A MARKET AND TECHNOLOGY ASSESSMENT FOR OFF-ROAD VEHICLE & EQUIPMENT ENERGY AND EMISSIONS INNOVATION

DEPARTMENT OF ENERGY
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1. EXECUTIVE SUMMARY

1.1 Intent and Purpose

A Market and Technology Assessment for Off-Road Vehicle & Equipment Energy and Emissions Innovation is a critical step in reducing transportation costs, expanding options for American consumers and businesses, spurring innovation, and ensuring these technologies meet the needs of the U.S. off-road industry while also working towards net-zero emissions by 2050. To reach these goals, this report characterizes the current information available about the off-road sector; identifies outcomes from key stakeholder engagement; outlines pathways to scale low- and net-zero emission fuels, energies, and technologies; strengthens the workforce; and expands complementary infrastructure. The work herein supports industry, workers, communities, local governments, and other interested parties that will reduce emissions across the off-road sector alongside the U.S. government. Significant progress is being made on the development of technologies, industrialization, supply chain, infrastructure, and policies needed to support this transition. The transportation sector is the largest source of greenhouse gas (GHG) emissions in the United States, and emissions from the transportation sector also contribute to poor air quality.

“Equipment” in this report generally refers to mobile, stationary, and hand-held items that are used for specific purposes such as digging or lifting. “Vehicles” are a subset of equipment that also provide their own motive power. For this report, *equipment* will most often be used because of its inclusive definition; however, *vehicles* will be used when referring exclusively to off-road equipment that is self-propelled.

1.2 Key Objectives

Achieving decarbonization of off-road vehicles and equipment will require bold action. Strong U.S. government leadership will set an example and help rally the domestic and international communities. To achieve the U.S. emissions targets, a multifaceted, strategic approach must be deployed.

OBJECTIVE: Improve accounting for the off-road equipment sector population, energy consumption, and emissions inventory.

OBJECTIVE: Build partnerships and collaborations with the off-road industry and communities to support their movement towards low-carbon solutions.

OBJECTIVE: Support off-road equipment research, development, and deployment efforts to enhance efficiency, operation on sustainable fuels and energy, and technology integration.

OBJECTIVE: Support the off-road sector by advancing sustainable liquid fuel (SLF) and clean energy infrastructure development.

OBJECTIVE: Strengthen and expand the off-road workforce by prioritizing safety, job security, and training.

1.3 The Off-Road Sector Today

The off-road sector is composed of many types of equipment, which are generally categorized as: agricultural, construction, industrial, underground mining, forestry, lawn and garden, powersport, and commercial. Within those categories, according to the U.S. Environmental Protection Agency's (EPA's) MOtor Vehicle Emission Simulator (MOVES), there are 85 unique equipment types (e.g., tractors, harvesters, wheel loaders, excavators, fork trucks, mowers, all-terrain vehicles, refrigerators), many of which run a gambit of installed horsepower (hp). Further, daily usage varies heavily by application. A small lawnmower (5 hp) may only be used for an hour per week, whereas a large mining haul truck (up to 4,000 hp) will typically run for 24 hours per day, 7 days per week. As of 2022, the vehicles in this sector were primarily compression or spark ignition engines with some electrification of equipment in the industrial and the lawn and garden subsectors. The large disparity in daily energy needs across all off-road vehicle types combined with unique operations drives a need for a variety of solutions.

The off-road sector GHG emissions are approximately 10% of all transportation-related GHG emissions (Figure 1). The sector fuel consumption (and therefore emissions) is dominated by construction, agricultural, and industrial applications; however, the greatest equipment volume is the lawn and garden area (Figure 2).

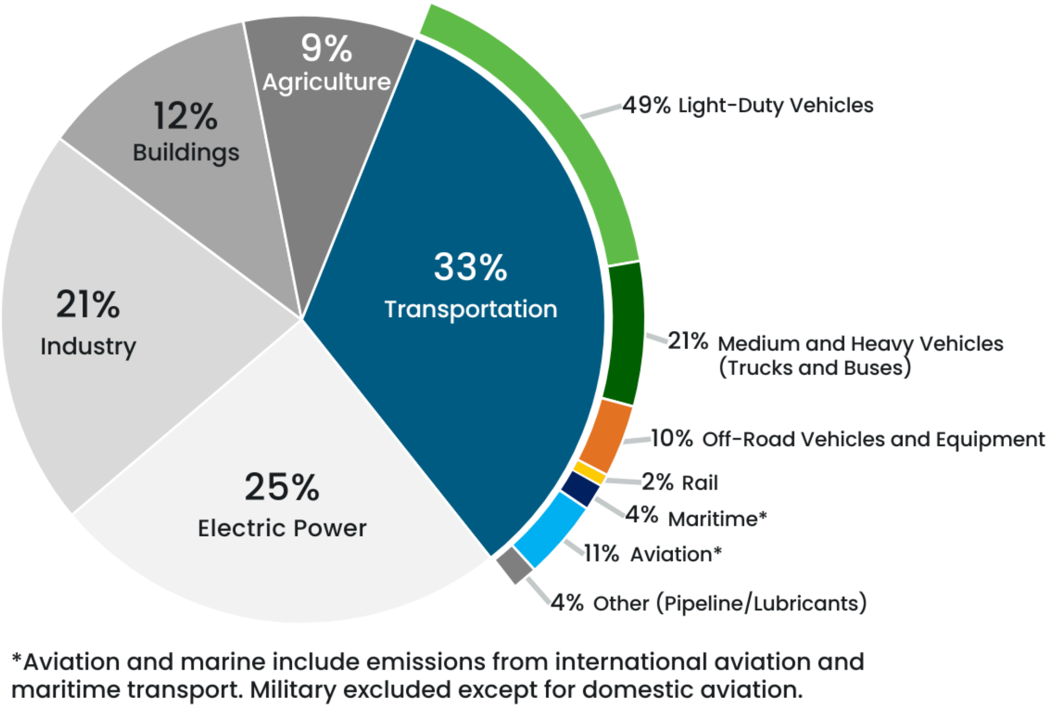

Figure 1. EPA GHG emissions by sector

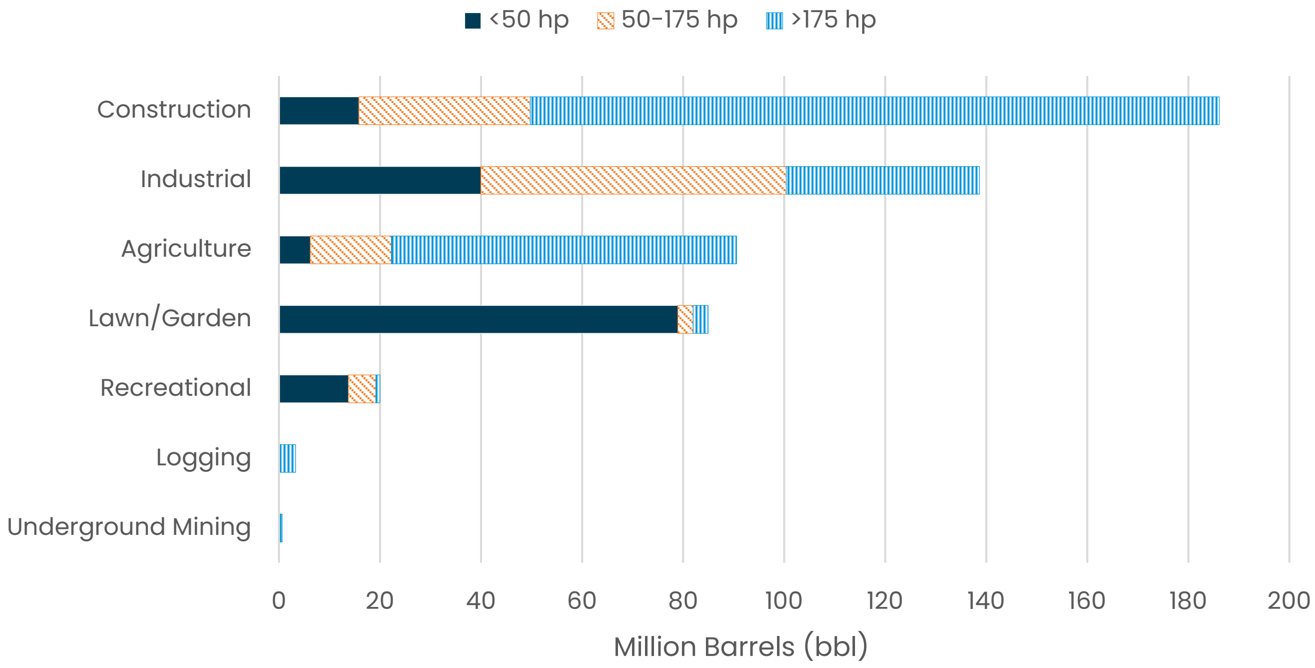

Figure 2. Fuel consumption of the off-road sector by segment and hp rating. Note: The Industrial and Commercial sectors from MOVES have been combined under the Industrial sector.

Table 1 on the following page shows some examples of equipment types and general descriptions of the seven most prominent segments of the off-road sector. This provides a better context to the variety of equipment and work that is covered within the off-road sector.

Table 1. Examples and Descriptions of the Equipment Across the Most Common Segments of the Off-Road Sector

Category	Examples	Description
Construction	Rubber tire loaders, crawler tractors/dozers, excavators, off-highway trucks, tractors/loaders/backhoes, skid steer loaders	Equipment that's used for moving demolition and building materials.
Industrial	Forklifts, air conditioning/refrigeration, sweepers, scrubbers	Equipment used for transporting cargo and loading or unloading it.
Agricultural	Agricultural tractors, combines	Equipment used on a farm for growing and harvesting crops.
Lawn and Garden	Commercial turf equipment, lawn and garden tractors, mowers, leaf blowers	Equipment that maintains the landscaping around houses and businesses.
Recreational	All-terrain vehicles (ATVs), off-highway motorcycles, snowmobiles	Vehicles used for powersports and racing.
Logging	Forwarders, feller bunchers, processors/harvesters	Forestry equipment used to cut and process trees.
Underground Mining	Mining loaders, personnel carriers	Equipment used to extract ore in underground mining.

One trait shared amongst almost all off-road equipment is the high utilization of installed power. Compared to on-road vehicles, which typically have short excursions to high-power operation, off-road vehicles may spend entire shifts operating above 75% of rated power. This is due, in part, to inefficient throttling of hydraulic power systems (digging or loading), but also often necessitated by the work task (plowing a field or hauling ore up a grade). This results in proportionally higher GHG emissions relative to rated power and the need for high-energy-density alternative fuels. Finally, these vehicles are normally operated off-road (except to travel between worksites), so fuel (energy) must be brought to them.

The environment in which off-road equipment operates, and the surrounding infrastructure, are other important considerations. The level of dust in the air, working surface, and vibrations can pose challenges for some technologies. Urban worksites may have easier access to electric and hydrogen infrastructure, but rural and remote worksites may not. The equipment is expected to operate in freezing temperatures in the northern parts of the United States, and extreme heat in the southern United States. There is a strong preference for availability of equipment; when needed (example: for emergencies, disaster relief, or farming harvest), equipment must operate for long periods of time reliably. For some operations, increased downtime is completely unacceptable.

1.4 Strategy to Decarbonize the Off-Road Sector

With the objective of achieving sector-wide net-zero GHG emissions, this report has developed the following strategies:

1. **Maximize the number of internal combustion engine (ICE)-powered equipment that can be affordably replaced by battery electric equipment (BEE) that still meets customer needs.**

   BEE technology, which has a fully electric powertrain, is currently limited to smaller machines that operate for up to 8 hours (depending on duty cycle) per workday and have the opportunity for recharging during or after the work shift. Many hand-held lawn and garden pieces of equipment have already begun to transition to BEE, as well as indoor forklifts and smaller agricultural machines, where infrastructure supports it. There is growing interest for mobile BEE, which is charged from high-power (>1 megawatt [MW]) mobile power sources, such as hydrogen fuel cell and low-carbon diesel gen sets, which can be brought to the worksite or remote locations, such as a construction site.

   Current barriers to electrification are related to cost, weight, charging downtime, and charging infrastructure. The cost of batteries makes achieving cost parity difficult for equipment with the need for long run times between charging. Total cost of ownership analysis can help to identify when and where reductions in operating costs can offset increased capital costs, whereas life cycle analysis (LCA) can identify the total GHG emissions impact. To amortize increased capital expense and initial GHG burden from battery manufacturing, it is important that this equipment has significant annual hours of operation. Battery weight is also a concern. In the case of smaller equipment, multiple batteries may be required to complete a task, or for large equipment battery weight may lead to soil compaction or issues with transportation. Finally, off-road equipment is operated in remote environments where charging infrastructure does not exist. In many applications, the energy must be delivered to, or generated, where the equipment operates.

2. **Enable transition to hydrogen as the fuel source, either by fuel cell or ICE, where practical.**

   Construction and material handling equipment have a large potential for hydrogen conversion because the worksites have room to support centralized hydrogen refueling stations and potentially on-site hydrogen generation. Further, daily fuel usage is predictable, which enables fueling contracts to lower prices, and daily run times usually coincide with a standard workweek, reducing the need for large on-vehicle tanks. Hydrogen offers faster opportunity refueling during work breaks, which are common and/or planned for those vehicles. Hydrogen internal combustion engines (H_2ICEs) may be preferred over fuel cells in some segments where dust in the air and machine vibrations are concerns, such as construction, agriculture, etc.

   Hydrogen fuel is still a nascent technology and requires significant infrastructure build-out. Early adopters have required large and predictable volumes to achieve reasonable total cost of ownership. Increasing the number of H_2ICE equipment in the fleet will increase hydrogen demand and may result in lower hydrogen prices and greater availability while having a lower technology barrier to entry than fuel cells. Fuel cells, while generally more efficient than H_2ICEs at low load operations, and without point source emissions, require complete vehicle electrification (which can be very expensive) and adequate air flow for cooling.

3. **For machinery and operations that still require high-energy-density liquid fuels, the objective is to reduce overall fuel consumption by efficiency improvements to the greatest extent possible, while enabling neat SLF compatibility.**

   Some equipment, either due to daily energy consumption requirements or because of the remoteness of their operation, will continue to require SLFs in the long term. However, the supply of SLFs is expected to be limited and as such, the total fuel consumption should be minimized through maximizing efficiency. Several mechanisms exist to reduce fuel consumption, but these are all application specific. For mobile off-road vehicles with large over-running loads (mining haul trucks, cranes, forklifts, etc.), powertrain hybridization should become standard. For other vehicles with large hydraulic loads (farm equipment, excavators, bulldozers, etc.), efficiency improvements from hydraulic throttling reductions or hydraulic hybrids may be necessary.

   Although the current supply of SLFs is limited, ongoing work seeks to increase available volumes in the coming years. Research activities target greater utilization of various renewable carbon resources, increased conversion yields, lower energy use, and overall reductions to the cost of production. As SLF production technologies advance and new capacity is installed, the volumes available for use in this sector will increase, but actions to reduce overall demand and consumption will be necessary to ensure that these fuels are available across sectors where they are needed. As biofuel production technologies have not been fully de-risked, their cost of production remains higher than that of their petroleum-derived counterparts without the support of incentives such as tax credits. As noted in the Biofuels Appendix, government support will continue to play an important role in developing technologies, building supply chains, and scaling up biofuels production to meet the need for low-carbon liquid fuels.

1.4.1 CONSIDERATIONS FOR SELECTION OF EQUIPMENT EMISSIONS REDUCTION STRATEGIES

Based on the highest GHG emitters in the sector and other important equipment types, considerations are provided in Table 2. Some of the near-term research and development needs are given for each technology pathway.

Table 2. Equipment Decarbonization Considerations

Technology Path	Considerations	Research & Development Needs
Battery Electric Equipment	• Smaller equipment (incl. handheld) • <8 hours cont. operation • Low onboard energy storage • Low weight and packaging • Opportunity charging • Significant annual usage	• Increased battery energy density • Decreased battery cost • Availability of worksite charging either from direct infrastructure or mobile charging • Analysis of equipment operation to optimize energy consumption • Electric hydraulic components with reduced cost and increased durability • Real-world demonstration of equipment • Reduced demand of critical materials
Hydrogen Fuel Cell	• Ram air cooling available • Low dust • Low vibrations • On-site hydrogen (H_2) storage • Predictable H_2 demand	• Durability and cost of fuel cells • Thermal management improvements • Reduced critical materials demand • Clean and low-cost H_2 • Cooperative demonstration projects with original equipment manufacturers • Analysis to determine if there is a long-term preference between H_2 fuel cells and BEE
H_2ICE	• Shaft power prioritized • High dust • High vibration • On-site H_2 storage • Predictable H_2 demand	• H_2 fuel storage density improvement • Modeling efforts to determine suitability of hybridization to reduce fuel consumption while maintaining operations • Clean and low-cost H_2
Sustainable Liquid Fuels	• Remote operations • High uptime demands • Lack of H_2 or charging infrastructure • Low onboard energy storage space/weight avail. • Low annual usage • Legacy equipment • Fuel stability for long shelf life	• Fuel production pathway improvements—yield, energy requirements, carbon intensity (CI) reductions • Local fuel consumption and production to reduce shipping burden • Production of large volumes of consistent and affordable low-CI feedstocks • Neat sustainable fuel compatibility

1.4.2 SECTOR-SPECIFIC EXAMPLES

Given the complexity of the off-road sector by equipment types, end uses, and locations, there is no one solution for substantial emissions reductions. However, it's possible to identify and evaluate the most important equipment types of each subsector.

Lawn and Garden: Examples of lawn and garden equipment include commercial turf equipment, lawn tractors/mowers, chippers, grinders, leaf blowers, etc. While this segment may only contribute to approximately 15% of off-road GHG emissions, it composes approximately 75% of the off-road population and its equipment is used around nearly every home and business. About 99% of equipment in this segment is rated less than 25 hp and has significant potential for battery electrification. There has already been a significant trend of battery-powered equipment adoption in this segment, and it is likely to continue.

Agriculture: The agricultural sector contributes to 20% of off-road GHG emissions, of which 86% comes from agricultural tractors specifically. For large tractors used for fieldwork, they will likely operate on compression ignition, i.e., conventional diesel engines with SLFs due to the long periods of continuous operation, remote location (poor infrastructure), and dusty conditions. However, for small and medium tractors used around the farm to perform less demanding work, alternatives like battery electric and hydrogen powertrains have potential.

Industrial: Forklifts make up approximately 50% of the equipment in this segment. Because forklifts often operate indoors at distribution centers and criteria pollutant emissions must be minimized or eliminated, there has been a significant trend towards battery electric and now hydrogen fuel cell equipment. These powertrains also help to reduce noise emissions.

Construction: While the construction segment is one of the smaller segments by equipment population, it contributes the most GHG emissions in the off-road sector. It's composed of a wide range of equipment, but the top six produce approximately 70% of this segment's GHG emissions. The six are rubber tire loaders, crawler tractors/dozers, excavators, off-highway trucks, tractors/loaders/backhoes, and skid steer loaders. The options for emissions reductions are more dependent on how and where the equipment is used than what type of equipment it is. In urban areas, where electrical charging infrastructure may be more available, BEE could see high adoption rates, especially if zero-point source emissions are required. In rural and remote areas, where electrical charging infrastructure is less likely, ICE powertrains operating on SLFs or hydrogen are more likely available. For non-urban worksites where delivery of hydrogen to fuel-cell-powered generators or battery stationary storage is possible, BEE may still be used along with off-grid charging.

1.5 Community Considerations for Off-Road Emissions Reductions

Achieving net-zero economy-wide GHG emissions by 2050 will have many benefits for the U.S. economy and communities—including promoting innovation, maintaining economic competitiveness on the global stage, and reducing the negative impacts of climate change and poor air quality. However, this transformation will require strategic transitions—including changes to vehicles, component manufacturing processes, fuel production processes, vehicle and infrastructure maintenance, and vehicle operations. A thoughtful, strategic approach to transitioning the U.S. workforce and communities will be essential to ensure a just and equitable transition for all Americans.

Transitioning to a lower-emission off-road sector will substantially affect a range of industries—including agriculture, construction, equipment and parts manufacturing, dealerships, and maintenance repair. Transitions will involve the increased production and jobs in net-zero equipment, component technologies, and fuels and infrastructure, as well as the reduced production of fossil fuels.[1]

1.6 Following Through With Action and Collaboration

In 2023, the United States government published the first-ever *U.S. National Blueprint for Transportation Decarbonization* (Blueprint), which reaffirmed the importance of addressing transportation emissions from all sources, including aviation.[2]

The Blueprint lays out a strategy to reduce nearly all GHG emissions in the U.S transportation sector, in line with the U.S. economy-wide goal of net-zero GHG emissions by 2050.[3] The transportation sector is the largest source of GHG emissions in the United States. Emissions from the transportation sector also contribute to poor air quality, and these effects disproportionately impact low-income communities. The Blueprint provides a roadmap for how to provide better transportation options, expand affordable and accessible options to improve efficiency, and transition to zero-emission vehicles and fuels.

