White Paper

Technology and Market Assessment of Zero-Emission Off-Road Equipment

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Table of Contents

List of Acronyms

Table 1. List of Acronyms

Acronym	Definition
CARB	California Air Resources Board
CHE	Cargo-handling equipment
CORE	Clean Off-Road Equipment Voucher Incentive Project
EPA	U.S. Environmental Protection Agency
FARMER	Funding Agricultural Replacement Measures for Emission Reductions Program
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
GSE	Airport ground support equipment
ICE	Internal combustion engine
LCFS	Low Carbon Fuel Standard
LSI	Large spark-ignition
OEM	Original equipment manufacturer
PM2.5	Particulate matter less than 2.5 microns in aerodynamic diameter
PM10	Particulate matter less than 10 microns in aerodynamic diameter

Acronym	Definition
POC	People of color
TCO	Total cost of ownership
TRL	Technology Readiness Level
TRU	Transportation refrigeration unit

Figures and Tables

FIGURES

TABLES

Executive Summary

> *Combined, all California off-road equipment contributed over 20.1 million metric tons of greenhouse gas emissions in 2019.*

This report provides a comprehensive survey of the technological status and market readiness of zero-emission off-road equipment. It includes in-depth analyses of various off-road markets, assessing their technological strengths and identifying areas for further market development in order to more rapidly electrify this equipment to meet climate and air quality goals.

On-road vehicles have been a first mover in the transition to zero-emission technology and are paving the way for off-road equipment by developing needed technology. Overall, off-road equipment electrification is progressing rapidly with 217 available models across eight distinct off-road categories. According to the most recent technology status snapshots, zero-emission light forklifts, airport ground support equipment (GSE), yard trucks, and transportation refrigeration units (TRUs) are technologically mature and are now facing market barriers rather than technological ones. These segments are helping to transition the heavier-duty segments of mining, rail, cargo handling, marine, and agriculture. According to recent market status snapshots in the California Air Resources Board's (CARB) 2022 Heavy-Duty Investment Strategy, infrastructure and cost are the two most prominent market barriers for off-road equipment. Charging infrastructure availability is often variable on job sites and some very heavy-duty equipment requires especially high charging rates, above what is currently commercially available. In addition, while many off-road segments assessed in terms of total cost of ownership (TCO) were found to be at parity with diesel vehicles, some construction and rail equipment was not yet at parity, even when taking into account available Low Carbon Fuel Standard (LCFS) and Clean Off-Road Equipment (CORE) Voucher Incentive Project incentives.

As zero-emission forklifts and yard trucks continue to gain market share, construction equipment is primed to be a "fast follower" of electrification in the off-road equipment sector. A mixture of proximity to electrical infrastructure on work sites, strong noise and pollution reduction policies in cities where construction equipment operates, and the general compactness of many pieces of construction equipment contribute to its strong potential for electrification through battery-electric and fuel cell electric technologies. By investing in and leveraging technologies and supply chains critical for zero-emission construction equipment, we can accelerate the transition to zero-emission equipment for more difficult-to-electrify segments which may have higher power requirements and less access to charging infrastructure.

The beachhead model shows that the electrification of heavier equipment can be achieved by using lighter equipment electrification as a starting point.

While satisfying longer operating times and large power requirements presents a challenge, the work of electrifying heavy off-road equipment is achievable. One way to identify and solve these problems is the "beachhead model," conceptualized by CALSTART and CARB. The beachhead approach focuses early attention on lighter electrified machinery and equipment; then, as battery, component technology, and supply chain advances are made, they are upscaled and incorporated into increasingly heavier equipment. The beachhead strategy has already proven successful in addressing the challenges and eliminating key barriers to electrifying the off-road equipment arena.

I. Introduction

1.1 The Growing Need for Zero-Emission Off-Road Equipment

In September 2020, California Governor Gavin Newsom issued Executive Order N-79-20, which established firm targets for the elimination of internal combustion equipment sales and operations within the state. The goal for this initiative is to help California achieve carbon neutrality by 2045, a sizeable contribution to the global effort to halt global warming and avoid its most damaging and dangerous impacts on the global climate.

The order focuses on the year 2035 for its targets, with the intention that setting this date would motivate industry to accelerate development of zero-emission equipment, implement complementary infrastructure, and allow adequate time for stakeholders to prepare for this transition. Specifically, Gov. Newsom's order stipulates that by 2035 all new passenger equipment sold must be zero-emission equipment. (This does not impact internal combustion passenger equipment purchased prior to this target.) All drayage trucks are required to be zero-emission by 2035. All buses and trucks sold and used in California are required to be zero-emission by 2045 where feasible. Executive Order N-79-20 also addresses the climate harm caused by internal combustion off-road equipment. This segment's operations are required to go zero-emission in the state by 2035.

CARB collects criteria and greenhouse gas (GHG) pollutant as well as toxic emissions data for off-road equipment from several sources, including in-house emissions testing, specifically contracted research projects, and fleet information under the In-Use Off-Road Diesel-Fueled Fleet Regulation[1]. CARB has developed the EMission FACtor (EMFAC) model to estimate emission inventories of on- and off-road sources in California. There are 17 categories and 1,564 subcategories of emissions for offroad sources. Off-road emission categories captured in this assessment include agricultural, airport ground support, cargo handling equipment, construction and mining, and

[1] For more information, visit: https://ww2.arb.ca.gov/our-work/programs/use-road-diesel-fueled-fleets-regulation

locomotive.

Off-road equipment leads to substantial criteria pollutant and GHG emissions across its various applications. Figure 1 below details how carbon dioxide emissions have risen in some sectors (construction and mining) and remained relatively stagnant in others (airport ground support and cargo handling equipment) since 2015. Agricultural emissions significantly increased in 2018 and 2019 compared to previous years. From 2017 to 2018, subcategories that increased (by orders of magnitude) include agricultural tractors (7x), bale wagons (4x), combine harvesters (9x), and nut and other harvesters (5-8x). Forklifts (agriculture) had the most significant increase from 0.5 tons/day CO_2 to 152 tons/day CO_2 in 2018-19. ATVs, which were previously not included in inventories, added an average of 0.07 metric tons CO_2 in subsequent years. While increases in agricultural fuel consumption contributed to higher emissions in 2018 and 2019, as seen in Figure 2, it is likely the more extreme increases are attributed to changes in calculation methodology. In 2019, off-road equipment contributed 20.1 million metric tons of carbon dioxide emissions (EMFAC, 2021), of which 46% were produced from non-ZEV equipment featured in this study.

Figure 1. Off-Road Greenhouse Gas Emissions, 2015-19 (Source: EMFAC2021 (v1.0.1) Emission Rates)

