbon fuels.
- Low-carbon fuels will be needed for the very large stock of existing vehicles to decarbonize the off-road sector in the near to medium term.
- Energy efficiency of operations and equipment ranks among the top priorities for all sectors.
- The cost of equipment for electrification is among the top barriers for all sectors.
- Decarbonization progress will require rapid, iterative learning, including product development cycles that are agile and happen in real time.
- DC microgrids can provide an example for power safety and protection needs.

The following sections detail strategies described and discussed during the industry panel.

3.1 Military Off-Road Decarbonization Strategies

Powertrain electrification provides a number of distinct benefits to the U.S. military, as it allows for more extended operations, silent mobility, and operational flexibility. Decarbonization is part of DOD missions and war-fighting objectives generally, as climate change is a broad risk for military missions. Fuel for tactical equipment makes up 73% of DOD energy costs, such that a lack of fuel can result in mission failure.

Major decarbonization objectives for the U.S. military are to:

- Focus on operational improvements, such as optimizing airlift, refueling, scheduling, ship routing, and cargo.
- Improve technology adaptation, including making vehicles more fuel efficient (e.g., drag reduction for ships) and hybridization of heavy-duty vehicles.
- Develop sustainable fuels.
- Develop resilient supply chains, prioritizing bulk fuel infrastructure investments.
- Pursue vehicle electrification, including anti-idling and powertrain hybridization—improvements that enable silent mobility and watch, reduce thermal signature, and add communications capability.

Presently, the U.S. military strategy is to rely on commercial-based equipment development and supply chains on the tactical side, as DOE applications often require higher-durability designs with very diverse and rugged climates, including extreme heat and sand conditions and tropical and arctic climates.

3.2 Mining Off-Road Decarbonization Strategies

Mining is a potential early adopter of decarbonization solutions. Focus areas for the industry are to increase adoption of fuel cells, battery-electric designs, and hybrid powertrains. There are multiple pathways for decarbonization of mining equipment, which often compete for R&D resources. These include battery-electric with trolley charging, battery-electric with stationary charging, hydrogen fuel cells, hydrogen internal combustion engines, biofuels, and synthetic fuels. Technologies specifically tailored for decarbonizing mining applications are generally not mature, and uncertainties in the market and technology availability may affect the decarbonization timeline due to long lead times to implement vehicles and infrastructure.

The mining industry has very specific needs that will affect its decarbonization: Mining involves a wide variety of equipment sizes, power levels, and functionality with highly variable duty cycles and power requirements up to 3,500 horsepower, with equipment use characteristics varying at different stages of mine development. This equipment may operate 24 hours a day, 365 days a year (typically 6,000 hours) and have very long life requirements—up to 25 years. Safety is also of prime importance to the mining industry, so decarbonization solutions that simultaneously reduce the probability and/or severity of operating hazards should be emphasized.

Because of site remoteness, mining will possibly need its own large-scale on-site renewable power generation. This could be coupled with smart- and fast-charging solutions and presents opportunities to investigate battery-swapping strategies that could minimize peak power demand and the scale of on-site power generation. There are also potential synergies between decarbonization and automation technologies for mining applications.

3.3 Construction Off-Road Decarbonization Strategies

Construction uses a wide variety of equipment, power levels, and duty cycles, so matching technologies with usage characteristics is critical. For example, smaller construction equipment operating several hours per day and consuming less than 50 kWh per hour is more amenable to battery-electric powertrains. Meanwhile, larger equipment that may operate continuously 18–24 hours per day and consume 75–200 kWh per hour could require fuel cells or low-carbon fuels in hybridized internal combustion engine powertrains. An additional consideration is that construction equipment is likely to be used for a variety of applications over its lifetime.

A number of zero-carbon commercial products for construction equipment are available, under development, or involved in customer pilot trials. Achieving carbon-neutral construction depends on the development of four key technology areas: battery-electric and fuel cell vehicles, low-carbon fuels for the existing internal combustion engine stock (near term), operational efficiency, and availability of green electricity and hydrogen. Safety is also critical to the construction industry.

Construction applications need to address charging and power demands across the full project timeline. One important factor is that construction sites are usually temporary, operating from months to a few years.

Changing power demand across the project period suggests opportunities for modular on-site power generation and charging stations for battery and fuel cell electric vehicles. It also opens opportunities for digitization, artificial intelligence, and automation to optimally coordinate operations. Notably, construction may be located near grid feeders, such that electrification could be more feasible with a grid interconnection. However, challenges remain for sourcing enough power at scale and integrating that power use with the grid.