The Blueprint is built on five principles:

1. Initiate bold action.
2. Embrace creative solutions across the entire transportation system.
3. Ensure safety, equity, and access.
4. Increase collaboration.
5. Establish U.S. global leadership.

Consistent with the Blueprint, this report seeks to capture the progress made over the past several years and identify opportunities for the United States to make continued progress toward this goal. Under the Blueprint, the U.S. government made commitments to develop modal plans that discuss, in detail, actions, investments, and research needed decade by decade to work toward the 2050 goal. This report, *A Market and Technology Assessment for Off-Road Vehicle & Equipment Energy and Emission Innovation*, presents high-level off-road emission reduction strategies. A more detailed modal plan for off-road will be developed that covers the broad range of actions needed from lawn equipment to construction vehicles, to fuels and stationary off-road equipment. Thus, this report should be read as a supplement to the overall national emission reduction work, providing a high-level off-road emission reduction strategy that can help put the off-road sector on a path to further GHG emission reductions in later years.[4]

2. BACKGROUND AND CONTEXT

Off-road equipment is primarily designed to operate away from existing roadways. This category contains a disparate and very diverse set of machines and use cases, including construction equipment (36% of off-road greenhouse gas [GHG] emissions), agriculture equipment (20%), industrial equipment (18%), lawn and garden equipment (13%), commercial equipment (8%), and others (5%), which includes oil field equipment, recreational vehicles, forestry, mining, etc.[5] Diesel provides the majority (68%) of the total fuel that off-road equipment currently consumes, especially for agricultural, construction, mining, and industrial equipment, with gasoline (19%), liquified petroleum gas (LPG) (11%), and compressed natural gas (CNG) (2%) making up the remaining fuel consumption. Lawn and garden equipment and recreational vehicles, in contrast, are primarily fueled by gasoline. Combined, off-road equipment is responsible for 10% of transportation GHG emissions. Due to the nature of these equipment and the work they do, the emissions from them are often mapped to the industrial and agriculture sectors in emissions accounting. Off-road equipment is included with transportation in this report since the technology solutions required to decarbonize them are well-aligned with solutions used to decarbonize other transportation modes.

There are a wide range of engine sizes, power requirements, duty cycles, and vehicle applications to be considered in the pathways for decarbonizing the off-road sector. Unlike most on-road vehicles, an off-road equipment engine typically provides power to propel the vehicle and to perform auxiliary work, such as digging or harvesting. As a result, different applications in the off-road sector have specific requirements for ruggedness, durability, and other operational constraints. Strategies for decarbonizing the off-road sector will leverage technologies similar to other sectors, including increased use of electric batteries, fuel cells, and sustainable fuels. However, the exact roles of different technologies and solutions across these use cases have many nuances. A deeper understanding of real-world operations and requirements is needed to enable comprehensive data-driven analysis that can identify viable pathways at the vehicle and system level. Hybridization can also help optimize engine operation, allow for engine downsizing, and increase overall efficiency. Finally, automation could offer opportunities to optimize vehicle design and use to reduce emissions.

Electrification is already taking place across parts of the off-road sector, particularly household lawn and garden equipment. As battery technology progresses, more opportunities for electrification in this wide category of vehicles will emerge. Large vehicles that run continuously or operate in remote areas far from refueling infrastructure might require hydrogen or sustainable liquid fuels (SLFs). Building infrastructure that brings sustainable fuel and/or electricity to worksites (or produces it there) will be a key strategy for decarbonizing the off-road sector.

2.1 The U.S. Off-Road Sector

Understanding the differences among equipment types in terms of population, energy consumption, emissions, and replacement rates is key to focusing attention on those sectors and approaches that could be most impactful for reducing GHG emissions in the coming years. It is important to note that equipment in each subsector is unique. Even though equipment types are grouped together within these sectors, there can be large differences in energy demands, duty cycle, hours of operation, and other characteristics on an equipment-by-equipment basis.

The U.S. Environmental Protection Agency's (EPA's) MOtor Vehicle Emission Simulator (MOVES) modeling system estimates fleet average emissions for both on-road and off-road vehicles.[6] The MOVES off-road module, which EPA named "Non-road," estimates emissions as the product of population, activity, rated power, and load factor multiplied by an emission factor. For the case of carbon dioxide (CO_2) emissions, MOVES uses an in-use adjusted brake-specific fuel consumption (BSFC) to compute CO_2 emissions directly (with an adjustment based on unburned hydrocarbon emissions).

The MOVES off-road data is primarily based on a 1998 database developed by Power Systems Research (PSR), which conducted several yearly surveys of equipment owners and determined a mean usage rate for engines by application and fuel type (gasoline and diesel only). EPA does not consider the effect of equipment age on activity.

The data from PSR relied on engine manufacturer sales surveys, experimentally determined engine life, and surveys of these engines' usage. The base population data that EPA used was from 1996–2000, depending on equipment type. EPA used projections to extend the historical population data into the future (e.g., to 2022), relying on four methods: equipment activity, census population, economic, and energy use projections.

The following subsections cover the data for each of the key factors in calculating CO_2 emissions from the off-road vehicles and equipment.

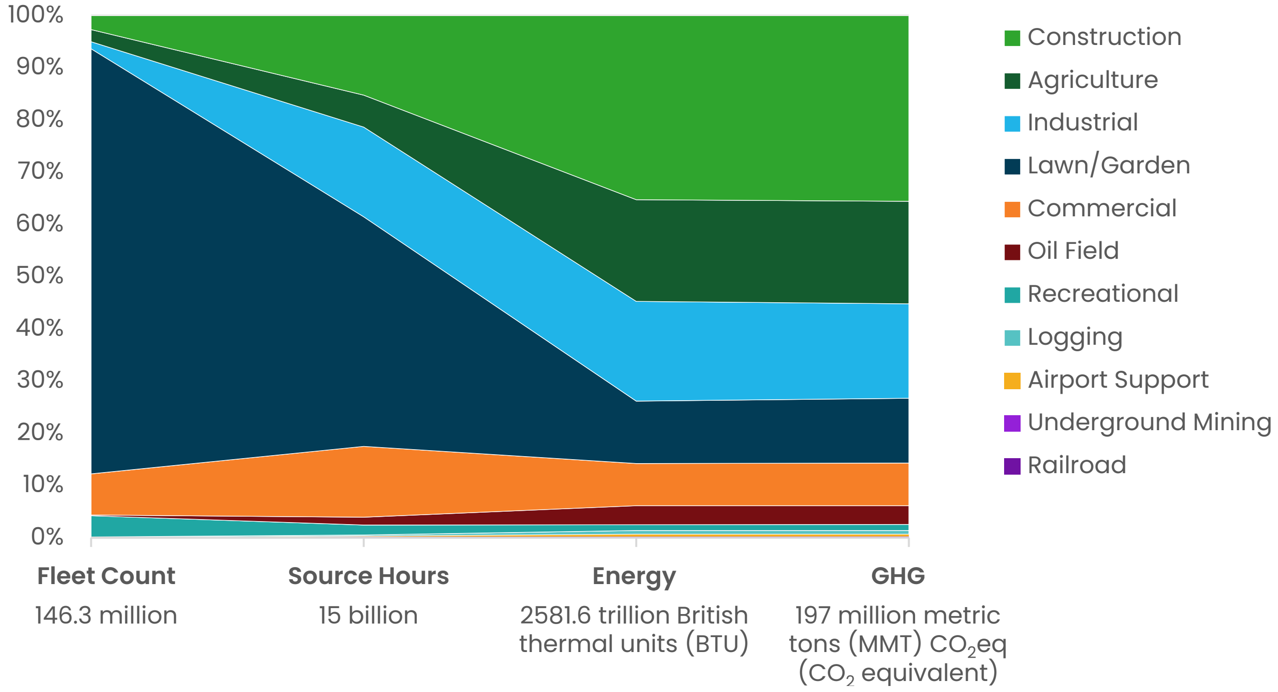

Figure 3. U.S. off-road equipment composition based on percent of fleet number, source hours, energy, and use-phase GHG emissions. Source: EPA MOVES3.

2.1.1 FLEET COMPOSITION

In 2022, MOVES estimated the off-road sector population to contain 146 million pieces of equipment, with a large majority (117 million) in the lawn and garden sector (Figure 4). EPA estimated that approximately 12% of lawn and garden equipment is owned by commercial users and approximately 88% is owned by residential users and stated that the equipment will have different usage patterns depending on its ownership. EPA does not specify ownership (or have resulting different usage) for other types of equipment (see Table 3).

Because the off-road sector is quite diverse, it can be segmented in multiple ways. EPA uses the MOVES non-road model to compute emission inventories for 88 types of off-road equipment in 12 subsectors. In this report, we do not include the Pleasure Craft subsector, which has three equipment types, as it is covered in the maritime plan. Also, for simplicity we have combined several MOVES subsectors: Airport Support and Commercial have been included in Industrial, and Oil Field and Railroad have been included in Construction (Table 3).

EPA estimates default base year populations as a starting point for estimating future and past year engine populations. The base year is the most recent year for which population data are available for specific engines and is 1996, 1998, 1999, or 2000. EPA tracks engines rather than equipment because off-road emissions regulations focus on engines, not equipment. For most engines, EPA uses the 2003 version of the PSR estimates of national populations. The PSR population estimates were determined from engine manufacturer sales surveys, experimentally determined engine life, and surveys of these engines' usage. Additionally, the MOVES equipment population does not include any electrified equipment or any projections of the population of those. This is a known deficiency within the MOVES data, and recommendations for remedy are identified later as part of future actions.

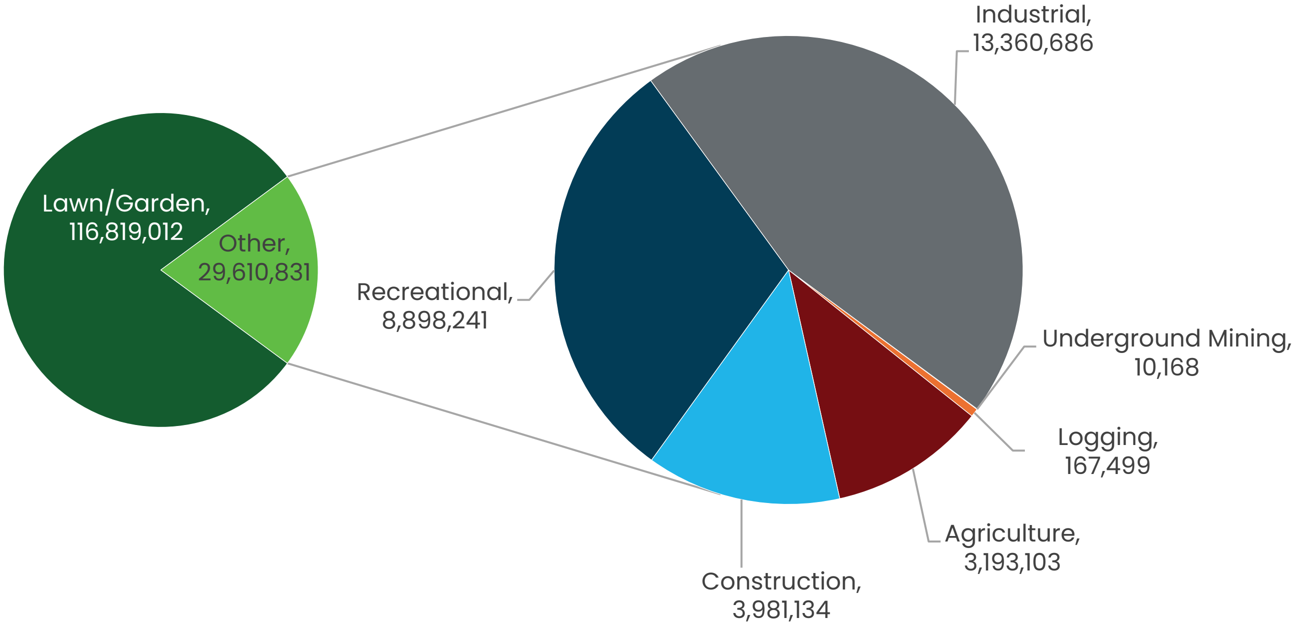

Figure 4. U.S. off-road population by sector

EPA identified historical datasets to serve as surrogates for constructing annual equipment sector-specific growth indices from the population base years (1996, 1998, 1999, or 2000) to 2014. For future projections (2014+), EPA used four primary methods for projecting non-road engine population growth trends: equipment activity projections, census population projections, economic projections, and energy use projections. For example, census region projections of energy consumption from the U.S. Energy Information Administration's *2016 Annual Energy Outlook* (AEO2016) are applied to the construction, agriculture, logging, oil field, and underground mining equipment sectors. Because the model assigns constant hours-per-year activity rates to each piece of non-road equipment, changes in emissions-generating activity levels are approximated by estimating changes in non-road engine populations.

Table 3. Off-Road Equipment by Sector

Sector	Equipment	2022 MOVES Population
Agriculture	2-Wheel Tractors	5,763
	Agricultural Mowers	9,287
	Agricultural Tractors	1,611,790
	Balers	25,852
	Combines	324,628
	Irrigation Sets	33,543
	Other Agricultural Equipment	55,420
	Sprayers	260,495
	Swathers	80,004
	Tillers >6 hp	786,321
Construction	Bore/Drill Rigs	202,646
	Cement & Mortar Mixers	371,764
	Concrete/Industrial Saws	161,639
	Cranes	45,128
	Crawler Tractor/Dozers	126,171
	Crushing/Proc. Equipment	23,376
	Dumpers/Tenders	46,670
	Excavators	164,173
	Graders	39,145
	Off-Highway Tractors	5,357
	Off-Highway Trucks	20,619
	Other Construction Equipment	17,793
	Other Oil Field Equipment	203,070
	Pavers	42,801

Sector	Equipment	2022 MOVES Population
	Paving Equipment	184,776
	Plate Compactors	195,813
	Railway Maintenance	33,149
	Rollers	119,920
	Rough Terrain Forklifts	2,774
	Rough Terrain Forklifts	145,895
	Rubber Tire Loaders	186,172
	Scrapers	22,217
	Signal Boards/Light Plants	84,601
	Skid Steer Loaders	701,281
	Surfacing Equipment	32,839
	Tampers/Rammers	229,204
	Tractors/Loaders/Backhoes	449,951
	Trenchers	122,193
Industrial	Air Conditioning/Refrigeration	388,816
	Aerial Lifts	211,525
	Air Compressors	327,678
	Airport Support Equipment	23,261
	Forklifts	966,325
	Gas Compressors	1,143
	Generator Sets	6,270,699
	Hydropower Units	41,360
	Other General Industrial Equipment	246,988
	Other Material Handling Equipment	15,652
	Pressure Washers	2,527,095
	Pumps	1,624,266
	Sweepers/Scrubbers	124,525
	Terminal Tractors	45,794
	Welders	545,558
Lawn/Garden	Chain Saws <6 hp (commercial)	1,068,448
	Chain Saws <6 hp (residential)	6,564,820
	Chippers/Stump Grinders (commercial)	147,520
	Commercial Mowers (commercial)	311,129
	Commercial Turf Equipment (commercial)	1,497,927

Sector	Equipment	2022 MOVES Population
	Front Mowers (commercial)	256,528
	Lawn & Garden Tractors (commercial)	587,202
	Lawn & Garden Tractors (residential)	15,253,987
	Lawn Mowers (commercial)	2,226,553
	Lawn Mowers (residential)	41,167,952
	Leaf Blowers/Vacuums (commercial)	1,548,782
	Leaf Blowers/Vacuums (residential)	9,251,565
	Other Lawn & Garden Equipment (commercial)	1,116,683
	Other Lawn & Garden Equipment (residential)	751,352
	Rear Engine Riding Mowers (commercial)	74,431
	Rear Engine Riding Mowers (residential)	2,232,179
	Rotary Tillers <6 hp (commercial)	891,008
	Rotary Tillers <6 hp (residential)	4,274,847
	Shredders <6 hp (commercial)	467,260
	Snowblowers (commercial)	901,451
	Snowblowers (residential)	5,886,867
	Trimmers/Edgers/Brush Cutters (commercial)	2,723,213
	Trimmers/Edgers/Brush Cutters (residential)	17,617,308
Logging	Chain Saws >6 hp	19,519
	Forest Equipment – Feller/Bunch/Skidder	16,065
	Shredders >6 hp	131,915
Recreational	All-Terrain Vehicles	4,807,660
	Golf Carts	212,841
	Off-Road Motorcycles	1,470,578
	Snowmobiles	1,799,041
	Specialty Vehicle Carts	608,122
Underground Mining	Other Underground Mining Equipment	10,168

2.1.2 ACTIVITY

The EPA MOVES model estimates equipment activity in average annual hours of operation. EPA does not provide data on variations of activity for specific equipment types based on power rating, age, or regional location. However, there is significant variation in the usage between equipment types in each of the sectors (Figure 5).

EPA does not account for the effect of equipment age on activity. However, EPA has information suggesting that activity declines as the equipment gets older but did not have enough data to model the relationship.

The default activity data is primarily based on a 1998 database developed by PSR. PSR conducted several yearly surveys of equipment owners and determined a mean usage rate for engines by application and fuel type. The survey data covered only gasoline and diesel fuels. EPA does not adjust for the effect of equipment age on activity. EPA has information suggesting that activity declines as the equipment gets older but did not have data to model the relationship.

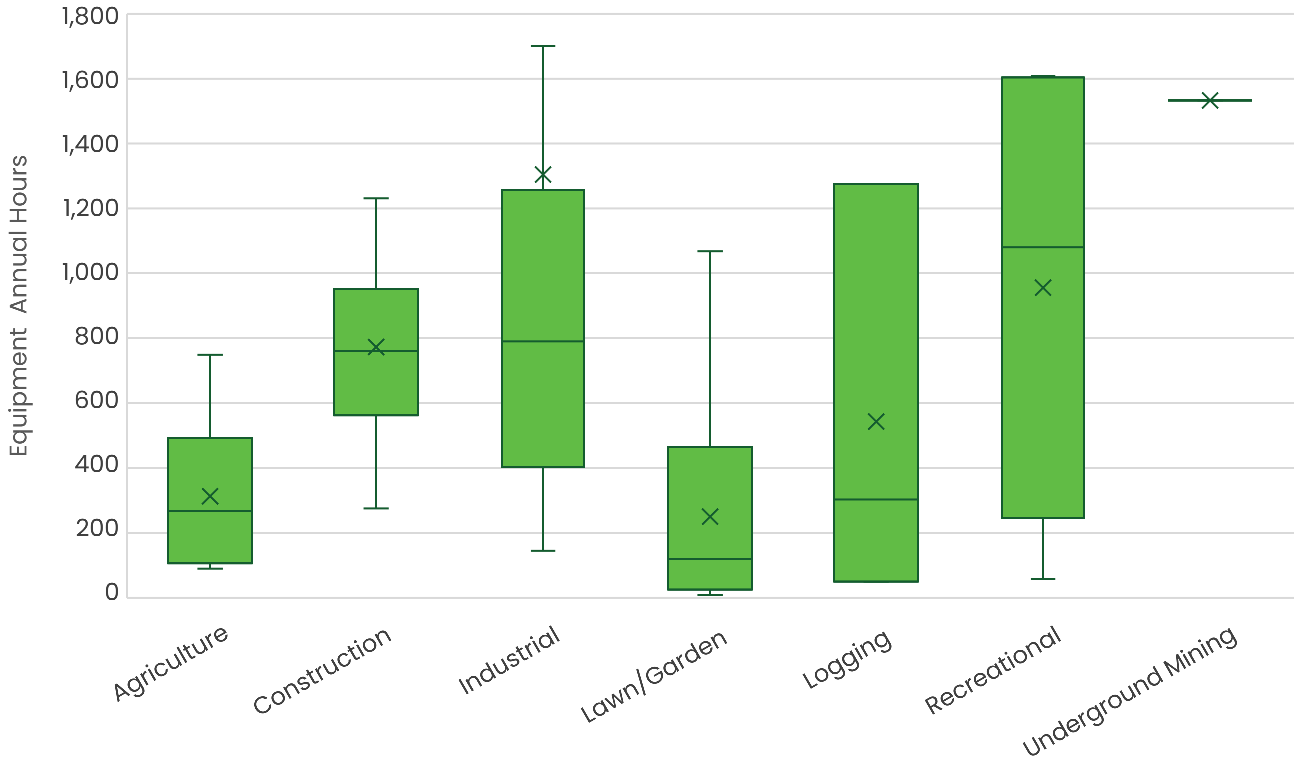

Figure 5. EPA MOVES3 off-road annual hours of operation by sector

2.1.3 FUEL CONSUMPTION

The EPA MOVES calculation for fuel consumption is based on three parameters: rated power, load factor, and BSFC. Rated power is the maximum power level that an engine is designed to produce at its rated speed, while load factor is the average proportion of that rated power being used during normal operation. For example, an engine rated at 100 hp with a load factor of 0.25 would be producing an average of 25 hp during its operation. The efficiency of the engine, which can be derived from the BSFC, is applied to the average power of the equipment to calculate the fuel consumption.