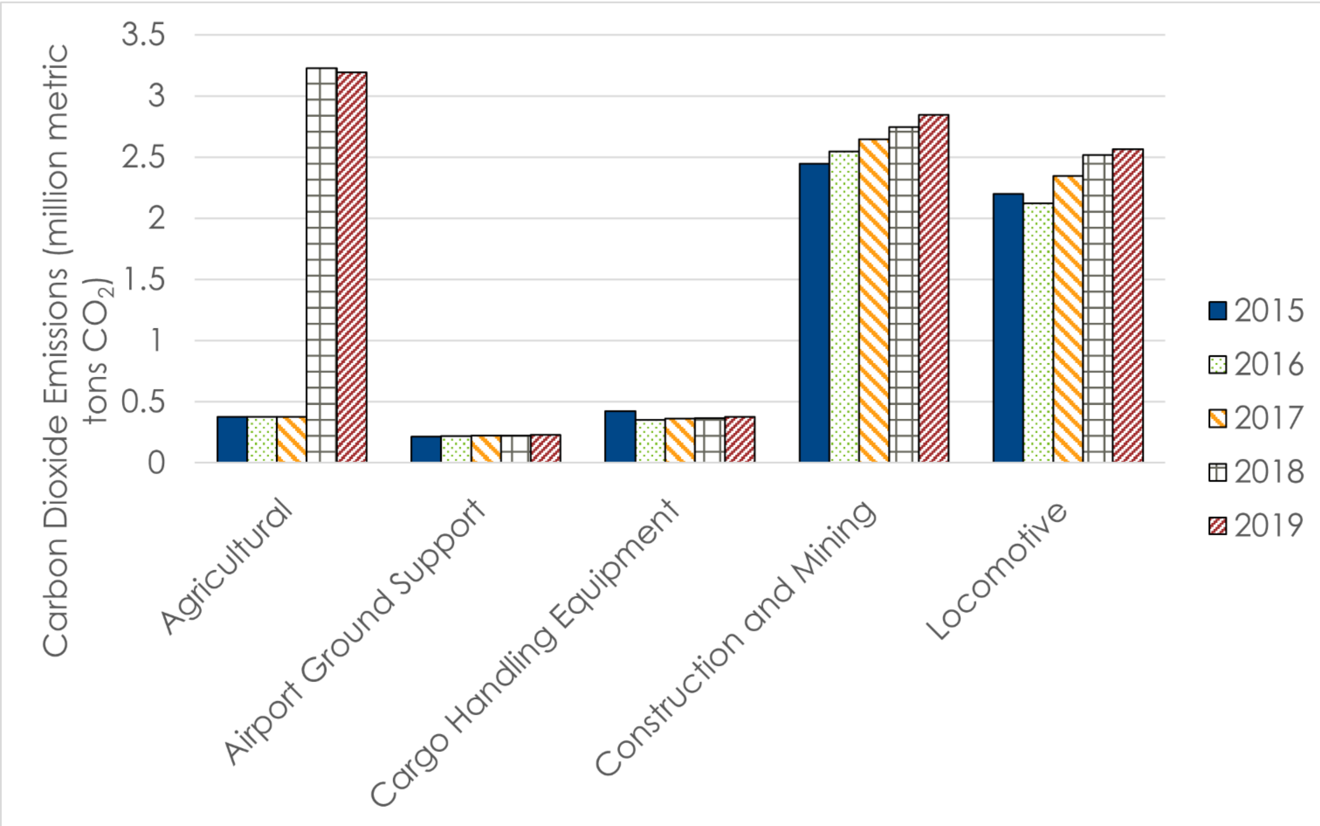
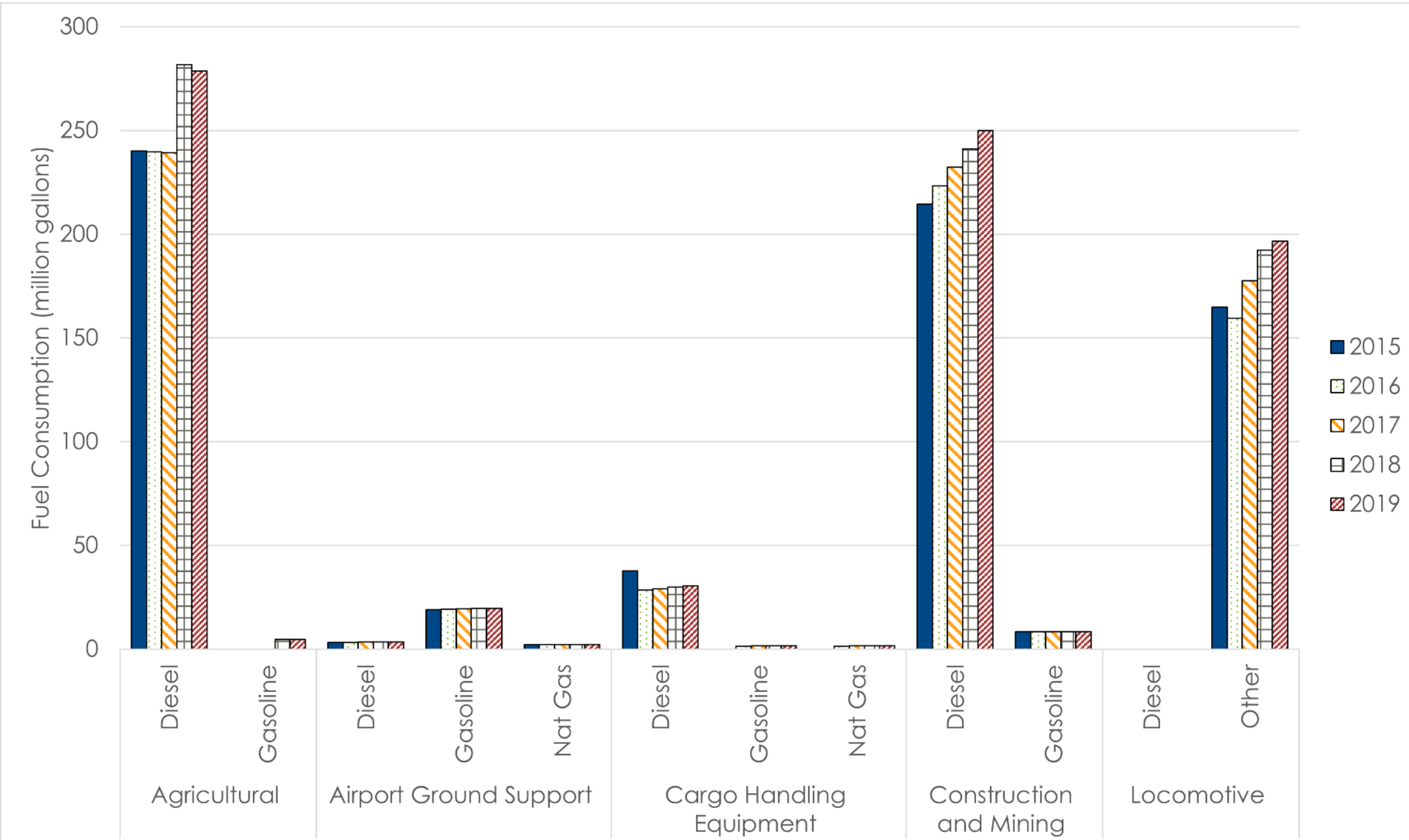


Figure 2. Off-Road Equipment Fuel Use, 2015-19 (Source: EMFAC2021 (v1.0.1) Emission Rates)



1.2 Potential Impact on Public Health and Disadvantaged Communities

Health

Exposure to diesel exhaust from off-road equipment poses considerable health risks, both for individuals working directly with the machinery and people residing in communities in proximity to the job sites where the equipment is being used.

Diesel exhaust is identified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen, meaning that there is sufficient evidence that exposure causes cancer in humans. Specifically, several studies have shown that diesel exhaust causes lung cancer and is also positively associated with bladder cancer.

Particle pollution from diesel exhaust can cause heart attacks in people who have heart disease and can worsen respiratory ailments including asthma and chronic obstructive pulmonary disease (COPD). Of critical importance recently, a study published in *Science* found that "exposure to fine particulate matter (PM2.5) has been linked to poor outcomes from COVID-19, adding urgency to the need to reduce air pollution, particularly for communities of color that are disproportionately affected by both" (Schwartzman, 2021).

Measures implemented in California to curb pollution were found to have significant health benefits to Californians. During the period 1990-2014, California reduced diesel pollution by 78%, compared to the 51% reduction on a national level after less stringent federal regulations were put in place. The positive health impact was substantial as researchers found that "excess deaths from heart and lung disease linked to diesel pollution dropped by 82% in California during that time." The researchers also reported that California's stricter regulations more than halved the number of deaths in California linked to diesel pollution that otherwise would have occurred if the state had followed federal regulations only.

Common Pollutants

The U.S. Environmental Protection Agency (EPA) established air quality standards for six common pollutants, known as "criteria" pollutants. CARB established air quality standards for the same six pollutants, adding four additional pollutants recognized as harmful. CARB further adds to this list by recognizing additional air pollutants as toxic. Many of these toxic air contaminants (TACs), which number around 200, can cause serious adverse health effects, even at low levels of exposure.

A common pollutant emitted by off-road equipment running on diesel engines is carbon monoxide (CO). CO exposure results in:

- Chest pain in patients with heart disease;
- Headache;
- Light-headedness; and
- Reduced mental alertness (CARB, 2021b)

Other common pollutants attributed to diesel engine off-road equipment use are nitrogen dioxide (NO_2) and nitrogen oxide (NO), collectively referred to as NO_x. As stated by CARB, NO_x exposure results in:

- Lung irritation; and
- Enhanced allergic responses

Off-road diesel equipment is also a source of harmful particulate matter (PM). PM is categorized as being PM2.5 (particulate matter less than 2.5 microns in aerodynamic diameter) or PM10 (particulate matter less than 10 microns in aerodynamic diameter).

Adverse health effects attributed to PM2.5 exposure include:

- Premature death;
- Hospitalization for worsening of cardiovascular disease;
- Hospitalization for respiratory disease;
- Asthma-related emergency room visits; and
- Increased symptoms, increased inhaler usage

According to CARB, exposure to PM10 results in higher rates of premature death and hospitalization, mostly from worsening respiratory disease. Outside of the body, PM10 emissions also decrease quality of life by contributing to reduced visibility, as well as material soiling.

Diesel engines currently used for most off-road equipment applications also emit sulfur oxides (SO_x). SO_x exposure results in:

- increased risk of mortality;
- exacerbated asthma symptoms;

- increased incidence of pulmonary disease and symptoms;
- decreased pulmonary function;
- increased medication usage; and
- emergency room visits (CARB, 2022b)

Disadvantaged Communities

A wide body of research supports the observation that lower income communities of color are at greater risk of adverse health effects from emissions from equipment, including diesel emissions from off-road industrial equipment. This effect is largely due to the proximity of these communities to equipment and machinery that produce harmful emissions. As explained by Cheryl Katz in a *Scientific American article*, “Due to high housing costs and historical discrimination, low-income and minority neighborhoods are clustered around industrial sites, truck routes, ports and other air pollution hotspots” (Katz, 2012).

In disadvantaged communities, higher levels of harmful pollutants are found across different demographic groups. For example, a study by the Union of Concerned Scientists found that Black Californians and Latinx Californians are exposed to 43% and 39% more PM2.5 pollution, respectively, than White Californians (Reichmuth, 2019). The same study observes that PM2.5 pollution is 13% higher than the state average where the lowest earning households in California are located. By contrast, PM2.5 pollution is 10% lower than the state average where the highest earning households in California are located.