DOE and the national laboratories can assist industry by contributing to the development of modular battery pack standards for form factor, voltage, connection, durability, and remove and replace architecture. This would enable battery swapping from one type of vehicle to another as activities dictate and/or downsizing the peak power needed on-site if some of the battery inventory is charged off peak load.

3.4 Agricultural Off-Road Decarbonization Strategies

Agriculture is characterized by precise requirements around timing: Planting and harvesting have short and specific time windows that require availability and uptime of vehicles. Agriculture requires robust equipment for harsh environments like high heat, moisture, dirt, and dust. It is also energy-intensive—a large agricultural tractor may consume three times more energy while operating than an over-the-road truck, and significant time is spent at maximum power. Such seasonal use patterns and power demands are distinct from other off-road industries. Technologies that take advantage of off-season downtime, such as vehicle-to-grid or microgrid applications, where feasible, can help increase the value proposition for powertrain electrification.

Agricultural applications present unique infrastructure challenges, with sites often situated in rural locations that lack grid interconnection or sufficient grid power capacity. This suggests a near-term opportunity for low-carbon fuels, as well as longer-term options for hydrogen fuel cells or hydrogen internal combustion engines. There is widespread availability of ammonia for fuel, but interest from industry appears low.

Electrification offers opportunities to schedule operations more precisely and is also ideal for automation. In time, automation of agriculture vehicles could potentially omit the cabin altogether and also raises issues related to retirement of labor.

3.5 Key Takeaways of Day 2

Across industries, there is a broad commitment to developing sustainable solutions, reflected in aggressive corporate targets for reducing carbon emissions and moving to more sustainable operations. Each industry speaker emphasized commitments from their companies to diversity, equity, and inclusion, developing a diverse workforce, and building awareness and representation of local needs and interests. These commitments overlap with the sector-wide need for a skilled workforce in the areas of engineering and technicians for new powertrain solutions.

The entire off-road sector has challenging technology requirements, including harsh environments, temperatures, duty cycles, dirt and dust, and lack of ventilation. Moreover, this technology is expected to stand up to 25-year lifespans. Much of the technology is immature but advancing rapidly, including batteries, motors, fuel cell systems, and inverters.

Industry partners and the Army described numerous vehicle and equipment technology solutions including battery-electric and fuel cell vehicles, hybridized internal combustion engines, and low-carbon fuel solutions—zero-emission liquid fuels are of especially high interest to the sector and are receiving renewed R&D interest. These could potentially supply the existing fleet that needs low-carbon drop-in replacement fuels to decarbonize. Potential synergies between DOD and commercial off-road technology development and supply chain should be investigated.

Common challenges across the off-road sector include balancing the development of multiple technology pathways while determining the best fit to meet their customer needs and regulatory requirements. Indeed, different regulatory environments between countries make operations more difficult for all industries.

Another challenge is understanding diverse duty cycles and finding the best technological fit for worksite loads. This opens a significant opportunity for designing more efficient powertrains specialized for applications, with mining being a potential early adopter of efficient powertrain technologies. Assessing total cost of ownership is an important need that integrates capital and operational costs for technology, energy, and vehicle performance (e.g., efficiency of various powertrain alternatives) with application duty cycles. Technologies that have the lowest total cost of ownership need to be identified for a wide array of applications, as these are the ones most likely to be adopted and catalyzed via precompetitive RD&D.

4 Energy Systems Integration Opportunities

Keynote speakers on Day 3 came from NREL and DOD and centered on energy systems integration, a major priority of NREL's new Advanced Research on Integrated Energy Systems (ARIES) buildout and a major capability for demonstrating off-road decarbonization solutions. Following the keynotes, an industry panel with representatives from site operations spoke on case studies and examples from the field.

Major takeaways from Day 3 are:

- Industry faces the challenge of integrating multiple infrastructures (e.g., electricity grid, hydrogen).
- There is no one-size-fits-all solution for energy systems integration. Options are site-specific and varied for each application, with different customer motivations driving project designs.
- Synergies could be available across industries by taking advantage of inverter and electrical integration. Optimization of the entire energy system (e.g., storage, hydrogen production, site loads, and on-site renewable generation) can provide least-cost pathways to decarbonization.
- The off-road sector should look for integration solutions that work across a range of applications and industries.
- Industries should look at opportunities for combined heat and power, for which the agriculture and possibly mining sectors appear best suited.
- Upfront costs can be very different and distinctly higher than in past projects. The sector should apply tools for investigating integrated energy system economics with new technologies.