The sources of this data were the late 1990s or early 2000s. The distribution of rated power for each equipment/powertrain type is based on PSR population data. Load factors were also derived by PSR using fuel consumption power and fuel consumption data from fleet surveys. The BSFC data came from various engine testing for different engine technologies. See Figure 6 for the calculated average engine efficiency by fuel type. Note that these are not the maximum efficiency of the engines, but rather the average efficiency of typical operation.

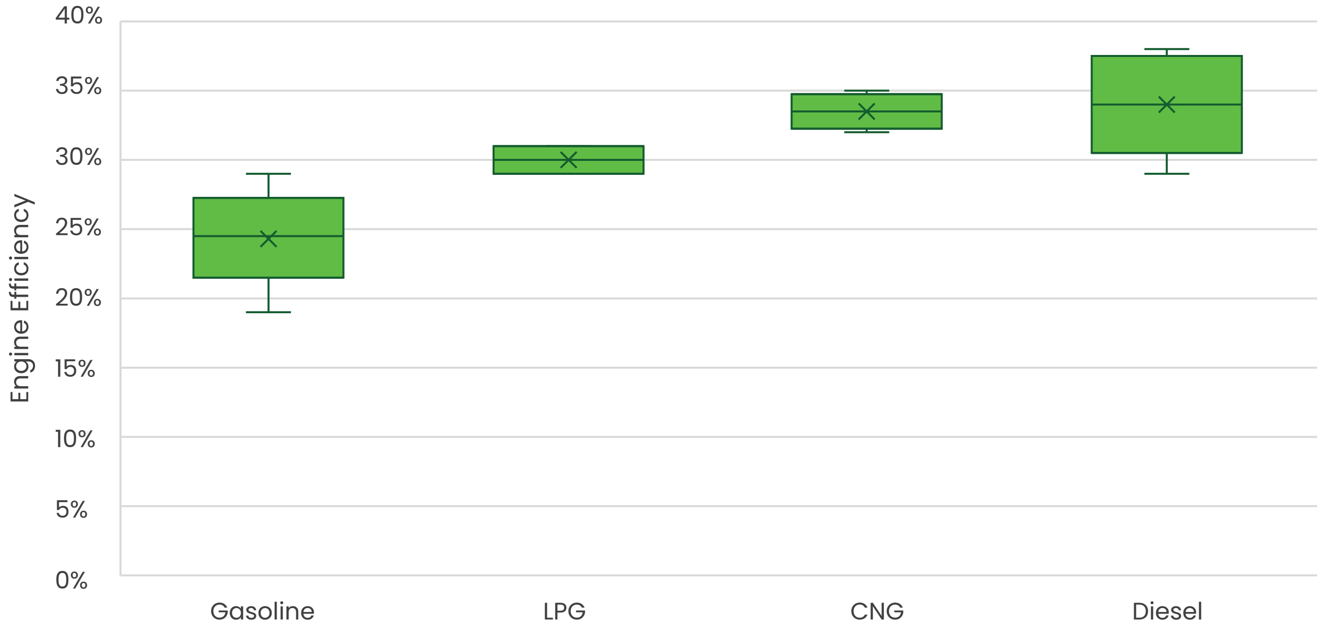

Figure 6. EPA MOVES3 off-road average in-use engine efficiency

Based on the equipment maximum power rating, average load factor, annual operating hours, and efficiency, the off-road sector fuel consumption can be calculated. Figure 7 breaks down the fuel consumption by subsectors of the off-road sector and by three horsepower (hp) bins, <50 hp, 50–175 hp, and >175 hp. The highest-powered equipment is responsible for most of the fuel consumption in the construction, agricultural, logging, and underground mining subsectors, while medium-powered equipment in the industrial subsector, and low-powered equipment in the lawn and garden and recreational subsectors. The vast majority of off-road sector fuel consumption is by the construction, industrial (here including commercial), agricultural, and lawn and garden subsectors.

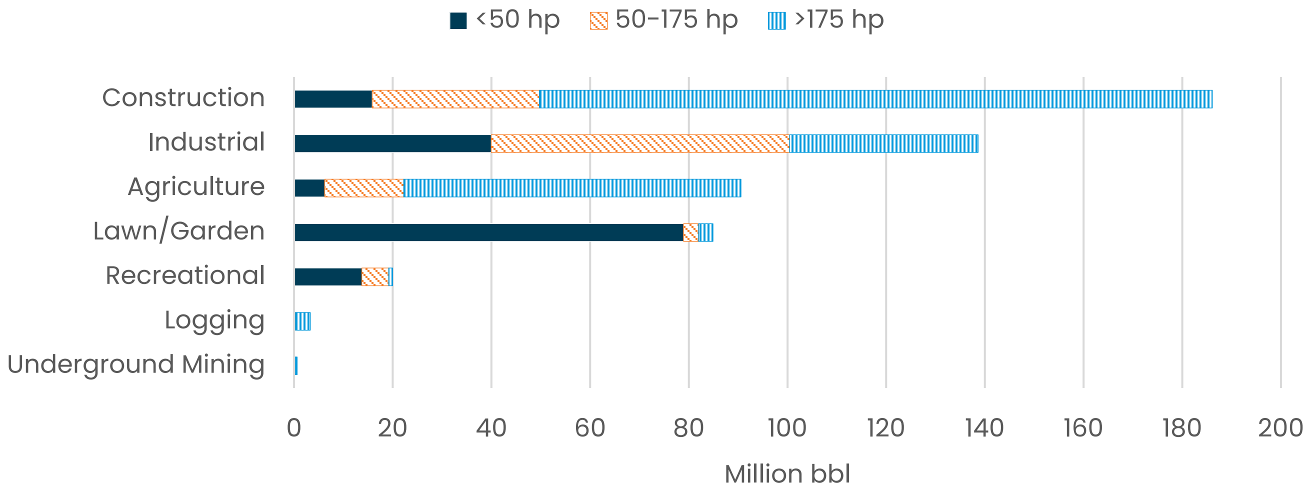

Figure 7. EPA MOVES3 off-road petroleum fuel consumption by sector and hp bin in 2022

2.2 Community Considerations

Community considerations in the off-road sector are concerns that highlight disparities in the distribution of environmental benefits and burdens, as well as the impact on low-income communities. Actions taken to lower emissions in the off-road sector should make every effort to mitigate and improve on these impacts. In addition, ensuring the creation, retention, and improved access to high-quality jobs and career pathways in low-income communities should be a priority. Several key aspects contribute to understanding these issues in the context of the off-road sector.

Air Pollution: Emissions from off-road equipment contribute to poor air quality, leading to adverse health effects for nearby residents. Communities residing near construction and industrial sites are disproportionately exposed to these pollutants. The emissions from material handling equipment, including nitrogen oxides (NO_x) and particulate matter (PM), contribute to air pollution in coastal areas.

Community and Safety Disruptions: The noise and vibrations generated by off-road equipment operations affect nearby communities. Construction and industrial activities contribute to noise, dust, and other community and safety concerns. Low-income communities near these operations may experience higher levels of stress and health issues due to constant disruptions.

Economic and Social-Environmental Disadvantages: Employment opportunities in the off-road industry are sometimes inequitably distributed. Disparities in regulatory compliance and enforcement can exacerbate environmental issues. Communities with less political influence and economic resources struggle to ensure that environmental regulations are enforced.

It is important to understand the above issues, including the historic context, so that they can be addressed or avoided in the future as the industry will undergo major changes as part of the move to a low-GHG and lower-emissions sector. Additional discussion of workforce issues is included later in the document.

3. EMISSIONS AND ACCOUNTING

3.1 Sector Emissions and Accounting

This report's baseline emissions data represents direct GHG emissions from the use phase of off-road equipment, often referred to as tailpipe emissions or tank-to-wheels (TTW) emissions. This data accounts for approximately 80%–90% of full life cycle or well-to-wheels (WTW) GHG emissions when operating on combustion of fossil fuels. However, the off-road sector also includes life cycle-based GHG emissions that come from direct and indirect sources associated with the production and distribution of fuels and electric power. These include GHG emissions from fuels/power used by onboard equipment, from equipment manufacturing and end-of-life disposition of equipment, and from construction, maintenance, and disposal of supporting infrastructure. Future versions of this report should account for these full life cycle emissions, as practicable, which are particularly important to consider when evaluating potential alternative fuels and energy. One example model for evaluating emissions on a life cycle basis is the Greenhouse gas, Regulated Emissions and Energy use in Technologies (GREET®) model, which the Department of Energy (DOE) developed to assess direct and indirect emissions across transportation sectors and adapted and customized for specific uses.

Many transportation emissions reduction solutions rely on electricity directly or indirectly through the production of hydrogen or other sustainable electro-fuels (e-fuels). Therefore, decarbonizing the electric grid by 2035, largely through new solar and wind energy development, will be an essential co-strategy to support transportation emissions reduction.

The carbon emissions from the full life cycle of a product or service—often referred to as "embodied carbon"—are significant and must be addressed in all strategies to decarbonize transportation and when considering alternative pathways. This is a core tenet of the overall Blueprint. Figure 1 identified transportation as contributing 33% of economy-wide emissions. To avoid double counting across sectors and modes within sectors, this figure only addresses direct emissions. Similarly, the baseline estimates of off-road emissions in Figure 8 represent the direct tailpipe GHG emissions. Although decreasing GHG emissions from other economic sectors (e.g., electric power generation, industry, commercial and residential, and agriculture) is the focus of other government-wide initiatives that complement the goal of decarbonizing the off-road sector, consideration of the overall life cycle emissions of fuel, energy, and equipment manufacturing and decommissioning is essential to avoid adopting policy solutions that inadvertently increase the sector's overall emissions rather than decreasing them.

3.1.1 ESTIMATED EMISSIONS

Combustion of fuel in internal combustion engines (ICEs) leads to emissions of GHGs and air pollutants. The MOVES model does not include electric or hydrogen-fueled off-road equipment, likely as its original development in the late 1990s was focused on TTW air pollutant emissions (and much of the underlying data has not been updated). Therefore, relying on its data will exclude the WTW emissions of that equipment. Recent PSR data shows about 12 million electric-powered equipment in the off-road fleet in 2023 that are not accounted for in the MOVES model because they do not have point source emissions.

EPA estimates tailpipe, or TTW, CO_2 emissions associated with off-road equipment use in the United States are estimated to total 205 million metric tons (MMT) CO_2 in 2022 (see Figure 8).

Construction-related equipment accounts for the largest proportion (77 MMT) with 75% of CO_2 emissions coming from high-hp engines. Lawn and garden equipment has by far the largest population but has a more modest contribution to CO_2 emissions (28 MMT), due to the sector primarily consisting of low-hp equipment that may have fewer annual hours of operation than much of the higher-hp equipment.

The CO_2 emissions of the off-road sector are concentrated in a relatively small number of equipment types, with the 20 highest emitters accounting for 80% of emissions (Figure 9). Agricultural tractors are the largest CO_2 source (33 MMT) followed by forklifts (22 MMT). Several major types of construction equipment (rubber tire loaders, excavators, crawler tractors/dozers, off-highway trucks, and tractors/loaders/backhoes) account for a significant portion of the sector's emissions (34 MMT).

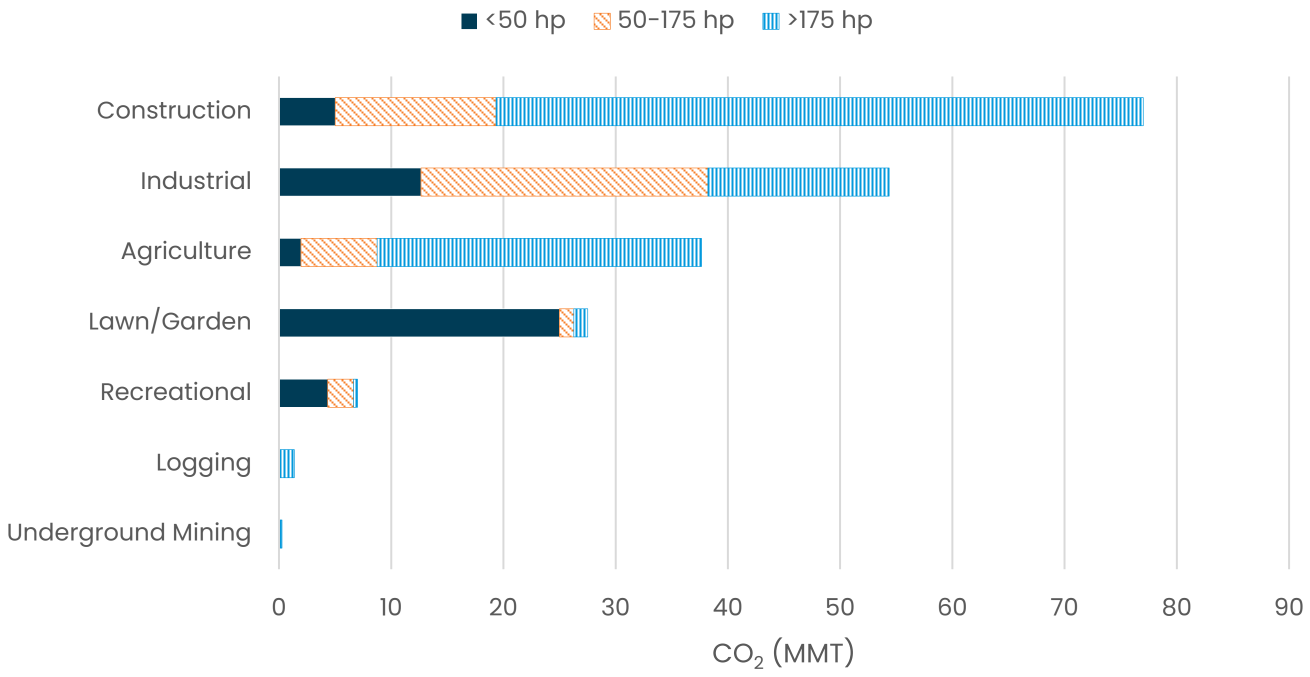

Figure 8. EPA MOVES3 off-road CO_2 emissions by sector and hp bin in 2022

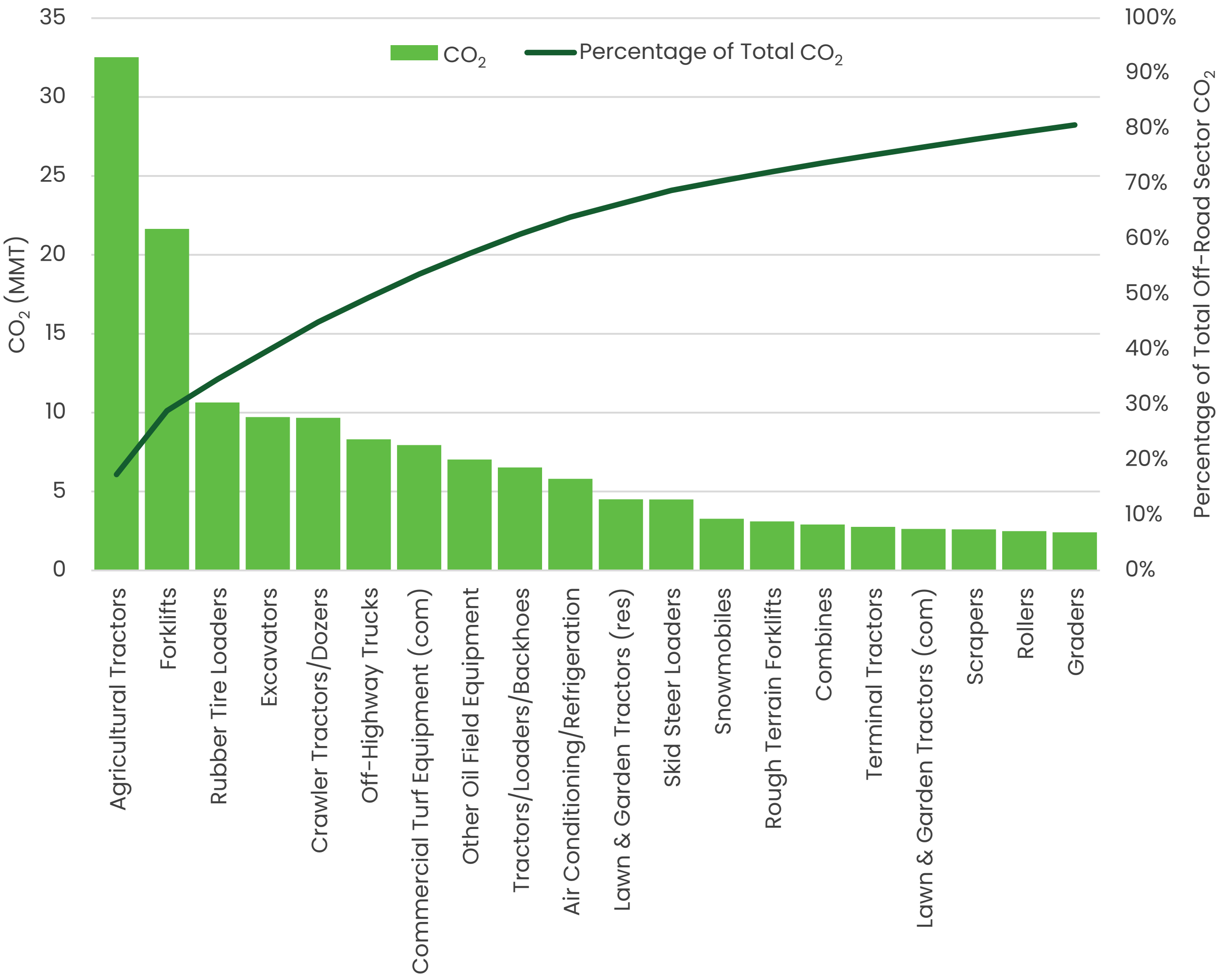

Figure 9. EPA MOVES3 off-road CO_2 emissions of "Top 20" equipment with percentage contribution to total off-road sector CO_2 emissions

3.1.2 ACCOUNTING FOR EMISSIONS (METHODS AND LIMITATIONS)

This report starts with 2019 TTW emissions for the initial GHG estimates of the off-road sector as they relate to the other U.S. transportation sectors, reported at 10% of total U.S. GHG emissions. These emissions correspond to the classification used by EPA in their Inventory of U.S. Greenhouse Gas Emissions and Sinks (Figure 1).[7] Upstream emissions, such as electricity production or equipment manufacturing, are accounted for in different sectors in the EPA GHG Emissions Inventory. To be consistent with the EPA methodology, we do not include life cycle emissions for our initial estimates for the off-road sector GHG emissions in this report. For the 2019 emissions, life cycle emissions track very closely with TTW emissions.

EPA's MOVES non-road model computes emission inventories for 85 types of off-road equipment in 11 subsectors (MOVES includes three additional marine vessel types that were not included in this analysis because they are covered in the Action

Plan for Maritime Energy and Emissions Innovation).

The MOVES model uses the following equation to calculate exhaust emissions from non-road engines.

$$Emissions = (Pop) \times (Power) \times (LF) \times (A) \times (EF)$$

Pop = Engine Population

Power = Average Rated Power (hp)

LF = Load Factor (average fraction of rated power utilized)

A = Activity (hr/yr)

EF = Emission Factor (g/hp-hr)

Emission factors for CO_2 are calculated based on BSFC.

The MOVES model uses in-use adjusted BSFC to compute CO_2 emissions directly, as shown in the equation below, accounting for unburned hydrocarbon emissions:

$$CO_2 \text{ EF (g/hp-hr)} = (BSFC * 453.6 - HC) * 0.87 * (44/12)$$

BSFC is the in-use adjusted BSFC in lb/hp-hr

453.6 is the conversion factor from pounds to grams

HC is the in-use adjusted hydrocarbon emissions in g/hp-hr

0.87 is the carbon mass fraction of diesel

44/12 is the ratio of CO_2 mass to carbon mass

3.2 Data Refinement – Known Discrepancies (Mega-Trends)

As discussed, the EPA MOVES model has multiple areas for discrepancies when accounting for the population, activity, energy consumption, and GHG emissions of the off-road sector.

3.2.1 POPULATION

Over the last couple of decades, there's been significant increases in electric-powered equipment in the off-road sector, as much as 12 million pieces of electric equipment based on recent PSR data, that are not accounted for in MOVES. To perform an accurate assessment of the off-road sector's life cycle WTW GHG emissions, the population of electric- and hydrogen-powered equipment will need to be accounted for. In addition, the location of operation of this equipment will also be important to account for variations in the carbon intensity (CI) of the electrical grid and hydrogen production.

The sales of utility terrain vehicles (UTVs) have increased significantly over the past couple of decades. UTVs can be used for recreation, but more often are being used for work: farming, facility maintenance, law enforcement, etc. They are larger than all-terrain vehicles (ATVs) and consume more fuel per hour of operation. This will likely increase the gasoline consumption and GHG emissions compared to current MOVES estimations.

It has become more common in the last few decades for medium-sized property owners and hobbyists to own small- to medium-sized tractors, skid steer loaders, and other off-road equipment that was historically used by construction firms and on farms. This equipment is powered predominantly by diesel engines and will likely increase the diesel fuel consumption and GHG emissions estimates.