Beyond the measure of harmful pollutants found in an area, according to recent Duke University research, the stress that members of disadvantaged communities face in their daily lives exacerbates the adverse effects of the pollutants. According to these findings, Katz explains that “the same amount of pollution may harm poor people, more than affluent people, or segregated minorities more than whites” (Katz).

A recent study published in *Science Advances* affirmed the fact that disadvantaged communities are exposed to greater amounts of harmful pollution (Tessum, 2021). Beyond that, this study singled out the role many diesel off-road applications play in exposing these communities to a disproportionate amount of PM2.5 pollution versus non-disadvantaged communities.

The researchers listed the six emissions source sectors causing the largest disparities in PM2.5 exposure for people of color (POC), Hispanics, Asians, and Blacks versus Whites.

Some of these sectors were the same for POC, Blacks, Hispanics, and Asians, including the construction industry and heavy-duty diesel equipment (as well as light-duty gasoline equipment).

The researchers of the report found that Blacks have a higher exposure than average to PM2.5 pollution across all the emissions source sectors they studied, including diesel off-road applications. By contrast, Whites have a lower exposure than average to PM2.5 pollution across most of the emissions sources. Clearly, emissions and the associated health impacts of internal combustion off-road equipment constitute an environmental justice issue that demands urgent action to correct.

II. Segments, Market Data, and Beachheads

To survey the growing availability of zero-emission off-road equipment, several segments have been defined according to where the equipment is primarily used. These segments are:

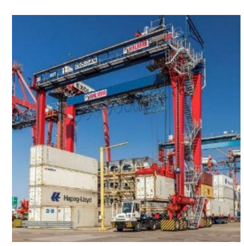
- Cargo-handling equipment, which is equipment commonly used in ports, rail yards, and distribution facilities;
- Agricultural and construction equipment, which are both grouped by their most common associations with either farm or building activities (in practice, however, equipment including a variety of loaders and dozers can often be found in both activities);
- The aviation segment, referring to ground support equipment and not aircraft; and
- Railway equipment, focusing on railcar movers and switchers and not on locomotives.

2.1 Segments Defined

Cargo-Handling Equipment

The Cargo-Handling Equipment (CHE) category consists of off-road equipment and equipment in intermodal rail yards or ports used to lift and move cargo transported by a ship, train, or other equipment. Ports and intermodal rail yards can also employ CHE for repair or maintenance purposes.

Table 2. Cargo-Handling Equipment Types and Descriptions

Equipment Type	Description	Image
Yard Truck	A type of semi-tractor with a short wheelbase and a single cab used to move semi-trailers within an intermodal facility, cargo yard, or warehouse. Yard trucks have a similar function to switcher locomotives that move railcars within a railyard. They are also called yard tractors, yard spotters, terminal tractors, yard dogs, yard goats, yard hostlers, or mules.	
Forklift	An industrial truck with rear-wheel steering used to lift and transport materials for short distances. Forklifts, ordinarily operating on level ground, use forks/blades to raise and lower standardized pallets.	
Container Handler	Material handling equipment that moves intermodal containers. Container handlers can transport containers short distances to and from vessels, railcars, or fleets at railyards, ports, and other terminals.	
Mobile Crane	A crane built to be easily moved to locations and used with different types of cargo and load with minimal or no setup. A mobile crane can be hydraulic-powered with a telescoping boom mounted on trucks or truck-type carriers, or cable-controlled and mounted on rubber-tired carriers or crawlers, or self-propelled.	
Rubber-tired Gantry Crane	A mobile version of a gantry crane, which is a crane built on a structure (a gantry) used to straddle a work zone or an object. Rubber-tired gantry cranes are usually used to pile or ground containers in intermodal operations and cover several lanes.	

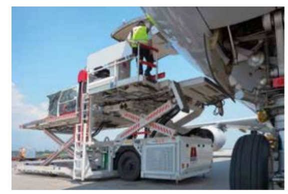
Equipment Type	Description	Image
Reach Stacker	Equipment used in medium-sized ports or small terminals to manage intermodal cargo containers. Reach stackers can quickly move containers short distances and stack them in two or three rows.	

Aviation (Heavy-Duty Ground Support Equipment)

The heavy-duty Ground Support Equipment category for aviation consists of equipment used by airports to service aircraft before departures and after landings. This powered, off-road equipment covers a wide range of operations, encompassing ground power operations, passenger and cargo loading, and aircraft mobility.

Table 3. Aviation (Heavy-Duty Ground Support Equipment) Types and Descriptions

Equipment Type	Description	Image
Refueler	Tank equipment used by airports to transport fuel to airplanes for refueling. Using an aircraft fueling nozzle, fuel is pumped into airplanes directly from large tanks on the back of refuelers.	
Belt Loader	Equipment with a conveyor belt used by airports to easily load and unload baggage and cargo onto and from an airplane. The equipment is usually placed at an airplane hold's door sill, where they can be used for rapid loading and unloading.	
Lavatory Service Equipment	Equipment that airports use to rapidly refill and empty airplane lavatories, which store waste in tanks on the plane. Once an aircraft lands, the lavatory service equipment is deployed to empty the lavatory tanks.	

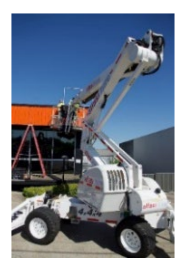
Equipment Type	Description	Image
De-icing Equipment	Equipment that coats airplanes with a mixture of ice-melting chemicals in cold weather to prevent low temperatures and frozen water from impacting the airplane's performance. Anti-icing equipment use a device similar to a cherry picker to reach the entire airplane and spray it with the anti-ice mixture.	
Cargo Loader	Equipment used for loading and unloading cargo placed on pallets or in containers. The cargo is conveyed using a wheel system or built-in rollers and moved into aircraft across the platforms.	
Tug and Tractor	Equipment used by airports to move ground support equipment that cannot move itself, including lavatory carts, bag carts, and air starters. Some larger tugs, known as pushback tugs, are used to push airplanes away from gates or pull aircraft into hangars.	

Construction Equipment

Construction equipment can be employed for a wide range of tasks including removing rocks and dirt, grading soil, demolition of existing structures, and laying foundations. Depending on their use, these machines move on wheels, rubber tracks, or steel tracks.

Table 4. Construction Equipment Types and Descriptions

Equipment	Description	Image
Excavator	A large construction machine designed to excavate earth with its shovel to make holes, trenches, and foundations. The shovel can be replaced with a different attachment so the excavator can clear brush, load and dump, grade jobsites, and drive piles.	

Equipment	Description	Image
Wheel Loader	A wheeled type of tractor ordinarily utilized to organize and load loose materials. Wheel loaders have a wide shovel mounted in front, connected to the end of two arms, or booms, that scoop up material such as sand, gravel, or dirt.	
Backhoe	An excavating machine, or digger, that has a digging shovel attached to a two-part arm consisting of a bar called a dipper that is hinged to a boom that can be drawn toward the equipment it is mounted on. This arm is usually mounted on the back.	
Skid-steer Loader	A versatile, lightweight machine used primarily for digging. These four-wheeled or tracked equipment can have their right-side wheels driven independently of their left-side wheels. Skid-steer loaders are maneuverable and compact.	
Grader	A form of heavy equipment, also known as a motor or road grader, that uses a long blade to flatten surfaces while grading. Most graders have an engine and cab on top of tandem rear axles, with steering wheels in front, followed by a blade.	
Bulldozer	A motorized machine on large tires or continuous tracks fitted with a metal dozer blade on its front. The blade can push various materials, including rock or rubble during construction or sand, snow, or soil.	
Aerial Lift	An equipment-mounted device used to elevate people. This category includes aerial ladders, articulating boom platforms, vertical towers, and extendable boom platforms. Due to their flexibility and mobility, aerial lifts are often used in place of ladders and scaffolding. Aerial lifts can be manually operated or powered.	
Trencher	A piece of construction equipment utilized to dig trenches, particularly for installing drainage or laying electrical cables or pipes. There is a wide range of sizes for trenchers, from tracked heavy equipment to attachments to small walk-behind models.	

Equipment	Description	Image
Wheel Tractor-scraper	A piece of heavy equipment, also known as a turnapull or a motor scraper, used for earthmoving. For carrying and loading material, the equipment has a hopper, also called a pan, with a horizontal front cutting edge that cuts into soil and fills the hopper.	
Asphalt Paver	A piece of equipment that lays asphalt concrete flat on surfaces including roads, parking lots, and bridges, providing minor compaction.	
Asphalt Roller	A piece of equipment, also known as a road roller and popularly as a steamroller, that uses the machine's weight to compress asphalt that was previously placed on a surface, including roads, parking lots, and bridges.	
Slipform Concrete Machine	A piece of equipment used to simultaneously level concrete on a surface while also preparing the concrete and pouring it. To help with this process, the machine pulls constantly across the surface that is being paved.	
Foundation Drill	A drill rig that bores a large hole deep into the ground to insert piles and other structures used to build a construction project's foundation.	
Pile Driver	A heavy-duty piece of equipment, often using a heavy weight between vertical guides above a pile, that drives piles into the ground to build pole-supported structures including bridges and piers.	

Agricultural

The off-road agricultural equipment category encompasses the many different types of equipment used for growing and harvesting crops and managing livestock on farms.