4.1 Power Grid Interconnection

Day 3 featured input from Xcel Energy on grid integration. From the utility perspective, mining needs reliability and power quality, construction needs flexibility and scalability, and agriculture needs accessibility. Generally, grid interconnection faces challenges regarding power capacity, charging coordination, and protection systems.

For mining, customers are typically located near the end of transmission lines and have high energy demand and high voltage requirements. Utilities are concerned with serving sufficient capacity and installing necessary protections at the site. For more electrified infrastructure, utility concerns are centered on coordinated charging, which will generally follow from the mine's operational strategy. Some off-road applications already incorporate sophisticated energy use data into operations to monitor battery charge and automate vehicle fleets. Data-driven automation of electric vehicles is also mature in medium-duty applications like warehouses and shipping. Integrating device data could become critical for electric fleets in off-road applications.

For construction, job sites vary widely, as do equipment size and extent of electric service. Because of this, construction could depend on temporary service, which might not be immediately present at the job site. Electrification could drive higher electrical demand early in the construction timeline, which could front-load costs and require more thorough project planning to ensure adequate capacity and protection throughout the project. Collocating renewables nearby project sites could support vehicle charging needs, and coordinated charging could be beneficial for both utilities and the customer.

Agricultural sites are often outside of grid service entirely or are serviced by a single wire. This creates difficulties, as agricultural vehicles require the greatest level of investment per kilowatt of power. For on-site renewable integration, questions arise about whether energy from renewables can meet electrification requirements.

Grid interconnection requires consideration of temporary power connections, a concern for construction in particular. Projects will draw substantial load in early phases, which affects grid planning and buildout. Microgrids are an option for the off-road sector—mining sites have begun to use high-power microgrid systems. Trolley assist equipment can also be useful for vehicle electrification.

4.2 Energy Storage Integration

Day 3 panel speakers discussed real system examples and upcoming approaches for energy storage integration, an all-around critical topic for the off-road sector. Already in the field, battery energy storage systems have been shown to have adequate controllability and grid-forming functions for operating microgrids (Lin et al. 2021). Panel speakers noted that in some projects, high-penetration renewable (60%–90%) is already the most cost-effective and reliable option, which could become even more beneficial as battery costs decline. One consideration of battery energy storage system integration is that they require high-step load capabilities in off-road applications.

Participants also discussed trade-offs of battery charging vs. battery swapping—especially in construction and mining—which could be specific to application and duty cycle. Beyond lithium-ion batteries, other storage pathways are being explored, such as new battery chemistries as well as gravitational and thermal storage technologies.

4.3 Renewable Energy Integration

Along with batteries, renewable energy (e.g., solar photovoltaics, wind) has been successfully applied in microgrids for mining. However, renewable energy systems have higher initial capital investments and require different operational approaches. Variable renewable energy introduces the challenge and opportunity of optimizing resource supply with operational demands. To smooth the variable renewable power, connection to electric vehicle fleets could provide flexible loads and energy storage, potentially reducing the magnitude of stationary battery needs.

Not only is renewable energy variable, but so are loads in off-road applications. Overall, the sector needs to develop standards for interoperability and coordination while allowing for some customization. This interoperability could drive technological and operational decisions on a site-by-site basis, requiring a more holistic view of a site's energy demands.

On a similar note, customer motivations can drive design of a project and play an important role in assessing how to integrate renewable energy. For example, customers are variously motivated by regulations, costs, technological competition, and other factors, which must become part of the equation when determining integration and interoperation strategies.

4.4 Hydrogen Integration

Early and upcoming hydrogen pilots are showing how integration is possible, but many open questions remain. From a fuel supply perspective, hydrogen needs are determined by scale of the off-road application. Hydrogen can be a direct replacement for diesel in most applications, with 1 kg of hydrogen roughly equaling 2.5 gallons of diesel. In the case of on-site production, electrolyzers can be scaled by multiplying the number of modules.

Designs and costs are driven by primary decisions such as whether the hydrogen is produced on-site or off-site, as well as how the hydrogen will be distributed. For example, on-site might make sense for long-duration projects and very large mines, whereas off-site could make better sense for smaller operations. There are also trade-offs in the state of hydrogen—gaseous or liquid—which affects delivery and storage requirements. For example, liquid on-road delivery could average around one trailer delivery per day, whereas gaseous on-road delivery could require nine trailer deliveries per day.