3.2.2 ACTIVITY

It is possible that the number of hours of annual operation of different equipment types has changed in the past couple of decades. However, when looking at alternative powertrains, it is essential to know how many hours of operation are performed in each workday, which the MOVES model does not have.

It is also possible that the average load factor of equipment operations has changed, and will likely change with hybridization, battery electrification, and adoption of hydrogen equipment. It is necessary to conduct new surveys to get a clear picture of equipment operational activity.

3.2.3 FUEL CONSUMPTION

Over the past couple of decades, engine efficiency has improved, decreasing fuel consumption per equipment-hour of operation. However, the equipment population has grown, so an accurate accounting of off-road fuel consumption requires up-to-date fleet population data. Electricity is another fuel that is used to power off-road equipment and needs to be accounted for, especially if a significant portion of the off-road fleet is expected to convert from ICEs to battery power.

3.2.4 EMISSIONS

It's important to baseline and track criteria pollutant emissions and GHG emissions from the off-road fleet. Once there is an accurate accounting of fuel and energy consumption (and its type), a full understanding of the off-road sector's criteria and GHG emissions can be performed on a TTW (tailpipe) as well as life cycle WTW basis. Once there is a better understanding of the specifications (e.g., battery, fuel cell, and hydrogen storage tank size), a better life cycle depiction of emissions can be made on a cradle-to-grave basis, including manufacturing and end of life.

ACCOUNTING FOR LIFE CYCLE EMISSIONS

The data reported in this document is direct emissions from the use phase of equipment and transportation systems (i.e., tailpipe emissions). However, the strategies and recommendations in this report consider full life cycle GHG emissions, including the production and end-of-life phases of equipment and fuels/energy sources. These life cycle emissions cover GHG emissions from fuel production and processing; equipment manufacturing and disposal; as well as construction, maintenance, and disposal of transportation infrastructure. Inclusion of these life cycle emissions is important as the U.S. transportation sector evolves towards new powertrain systems with new fuels/energy sources. DOE has a long history of using life cycle analysis (LCA) to assess energy technologies and inform how we can advance these systems and reduce their environmental footprint. For the transportation sector, the GREET model is a suite of publicly available, best-in-class models used by the federal government and other stakeholders to assess the energy and environmental impacts of vehicles, fuels, chemicals, and materials across their life cycles. While the GREET model originated with a focus on transportation technologies, GREET currently covers the full life cycle, including manufacturing, industrial, and power sector impacts.

Reducing and ultimately eliminating life cycle emissions from these sectors is critical to achieving a fully sustainable transportation future and economy-wide emissions reductions. For example, decarbonizing the electric power sector is identified as a key long-term strategy of the United States. Although outside the scope of this report, this strategy would greatly reduce the emissions associated with energy production that is used to power electric vehicles (EVs) and transportation systems.

4. OFF-ROAD EMISSIONS REDUCTION TECHNICAL CONSIDERATIONS

The off-road vehicle sector is comprised of several types of equipment which are generally categorized as: agricultural, construction, industrial, mining, forestry, lawn and garden, powersport, and stationary power (commercial in MOVES). Within those categories, according to EPA MOVES3, there are at least 88 unique equipment types (e.g., tractors, harvesters, wheel loaders, excavators, fork trucks, mowers, ATVs, refrigerators) many of which run a gambit of installed hp. Further, daily usage varies heavily by application. A small lawnmower (5 hp) may only be used for an hour per week whereas a large mining haul truck (up to 4,000 hp) will typically run for 24 hours per day, 7 days per week. As of 2022, the vehicles in this sector were primarily compression or spark ignition engines with some electrification of the industrial sector. The large disparity in daily energy needs across all equipment types combined with unique operations drives a need for a variety of solutions.

Note: this sector, unlike others, must also consider stationary equipment associated with activities such as mining even though they are not "transportation." Emission reduction solutions considered herein apply equally to such stationary equipment as for mobile sources.

One trait shared amongst most off-road vehicles is the high utilization of installed power. Compared to on-road vehicles, which typically have short excursions to high power operation, off-road vehicles may spend entire shifts operating above 75% of rated power. In part, this is due to inefficient hydraulic power systems (for digging or loading), but also often necessitated by the work task (plowing a field or hauling ore up a grade). This results in proportionally higher GHG emissions relative to rated power and the need for high-energy-density alternative fuels. These vehicles and equipment are normally operated off-road (except to travel between worksites), so fuel (energy) must be brought to them.

Another common attribute for the off-road sector is the use of compression-ignition diesel engines because of their durability, low-speed torque, and fuel efficiency. Engine efficiency can be increased through combustion system improvements, integration with advanced powertrains (including electrification), waste heat recovery, efficient air handling and accessories, and improved idle efficiency. Many of these technology areas have been commercialized for engines used in on-road vehicles and can also be applied to common off-road engines, particularly to engines with less than 15 L displacement. However, experts state it is critical that engine design and specification be performed with knowledge of the expected operational conditions.

Off-road equipment is often reliant on hydraulic fluid power systems. Because of shock tolerance, fluid power systems are generally the actuation source of choice in challenging and harsh environments since pressure relief valves prevent system damage. These hydraulic systems use throttling for control, which results in reduced efficiency.

Vehicle efficiency should be viewed from the whole-system level, rather than at the level of the individual components. A deeper understanding of real-world operation is needed to further optimize not only the engine and fluid power components but also the overall system. At the system level, there are also opportunities for improved energy efficiency through automation and electrification. Vehicle automation may be able to standardize operation, leading to more consistent and predictable fuel usage. Electro-hydraulic architectures combine the benefits of electric motors and hydraulics, improving energy efficiency by eliminating throttling losses, while maintaining the power density of hydraulic actuation and managing the system cost of motors and batteries. For vehicles that make many repetitive movements, there are opportunities for energy recovery. Onboard energy storage and hybridization can help smooth transients in engine operation and allow for engine downsizing, both of which increase the vehicle efficiency. Depending on vehicle usage and availability of charging infrastructure, full battery electric vehicles may be an appropriate solution to increased efficiency.

Many experts say off-road vehicle energy efficiency could be increased by at least 15% with improvements to engines, hydraulic systems, and more efficient vehicle operation. Technologies that lead to diesel engine efficiency improvement can typically be adopted by all sectors in which the diesel engine is used, including on- and off-road sectors. However, many of these efficiency improvements have been developed for over-the-road vehicles that have very different operating profiles than off-road vehicles. Therefore, opportunities may exist that lead to advances that are specific to applications within the off-road sector.

Typical customers for off-road equipment, especially fluid-powered equipment, require a quick payback and are hesitant to adopt technologies that might adversely affect reliability or equipment service life. Industry stakeholders consistently feel that technical progress in off-road vehicles and engines should be measurable and quantifiable and should account for operational requirements for vehicle performance. System-level enhancements, such as more precise vehicle control and automation, have the potential to reduce fuel consumption but need to be tailored to specific applications, given the breadth of use cases in the industrial off-road vehicle sector.

Unlike most highway vehicles, off-road vehicles typically provide the conveyance function of mobile equipment, with the engine's power used both to propel the vehicles and to perform auxiliary work, such as digging (e.g., excavators) or harvesting (e.g., combines). Auxiliary work is often performed using hydraulic actuation, which can supply high specific power density and tolerate shock and harsh environments while being safer and more precise than power takeoff directly from the engine. Because there are many differences in operational conditions, the engines used in off-road vehicles vary greatly in displacement, duty cycles, and power ratings. For example, agricultural tractors operating on even terrain can have a very steady load, whereas the duty cycle for an excavator is extremely transient. Therefore, the power rating of off-road vehicles varies tremendously, over orders of magnitude. For the most powerful of these vehicles, the engine is generally designed for its peak load, which may lead to frequent operation at lower power in a relatively inefficient operating regime. This diversity of equipment size and function presents an overall barrier to optimizing efficiency.

4.1 Sustainable Off-Road Equipment Fuels and Energy Sources

Traditionally, petroleum-derived diesel and gasoline have been the primary fuels used for off-road vehicles, with CNG and LPG also being utilized for a smaller subset of equipment. These fuels are responsible for substantial emissions into the air. GHG agents such as CO_2, CH_4, and N_2O, as well as criteria air pollutants such as PM, oxides of nitrogen (NO_x), and sulfur oxides (SO_x) are emitted primarily during the combustion of these fuels, but also during their production.

To move towards a sustainable future, the off-road industry must increase the availability and uptake of sustainable fuels and ensure that vehicles and equipment have the technology to use them. These fuels, derived from renewable carbon resources like biomass, fats, oils, and greases (FOGs), waste streams, and captured CO_2, offer a transformative opportunity. The United States aims to completely eliminate GHG emissions from the off-road sector by 2050, a critical step towards meeting global climate goals. However, the mass or volume of sustainable fuels this goal will require will depend on the fuel characteristics, such as density and lower heating value (LHV) (Figure 10). If the density and heating value is low, it will require more fuel by volume to achieve the same quantity of energy value as a conventional fuel. The net effect of this would be an impact to the total cost of ownership, a key metric for the off-road transportation sector.

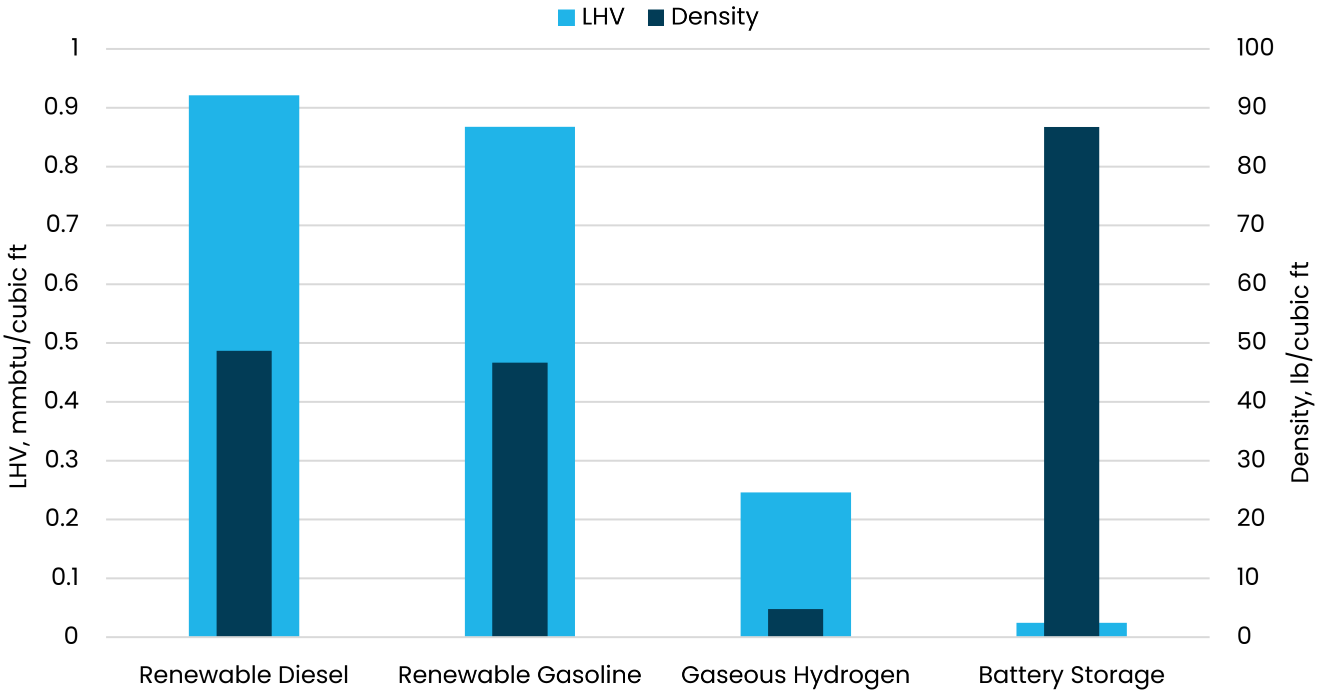

Figure 10. LHV and density of fuels and energy sources for off-road equipment

Note: For electricity, volumetric energy density or mass refers to energy content per battery volume.

The total life cycle GHG emissions from each fuel production pathway determines its WTW GHG emissions. It is important that sustainable, low-CI versions of these fuels be domestically available as the industry moves to equipment that can run on new fuel types.

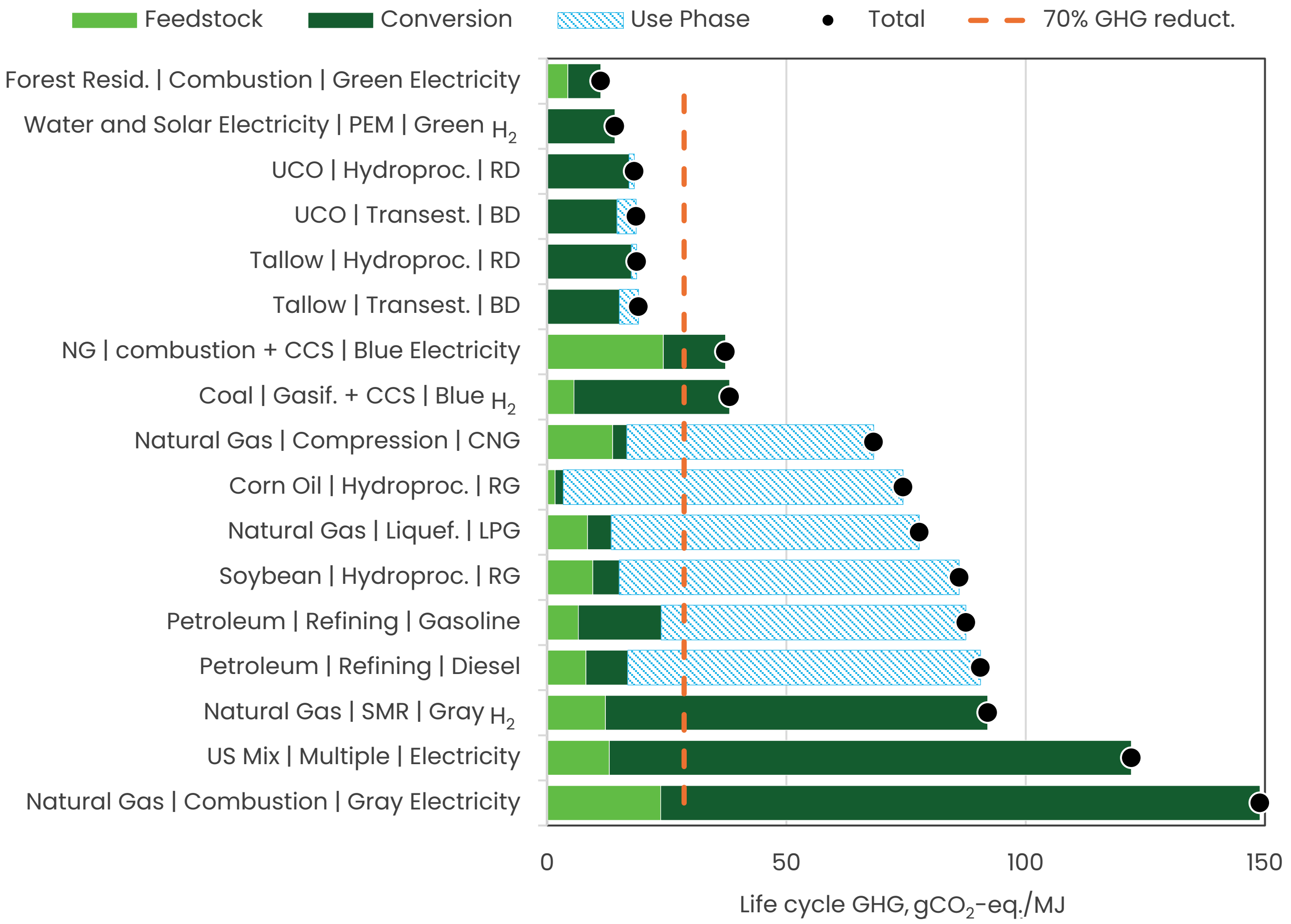

Figure 11. Life cycle GHG emissions of fuel options for off-road equipment.[a] *The 70% GHG reduction line is relative to conventional diesel. Results reflect consistent system boundaries, calculation approaches, and background data. The life cycle analysis (LCA) results will vary depending on case-specific details and differences in calculation approaches specific to the intended use. These results are representative and do not reflect determinations for fuel credits or other regulatory purposes.*

4.1.1 SUSTAINABLE ENERGY FOR OFF-ROAD EQUIPMENT

As the use of alternative fuels increases, and the policy and regulatory framework are developed, it is important to know the definition of “sustainable off-road equipment fuels.” For the purposes of this report, fuels are sustainable off-road fuels if it meets requirements for: (1) environmental and socio-economic sustainability and (2) significantly reduced GHG intensity relative to its petroleum-based counterpart. Examples of sustainable off-road fuels include renewable diesel (RD) and renewable gasoline (RG), which are “near drop-in” liquid fuels, alcohols (e.g., ethanol and methanol), biodiesel (BD), as well as renewable natural gas (RNG) and renewable propane (RP), which are gasses at standard temperature and pressure. It is important to note

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[a] Abbreviations: SMR = steam methane reforming; LNG = liquefied natural gas; UCO = used cooking oil; Hydroproc. = hydroprocessing; Gasif. = gasification; Liquef. = liquefaction; MeOH = methanol; BD = biodiesel; RD = renewable diesel; Resid = residue.

that a substantial percentage of off-road vehicles and equipment that utilize gaseous fuels such as CNG and LPG have operating requirements that will be supported by a transition to battery or hydrogen solutions in future years. Technologies are being developed to produce RNG and RP, but the majority of future sustainable off-road fuels demand will be for SLF like RD, RG, and BD. As important as sustainable off-road fuels will be to the U.S. off-road sector, the use of electrification and fuel cell technologies where possible will also be very important for certain vehicles and equipment. The following simply highlights the variety of alternative fuels available.

Electricity

Electrifying off-road vehicles and equipment can take the form of battery electric (Battery Electric Equipment) or hybridization where batteries support or supplement ICE power needs. For hybrid equipment and vehicles, batteries and hybridized ICEs work together to optimize the efficiency over a traditional ICE propulsion system. Various off-road equipment such as excavators, bulldozers, and cranes can be electrified; there are many examples already in practice. In the agricultural space, smaller tractors, tillers, planters, harvesters, and irrigation by groundwater can use electricity to replace diesel. In forestry applications, several types of equipment such as chainsaws and young tree harvesters can be (and some already are) electrified. In the lawn and garden sector, many electric options for equipment such as lawn mowers, bush trimmers, leaf blowers, snow blowers, and lawn aerators are already popular. In the recreational space, examples of off-highway motorcycles and ATVs are already on the market, albeit with reduced range.

Typical operating voltages are small for handheld equipment but may be over 1000V for large equipment. There is no standardized plug and, for larger equipment, the charging infrastructure in rural and remote areas is dramatically inadequate. Handheld equipment has become dominated by battery electric equipment (BEE), whereas large mobile equipment is transitioning. Conversion from traditional shaft power (from ICE) to BEE has energy inefficiencies in some cases. Battery chemistries and formats were largely developed for light-duty motor vehicles and have struggled when adapted directly to off-road equipment.

In some cases, significant GHG reductions have been estimated, but such GHG reductions must be evaluated on a case-by-case basis. For example, when annual usage is low, but daily usage is high—as is the case for farm equipment—the embodied GHG in the battery may be difficult to offset, especially when grid GHG is high.

Hydrogen

Hydrogen is the simplest and most abundant element, and clean hydrogen can be produced using diverse domestic resources. Pure hydrogen can be combusted to produce thermal energy in a modified combustion engine, or it can produce electrical energy in a fuel cell by combining pure hydrogen with pure oxygen.[8] Fuel cells can create power from hydrogen without criteria emissions, while at the same time, hydrogen ICEs are not as sensitive to impurities and will likely be part of the emissions reduction solution. In the off-road sector today, hydrogen is used primarily to power cranes and forklifts. It can also be used in drills and loaders for mining purposes. In the agricultural sector, hydrogen can be used to power tractors, tillers, planters, and harvesters.

A decarbonized off-road sector needs to shift away from fossil-based hydrogen and focus on clean hydrogen. According to H2Hubs, clean hydrogen is produced with equal to or less than 2 kg CO_2e per kg of hydrogen.[9] Currently, most of the hydrogen produced worldwide (approximately 70 million tons annually) comes from fossil-fuel sources such as natural gas (48%), oil (30%), and coal (18%).[10] When electricity from nuclear, hydropower, solar, or wind sources is used to produce hydrogen via water electrolysis, it is referred to as clean hydrogen.