Table 5. Agricultural Equipment Types and Descriptions

Equipment	Description	Image
Combine	A machine, also known as a combined harvester, that can efficiently harvest a wide range of grain crops. The machine combines four distinct harvesting operations: reaping, threshing, gathering, and winnowing.	
Tractor	A low-speed, high-powered piece of equipment with large rear wheels made to pull farming implements, trailers, and other machinery most frequently used in farming, but also in construction, road building, and mining.	
Crop-Specific Self-Propelled Harvester	Harvest equipment and other specialty equipment, including hay swathers and bailers, cotton picker machines that harvest cotton balls, and nut harvesters.	
Self-Propelled Spraying and Cultivation Equipment	Equipment that applies chemicals to control insects, weeds, and diseases, as well as equipment that tills the surface of the soil to manage residues and weeds.	
Loader	A tracked or wheeled tractor with a bucket or shovel at the end of articulated arms, used to raise material and load It onto a truck. The attachments may be permanently mounted onto the equipment or removable.	

Rail

The railway equipment category encompasses equipment used around railyards and on railways themselves.

Table 6. Rail Equipment Types and Descriptions

Equipment	Description	Image
Railcar Mover	Equipment capable of traveling on both rail tracks and roads fitted with couplers for moving railroad cars and service equipment around small yards or rail sidings.	
Switcher	A small locomotive, geared to produce high torque, used for moving railroad cars short distances within a railyard, assembling them for a locomotive to take over.	
Locomotive	The train's power unit equipment that pulls railroad cars, coaches, and wagons, but does not carry freight or passengers itself. Also known as engines, locomotives are most frequently seen at the train's front or back, and sometimes both.	
Track Maintenance Equipment	Work vehicles and machines, such as ballast regulators, maintenance wagons, track ballast cleaners, rerailing equipment, track inspection vehicles, and track laying machines.	

2.2 In-Depth Market Segment Analysis

Overview

CARB's goal is to improve air pollution and mitigate greenhouse gas emissions as expediently as possible. Eliminating emissions from off-road equipment presents a challenge because much of the equipment is extremely large. Electrifying this equipment requires very large batteries or fuel cell electric systems and the installation of adequate and convenient infrastructure for recharging or refueling.

In the off-road space, the most successful strategy will focus on selecting the right initial targets for first electrification. Compact equipment presents the most promising early opportunities for transition to zero-emission technology. There are a variety of immediate opportunities for electrifying larger equipment today, particularly in specialized applications such as recycling facilities. Nevertheless, electrifying compact off-road equipment is a logical place to start because it can be done on a widespread basis enabling it to form a "beachhead."[2]

The beachhead concept, which will be explored in more depth later in this document, is built on a successful theory of change for accelerating technology transformation. It focuses early efforts on equipment categories most conducive to electrification, as defined by several considerations, including power demand, application, work cycle, business case, and technological readiness. Targeting initial electrification on these first-success applications and categories of equipment will have a spillover effect, in the form of increased component volumes, development of supply chains, and success cases for users. Because many components, such as energy storage, motors, controllers, and power electronics, are highly transferrable across equipment categories, this strategy can result in the necessary capability, know-how, and industry acceptance to electrify larger equipment and multiple applications across industry categories.

This section of the report provides a detailed analysis of the current state of play and likely prospects regarding electrification in four major off-road equipment applications: construction, agriculture, mining, and ports. It also examines the forklift equipment market. This section outlines market trends including current and future penetration levels, examines segments that have high potential for electrification and those which

[2] https://calstart.org/beachhead-model-background/

are more of a challenge, and looks at complementary zero-emission strategies such as hydrogen fuel cells.

Market Trends

CONSTRUCTION EQUIPMENT

The construction equipment market splits into seven main categories which represent the largest volume products in the sector. These categories include: mini excavators, small excavators, medium excavators, large excavators, wheeled loaders, backhoes, and skid-steer/compact tracks. Additionally, there are many small volume product categories, and within these small volume categories there are already many electrified examples.

Of the seven main categories listed above, smaller equipment has experienced the largest market penetration of battery-electric models to date, though other segments are expected to electrify in the coming years (see Figures 3 and 4). For example, battery-electric mini excavators accounted for 5% of the U.S. market in 2021 (though these sales did not penetrate the California market at all in 2021).

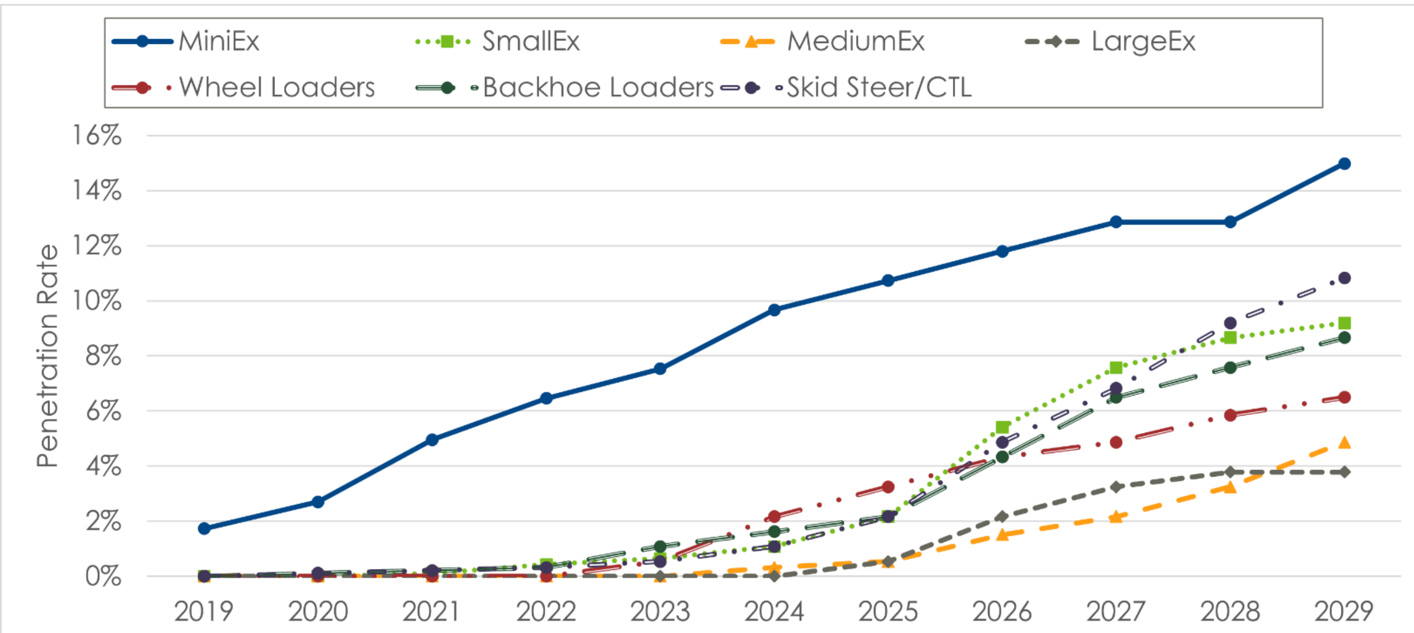
By 2029, this figure is projected to grow to around 15% of the market for both the U.S. and California, showing that over the medium-term California is expected to electrify this category at a faster rate than the country overall. The other categories with the largest electrification shares by 2029 will be small excavators (9% in both the U.S. and California), wheeled loaders (6% in both the U.S. and California), backhoes (9% in both), and skid-steer/compact tracks (11% in both).

Beyond U.S. markets, the diversity of battery-electric excavation and construction equipment in service broadens further when considering demonstrations and early commercial conversions across Europe and Asia.

Hydrogen fuel cells are significantly behind in terms of deployment in all cases, reflecting a lack of scale in terms of innovation and research and development investment in the fuel cell electric sector compared to the battery-electric sector. However, demonstrations are underway internationally and multiple OEMs such as Volvo are developing products (Construction Equipment, 2022).