Other design considerations include whether a site will use its hydrogen for internal combustion engines or fuel cells, whether high-voltage resources will be used to power hydrogen production, and whether there is an existing pipeline nearby. Although questions remain about how best to integrate and source hydrogen for a project, the technology exists in most use cases.

Costs of renewable hydrogen production (i.e., electrolysis) are still high relative to DOE targets, but NREL analyses are showing that for some applications and jurisdictions, hydrogen fuel could already be cost-competitive (Guerra et al. 2019). Early large-scale deployment projects, as presented in this workshop, could help to drive down costs by de-risking the technology and attracting new demand.

4.5 Key Takeaways of Day 3

Decarbonizing the off-road sector will require the intersection of multiple infrastructures, with a large variety of technological options and operational strategies to select from. Renewable energy and storage integration opens up new possibilities for project design, dramatically expanding options from what was historically just fossil fuel to many feasible alternatives.

Although standardized approaches to interoperability will be important for the sector, there are no one-size-fits-all solutions, so customizability of projects will be important. This variety in alternatives can be used to narrow down project designs to best-fit, optimal solutions given site-specific requirements and customer motivations. New synergies are also available via electrification and on-site fuel production (i.e., hydrogen), which can further reduce the costs of renewable energy integration.

One challenge for the sector will be higher upfront costs of projects in order to establish the necessary infrastructure at a site. In some cases, this could reflect in power grid interconnection; in other cases, microgrid development. Another challenge will be designing and implementing complex microgrid controls to manage and orchestrate charging given different duty cycles, variable energy supplies, and cost optimizations.

Opportunities exist for DOE and industry to leverage ARIES assets to help address the system integration challenges related to remote site operations and off-road applications. Specifically, ARIES assets for renewable hydrogen production and storage, behind-the-meter storage, controllable grid interface, and other ARIES microgrid research circuits are particularly relevant to addressing off-road sector systems integration problems.

5 Conclusions

The off-road sector, comprising construction, mining, agriculture, and the military, shares a set of very specific and demanding performance requirements. These stem from harsh and rugged operating environments, long product lifetimes, around-the-clock operation, high-power components, and frequent duty cycling. These requirements add unique challenges to decarbonization of the sector and limit the amount of shared knowledge and technical solutions that can be derived from decarbonization in the light- and medium-duty transportation sector.

Still, all off-road industries are mobilizing behind decarbonization, showing clear commitment to developing sustainable solutions. This workshop gathered input from representatives across industries and facilitated discussion about needs and opportunities for the sector.

A standout need of the sector is increased RD&D led by DOE. Research is needed across all components and infrastructure, and demonstration projects can help de-risk new technologies, integration, and operational strategies. Decarbonization technologies for the sector are not yet mature, but developments at the subcomponent level could serve all industries, and early adopters could provide case studies with useful data around what works best. Additionally, DOE can help determine total cost of ownership of projects, which will be distinctly different for a decarbonized sector, with higher upfront capital costs.

DOE has an important role in developing and clarifying the potential for biofuels and low-carbon fuels. The sector is currently dependent on biofuels for achieving near-term decarbonization, which have a highly constrained supply and are allocated across a variety of sectors. DOE research can help identify applications that favor biofuel over other options such as electrification.

DOE can facilitate outreach across offices and numerous stakeholders within the off-road sector and will be critical in providing techno-economic analyses of decarbonization pathways. Awareness of DOE project opportunities and data sharing can help the sector decarbonize more quickly and collectively. DOE's role is especially important for researching and demonstrating customized solutions that match fuel types to drivetrains and operational strategies to site-specific requirements and resources.

Given the wide range of technological options and infrastructure becoming available to the off-road sector (e.g., renewable energy, battery-electric, hydrogen, low- and zero-carbon fuels, energy storage, microgrids, combined heat and power, biogas capture), there is no single track toward decarbonization. Rather, the variety of technologies suggests an opportunity for customized, integrated solutions that synergize locally available resources, project applications, and customer motivations. However, standardized approaches to a variety of decarbonization approaches will be a useful starting point for projects to build from. This is especially true given the technical difficulty in designing optimized coordination of charging and operation.