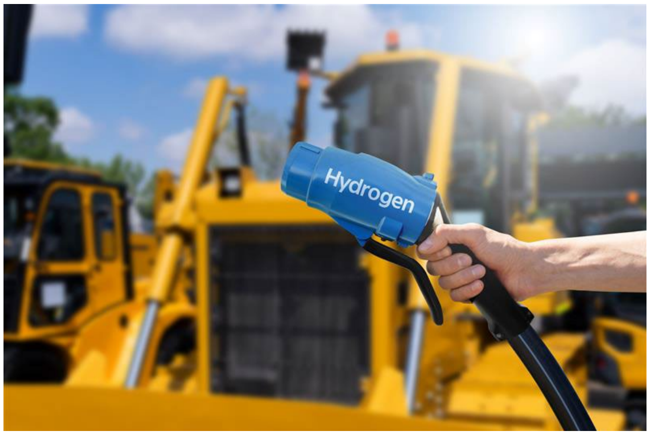
Hydrogen proton-exchange membrane fuel cells use hydrogen to produce electricity. When used onboard, the needs are the same as BEE, with the additional requirement for air flow cooling. Given the cost and economies of scale, and limited onboard space for hydrogen storage, fuel cells have seen limited penetration in mobile equipment. However, where implemented, fuel cells have proven to be highly efficient and economically viable. Fuel cells have seen significant use in material handling, however mostly as a replacement for battery-electric propulsion to eliminate the re-charging downtime.

Off-road applications in agriculture and construction that typically operate in dirty or dusty environments are more challenging. Fuel cells operate at lower temperatures than diesel engines, making thermal management difficult. Additionally, the more stringent cooling requirements for the fuel cell system require additional heat rejection, and since these machines do not travel at highway speeds, they do not benefit from ram-air cooling. This requires larger radiators and cooling fans, which are difficult to package and decrease the system efficiency. Onboard hydrogen storage concerns where liquid fuels currently dominate present a packaging challenge as well.[11, 12]

One application that has shown interest is off-highway mining trucks. The packaging of larger cooling components and hydrogen storage, while difficult, appears to be possible. Fuel cells for remote power generation has also been proposed to rapidly charge BEE through a centralized storage and charging facility, which reduces the need for high-power electric transmission.

Powertrains based on both hydrogen fuel cells and hydrogen-fueled internal combustion engines (H_2ICEs) present workable net-zero carbon emission solutions. The potential for more rapid deployment of H_2ICEs can help overcome a significant barrier to market penetration of fuel cell powertrains: lack of a fueling infrastructure.[13]

Hydrogen internal combustion can be a way to introduce clean hydrogen without requiring major changes to the equipment architecture. Major original equipment manufacturers (OEMs) have made public announcements regarding their plans to offer H_2ICEs in the near future. The majority of the existing powertrains can be used with hydrogen as an alternative fuel. Several projects in the Vehicle Technologies Office have demonstrated the viability of the H_2ICE for excavators and other construction equipment. Tolerance to vibration, dirty environments, and less-demanding heat rejection makes H_2ICEs an attractive alternative for off-road equipment. However, onboard hydrogen storage concerns as well as materials compatibility remain areas of research interest.



Sustainable Off-Road Equipment Fuels

Sustainable off-road equipment fuels are “near drop-in” liquid or gaseous fuels produced from converting biomass or other waste sources[14] (e.g., woody materials, crop waste, municipal solid waste, swine manure, sewage sludge, purpose-grown energy crops, and biogenic CO_2). RD, RG, alcohols, BD, RNG, and RP are examples of sustainable off-road equipment fuels. To qualify as sustainable fuels under various state and federal programs, sustainable off-road equipment fuels must demonstrate a minimum 50%

reduction in GHG emissions relative to their petroleum-derived counterpart.

In addition to a lower CI, sustainable off-road equipment fuels can be lower in sulfur and nitrogen (N_2) depending on the feedstock attributes and processing conditions. Utilizing low-CI feedstocks, efficient conversion processes, clean sources of electricity and hydrogen, carbon sequestration, and other GHG-reduction measures, sustainable off-road equipment fuels can exhibit significantly reduced emissions and can be net-negative in some cases.

Although sustainable off-road equipment fuels, especially RD and RG, are often considered a direct replacement for fossil fuels (diesel and gasoline, respectively), their actual chemical composition differs slightly from their conventional counterparts. Testing is performed to ensure that fuel properties meet the specification outlined in the appropriate ASTM standard. For example, RD that meets the specification for ASTM D975 is able to be used as a 100% drop-in fuel. Undergoing this type of testing, certification, and related safeguards ensures that these fuels are compatible with and optimized for the highly refined engines and equipment in which they will be used.

RD and RG are already gaining momentum in the sustainable fuel industry. In 2023, the RD market was valued at $12.7 billion, projected to increase to $50 billion by 2044.[15] Meanwhile, the renewable gasoline market was projected to reach approximately $3.1 billion by 2026.[16] The market for renewable natural gas (RNG) is projected to reach $4 billion in 2030.[17] However, many of these fuels will also be in demand by other transportation and non-transportation sectors, which adds another challenge to decarbonizing the off-road sector.

Additional information on sustainable off-road equipment fuels can be found in the Biofuels Appendix.

Electrofuels (E-Fuels)

E-fuels refer to a group of synthetic fuels that provide significant CO_2 reduction opportunities if the source of electricity is renewable because the primary feedstock for the e-fuels—CO_2—is captured from the atmosphere or industrial emissions. The carbon atoms in these CO_2 molecules are combined with clean hydrogen produced, for example, by electrolyzing water with renewable electricity generated from wind, solar, hydro, or nuclear sources. Specific fuels within the e-fuels group, such as e-diesel and e-gasoline, can be readily used in the off-road sector.

The major benefit of e-fuel is its potential to reduce GHG emissions. However, it needs to be ensured that the source of electricity is decarbonized and not displacing renewable electricity already being used for other purposes, such as EV charging. Another benefit of e-fuels is that they have the potential to be a 100% drop-in fuel. As the grid decarbonizes in the United States, e-fuels are becoming increasingly of interest. However, e-fuels require a significant additional availability of decarbonized electricity, due to the low power-to-fuel conversion efficiency.

Table 4. Opportunities and challenges of sustainable liquid fuels and energy carriers.

Fuel	Pros	Cons
Sustainable Liquid Fuels	• Can be a near drop-in petroleum fuel replacement, blendable, and can use much of today's infrastructure • High-energy-density (Figure 10 above) • Pathways to negative CI on full life cycle basis (Figure 11 above)	• Wide variation in life cycle GHG emissions; some biofuels are more GHG-intensive than traditional fuels on a WTW basis • Criteria air pollutants remain • Feedstock resource limitations exist and will need significant increase in feedstock production to the full U.S. potential[18] • End-use competition (aviation, marine, rail, etc.)
Hydrogen	• Large potential to reduce GHG • No criteria air pollutant emissions (with fuel cells) • Large ongoing U.S. investment (Regional Clean Hydrogen Hubs Program[19])	• Large market competition for clean hydrogen (sustainable fuels production for all modes of transportation, chemical production, traditional petroleum refining) • Difficult to store both on- and off-board vessels • Low energy density of gaseous hydrogen
Electricity	• Large potential to reduce GHG • No local criteria air pollutant emissions • U.S. commitment to 100% clean electricity by 2035[20]	• Charging infrastructure requirements • Energy density and battery efficiencies need to be increased • Route predictability and length requirements
E-fuels	• Large potential to reduce GHG by using captured carbon from the atmosphere or carbon that would have been emitted in industrial processes otherwise • Can be a near drop-in petroleum fuel replacement, blendable, and can use much of today's infrastructure • U.S. commitment to 100% clean electricity by 2035, which will help in producing e-fuels with clean electricity[21]	• Huge requirement of clean electricity • Cost of carbon capture • Criteria air pollutants emission remain

4.2 Equipment Categories Covered

4.2.1 AGRICULTURAL

Agricultural equipment is chiefly used for farming operations and has two main GHG sources: tractors and combine harvesters. Farm tractors span a large range of power consumption, from lower-power tractors (25 hp) used for occasional chore work to high-power tractors (over 500 hp) used for long durations of field work. Tractors usually provide power take-off and hydraulic functions for towed implements. Similarly, harvesters operate for long periods of time at high loads, but they may only be used for a few months of the year. Finally, some agricultural equipment is also stationary and provides power for niche needs, such as irrigation. Farms generally lack the infrastructure to support high-power-demand charging for EVs and are mostly remote in location. They produce many of the crops used for biofuel production and are located near production facilities, which creates easy access to biofuels. Smaller farms (such as vineyards), which do not require high energy consumption, have already begun to invest in BEE technology. One OEM is actively developing hydrogen fuel-cell technology in a medium-sized farm tractor.

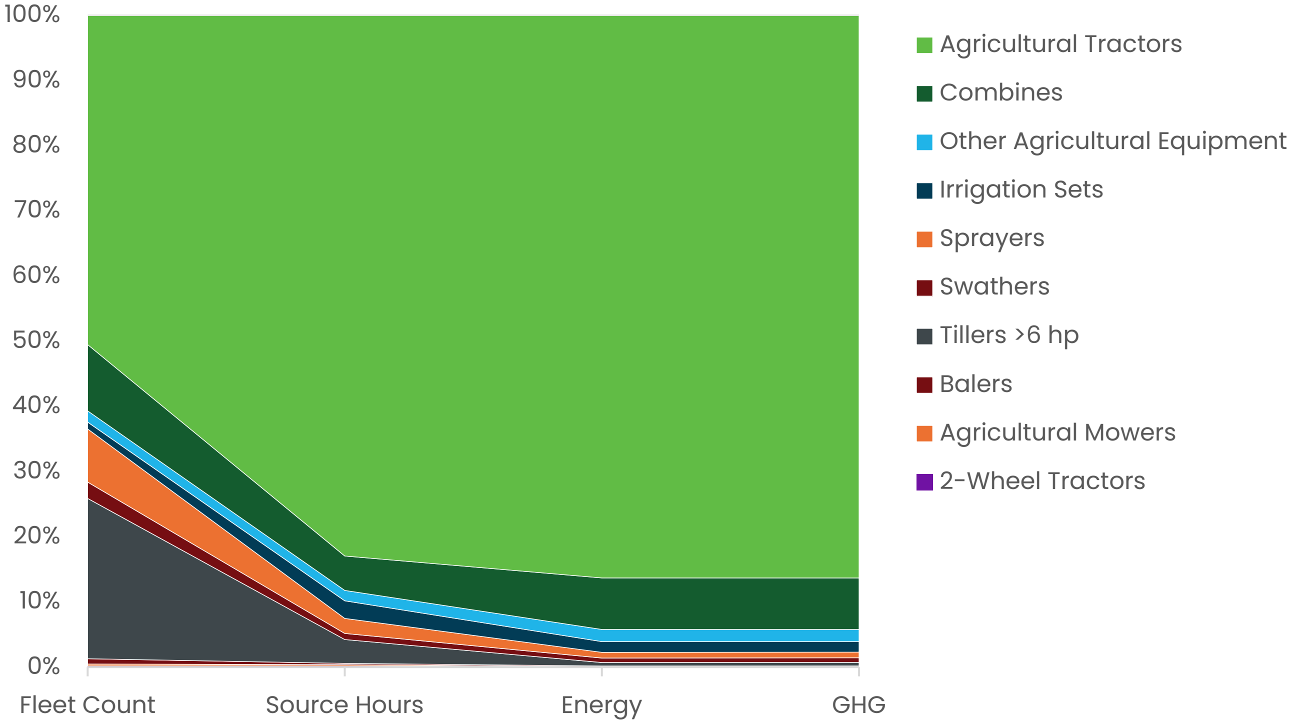


Figure 12. Agricultural sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions

4.2.2 CONSTRUCTION

Construction vehicles are used to dig, haul, and lift materials for the construction or demolition industries. They range in power from 50 to 500 hp and mostly provide power to a large hydraulic pump, which is then used to operate the machine. Some large bulldozers may be direct-driven through conventional transmissions. Examples include skid-steer loaders, backhoes, bulldozers, cranes, excavators, dump trucks, loaders, pavers, trenchers, rollers, and compactors. There is some stationary and handheld equipment as well.

Construction equipment is often used for the digging, lifting, spreading, and dumping of loose materials such as dirt or stone. It may also be used for materials handling in off-road environments where surfaces are usually unimproved. Other machines may be more specialized and have one specific task, such as precision grading of the soil or craning heavy objects high onto buildings. Crucially, construction equipment is used to raise or build infrastructure, including the green power sources of the future.

Construction sites may lack infrastructure for electric charging, but some notable examples of battery-powered equipment are already available (skid-steer loaders and tracked excavators). There are also hydrogen fuel cell and tethered electric examples in development. Several OEMs are also developing hydrogen combustion engines. Daily usage of equipment varies significantly, but increased downtimes are not acceptable. Some engines are already compatible with SLFs. To accelerate electrification of this sector, there is growing interest in mobile charging, which may be centrally fueled from net-zero GHG sources such as hydrogen or SLFs.

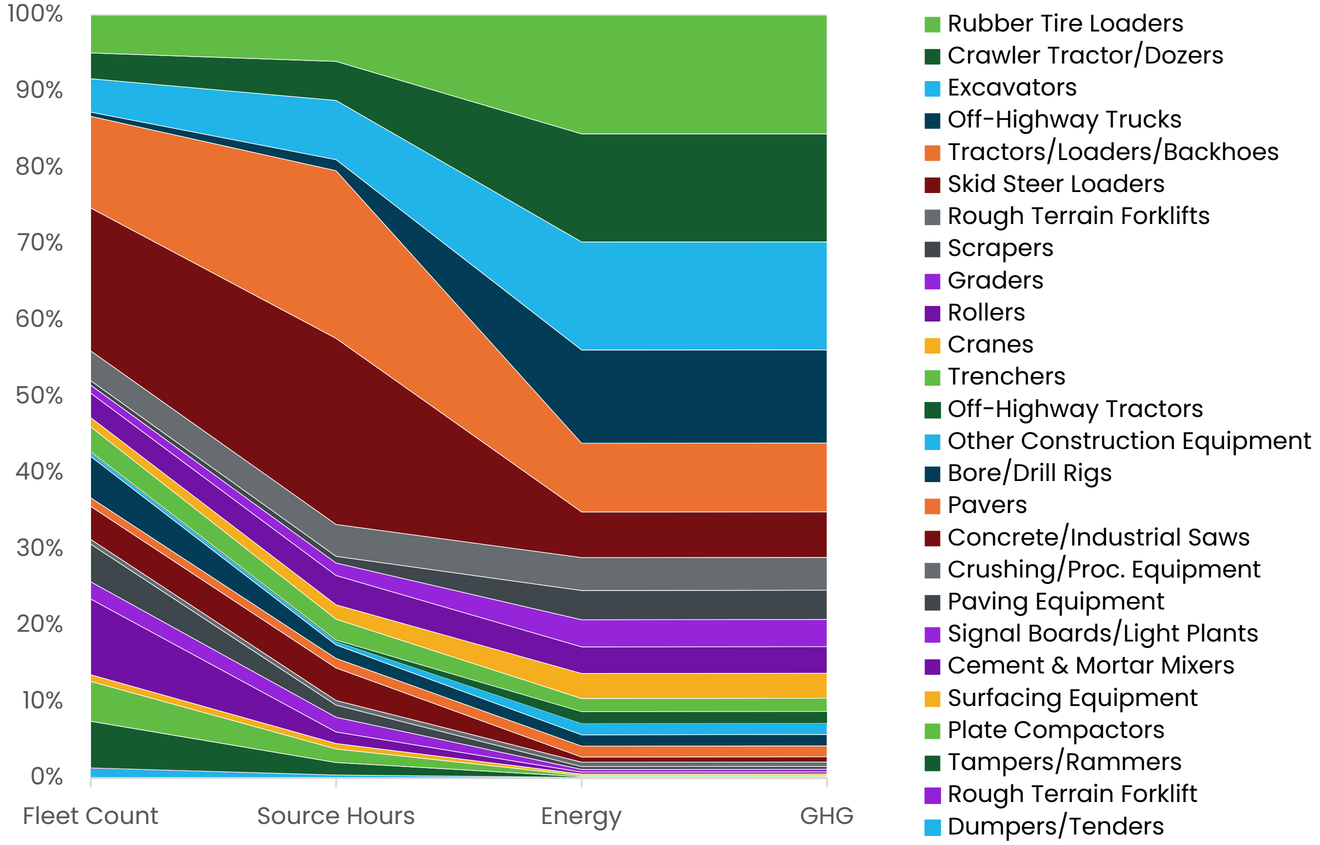


Figure 13. Construction sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions.

4.2.3 INDUSTRIAL

Industrial equipment is used for a variety of material handling purposes and include forklift trucks, terminal tractors, areal lifts, and cranes. Forklift trucks are used primarily to move palletized items inside of warehouses or on otherwise smooth surfaces. They are used for loading/unloading semi-trucks and containers as well as inventory management. Terminal tractors are used at ports and warehouses to move trailers and cargo container chassis short distances. They are generally not operated over-the-road. Air-conditioned refrigeration equipment is used for large cold-storage warehouses and mobile semi-trailers. Industrial equipment is typically less than 175 hp, except terminal tractors, which may be up to 300 hp.

There are already many examples of battery electric forklift trucks and several terminal tractors. Over 70,000 hydrogen fuel cell forklift trucks are in service in the United States. Given that infrastructure of industrial areas tends to be well-developed, this is expected to continue and grow the demand for hydrogen and BEE.

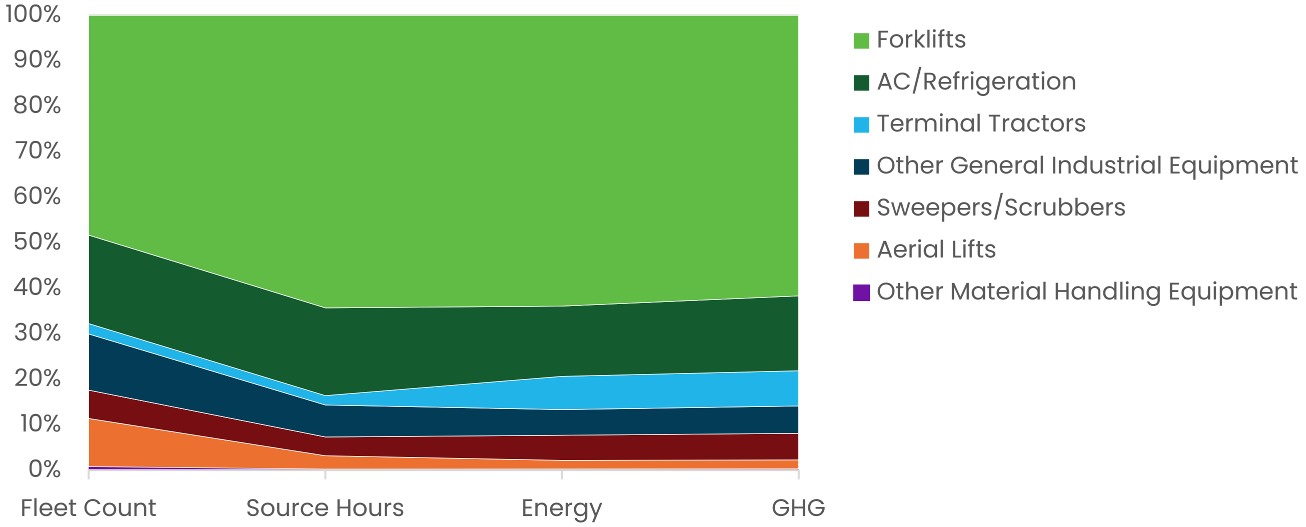


Figure 14. Industrial sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions

4.2.4 MINING

Mining vehicles are used to extract minerals from the ground, sometimes in underground operations. They are also used to haul extracted material to processing centers. These are typically very large vehicles (like haul trucks and excavators) with greater than 1,000-hp diesel engines. Mining also includes drill rigs and some stationary equipment for pumping and ventilation. They operate in extremely remote locations, often for 24 hours per day.

Some underground operators have communicated that electrification is feasible and becoming economical because of the reduced ventilation costs and power requirements compared to operating diesel engines underground. Other open-pit operators have begun exploring catenary/hybrid haul trucks. One company is even retrofitting haul trucks with hydrogen fuel cells. Although mines are usually in remote locations, capital to improve infrastructure is available due to the power needs of processing equipment and the value of extracted minerals.

4.2.5 FORESTRY

Forestry vehicles are highly specialized equipment used for harvesting trees and transporting them to either on-road vehicles or end users. Daily usage can be high, and infrastructure is very poor to nonexistent. Common vehicles are forwarders and skidders. Equipment is normally operated in 8-hour shifts and may not run every day. Little is known of existing emission reduction efforts for forestry equipment.

4.2.6 LAWN AND GARDEN

Lawn and garden equipment is mostly used to mow and care for grounds. This includes riding mowers down to handheld trimmers. Most equipment is less than 50 hp, but they account for over 80% of all off-road vehicles by population. There is significant electrification in the current equipment. Emissions reduction is expected to be a continuation of this trend, with the notable exception of commercial-use equipment. Commercial equipment should follow trends for other lower-power, high-use equipment and may be reliant on SLFs.