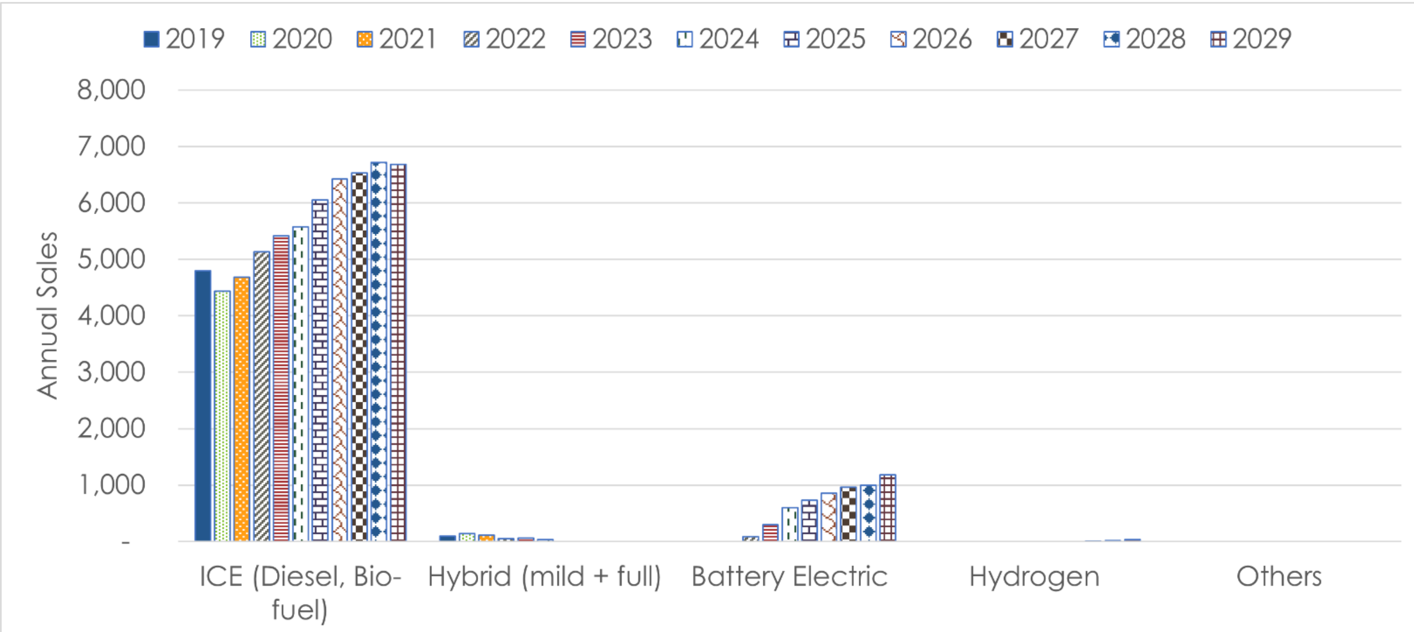
Meanwhile, the only segment where hybrid electric (mild and full)[3] is projected to come close to battery-electric in terms of market penetration by 2029 is wheeled loaders, where diesel-electric hybrid drivetrains have been commercialized for several years, particularly in the largest sizes.

Figure 3. Projected Penetration Rate of U.S. Annual Sales of Battery-Electric Construction Equipment by Type (Source: Hayfield & Zhang, 2021)



[3] Mild hybrid refers to equipment that cannot operate in electric only mode, whereas full hybrid equipment can.

Figure 4. Projected Annual Sales of Mini Excavators in California by Powertrain Type (Source: Hayfield & Zhang, 2021)



AGRICULTURAL EQUIPMENT

According to the EPA, agriculture accounts for around 11% of annual U.S. greenhouse gas emissions (EPA, 2022). However, agricultural equipment constitutes only a very small proportion of overall agricultural emissions. Despite this, zero-emission technology is advancing rapidly, and it is already possible to decarbonize many lighter categories of agricultural equipment.

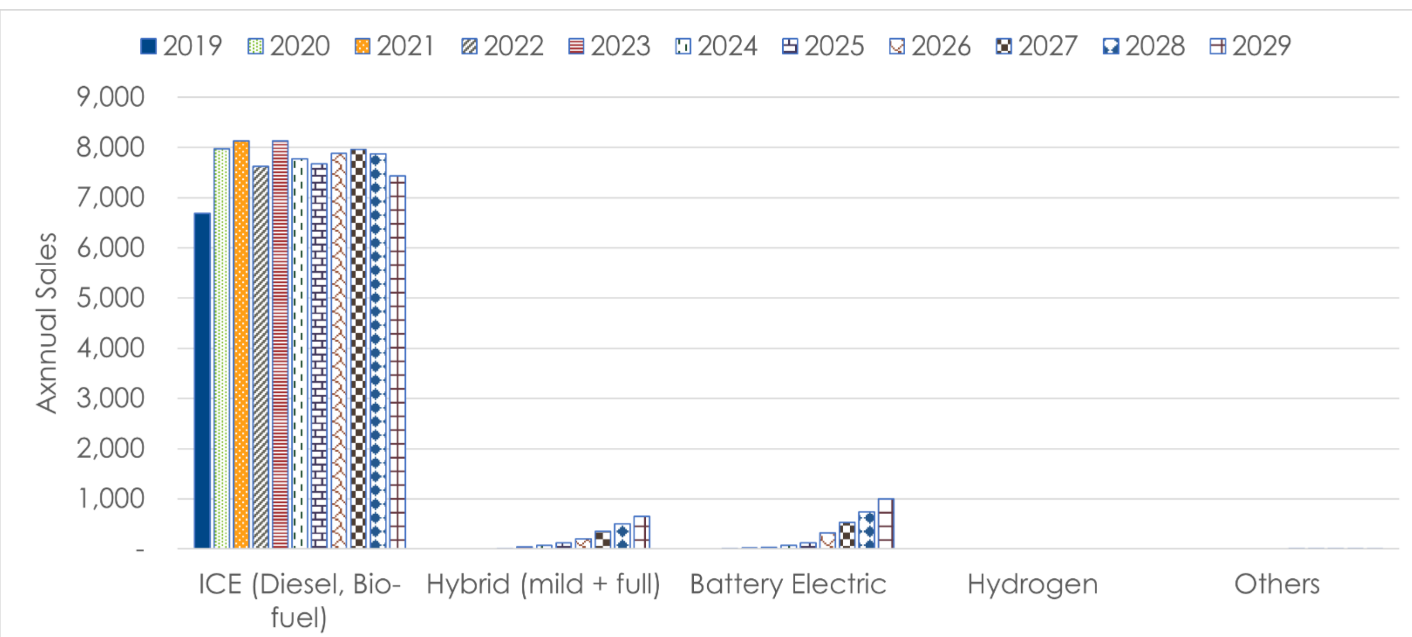
Original research conducted by market research company Interact Analysis (a collaborator on this report) with both manufacturers and end-users has resulted in projections regarding the penetration of battery-electric and hybrid electric tractors in the U.S. market. As of August 2022, there were 57 battery-electric tractors sold in the U.S. that year, making up 0.02% of total U.S. tractors sales. By 2029, there are projected to be over 3,000 battery-electric tractors sold in the U.S., equating to nearly 1% of total U.S. tractor sales. Additionally, hybrid electric tractors are projected to make up approximately 8% of the U.S.'s total annual tractor sales by 2029, numbering over 21,900 (see Table 7).

Table 7. Projected Annual U.S. Tractor Sales by Powertrain Type (Source: Hayfield & Zhang, 2021)

Technology	2022	2023	2024	2025	2026	2027	2028	2029
ICE (diesel, biofuel)	256,822	273,748	261,707	258,574	265,542	268,019	265,077	250,477
Hybrid (mild & full)	508	1,521	2,434	4,035	6,992	11,981	16,970	21,948
Battery-Electric	57	103	217	385	984	1,613	2,235	3,028
Hydrogen Fuel Cell Electric	-	-	-	-	-	-	-	-
Others	-	-	-	26	54	167	316	614

In California, Interact Analysis' research showed that by 2029 12% of approximately 8,000 annual tractor sales will be battery-electric, with another 8% being hybrid electric (see Figure 5).

Figure 5. California Annual Agricultural Tractor Sales by Powertrain (Source: Hayfield & Zhang, 2021)



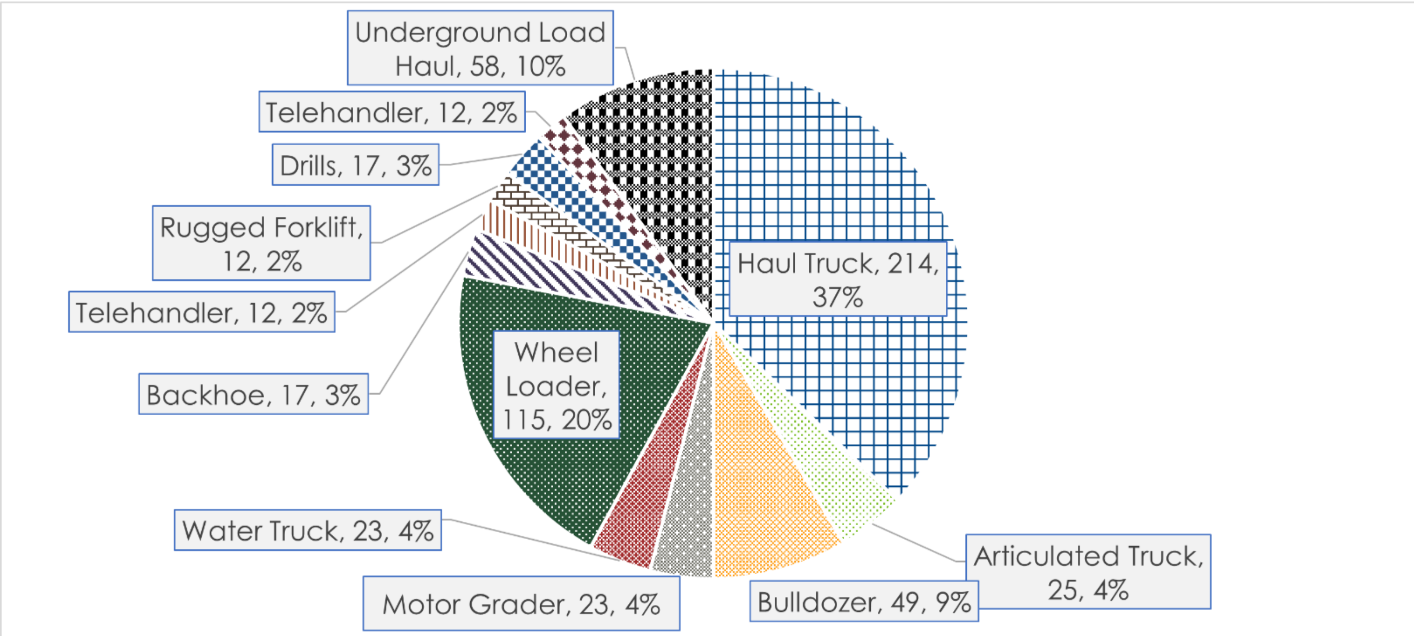
MINING EQUIPMENT

Mining equipment offers another market opportunity for zero-emission off-road equipment, though current data points to a relatively limited use of zero-emission solutions in mines. This is in part due to the relatively long lifecycles of many pieces of heavy mining equipment. For example, research from Interact Analysis shows that only 5% of hauler/dump trucks in mines are projected to be battery-electric by 2028. Nevertheless, there are compelling reasons why clean energy should be introduced into the mining sector.