Standardized regulations can also accelerate decarbonization of the sector, which faces irregular requirements across countries and project sites. A clearer outlook and structure to project requirements can simplify (i.e., narrow the possibilities of) which direction to take decarbonization across the sector.

In the midst of this transition, high priorities for the sector include safety—following from the high-power, large equipment, and harsh environments—and diversity, equity, and inclusion. As the sector makes a technological shift, new specialists are needed with competence in drivetrain and system controls, among other areas. Industries are prioritizing diversity in seeking new talent and are focused on contributing to societal education to prepare the workforce, specifically through community engagement.

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Tuesday, March 22

Appendix 1: Workshop Agenda

High-Level Perspective of Needs and Challenges

11:00 a.m.	Opening Remarks John Farrell, Laboratory Program Manager – NREL
11:10 a.m.	Welcome Peter Green, Deputy Laboratory Director – NREL
11:15 a.m.	U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Keynote Kelly Speakes-Backman, Principal Deputy Assistant Secretary – EERE, DOE
11:25 a.m.	Michael Berube, Deputy Assistant Secretary – EERE, DOE
11:45 a.m.	U.S. Department of Defense (DOD) Keynote Oliver Fritz, Principal Director – ODASD for Environment and Energy Resilience at Office of the Secretary of Defense, DOD
12:05 p.m.	Off-Road Environmental & Regulatory Agency – California Air Resources Board (CARB) Keynote Craig Segall, Deputy Executive Officer – Mobile Sources and Incentives, CARB
12:25 p.m.	Off-Road Environmental & Regulatory Agency – U.S. Environmental Protection Agency (EPA) Keynote Bill Charmley, Director – Assessment and Standards Division, Office of Transportation and Air Quality, EPA
12:45 p.m.	Industry Perspective Keynote Jason Malcore, Director – Global Standards & Compliance, Association of Equipment Manufacturers Steve Berry, Truck and Engine Manufacturers Association
1:15 p.m.	Break
1:25 p.m.	Panel Discussion Michael Berube, DOE (moderator)
2:25 p.m.	Wrap-Up John Farrell, Laboratory Program Manager – NREL
2:40 p.m.	Adjourn

Vehicle and Equipment Decarbonization Strategies

11:00 a.m.	Welcome Ken Kelly, Chief Engineer – Commercial Vehicle Electrification, NREL
11:10 a.m.	Keynote: U.S. Army Ground Vehicle Systems Center – Powertrain Electrification Dean McGrew, Branch Chief – Power Electrification Team, U.S. Army, GVSC
11:30 a.m.	Oak Ridge National Laboratory (ORNL)/DOE Off-Road Decarbonization Questionnaire Summary Josh Pihl, Group Leader – Applied Catalysis & Emissions Research, ORNL
11:50 a.m.	Mission Innovation Hydrogen Fuel Cells Off-Road Workshop – Report-Out Pete Devlin, Technology Development and Intergovernmental Coordination Manager – DOE
12:10 p.m.	Q&A
12:40 p.m.	Break
12:50 p.m.	Vehicle-Level Perspective – Industry Panel Darren Almond (John Deere), Ray Gallant (Volvo), John Pendray (Cummins), Michael Lewis (Komatsu), Mihai Dorobantu (Eaton), Mike Rochford (Caterpillar)
2:35 p.m.	Panel Discussion and Q&A
3:20 p.m.	Wrap-Up Ken Kelly, Chief Engineer – Commercial Vehicle Electrification, NREL
3:30 p.m.	Adjourn

Thursday, March 24

Energy Systems Integration Opportunities

11:00 a.m.	Welcome Matt Thornton, Strategic Program Manager – NREL
11:10 a.m.	Energy Systems Integration Keynote Jennifer Kurtz, Director – Energy Conversion and Storage Systems Center, NREL
11:30 a.m.	DOD – Micro Grid and Base Energy Systems Integration Michael McGhee, Executive Director for Climate Resilience – DOD
11:50 a.m.	Q&A
12:05 p.m.	Break
12:15 p.m.	Site Operator – Industry Panel Suresh Reddy (Caterpillar), Amiram Roth-Deblon (juwi AG), Dave Edwards (Air Liquide Hydrogen Energy), Joe LaCasse and Jeremy Hutchinson (Xcel Energy), Chris Walters (FPT Industrial)
2:00 p.m.	Panel Discussion and Q&A
2:45 p.m.	Next Steps and Key Takeaways John Farrell, Laboratory Program Manager – NREL
3:20 p.m.	Adjourn

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