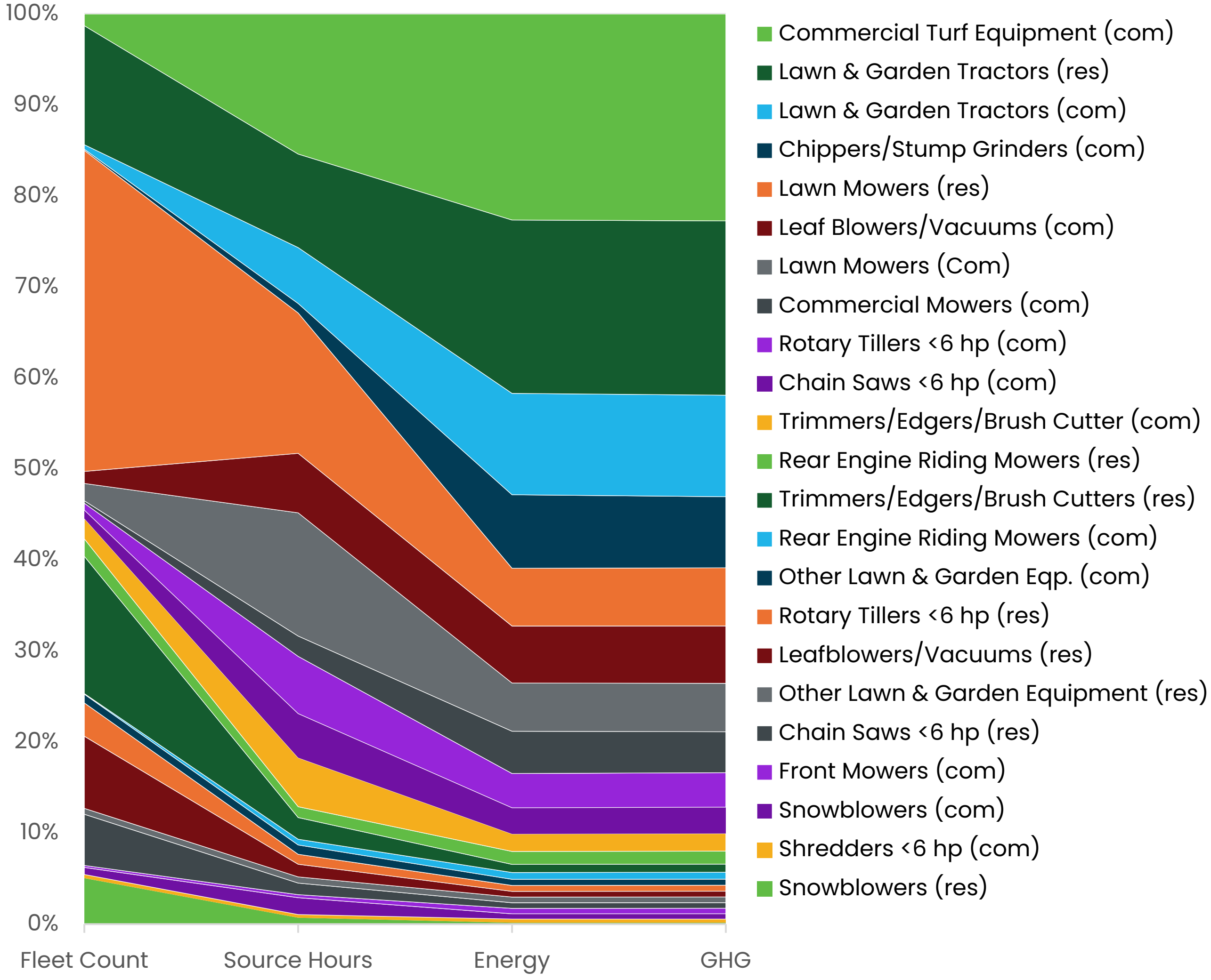


Figure 15. Lawn and garden sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions

4.2.7 RECREATIONAL

Powersport vehicles are used chiefly for recreation (snowmobiles, ATVs, UTVs, and off-highway motorcycles). Others, such as side-by-side UTVs, are used for off-road transportation of personnel and materials. They have become more popular for local law enforcement and emergency responders in recent decades. Duty cycles are low, so battery electric is the emissions reduction pathway. However, remote charging infrastructure and range are still important concerns. For vehicles that require extended run times or that are in remote areas, SLFs are also considered. Several engine OEMs have noted that H_2ICE is interesting and started development programs.

4.3 Available Technologies to Improve Efficiency

In general, the typical customers for off-road equipment, especially fluid-powered equipment, require a quick payback and are hesitant to adopt technologies that might adversely affect reliability or equipment service life. Different applications in the off-road sector have different requirements for ruggedness, durability, and operational factors such as speed and acceleration, and the priorities for features differ between applications. For example, for agricultural equipment, survey data indicated that initial cost is more important than reliability and durability, which are more important than fuel cost; whereas for construction equipment, fuel cost was listed as more important than reliability and durability, which are more important than initial cost.[22] Because of these varied requirements, today's technologies may be cost-effective for some vehicles and not others. Leased equipment presents an additional barrier: although equipment operators may realize savings from increased fuel efficiency, equipment purchasers may not. The purchasers therefore have low incentive to pay a higher initial cost for more efficient equipment.[23]

4.3.1 FLUID POWER EFFICIENCY

Fluid power, comprising hydraulics and pneumatics, is frequently used in high-power off-road equipment. Hydraulics and pneumatics are typically high-force, low-speed actuators that can directly drive a load without the need for gear reduction. Commercial off-road equipment frequently uses hydraulic actuators. The energy for the hydraulic system is typically supplied by a combustion-engine-driven pump, and this energy is redirected to perform useful work. Because of shock tolerance, fluid power systems are often the actuation source of choice in challenging and harsh environments, since pressure relief valves prevent system damage. Also, the high specific power for hydraulics translates to low weight and volume, important for many mobile applications.[24]

The low energy-efficiency of fluid power systems is one of their relative weaknesses. Based on older data, reports state that the average efficiency of fluid power systems is 21%, and newer systems may be more efficient.

4.3.2 OPERATIONAL AND SYSTEM ARCHITECTURE IMPROVEMENTS

When considering vehicle efficiency, the entire vehicle should be considered as a system (rather than appraising efficiency at the component level). At the system/worksite level, efficiency can be gained by reducing unnecessary movement of vehicles and equipment. This approach would minimize waiting and idling, thereby improving productivity and reducing fuel use. One example is "precision agriculture," which employs sensors and GPS to guide equipment to a targeted destination for a specific application.[25] Sensors and connectivity can be used for remote and automated operation, which are beginning to be used in agriculture and mining.

The use of telematics and related tools can improve fleet management and help to minimize fuel consumption. Telematics refers to the use of information technology and telecommunications to track and communicate vehicle operational data to operators, site managers, and fleet managers. One paper has noted that individual operators using similar equipment for similar jobs can have fuel consumption rates that vary by more than a factor of two, indicating the large potential improvement in efficiency from operator training for more efficient operation.[26] Driver feedback and training systems can use telematics data to improve operations, which lead to consistency and increased efficiency with all operators. Such data can enable better planning and construction site management to avoid unnecessary equipment and material movement, thereby saving fuel, as well as improve operational efficiency of agricultural and mining equipment.

5. OFF-ROAD EMISSIONS REDUCTION STRATEGY

Emissions reduction in the off-road sector is complicated by the number of equipment types, end-uses of those equipment, their operating environment (urban, rural, or remote), and their region of use (i.e., Southwest versus Upper Midwest). For each of these equipment types, operating profiles, and locations, the following strategy is recommended.

1. **Maximize the number of ICE-powered equipment that can be replaced by BEE.**

   BEE technology is currently limited to smaller machines, which operate for up to 8 hours (depending on duty cycle) per workday and have opportunity for recharging during or after the work shift. There is growing interest for mobile BEE, which is charged from high-power (>1 megawatt [MW]) mobile sources (e.g., hydrogen fuel cell and low-carbon diesel generator sets) which can be brought to the worksite, such as a construction site. Many handheld lawn and garden pieces of equipment have already begun to transition to BEE, as well as indoor forklifts and smaller agricultural machines where infrastructure supports it.

   Current barriers to electrification are related to cost, weight, charging downtime, and charging infrastructure. The cost of batteries makes achieving cost parity difficult for equipment with the need for long run times between charging. Total cost of ownership analysis can help to identify when and where reductions in operating costs can offset increased capital costs, whereas LCA can identify the total GHG emissions impact. To amortize increased capital expense and initial GHG burden from battery manufacturing, it is important that this equipment has significant annual hours of operation. Second, battery weight is also a concern. In the case of smaller equipment, multiple batteries may be required to complete a task or for large equipment battery weight may lead to soil compaction or issues with transportation. Finally, off-road equipment may be operated in remote environments where charging infrastructure does not exist. In many applications, the energy must be delivered to, or generated, where the equipment operates.

2. **Enable transition to hydrogen as the fuel source, either by fuel cell or ICE.**

   Construction and material handling equipment, in particular, have a large potential for hydrogen conversion, because the worksites have room to support centralized hydrogen refueling stations and potentially on-site hydrogen generation. Further, daily fuel usage is predictable, which enables fueling contracts to lower prices, and daily run times usually coincide with a standard workweek, reducing the need for large on-vehicle tanks. Hydrogen offers faster opportunity for refueling during work breaks, which are common and/or planned for those vehicles. H_2ICEs may be preferred over fuel cells in some segments where dust in the air and machine vibrations are concerns, such as construction, agriculture, etc.

   Hydrogen fuel is still a nascent technology and requires significant infrastructure build-out. Early adopters have required large and predictable volumes to achieve reasonable total cost of ownership. Increasing the number of H_2ICE equipment in the fleet will increase hydrogen demand and may result in lower hydrogen prices and greater availability while having a lower technology barrier to entry than fuel cells. Fuel cells, which do not have point source emissions, require complete vehicle electrification (which can be very expensive) and adequate airflow for cooling. In low to medium load operations with adequate natural cooling, fuel cells have higher efficiency than H_2ICEs. However, for equipment that operates consistently at high loads with low natural cooling, fuel cells have comparable efficiency to H_2ICEs.

3. **For machinery and operations which still require high-energy-density liquid fuels, the objective is to reduce overall fuel consumption by efficiency improvements to the greatest extent possible, while enabling neat biofuel compatibility.**

   Some off-road equipment, either due to daily energy consumption requirements or because of the remoteness of their operation, will continue to require SLFs in the long term. However, the supply of SLFs is expected to be limited and, as such, the total fuel consumption should be minimized through maximizing efficiency. Several mechanisms exist to reduce fuel consumption, but these are all application-specific. For mobile vehicles with large over-running loads (mining haul trucks, cranes, forklifts, etc.), powertrain hybridization should become standard. For other off-road vehicles with large hydraulic loads (farm equipment, excavators, bulldozers, etc.), efficiency improvements from hydraulic throttling reductions or hydraulic hybrids may be necessary.

   Although the current supply of SLFs is limited, ongoing work seeks to increase available volumes in the coming years. Research activities target greater utilization of various renewable carbon resources, increased conversion yields, lower energy use, and overall reductions to the cost of production. As SLF production technologies advance and new capacity is installed, the volumes available for use in this sector will increase, but actions to reduce overall demand and consumption will be necessary to ensure that these fuels are available across sectors where they are needed. As biofuel production technologies have not been fully de-risked, their cost of production remains higher than that of their petroleum-derived counterparts without the support of incentives such as tax credits. As noted in the Biofuels Appendix, government support will continue to play an important role in developing technologies, building supply chains, and scaling up biofuels production to meet the need for low-carbon liquid fuels.

The considerations for adopting each of the equipment powertrain emissions reduction pathways are summarized in Table 5.

Table 5. Considerations for Equipment Emissions Reduction

Powertrains	Considerations
Battery Electric Equipment	• Smaller equipment (incl. handheld) • <8 hours cont. operation • Low onboard energy storage • Low weight and packaging • Opportunity charging • Significant annual usage
Hydrogen Fuel Cell	• Ram air cooling available • Low dust • Low vibrations • On-site H_2 storage • Predictable H_2 demand
H_2ICE	• Shaft power prioritized for auxiliaries • High dust • High vibration • On-site H_2 storage • Predictable H_2 demand
Low Carbon Liquid Fuels	• Remote operations • High uptime demands • Lack of H_2 or charging infrastructure • Low onboard energy storage space/weight avail. • Low annual usage • Legacy equipment

There are several limitations to the adoption of each of the proposed powertrain options. For BEE, it is dependent on battery energy density, cost, charger infrastructure, and sufficient utilization of the equipment. For hydrogen fuel cell and H_2ICE equipment, they both require sufficient on-site storage and a predictable demand. Unique considerations for fuel cell equipment include ram air cooling (or larger radiator) and low dust and vibrations, while H_2ICE equipment does not require ram air for cooling and can withstand dusty environments and vibrations. For equipment operating on low carbon liquid fuels, whether conventional or hybrid ICE powertrains, criteria pollutant emissions can still be a concern and a barrier for utilization in urban areas. For any of these powertrain options, for actual emissions reduction, the primary energy carrier (electricity, hydrogen, and low-carbon liquid fuels) needs to have a net-zero or near net-zero CI on a WTW life cycle basis to reach the 2050 emissions reduction goal. This also includes net-zero or near net-zero manufacturing of the equipment (e.g., batteries, fuel cell stacks, and hydrogen storage tanks). These options also need to be economically viable on a total cost of ownership basis.

To achieve these goals, this report outlines six objectives with distinct targets and activities supporting each.

OBJECTIVE: Improve accounting for the off-road equipment sector population, energy consumption, and emissions inventory.

The current fleet tracking has little federal government support. The state of MOVES3 has been extrapolated for over 20 years. There is a strong need to understand the size of the fleet, individual equipment real-world activities, energy consumption, the type of energy consumed, and GHG and criteria-pollutant emissions. Further compounding this issue, the engines are tested only in laboratory conditions for criteria emissions; there are no sector-wide GHG standards. There have been LCA tools developed by the national laboratories: notably GREET. Life cycle analyses demonstrate the difficulty in full sector-wide emissions reduction without burden-shifting. For example, the current electrical grids in the Midwest have higher GHG emissions intensity compared to cleaner grids on the coasts. Further, the embodied GHG in the battery construction leads to a need for high utilization. For example, with large agricultural tractors, the greatest real-world GHG reductions are predicted to be from SLFs. As the electrical grids become cleaner and the availability of clean hydrogen increases, potential powertrain options that lead to real-world emissions reductions will increase, but the short term requires good resource management. A standardized, data-driven LCA methodology is needed to inform consumers and producers to continue GHG reduction progress.

Moreover, immediate research is necessary to correct the fleet size, activity, energy consumption, and GHG emissions estimates; this is expected to rely on industry advocacy group data rather than federal data. Relevant, standardized work cycles will be necessary to determine accurate fuel consumption in real-world conditions. To accomplish this, information will be needed from industry partners.

☑ **OBJECTIVE:** Build partnerships and collaborations with the off-road industry and communities to support their movement towards low-carbon solutions.

Identifying the best emissions reduction solutions for the numerous types of equipment, activities, and locations is very challenging. Throughout the off-road industry there are examples of consumer-driven trends toward lower energy consumption and GHG emissions. Further analysis is needed to collaborate with industry to identify the best emissions reduction opportunities. Further research, development, and deployment of advanced technologies and expansion of sustainable energy infrastructure will also help the off-road industry to create more practical applications of decarbonized technologies.

☑ **OBJECTIVE:** Support off-road equipment research, development, and deployment efforts to enhance efficiency, operation on sustainable fuels and energy, and technology integration.

SLFs are currently more expensive and are not projected to be in sufficient supply for large-sector consumption for the foreseeable future. Most SLF production today can provide 70% life cycle GHG reduction but will still have some criteria emissions from combustion. By improving the off-road sector's energy efficiency, reduced fuel consumption will also provide the knock-on benefit of emissions reductions. Current battery technology is not sufficient for long-duration equipment operation, but it has made significant inroads from smaller handheld to medium-sized mobile equipment. Most lawn and garden and some construction and industrial equipment have been identified as good candidates because of their predictable workday routines. There are several OEMs who have begun producing BEE such as excavators and bulldozers with batteries known to provide about 2–4 hours of worktime. Despite this obvious limitation, interest from some operators has been strong due to the reduction in fuel cost, noise, and vibrations. Hydrogen-powered equipment will continue to be adopted in freight centers where operations are in a closed environment near hydrogen refueling and emissions cannot be tolerated.

☑ **OBJECTIVE:** Support the off-road sector by advancing sustainable liquid fuel (SLF) and clean energy infrastructure development.

Despite the limited supply of SLFs, the GHG reductions compared to conventional fuels are significant. The equipment in the off-road sector is long-lived. There are few examples at present that can operate on 100% SLF. The need to quickly transition to neat compatibility enables both a future-proof solution for long-lived equipment and a significant reduction in GHG at present. To complete a workday, either battery swapping or rapid charging is required. Battery swapping has not seen much industry adoption or interest, while MW charging has. In locations where multi-MW charging is unavailable, portable charging solutions have been successful in maintaining equipment operations. Current charging solutions have been diesel-based, which still have emissions. Future solutions must focus on clean hydrogen to remove all point-source emissions. Fuel cells can operate efficiently at constant load, and onboard batteries may provide the high peak charge rates required to complete quick equipment charging.

OBJECTIVE: Strengthen and expand the off-road workforce by prioritizing safety, job security, and training.

The United States is well-known for producing and utilizing high-quality off-road equipment. As the fleet transitions to new advanced decarbonized technologies, it will be important to educate the American workforce on how to take advantage of this equipment, while prioritizing safety and security.

6. NEXT STEPS

6.1 Funding and Financing Development

U.S. investments in the off-road sector will help ensure national competitiveness and stability of trade flows, promote American manufacturing, and improve public health for under-resourced communities.

To help advance clean technologies and related fueling infrastructure, the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) provide billions of dollars in funding to support the development, demonstration, and deployment of low- and zero-emissions technology solutions. These historic investments support the goal of reaching net-zero emissions by 2050 by employing efficient and cost-effective strategies.

The BIL provided substantial investment in hydrogen through the $8 billion hydrogen hub program. The H2Hubs administered by DOE include up to $7 billion to establish regional clean hydrogen hubs across America. Additionally, up to $1 billion is dedicated to the Clean Hydrogen Hubs Demand-Side Initiative.

The IRA made several new tax credits available for clean energy projects. The Clean Hydrogen Production Tax Credit (section 45V) created a new 10-year incentive for clean hydrogen of up to $3/kilogram that can help reduce the cost of hydrogen-based fuels.[27] The level of the credit is based on CI, up to a maximum of 4 kilograms of CO_2e per kilogram of hydrogen.[28]

IRA also provided a tax credit for commercial on-road vehicles and some off-road equipment (section 45W). It provides up to $40,000 in tax credits per piece of qualified commercial clean vehicles, which could include “mobile machinery.” As of the writing of this document, the details of applying the section 45W tax credit are still under consideration; however, many off-road sector vehicles should qualify.[29]

DOE’s Loan Programs Office (LPO) works with the private sector to finance the deployment and scale-up of innovative clean energy technologies, build energy infrastructure and domestic supply chains, create jobs, and reduce emissions in communities across the United States. The office works across multiple innovative clean energy and advanced transportation sectors, including advanced vehicles and components, biofuels, hydrogen, and renewable energy. In July 2024, LPO’s long-standing Advanced Technology Vehicles Manufacturing Loan Program (118) was updated with new authorities to finance the manufacturing facilities for additional types of advanced vehicles.[30] In addition, LPO can finance projects in the United States that support clean energy deployment and energy infrastructure reinvestment to reduce GHG emissions and air pollution through Title 17’s Clean Energy Financing Program (Title 17).[31] As amended by the Infrastructure Investment and Jobs Act and the IRA, Title 17 has tens of billions in available loan authority.

6.2 Data and Research Needs

6.2.1 ADDRESSING INFORMATION AND ANALYSIS GAPS

- **Sector-Wide Accounting:** Understanding the sector-wide emissions is necessary to measure how this sector is achieving its emission reduction goals. However, no consistent methodology currently exists. Further compounding this, the total number of machines, along with representative work cycles, is not known. Work should continue to understand the current sector’s equipment population, activity, energy consumption (also by type), and total life cycle emissions, as well as how these vary across different regions of the United States. The regionality of access to low carbon energy is also an important aspect to evaluate.

- **Hesitancy to Technology Adoption:** Many end-users are hesitant to adopt new electrified or hydrogen fuel cell equipment. Analysis and communication with end-users can help to clarify the major concerns. Modeling is needed to identify current technology capabilities, as well as the research needed to address major concerns. One suggestion provided in the request for information was the need for full-scale testing of novel power sources in the real world, but modeling and analysis may be low-cost options for exploring different technology options.
- **Cost Minimization:** New decarbonized technology equipment typically requires a higher capital investment than their conventional powertrain counterparts, but they can offer reductions in total cost of ownership through reduced operating expenses. Evaluation of total cost of ownership, as well as equipment productivity/profitability, is needed across the wide range of equipment types and work functions.
- **Resource Availability:** Over the next couple of decades, demand for clean energy and critical materials for clean machines will grow significantly. However, the rate of emissions reduction of the prime energy sources and recharging/refueling infrastructure will vary by location. Along the transition process, efforts are needed to match the best equipment emissions reduction technology with the energy availability of that region, while still fulfilling the work requirements needed. With so many emission reduction options available to the sector, additional analysis is needed to determine the optimum uses of each technology and to reduce the total fuel consumption while capitalizing on limited energy and material resources.