First, mining equipment is often operated almost continuously. While the number of machines in operation is small, the size of the machines and their duty cycle means that emissions have an outsized impact from mining equipment. Second, there is intense scrutiny globally over the sustainability of extractive industries. Where do resources come from? Are they extracted with care for the environment? Are local populations close to mines benefitting from operations? Operating the machinery using clean energy is one part of how mining companies can both meet U.N. sustainability goals and show that they are committed to sustainable action.

Mining companies have been making commitments to decarbonize over the longer term. For example, Rio Tinto has committed to net zero emissions by 2050 (Rio Tinto, 2022). OEMs such as Caterpillar, Komatsu, Sandvik, and many others are already developing or already have electrified heavy-duty solutions for mines, as will be shown in a later section of this report. Figure 6 below shows mining equipment in California by vehicle type.

Figure 6. Inventory of Mining Equipment in California by Equipment Type (Source: Hayfield & Zhang, 2021)



FORKLIFTS

Zero-emission equipment has already significantly infiltrated the U.S. forklift market, which is currently split roughly 70/30 between battery-electric and diesel equipment. The market continues to shift even more in favor of the battery-electric option. Several lithium-ion battery suppliers for forklifts in North America have annual sales of approximately $30 million (Hayfield & Zhang, 2021). They expect to see these yearly sales rise to between $60 million and $80 million within the next three years. Some of this rise will be accounted for by the replacement of diesel models with battery-electric versions as local and national environmental legislation comes into force.

Regulations in California are particularly stringent. According to trade magazine ForConstructionPros.com, "California leads the way" when it comes to regulations encouraging the electrification of forklifts (Jimenez, 2022). CARB is writing regulations that that will "eliminate the sale of large spark-ignition (LSI) forklifts [of] up to and including 12,000 pounds beginning in 2026" (Jimenez, 2022).

The research forecasts total annual sales of over 330,000 forklifts in the U.S. by 2029, of which nearly 250,000 will be battery-electric (88,000 lead-acid and 156,000 Li-ion) (see Table 8). Meanwhile, over 10,000 are expected to be powered by hydrogen fuel cells.

Table 8. Projected U.S. Sales of Forklifts by Powertrain Type (Source: Hayfield & Zhang, 2021)

Technology	2022	2023	2024	2025	2026	2027	2028	2029
ICE (diesel, biofuel)	84,356	85,419	86,340	84,903	81,428	81,443	82,174	78,966
Battery-Electric lead acid	116,815	112,431	105,227	106,860	103,302	93,192	87,905	87,982
Battery-Electric Li-ion	50,240	66,734	85,284	95,502	113,374	131,769	144,225	156,413
Hydrogen Fuel Cell Electric	3,440	4,029	4,387	5,504	6,084	7,213	8,722	10,001

California will see a similar distribution of the different kinds of powertrain technologies in its projected 2029 forklift sales of around 39,000 units: nearly 30,000 zero-emission, including approximately 28,500 battery-electric and 1,170 fuel cell electric (see Table 9).

Table 9. Projected Annual Sales of Forklifts in California by Powertrain Type (Source: Hayfield & Zhang, 2021)

Technology	2022	2023	2024	2025	2026	2027	2028	2029
ICE (diesel, biofuel)	9,870	9,994	10,102	9,934	9,527	9,529	9,614	9,239
Battery-Electric lead acid	13,667	13,154	12,312	12,503	12,086	10,903	10,285	10,294
Battery Electric Li-ion	5,878	7,808	9,978	11,174	13,265	15,417	16,874	18,300
Hydrogen Fuel Cell Electric	403	471	513	644	712	844	1,020	1,170

PORT EQUIPMENT

The San Pedro Bay Ports, comprised by the Ports of Long Beach and Los Angeles, present an example of a powerful work in progress toward lowering emissions in port environments. The twin ports complex has set its target of emission-free goods movement by 2030. The San Pedro Bay Ports' 2021 clean air assessment reports that the four main categories of port equipment are currently dominated by ICE technology (San Pedro Bay Ports, 2021). These categories include: 1,615 yard tractors, of which 80% are powered by conventional diesel engines; 560 forklifts, of which nearly 40% are heavy capacity powered by diesel technology; 159 RTG cranes, which are almost wholly powered by diesel engines; and 389 container handlers. Meanwhile, 23%

of the cranes use advanced ICE/hybrid electric technology that achieves higher efficiency and reduces emissions. The San Pedro Bay Ports' latest assessment differs from their 2018 version in that it highlights the use at port facilities, either in full deployment or in the pilot stage, of at least 20 pieces of battery-electric or fuel cell electric cargo handling equipment. These include yard tractors, container handlers, and large capacity forklifts. While the development of this equipment is in its early stages, it indicates that cargo handling equipment manufacturers are making significant advancements in the powering of heavy-duty container handling equipment with low or zero-emission powertrains.

Equipment Segments with High Potential for Electrification

Regardless of the equipment category, reduced maintenance costs are a significant advantage of zero-emission off-road equipment. Because battery-electric equipment (Raftery, 2018) has around 20 parts in the drivetrain, compared to more than 2,000 parts for internal combustion engines, there are significant reductions in maintenance costs and in unplanned breakdowns for electric equipment. Reports show that spending on repair and maintenance of battery-electric equipment is often almost half the price compared to corresponding ICE models (Office of Energy Efficiency and Renewable Energy, 2021).

The other sizeable cross-category advantage is fuel costs. A March CNBC story showed that diesel was already over $5 per gallon across the U.S. (Domm, 2022). Research from Interact Analysis (see Table 10) compares a range of costs to show the total cost of ownership for a 2.5-ton mini excavator in California over a five-year period. The TCO for the electric model is already lower than that of the ICE model, and this gap will widen considerably as such equipment moves into mass production, bringing down the retail price of the battery-electric machines. On maintenance and service, battery-electric machines are already 50% less costly, while the cost of fuel over five years is $24,554 for the ICE model compared to $2,100 for the battery-electric model.

Table 10. TCO Calculation for a 2.5 Ton Mini Excavator in California for a 5-Year Ownership Period (Source: Hayfield & Zhang, 2021)[4]

Mini Excavators	Electric	ICE
Retail price ($)	90,000	40,000
Residual price @ 5 years ($)	50,000	22,500
Fuel price ($)	$0.14/kWh	$5.50/gallon
Fuel efficiency (liters/hr)	4.0	4.5
Fuel cost over 5 years ($)	$2,100	$24,554
Maintenance & service ($)	$2,500	$5,000
TCO	**$44,600**	**$47,054**

In addition to reduced fuel and maintenance costs, electrification of off-road equipment can deliver added benefits in enclosed or restricted environments such as factories and warehouses, mines, indoor spaces, and urban settings. These added benefits include improvements to air quality and the reduction of noise pollution.

Funding Incentive Options

The off-road segment has strong potential to transition to zero-emission technologies, though to date the market has been slow to adopt them. Increasing interest and resources are leading to real-world incentives designed to support this transition. This trend will accelerate with the recent inclusion of off-road equipment in California Governor Gavin Newsom's 2021 Executive Order N-79-20. Sales of off-road equipment in California will transition entirely to zero-emission models by 2035, which is expected to have broad impact on sales and usage of zero-emission models across the country. Programs that have funding allocated to incentivize purchases of zero-emission off-road equipment are discussed below.

CORE

Akin to the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), the Clean Off-Road Equipment Voucher Incentive Project was created to motivate users in California to buy or lease zero-emission off-road freight equipment. With $194 million in 2022 funding procured through proceeds from the state's Cap-and-Trade Program, CORE offers a streamlined voucher process enabling buyers to gain funding

[4] TCO assumptions include: 2022 prices; no infrastructure cost, that a high diesel price remains locked in; residual value is a best guess given the absence of previous data points to support it; and that contractors can procure electricity below commercial rates but above wholesale costs

to offset the higher up-front price of zero-emission equipment versus existing internal combustion models. There is no scrappage requirement for purchasers. The program offers additional funding for the implementation of zero-emission freight equipment and corresponding infrastructure in disadvantaged and low-income communities.