6.2.2 TECHNOLOGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION (RD&D)

Several technology areas within the off-road sector have been identified as needing additional RD&D.

- **Battery Electric Equipment:** Batteries have been developed with a primary focus on light-duty automotive vehicles. The chemistries used are prone to failure from vibration and not ideal for cycling between high and low state of charge. Recently, lithium iron phosphate batteries emerged, but many issues remain, including battery energy density, cost, charging availability, and need for electrified hydraulic components. In order to create efficient BEE powertrains, near clean-sheet designs are required to convert shaft-powered transmissions and hydraulics for BEE.
- **Hydrogen ICE:** Materials compatibility and fuel injections systems are needed. Fuel storage continues to be a problem for hydrogen equipment. There is also a need for analysis to determine the optimal split between BEE, fuel cell electric, and H_2ICE.

Given the reduced energy storage associated with hydrogen, there is also a need for hybridization research to reduce fuel consumption. However, H_2ICE technology capitalizes on existing powertrain design practices and manufacturing infrastructure, making it an attractive solution for existing powertrains.

- **Fuel Cell Equipment:** Hydrogen fuel cells are limited by airflow cooling and packaging constraints. In order to maintain high efficiency, either the fuel cells need significantly high installed power or high ram-air cooling. Both are considerably constrained in most mobile equipment. Fuel cells also need onboard batteries and complete vehicle electrification. Research should focus on improving the cooling needs to improve efficiency. Fuel cells also make use of many rare earth metals, and more work is necessary to reduce this dependency.
- **Hybridization:** Electrification and hybridization enable efficiency improvements. For conventional fuel powertrains, hybridization requires further work to determine where the efficiency gains exist. Additionally, individual electric components and materials are needed to replace existing transmission hydraulic systems.
- **Sustainable Liquid Fuels:** SLFs are needed in high quantities, at reasonable cost, and with significant (if not 100%) reductions in life cycle GHG emissions. Continued work is needed to identify SLF production pathways and to grow them for the future.
- **Charging Infrastructure:** Access to high-power charging continues to inhibit zero-tailpipe-emissions equipment adoption, especially in rural and remote areas where even 220V electric access is still limited. There is also limited access to charging points in many urban locations, especially as equipment is used to build infrastructure projects. Mobile charging is only a partial solution but does enable machine BEE conversion. Given the power levels of vehicles, higher-power charging standards will be necessary.
- **Hydrogen Infrastructure:** Hydrogen faces similar challenges with storage, delivery, and production limitations. The DOE hydrogen hubs are the start to solving this problem. There is also a need to create alternative fuels in close proximity to consumption to reduce emissions from transportation, especially for lower-density hydrogen. Hydrogen storage tank standardization and operation continue to be developed by different suppliers with little commonality.
- **Technology Demonstrations:** Demonstrations of decarbonized technology equipment in actual work environments and various regions and climates are needed to lower the risk of adoption and help the U.S. off-road industry in developing high-quality products that meet the demands of the operators. Development of real-world duty cycles and test cycles is needed to identify actual operating hours and effects of environmental conditions.

6.2.3 U.S. TECHNOLOGY AND MANUFACTURING

- Enhance understanding of necessary upgrades to the electric grid, infrastructure build-out, and conversion of existing infrastructure for accelerated uptake of alternative fuels and electricity by the various subsectors of off-road equipment.
- Enhance understanding through review of data and in situ demonstration of various operations' optimization practices, such as real-world demonstration testing.
- Assess the readiness of U.S. contractors, design firms, warehouses, and equipment owners to implement these technologies for new and existing equipment and the current U.S. technology and manufacturing capabilities to address RD&D needed to grow these applications through outreach and engagement.
- Systematically assess U.S. capabilities, challenges, and opportunities, as well as research to produce recommendations on how federal financing and expertise can expedite their development.

6.3 Policy/Regulatory Opportunities/Gaps

- There is no regulation for GHG reporting, nor any regulated reductions planned. Compounding this difficulty, no standardized, representative operating cycles for off-road equipment exist.
- Electric charging for BEE equipment lacks any standardization beyond the basic combined charging system standard and will likely need multi-MW capabilities.
- Similarly, there is little regulation for hydrogen distribution or storage, especially to rural and remote worksites.

7. CONCLUSIONS

7.1 A Holistic, Comprehensive, Approach

Transportation is the largest source of GHG emissions in the United States. Decarbonizing the transportation sector is integral to achieving a net-zero emissions economy that benefits all communities. Decarbonizing the transportation sector is not only critical to reducing overall GHG emission, but the accompanying transformation of transportation systems toward sustainable solutions and technologies will reduce costs, increase options, and increase technological competitiveness in the United States.

To accomplish this, it is necessary to identify near-, mid-, and long-term actions to achieve net-zero emissions. This phased approach leverages the historic federal BIL and IRA funding; encourages deployment of scalable, market-driven technologies; provides industry and stakeholders with certainty about transforming the transportation sector; recommends planning and proposes policy opportunities at multiple levels of government; and promotes expanded research, development, demonstration, and deployment (RDD&D) to support innovative approaches to decarbonize the transportation sector, including new technologies and fuels.

7.2 Reducing Emissions in the U.S. Off-Road Sector

This report for off-road vehicles and equipment proposes actions to demonstrate, scale, increase data and information, and support low- and net-zero emissions technologies and solutions to reduce and ultimately eliminate emissions in the sector. Off-road equipment consists of a diverse array of equipment used for many different tasks, from lawn care to critical infrastructure construction and maintenance. It also includes agricultural equipment used to grow the U.S. food source. Equipment efficiency and durability are paramount among the concerns for end-users.

Over the long term, solutions must focus on a full transition to net-zero emissions equipment across the entire fleet, along with deployment of critical infrastructure. The United States must continue international leadership in the sector by promoting and deploying low- and zero-emissions fuels and technologies. We also need to implement solutions and actions to reduce or eliminate emissions of GHGs and criteria pollutants, especially in overburdened communities near port facilities, industrial sites, and mines. In addition, there are several cross-cutting actions: develop a framework to collect the data necessary to track progress with the emission reduction objectives; support development of the workforce needed to manufacture and maintain new vehicle technologies and infrastructure; and decarbonize the national electricity grid.

7.3 Next Steps

Transforming the off-road sector, other transportation modes, and the entire national transportation system over the next three decades will be a complex endeavor, but by taking a comprehensive and coordinated approach it is a challenge that we can, and must, solve. There is no one technology, policy, or approach that will solve our transportation challenges unilaterally; we need to develop, deploy, and integrate a wide array of technologies and solutions to ensure we achieve our goals.

This report, *A Market and Technology Assessment for Off-Road Vehicle & Equipment Energy and Emission Innovation,* presents high-level off-road emission reduction strategies. There is recognition that concrete actions need to be developed to ensure a whole-of-government approach to off-road emissions reductions, as well as engagement from a variety of stakeholders to understand needs and pathways that can scale these technologies. A more detailed modal plan for off-road will be developed that covers the broad range of actions needed to meet the needs of U.S. consumers and industries as well as meet emissions goals.

In addition to leadership at the federal level, reaching these ambitious climate goals will require collaboration with all levels of government, industry, communities, and nonprofit organizations. Developing pathways for substantial emissions reductions, and eventually action plans, is intended to send a strong signal to our partners and other stakeholders, to use the documents as guideposts and frameworks to support and complement their own planning and investments, and to coordinate actions in each sector. We will continue to set bold targets for improving our transportation systems and transitioning to zero-emissions vehicles, vessels, and fuels on a timeline consistent with achieving economy-wide 2030 and 2050 emissions reduction goals. As we decarbonize our transportation system, we can create a more affordable and equitable transportation system that will provide multiple benefits to all Americans for generations to come. We must act decisively now to provide better mobility options, reduce inequities, and offer affordable and clean mobility solutions to ensure the health of the planet for future generations. It is up to all of us to make that vision a reality and move forward with creative and innovative solutions toward a better future for all.

ACRONYM LIST

BD	biodiesel
BEE	battery electric equipment
BIL	Bipartisan Infrastructure Law
BSFC	brake-specific fuel consumption
CI	carbon intensity
CNG	compressed natural gas
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
GHG	greenhouse gas
GREET	Greenhouse gas, Regulated Emissions and Energy use in Technologies
H_2	hydrogen
H_2ICE	hydrogen internal combustion engine
hp	horsepower
ICE	internal combustion engine
IRA	Inflation Reduction Act
LCA	life cycle analysis
LHV	lower heating value
LPG	liquified petroleum gas
LPO	Loan Programs Office
MMT	million metric tons
MOVES	MOtor Vehicle Emission Simulator
MW	megawatt
OEM	original equipment manufacturer
PM	particulate matter
PSR	Power Systems Research
RD	renewable diesel
RDD&D	research, development, demonstration, and deployment
RG	renewable gasoline
RNG	renewable natural gas
RP	renewable propane
SLF	sustainable liquid fuel
TTW	tank-to-wheels
WTW	well-to-wheels

APPENDIX A. BIOFUELS' ROLE IN DECARBONIZING THE TRANSPORTATION SECTOR

Context

Historically, the U.S. transportation sector has overwhelmingly relied on liquid petroleum-based fuels, which supplied over 90% of its energy needs in 2022.[32] The U.S. Transportation Decarbonization Blueprint laid out a bold plan to move the transportation sector to net-zero emissions, using a range of low-GHG fuels, including electrification, hydrogen, and liquid fuels from biomass and other waste carbon resources, such as CO2 and food waste (referred to here collectively as "biofuels"). Biofuels already contribute to on-road light-, medium-, and heavy-duty transportation on the order of billions of gallons, driven by decades of U.S. policy objectives such as energy security, clean air, lead-free octane enhancement of gasoline, climate change mitigation, and rural economic development. The Blueprint identifies aviation as the transportation sector with the greatest long-term opportunity for biofuels, as aviation is limited in low-GHG options. Due to biofuel compatibility with existing fleets and fueling infrastructure, biofuels will play an important role in reducing carbon emissions across all modes during the transition to zero-emission solutions. In particular, biofuels will be important in decarbonizing the legacy fleet in the rail, marine, and off-road sectors due to long equipment lifetime and slow fleet turnover in these modes. The Blueprint also recognizes that biofuels will play a supporting role where electrification and hydrogen may not be as practical. Successfully managing these competing demands for biofuels will be a key challenge going forward. Converting bioenergy from one sector to another does not automatically reduce transportation GHG emissions unless the first sector is reduced or carefully replaced with another energy source. More biofuels beyond current production are needed. To avoid direct land-use actions such as converting to more agricultural land for producing corn and soybeans currently used for biofuels, a critical near-term action within approximately 10 years for biofuels is to pivot to accessing unused and underused biomass already available, which is estimated at around 350 million dry tons per year, including over 130 million dry tons of agricultural residues, over 170 million dry tons of a variety of wastes, and over 30 million dry tons of forestland resources.[33]

The United States Aviation Climate Action Plan establishes a goal of net-zero emissions from U.S. aviation by 2050. The SAF Grand Challenge establishes a goal of, by 2030, 3 billion gallons of sustainable aviation fuel (SAF) that achieves at least a 50% reduction in emissions on a life cycle basis and 35 billion gallons by 2050.[34] The SAF Grand Challenge Roadmap,[35] which was developed by USG agencies with extensive input from researchers, nongovernmental organizations, and industry, outlines a whole of-government approach with coordinated policies and activities that should be undertaken by federal agencies to achieve both the 2030 and 2050 goals. In the SAF Grand Challenge Roadmap, the vast majority of the policies and activities focus on the needs for innovation in feedstock and conversion technologies that are largely agnostic to fuel type. As discussed in the action plans, decarbonizing maritime freight may require large volumes of methanol, decarbonizing noncommercial maritime vessels may require significant volumes of green gasoline, and decarbonizing the off-road, rail, and long-haul heavy-duty modes may require large volumes of biomass-based diesel. The Blueprint recognizes that biofuels will play a leading role for aviation decarbonization while playing a supporting role for decarbonizing other transportation sectors.

In addition to the Blueprint, the U.S. goals and strategies for biofuels are also driven by the National Biotechnology and Biomanufacturing Initiative and coordinated through the National Bioeconomy Board. This appendix seeks to complement modal plans by summarizing USG goals and strategies for biofuels that are not specific to individual modes of transportation and thus not fully integrated within specific modal plans.

Biofuels Background

The United States is the world's largest biofuels producer, producing 15 billion gallons of ethanol and over 3 billion gallons of biomass-based diesel in 2022.[36] These fuels are typically blended into gasoline and diesel, respectively, for use in on-road transportation. Most U.S. ethanol is produced from fermentation of cornstarch. U.S. biomass-based diesel is currently produced via either hydroprocessing, co-processing, or transesterification and uses lipid feedstocks that include oilseeds (e.g., soy, canola) and waste fats, oils, and greases (FOGs), such as used cooking oil. While the United States has these domestic supplies of biofuels, the supply is far from sufficient to satisfy the energy needs of the entire U.S. transportation sector.

Maximizing the impact of biofuels in support of the Blueprint will require expanding biofuels production, primarily through new feedstocks and production pathways. Government support will continue to play an important role in developing technologies, building supply chains, and scaling up biofuels production to meet the need for low-carbon liquid fuels. Policy and regulation at the federal and state levels have played and will continue to play a critical role for biofuels production in the United States to drive down CI and expand production.

Domestic Resource Potential for Biofuel Production

Currently, most biofuels in the United States are produced from corn and soybean planted on agricultural land. It is important for the U.S. agricultural system to prioritize its most productive land to produce food, feed, and fiber. Therefore, there are limits to the amount of agricultural land that can be used for biofuel production to meet the energy demands of our transportation sector. While productivity improvements can increase the amount of biofuel feedstock produced from the same acreage, these gains are modest in comparison to the needs for biofuels expansion. USDA projects 2% annual yield improvements for corn and 0.5% yield improvements for soy over the next 10 years.[37] The deployment of intermediate oilseeds that are planted and harvested in between these cash crop rotations could also sustainably expand lipid feedstock supply that can be converted using commercially ready technologies to increase production of SAF and biomass-based diesel with little impact on land use.[38] However, in order to support decarbonization, domestic biofuels production must expand primarily through the use of new feedstocks resources that are not grown on prime agricultural land.

The *2023 Billion-Ton Report* (BT23) estimates the United States has the capacity to sustainably and economically produce 1.3 to 1.5 billion tons of biomass and organic wastes per year in the future, over triple the amount the current U.S. bioeconomy utilizes today.[39] These resources include:

- Agricultural residues (e.g., corn stover, wheat straw) from the production of food, grain, and fiber
- Wastes, including animal manure; wastewater sludge; inedible FOGs; sorted municipal solid waste including unrecyclable paper/cardboard waste, yard waste, and food waste; and landfill gas

- Forest thinnings from small-diameter trees that need removal to increase forest health and reduce wildfire potential, and logging and mill processing residues
- Purpose-grown energy crops (e.g., perennial grasses, fast-growing trees) that can be grown on less productive land with improved environmental performance and lower carbon-intensity than traditional agricultural production.

Because biomass production potential is contingent upon market pull, the BT23 presents production capacity by market scenario. One scenario presented in the BT23 is the "near-term scenario", which illustrates resources that exist today[b] (and in 2030). This includes 350 million tons per year of unused biomass (including ~250 million tons per year of cellulosic biomass) in addition to the ~340 million tons of biomass currently used for energy and coproducts (Figure B1). The mature-market scenarios, adding ~440–800 million tons more biomass, include energy crops, which will not be fully deployed by the 2030 SAF target. However, the 2030 SAF target of 3 billion gallons per year would require 50–60 million tons of biomass per year[c], which is merely ~15% of the Near term scenario untapped production capacity. (See BT23 Figure ES-1 and Table ES-2).

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[b] Near-term presents resources that are annually available (within specified environmental constraints, at specified prices, and available for collection).

[c] At an assumed average conversion rate of 55 gallons of biofuels per ton.

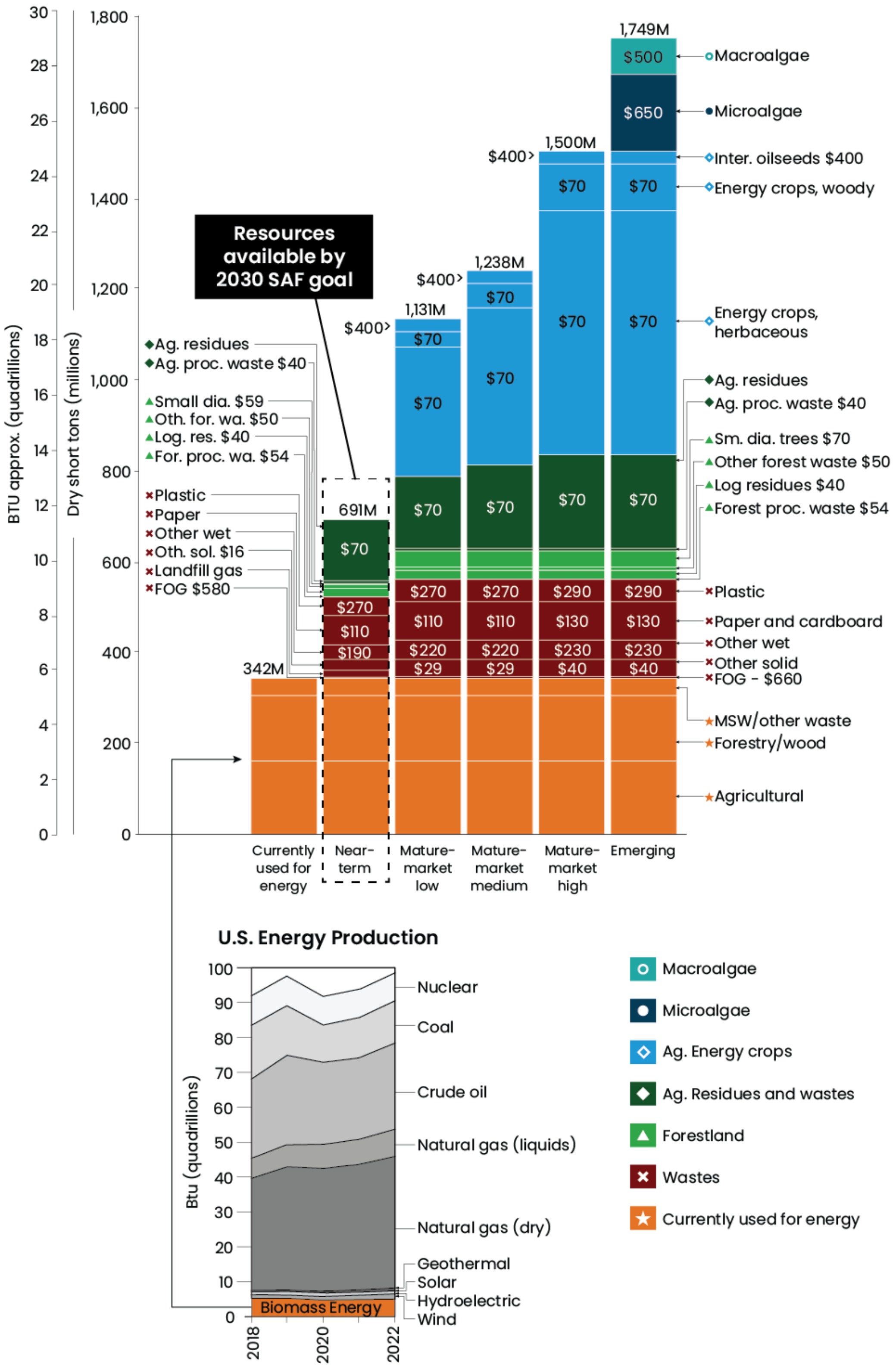

Figure A1. Estimated biomass production capacity of the US. The near-term scenario is highlighted, which identifies production capacity in 2030, including 235 million tons per year of unused cellulosic biomass resources. (Source: USDOE 2023 Figure ES-1[40].)

USG Goals and Strategies for Biofuels

The U.S. Transportation Decarbonization Blueprint prescribed five guiding principles to guide future policymaking and research, development, demonstration, and deployment in the public and private sectors, which are exemplified by the USG's coordinated approach and leadership on biofuels:

- Implement bold actions to achieve measurable results.
- Embrace creative solutions across the entire transportation system.
- Ensure safety, equity, and access.
- Increase collaboration.
- Establish U.S. leadership.

The USG has a long history of biofuels coordination since the Biomass Research and Development Act of 2000. Since then, the Biomass R&D Board has coordinated biofuels-related activities to advance a range of policy objectives, including climate change, energy security, domestic manufacturing and competitiveness. In recent years, these efforts have been driven by the National Biotechnology and Biomanufacturing Initiative and the SAF Grand Challenge with the mutual objectives of increasing domestic production of biofuels and improving the CI of biofuels production.

Federal government agencies developed a series of Bold Goals for U.S. Biotechnology and Biomanufacturing R&D in March 2023,[41] which include several goals that align with the U.S. Transportation Decarbonization Blueprint. These goals focus on expanding the availability and sustainability of feedstocks for the production of biofuels and increasing the production of SAF and biofuels for other hard-to-decarbonize modes of transportation.

Bold Goals for U.S. Biotechnology and Biomanufacturing R&D:

GOAL 1.1 Expand Feedstock Availability – In 20 years, collect and process 1.2 billion metric tons of conversion-ready, purpose-grown plants and waste-derived feedstocks and utilize >60 million metric tons of exhaust gas CO2 suitable for conversion to fuels and products, while minimizing emissions, water use, habitat conversion, and other sustainability challenges.

GOAL 1.2 Produce SAF – In 7 years, produce 3 billion gallons of SAF with at least 50% (stretch 70%) reduction in GHG life cycle emissions relative to conventional aviation fuels, with production rising to 35 billion gallons in 2050.

GOAL 1.3 Develop Other Strategic Fuels – In 20 years, develop technologies to replace 50% (>15 billion gallons) of maritime fuel, off-road vehicle fuel, and rail fuel with low net GHG emission fuels.

GOAL 3.1 Develop Measurement Tools for Robust Feedstock Production Systems – In 5 years, develop new tools for measurement of carbon and nutrient fluxes in agricultural and bioeconomy feedstock systems that contribute to a national framework.

GOAL 3.2 Engineer Better Feedstock Plants – In 5 years, engineer plants and manipulate plant microbiomes to produce drought-tolerant feedstocks capable of growing on underutilized land with >20% improvement in nitrogen and phosphorus use efficiency.

STRATEGIES TO ACHIEVE NEAR-TERM BIOFUEL GOALS

BT23 estimates there are 350 million dry short tons per year of biomass above current uses that are near-term opportunities that could be accessible for biofuels in the next 5–10 years. Some of these resources, such as wastes, are already collected but then landfilled. Others, such as agricultural residues and timberland resources, exist in fields and forests but must be collected for use. Most of this near-term biomass is lignocellulosic. Technologies to produce liquid fuels from lignocellulosic biomass have not been fully derisked. Given the significant lead time required for biofuels production infrastructure to be built, the path to meeting near-term goals focuses on actions to scale the harvesting/collection and scaling of these resources and the production facilities that can turn them into biofuels as quickly as practicable. These actions include:

- Demonstrate new biofuel pathways that can produce biofuels from additional feedstocks beyond lipids and starch.
- Build and support stakeholder coalitions through outreach, extension, and education to set the stage for biofuel feedstock and biofuel supply chains to develop and sustain themselves and replicate with continuous improvement.
- Increase deployment of alternative lipid feedstocks including intermediate oilseeds that can be readily converted to SAF and biomass-based diesel through commercially available conversion technologies.
- Improve the CI of biofuels production using commercially available feedstocks and infrastructure.
- Develop improved environmental models and data for biofuels to support optimization of existing policies and implementation of new policies that could be enacted.
- Inform biofuels policy development with analysis of gaps and impacts of policies under consideration.
- Stakeholder outreach and engagement on sustainability to exchange data and information about best practices to reduce lifecycle GHG emissions from agricultural and forest-derived feedstocks and optimize other environmental and social impacts.
- Enable use of drop-in unblended biofuels and biofuel blends up to 100% to simplify blending requirements, reduce cost of logistics, and facilitate supply.

STRATEGIES TO ACHIEVE LONG-TERM BIOFUEL GOALS

The path to meeting long-term biofuel and decarbonization goals requires a continuing focus on innovation, including research, development, and demonstration (RD&D) of new feedstock and conversion technologies, increasing production capacity with continued progress in cost reductions and CI. This effort occurs simultaneously with the near-term strategies above such that these innovations can be demonstrated and scaled by 2050. Technologies in this portfolio are expected to result in a dramatic build-out and expansion of alcohol, waste-based, lignocellulosic, and waste and captured carbon gas pathways.

- Conduct RD&D on scaling and sustainability of biomass, waste, and residue feedstocks to enable innovations in technologies and strategies that increase the availability of purpose-grown energy crops, wastes, and agricultural and forestry residues at reduced CI and cost. This includes addressing the social, environmental, and economic sustainability aspects of feedstock supply chains.
- Conduct RD&D on feedstock logistics and handling reliability to increase efficiencies and decrease cost and CI of supply logistics from the producer's field to the conversion facility door.
- De-risk scale-up through R&D and integrated piloting of critical pathways by 2030 to accelerate fuel conversion technology scale-up and improve financeability of critical conversion pathways that utilize the full potential of an expanded feedstock supply.

- Model and demonstrate sustainable regional supply chains for critical pathways by 2035 to promote commercialization of biofuel supply chains through process validation and risk reduction via access to critical data and tools that empower rapid, informed decision making when evaluating biofuel supply chain options.
- Build and support regional stakeholder coalitions through outreach, extension, and education to continue to expand a biofuels industry that improves environmental and economic performance while supporting job creation and social equity in multiple regions of the country.
- Continue to invest in industry deployment to help overcome barriers to project financing through creative financing, government loans and loan guarantees, and outreach.
- Continue to inform biofuel policy development to enable aligned policy incentives that will support long-term biofuel deployment.

Conclusion

Biofuels will play an important role in reducing carbon emissions across all modes of transportation, whether as a long-term decarbonization strategy or as a transition to zero-emission solutions. USG agencies have identified goals and strategies to improve CI and sustainability of biofuels and to expand biofuels production—particularly through developing supply chains and technology necessary to produce biofuels from purpose-grown energy crops, wastes, and agricultural and forest residues. While USG has placed a priority on producing biofuels for aviation due to the lack of alternative low-GHG options, it will be important to periodically assess fleet turnover and zero-emission vehicle adoption rates across various modes of transportation to inform the optimal allocation of biofuels across these modes to maximize the GHG benefits of biofuel use.

APPENDIX B. FIGURE DATA

Figure 2. Fuel consumption of the off-road sector by segment and hp rating. Note: The Industrial and Commercial sectors from MOVES have been combined under the Industrial sector.

Sector	<50 hp	50-175 hp	>175 hp	Total
Underground Mining	0.007542568	0.211120449	0.411182829	0.629845846
Logging	0.213365793	0.079597993	2.997849602	3.290813388
Recreational	13.72475572	5.456901494	0.806119415	19.98777663
Lawn/Garden	78.94668165	3.029906264	2.941000868	84.91758878
Agriculture	6.20916916	16.03505977	68.33161122	90.57584015
Industrial	39.9622179	60.46661604	38.20385485	138.6326888
Construction	15.82751786	33.90439304	136.3692835	186.1011944

Figure 3. U.S. off-road equipment composition based on percent of fleet number, source hours, energy, and use-phase GHG emissions. Source: EPA MOVES3

Sector	Fleet Count	Source Hours	Energy (MMBtu)	GHG (tonnes CO_2eq)
Railroad	29692.33412	16556273.54	2962679.574	228540.3609
Underground Mining	10614.17812	15645706.79	3411682.05	262856.4987
Airport Support	23037.89365	16300097.68	11270782.3	867517.3376
Logging	174946.9843	32855425.33	18148674.87	1400976.216
Recreational	5949990.225	287394471.6	28964496.71	2305770.304
Oil Field	204314.6883	225744351.1	94222214.49	7046094.746
Commercial	11526864.57	2045077174	208429972.3	16124107.94
Lawn/Garden	119117685.1	6623761802	308494096.1	24493732.5
Industrial	1977693.919	2588480054	492563370.8	35686190.81
Agriculture	3404860.78	923196666.4	502783982.6	38733671.5
Construction	3904513.509	2295175226	910062771.7	70142096.37

Figure 4. U.S. off-road population by sector

Sector	Pop.
Underground Mining	10167.718
Logging	167498.7588
Agriculture	3193102.892
Construction	3981133.673
Recreational	8898241.329
Industrial	13360686.48
Lawn/Garden	116819011.9

Figure 5. EPA MOVES3 off-road annual hours of operation by sector

Sector	Source Hours
Agriculture	544
Agriculture	363
Agriculture	475
Agriculture	95
Agriculture	150
Agriculture	749
Agriculture	381
Agriculture	90
Agriculture	110
Agriculture	172
Construction	466
Construction	275
Construction	580
Construction	990
Construction	936
Construction	955
Construction	566
Construction	1092
Construction	962
Construction	855
Construction	1641
Construction	606
Construction	1231
Construction	821
Construction	622

Construction	484
Construction	943
Construction	760
Construction	413
Construction	662
Construction	761
Construction	914
Construction	535
Construction	818
Construction	561
Construction	460
Construction	1135
Construction	593
Industrial	1341
Industrial	384
Industrial	815
Industrial	732
Industrial	1700
Industrial	8500
Industrial	338
Industrial	790
Industrial	878
Industrial	421
Industrial	145
Industrial	403
Industrial	1220
Industrial	1257
Industrial	643
Lawn/Garden	303
Lawn/Garden	13
Lawn/Garden	465
Lawn/Garden	480
Lawn/Garden	1068
Lawn/Garden	86
Lawn/Garden	544
Lawn/Garden	45
Lawn/Garden	406
Lawn/Garden	25

Lawn/Garden	120
Lawn/Garden	10
Lawn/Garden	433
Lawn/Garden	61
Lawn/Garden	569
Lawn/Garden	36
Lawn/Garden	472
Lawn/Garden	17
Lawn/Garden	50
Lawn/Garden	400
Lawn/Garden	8
Lawn/Garden	137
Lawn/Garden	9
Logging	303
Logging	1276
Logging	50
Recreational	1608
Recreational	1080
Recreational	1600
Recreational	57
Recreational	435
Underground Mining	1533

Figure 6. EPA MOVES3 off-road average in-use engine efficiency

Fuel Type Name	Calculated Efficiency
Gasoline	0.19
Gasoline	0.2
Gasoline	0.22
Gasoline	0.23
Gasoline	0.24
Gasoline	0.25
Gasoline	0.26
Gasoline	0.27
Gasoline	0.28
Gasoline	0.29
LPG	0.29
LPG	0.3
LPG	0.31

CNG	0.32
CNG	0.33
CNG	0.34
CNG	0.35
Diesel	0.29
Diesel	0.32
Diesel	0.34
Diesel	0.37
Diesel	0.38

Figure 7. EPA MOVES3 off-road petroleum fuel consumption by sector and hp bin in 2022

Sector	<50 hp	50-175 hp	>175 hp	Total
Underground Mining	0.007542568	0.211120449	0.411182829	0.629845846
Logging	0.213365793	0.079597993	2.997849602	3.290813388
Recreational	13.72475572	5.456901494	0.806119415	19.98777663
Lawn/Garden	78.94668165	3.029906264	2.941000868	84.91758878
Agriculture	6.20916916	16.03505977	68.33161122	90.57584015
Industrial	39.9622179	60.46661604	38.20385485	138.6326888
Construction	15.82751786	33.90439304	136.3692835	186.1011944

Figure 8. EPA MOVES3 off-road CO_2 emissions by sector and hp bin in 2022

Sector	<50 hp	50-175 hp	>175 hp	Total
Underground Mining	0.002387847	0.089274754	0.173873474	0.265536076
Logging	0.067547938	0.033658944	1.267675809	1.368882691
Recreational	4.34502144	2.307514698	0.340877034	6.993413172
Lawn/Garden	24.99316063	1.281231344	1.243636656	27.51802864
Agriculture	1.965716088	6.780612797	28.89482198	37.64115086
Industrial	12.65135039	25.56901666	16.15494739	54.37531444
Construction	5.010719742	14.33686962	57.66534845	77.01293781

Figure 9. EPA MOVES3 off-road CO_2 emissions of "Top 20" equipment with percentage contribution to total off-road sector CO_2 emissions

Equipment Description	CO_2	Percentage of Total CO_2
Agricultural Tractors	32.52458943	17.37%
Forklifts	21.64318146	28.93%

Rubber Tire Loaders	10.64883175	34.61%
Excavators	9.71535358	39.80%
Crawler Tractor/Dozers	9.676712393	44.97%
Off-Highway Trucks	8.306513982	49.40%
Commercial Turf Equipment (com)	7.94578048	53.65%
Other Oil Field Equipment	7.029718068	57.40%
Tractors/Loaders/Backhoes	6.522562613	60.88%
AC/Refrigeration	5.809356354	63.99%
Lawn & Garden Tractors (res)	4.509331201	66.39%
Skid Steer Loaders	4.495844408	68.80%
Snowmobiles	3.278646234	70.55%
Rough Terrain Forklifts	3.110934292	72.21%
Combines	2.914719965	73.76%
Terminal Tractors	2.765914104	75.24%
Lawn & Garden Tractors (com)	2.631660755	76.65%
Scrapers	2.606771413	78.04%
Rollers	2.488993915	79.37%
Graders	2.418033224	80.66%

Figure 10. LHV and density of fuels and energy sources for off-road equipment

	Units	MDO (0.1% sulfur)	Liquefied Natural Gas (LNG)	Renewable diesel	Methanol	Ammonia
LHV	MJ/kg	41	48.63	44	19.74	18.8
Density	kg/L	0.91	0.43	0.78	0.79	0.6

	Units	HFO (0.1% sulfur)	Liquefied Natural Gas (LNG)	Renewable Diesel	Renewable Gasoline	Methanol	Ammonia	Gaseous Hydrogen	Battery Storage
LHV	btu/lb	17,627	20,907	18,917		8,487	8,083	51585.01	
Density	lb/gal	8	4	7		7	5	1	
LHV	btu/gal	133863.7044	75025.74473	123135.9511	115983	55951.51	40471.26	32879.819	
LHV	mmbtu/cu ft	1.049910009	0.56123167	0.921121085	0.867613283	0.418546	0.302746	0.2459582	0.02452
Density	lb/cu ft	61.87695641	26.84402344	48.69380997	46.67158493	49.31809	37.45678	4.7680161	86.74

Figure 11. Life cycle GHG emissions of fuel options for off-road equipment. The 70% GHG reduction line is relative to conventional diesel. Results reflect consistent system boundaries, calculation approaches, and background data. The life cycle analysis (LCA) results will vary depending on case-specific details and differences in calculation approaches specific to the intended use. These results are representative and do not reflect determinations for fuel credits or other regulatory purposes.

Numbering	70% GHG reduct.
0.5	28.626
1.5	28.626
2.5	28.626
3.5	28.626
4.5	28.626
5.5	28.626
6.5	28.626
7.5	28.626
8.5	28.626
9.5	28.626
10.5	28.626
11.5	28.626
12.5	28.626
13.5	28.626
14.5	28.626
15.5	28.626
16.5	28.626

Figure 12. Agricultural sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions

Equipment type	Fleet Count	Source Hours	Energy (MMBtu)	GHG (tonnes CO_2eq)
2-Wheel Tractors	6141.349	1772915.78	154214.6487	12282.08953
Agricultural Mowers	9896.559	1686939.477	163305.716	12912.75562
Balers	27556.09	1924790.629	571366.4979	45033.4899
Tillers > 6 HP	837947.9	33786334.94	2688399.982	214580.6022
Swathers	85324.76	8615559.85	3455613.986	267861.4858
Sprayers	277649.3	21336488.65	4382196.646	340533.9164
Irrigation Sets	35745.52	24847633.64	8345314.856	622985.9732
Other Agricultural Equipment	59089.41	14719594.45	9365094.424	723449.0961
Combines	346269.5	48693332.94	39748385.37	3062730.608
Agricultural Tractors	1719240	765813076	433956432.3	33438933.9

Figure 13. Construction sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions.

Equipment type	Fleet Count	Source Hours	Energy (MMBtu)	GHG (tonnes CO_2eq)
Dumpers/Tenders	48626.68629	8108150.81	370762.2673	29133.86731
Rough Terrain Forklift	2891.96292	1137505.415	412954.9597	30697.51567
Tampers/Rammers	238963.6988	37373978	871977.4945	69545.25139
Plate Compactors	204153.9045	41164314.88	1425040.701	112793.6637
Surfacing Equipment	34218.9392	16223246.9	1742717.356	135734.5141
Cement & Mortar Mixers	387596.8125	34552128.45	2277270.077	180443.059
Signal Boards/Light Plants	88213.49439	44498445.04	3256304.398	251029.2269
Paving Equipment	192632.1494	36645471.43	3324838.282	259938.6127
Crushing/Proc. Equipment	24364.622	13797231.06	5307542.974	409307.866
Concrete/Industrial Saws	168484.6055	97629938.86	6091405.369	480134.876
Pavers	44626.72515	29085776.2	13031809.74	1004447.854
Bore/Drill Rigs	211282.3098	40081007.06	13416342.49	1034022.185
Other Construction Equipment	18551.99178	10278012.52	13699294.37	1054536.591
Off-Highway Tractors	5585.95674	4548564.774	13943008.3	1074346.364
Trenchers	127375.1577	62970205.63	15768447.59	1215925.634
Cranes	47054.43813	43004395.01	29818799.64	2297033.669
Rollers	125039.061	88389476.73	31731065.18	2445593.111
Graders	40816.20039	37395414.07	32323563.62	2490617.685
Scrapers	23165.34612	20164882.24	34905878.54	2689592.009
Rough Terrain Forklifts	152125.0935	95911249.41	39259419.87	3025044.101
Skid Steer Loaders	731217.2322	559734793.8	54427428.06	4192204.915

Tractors/Loaders/Backhoes	469163.7704	503997345.2	81957170.84	6316966.681
Off-highway Trucks	21499.37517	33600452.05	111227754.8	8570398.253
Excavators	171183.814	178031166.5	128854962.4	9928622.103
Crawler Tractor/Dozers	131558.5803	117275077.3	128858875.7	9928923.629
Rubber Tire Loaders	194121.5812	139576997.1	141819329	10924749.47

Figure 14. Industrial sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions

Equipment type	Fleet Count	Source Hours	Energy (MMBtu)	GHG (tonnes CO_2eq)
Other Material Handling Equipment	15480.28193	6154595.595	1278181.965	97993.79379
Aerial Lifts	209258.4415	75836827.15	9342160.994	708083.902
Sweepers/Scrubbers	123193.2773	107026385.3	27229348.65	2090342.424
Other General Industrial Equipment	244306.1183	181871879.6	27773510.67	2146325.074
Terminal Tractors	45318.14455	53300837.11	35936116.73	2762068.841
AC/Refrigeration	384507.234	499550496.6	76198320.68	5871108.137
Forklifts	955630.4215	1664739032	314855362.7	22016862.71

Figure 15. Lawn and garden sector distribution by equipment type for fleet count, source hours, energy consumption, and GHG emissions

Equipment type	Fleet Count	Source Hours	Energy (MMBtu)	GHG (tonnes CO_2eq)
Snowblowers (res)	6020845.714	46828800	477026.215	38077.36265
Shredders < 6 HP (com)	476923.8857	23183800	1246727.829	99516.76901
Snowblowers (com)	922611.7603	122170473.5	1778465.03	141716.5723
Front Mowers (com)	261833.544	21892193.54	1848592.79	147559.0561
Chain Saws < 6 HP (res)	6698293.714	84658990	1908914.408	152374.0706
Other Lawn & Garden Equipment (res)	767169.9566	45497440.48	1921312.594	153363.7232
Leafblowers/Vacuums (res)	9439653.6	91774410	1927360.443	153846.4768
Rotary Tillers < 6 HP (res)	4364845.303	72141193.2	2011238.73	160541.8404
Other Lawn & Garden Eqp. (com)	1139777.125	67940689.09	2076639.084	165626.459
Rear Engine Riding Mowers (com)	75970.04091	42026204.58	2309181.124	184324.3082
Trimmers/Edgers/Brush Cutters (res)	17975435.66	157285062	2756075.54	219996.4793
Rear Engine Riding Mowers (res)	2279167.231	79770853.08	4383186.933	349876.3656
Trimmers/Edgers/Brush Cutter (com)	2667907.092	355350403	5920166.844	472561.7434
Chain Saws < 6 HP (com)	1090035.771	321106371	8870862.033	708093.2242
Rotary Tillers < 6 HP (com)	909434.6743	417329467.2	11634813.56	928718.3832
Commercial Mowers (com)	317387.0613	148113961.9	14315056.81	1103013.705
Lawn Mowers (Com)	2271538.226	896626616.5	16339839.54	1304284.704

Leaf Blowers/Vacuums (com)	1580074.056	433119853.9	19341894.27	1543910.103
Lawn Mowers (res)	42004945.54	1020953538	19585590.51	1563368.236
Chippers/Stump Grinders (com)	150511.5002	69251722.22	24934204.52	1915304.588
Lawn & Garden Tractors (com)	599301.5386	406300727.7	34345954.12	2733392.13
Lawn & Garden Tractors (res)	15575120.74	681411532.5	58781278.1	4692060.881
Commercial Turf Equipment (com)	1528901.397	1019027499	69845257.53	5569319.618

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