The CORE Voucher Funding Map (Clean Off-Road, 2022) on CORE's website is a tool intended to visually represent the distribution of vouchers approved and redeemed in the CORE Project throughout California. The map allows users to filter data based on the types of equipment funded by geographic areas in which they operate, such as the air district, the county, and state assembly and senate districts. The map also allows users to refine information by the voucher status, the equipment manufacturer, utility territory, and whether they operate within priority populations—meaning disadvantaged or low-income communities.

Volkswagen Mitigation Fund

The Volkswagen Environmental Mitigation Trust was established to disburse funding made available because of partial settlements with Volkswagen over their use of illegal emissions testing defeat devices to alter emissions data from their diesel equipment. The trust offers approximately $423 million to California to mitigate excess NO_X emissions caused by the manufacturer through the use of these devices.

Potential purchasers who wish to "scrap and replace" heavy-duty off-road equipment (as well as on-road equipment) can access this funding to purchase zero-emission models. Among such equipment are: forklifts, marine vessels, and port cargo handling equipment. As directed by legislation, CARB seeks to allocate 35% of the available funds for California to equipment deployments that help reduce air pollution for disadvantaged or low-income communities (California VW Mitigation Trust, 2019).

Carl Moyer Program

Named for a leading figure in the development of California's air quality standards, the Carl Moyer Memorial Air Quality Standards Attainment Program (Moyer Program) provides around $60 million annually to replace polluting engines in California (CARB, 2022a). The program currently addresses the need for zero-emission and near-zero-emission equipment via funding incentives that can be combined with those from other funding sources. The program has a scrappage requirement. At present, for the off-road equipment sector, certain agricultural tractors developed for off-road use are eligible for Moyer funds.

Funding Agricultural Replacement Measures for Emission Reductions Program (FARMER)

In September 2017, CARB received $135 million to reduce emissions from the agricultural sector from Assembly Bill (AB) 134 (Committee on Budget, Chapter 254, Statutes of 2017) and AB 109 (Ting, Chapter 249, Statutes of 2017). The bills provide funding for agricultural harvesting equipment, heavy-duty trucks, agricultural pump engines, tractors, and other equipment used in agricultural operations. CARB staff worked with local air districts and stakeholders to develop the proposed Funding Agricultural Replacement Measures for Emission Reductions (FARMER) Program Guidelines, which set the minimum requirements for the program and ensure that the projects funded will provide the intended emission reductions. Since the program's inception, FARMER has allocated $535 million statewide and has funded 6,662 pieces of equipment for a total of $289.7 million (CARB, 2022a). Of that, FARMER has funded 2,333 pieces of zero-emission equipment totaling $28.3 million.

Diesel Emission Reduction Act (DERA)

The Diesel Emission Reduction Act (DERA)[5] program was authorized by Congress in 2005 and reauthorized in 2010. DERA's objective is to fund cost-effective projects, targeting disproportionately affected communities. The DERA State Program, National Program, and Tribal & Insular Area Program provide project funding to eligible entitles to achieve significant reductions in diesel emissions that impact a variety of sectors and types of equipment including, but not limited to, on-road, off-road, locomotive, and marine. Projects can include equipment replacements, engine replacements, idle-reduction, exhaust retrofits, and more. Eligible uses of funding include off-road engines and equipment used in: construction, handling of cargo (including at a port or airport), agriculture, mining, and energy production (including stationary generators and pumps).

[5] For more information, visit: https://www.epa.gov/dera

TARGETED AIRSHED GRANTS

The Targeted Airshed Grants program was authorized by Congress in 2010, and it has been renewed every year since 2015 (U.S. EPA, 2022). This program helps local, state, and tribal air pollution control agencies develop plans and implement projects to reduce air pollution in nonattainment areas identified by the EPA. The Targeted Airshed Grants program's overall purpose is to minimize air pollution in parts of the country with the highest levels of ozone and PM2.5 ambient air concentrations. Projects funded through Targeted Airshed Grants can include equipment replacements, engine replacements, idle-reduction, exhaust retrofits, and more. A list of recent recipients can be found on EPA's grant recipient page.

Beachhead Model Application for Off-Road Equipment

In conjunction with CARB, CALSTART developed the "beachhead model," an organized strategy to advance technological development and adoption of zero-emission technologies. In historical terms, the word "beachhead" most commonly refers to efforts by Allied troops in World War II to secure portions of the beach in Normandy. Once beachheads were established, they gave an entry point for forces to spread out across Europe.

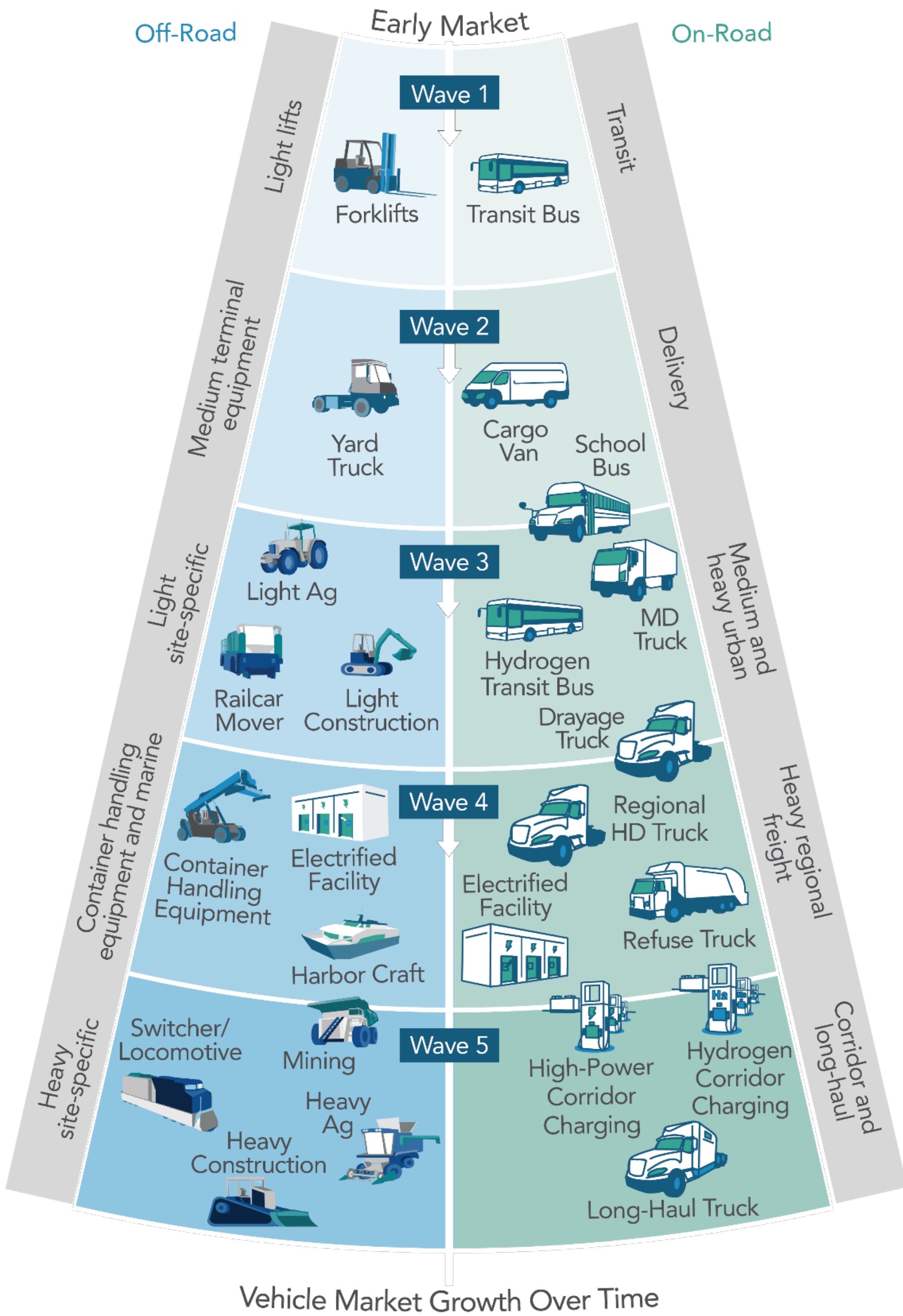
Similarly, the first successful applications of new off-road zero-emission equipment technologies can be thought of as beachheads. As a direct result of those first successful applications, further rounds of equipment applications can reach the market, from different versions of the same equipment to different equipment in adjacent markets. These further efforts build upon the initial success of this "beachhead" by leveraging the established business cases as well as expansions in infrastructure and increased supply of shared components. Progress in the beachhead model is not siloed on either side of an on-road and off-road "divide." Instead, there is a large degree of overlapping and intertwining between the two.

In Figure 7 below, it is clear that forklifts served as the first mover for off-road zero-emission equipment. The market success of both battery-electric and fuel cell electric forklifts has paved the way for the next wave of zero-emission equipment, most notably off-road yard trucks, cargo vans, and school buses for on-road zero-emission equipment. Another example of the development of zero-emission drive components is showcased in early-model hybrid electric buses which led to their use in fully emission-free buses. Progress in further developing clean powertrains in on-road equipment can lead to advances in implementing zero-emission off-road equipment such as tractors.

Equipment in later waves builds off advances in previous waves as a result of:

- Increases in available infrastructure, for example at ports and airports;
- A broader understanding of the business case, as well as heightened confidence in product performance;
- Shared components, including motors and energy storage;
- Larger and more efficient supply chains; and
- Reduced costs for components and energy storage, leading to greater capabilities in implementation

Figure 7. Visualization of Off-Road and On-Road Zero-Emission Equipment Implementation Progress Using the Beachhead Model Framework



For more information about the CALSTART beachhead strategy, refer to CALSTART's dedicated beachheads white paper (CALSTART, 2022).

The next section examines equipment segments that are currently making rapid electrification progress. These are segments forming the beachheads that will ultimately allow electrification to extend across the entire off-road equipment ecosystem.

UNDERGROUND MINING EQUIPMENT

Underground mining equipment is one of the most promising sectors where moving toward complete electrification of certain equipment types is concerned. CALSTART's research has concluded that most categories of underground mining equipment, such as load, haul, dump (LHD) machines, and drills will be almost entirely battery-electric by 2030 (or by 2035 at the latest). The advantages the electrification of mining equipment can offer are broad, in that it reduces heat, noise, and pollution, in addition to delivering major and immediate cost benefits because there is no longer the need for the large infrastructure and power systems such as air filtration and thermal management systems which are required when internal combustion engines are used underground.

Using electrified equipment in mines offers additional benefits as well. Battery-electric machines have more low-end torque than their ICE equivalents, giving them greater hauling power at low speeds. They can also complete necessary tasks more rapidly. Trials of Sandvik's 750 50-ton underground dump truck at New Gold's New Afton gold mine in British Columbia saw a 56% decrease in the mucking cycle time compared with a diesel-powered equivalent and a 70% increase in ramp speed (on a 17% ramp) (Gleeson, 2022). There were also decreases of 80% and 90% in energy use and heat generated, respectively. Battery-electric equipment is also smaller. According to Sandvik, "a 50-ton capacity battery-electric truck is the size of a 40-ton traditional truck." This means that tunnels can be smaller, so less waste is created as they are dug, and they are cheaper to build.

There are a number of "Ultra class" 100-200+ ton payload capacity range zero-emission haul trucks in demonstration, both battery-electric and fuel cell electric. For example, major global OEMs such as Caterpillar have been demonstrating their equipment with BHP and Rio Tinto. There are also in particular on the fuel cell electric haul truck side at least five efforts underway: a Volvo prototype construction rock truck, an Anglo

American 900kw fuel cell electric truck recently assembled in South Africa, a Fortescue fuel cell electric truck in Australia, vehicles that the HYDRA consortium is developing for Chile, and trucks made by Weichai Power together with CRRC Yongji. These very large machines have been receiving high priority for electrification specifically because of their immense size and high fuel consumption.

CONSTRUCTION EQUIPMENT

In the construction sector, though there has been limited progress in electrification beyond small compact equipment such as mini excavators, small wheel loaders, and dump trucks, many categories of equipment are well-suited for electrification. In fact, construction equipment could be described as the "low-hanging fruit." The relative lack of federal or state-level government financial incentives in the United States, compared to Europe, is challenging for U.S.-based equipment operators. However, California is an outlier in this regard, providing significantly more government funding for decarbonization of off-road equipment than most U.S. states (for more details, see page 28 above).

Another hurdle is the perception of electrified equipment within the construction industry. The challenge is that it is widely believed that a piece of electrified equipment cannot complete tasks because it would run out of charge too quickly to be practicable. When it comes to the largest high energy consumption machines, this is indeed currently the case, although there are examples of significantly sized equipment that can run a full shift.

Access to charging may also require innovative solutions for the construction sector. While charging is typically less of an issue for industrial applications or urban construction sites, it can be particularly challenging on remote sites.

These conditions are rapidly changing as experience with equipment grows and innovative solutions are developed. The heavy-duty equipment market will ultimately need to decarbonize and, when it does, whatever solutions can power large trucks will very likely also be applicable to the largest construction equipment, as the powertrains and energy storage components are highly transferrable.

Already, many zero-emission construction equipment types are available in the U.S., enabling adoption for large swaths of the construction equipment market (Doyle, 2021). Many smaller machines already have battery lives of over 8 hours, and there are strong benefits to electrification that are not yet fully understood by the U.S.

construction market. A major benefit is a positive TCO. One example is Bobcat, which has introduced the T7X compact track loader (for which it received the 2022 CES innovation award). Other examples include JCB, which has introduced the I9C-IE battery-electric compact excavator (JCB, 2022), and Volvo, which offers a recently expanded battery-electric construction equipment range (Volvo, 2022).

In April 2019, McKinsey, in its insight "Harnessing momentum for electrification in heavy equipment," contended that battery-electric technologies could be economically viable in all machine types in the construction industry by 2023 (Forsgren *et al*, 2019). Their positive cost assumptions are based on the 40% to 60% lower operating costs of battery-electric equipment, as compared to ICE equipment, owing to the much greater efficiency of battery-electric propulsion, with a 70% to 75% higher tank-to-wheel energy efficiency, which reduces fuel consumption. McKinsey also factored in the lower maintenance costs of a battery-electric powertrain, compared with a diesel powertrain. As with all battery-electric equipment, fuel costs can be greatly reduced. One Volvo pilot project which measured 400 operating hours of battery-electric equipment use saw fuel savings of $2,400 per unit (Doll, 2021).

Aside from clear environmental benefits, battery-electric construction equipment is very quiet compared to its internal combustion equivalents. This means there is significantly reduced risk of hearing damage to equipment operators, as well as a reduced need to use ear protection (Volvo, 2021). Communication at work sites can be increased with lowered noise levels, carrying the potential for greater operator safety. Reduced noise also brings significant potential business benefits. The first of these is that it becomes possible to work longer hours on urban construction sites without disturbing nearby residents. This may allow operators to finish urgent projects faster. Reduced equipment noise will likely also make it easier to acquire planning permission for new developments in built-up areas. The Clean Construction Declaration, which has been signed up to by both San Francisco and Los Angeles, has committed to use the power of city procurement to encourage the use of low-emission construction machinery. The declaration specifically singles out construction machinery, requiring the use of "zero-emission construction machinery in municipal projects from 2025" (C40 Cities, 2021).

SMALL TRACTORS

There are three guiding factors that farmers and policy makers can consider in the short- to medium-term with regard to the decarbonization of agricultural equipment:

which equipment niches can be decarbonized immediately; what more can be done to reduce larger equipment emissions where switching out internal combustion engines is not an immediate option; and what funding is available. Broadly speaking, the agricultural equipment segments that are currently primed for decarbonization are those segments that use low speed, lightweight equipment. Policy makers and farmers who want to achieve immediate agricultural equipment decarbonization successes should consider focusing on these niches. This requires taking a local view. Different climates mean that most regions of the U.S. produce different agricultural products, so the lightweight agricultural machines in use in a place such as Oregon are likely to be very different from those used in Florida, for example. For this reason, state-level actors (and farmers themselves) are best placed to take action. That said, there are often common powertrain components that could be used even across multiple types of different machine applications.

In the case of California, one important sector where equipment decarbonization has already begun is the state's numerous vineyards and orchards. In August 2021, Organic Grower reported that the Solectrac e70N battery-electric tractor was being deployed in two vineyards: Arroyo Lindo Vineyard in Windsor and Old School Vineyard in Napa, as well as at The Mushroom Farm in Pescadero (Organic Grower, 2021). This machine is a narrow width model, purpose built for vineyards and similar smaller scale farming operations, and it offers up to eight hours of operation from a single charge, as well as the ability to extend this with swappable battery packs. Another provider is Monarch, which has also published case studies of California vineyards using their battery-electric tractors. One example is Wente Vineyards, which reported significant benefits including fuel cost savings. According to a 2021 case study published by Monarch, Wente are saving an average of $2,655 in fuel per tractor (assuming 1,000 hours annual run time), with approximately $0.16/kWh electricity prices compared to nearly $3/gallon diesel prices (Monarch, 2021). Conventional fuel prices as of the writing of this report were nearly double that, accelerating the payback period for zero-emission tractors.

However, upfront purchase price for these tractors remains significantly more expensive than ICE tractors. For example, Solectrac's tractors cost 20% more than the diesel equivalent. Additionally, even a basic agricultural battery charger suitable for light equipment can cost up to $50,000, varying greatly depending on the power available on site. This significantly limits the addressable market for battery-electric agricultural equipment. In terms of farmers themselves, they are only likely to opt for battery-electric equipment if they have strong personal convictions about climate change or sustainability (and the money to fund these convictions), or if they have higher margin products that can afford to absorb the equipment price and perhaps use sustainability as a marketing tool (such as potentially with organic farms or sustainable vineyards, where consumers may actively want to purchase a product that has a low carbon footprint). Government support to help overcome this purchase price disparity is therefore crucial to get this industry off the ground.

Enacting and providing funding now could result in industry leadership in the future. For example, both Solectrac and Monarch are based in California. There is a very good reason for that: California has the political will to decarbonize. This manifests itself in the form of significant funding opportunities for the replacement of high polluting equipment, which is driving local deployment of decarbonized agricultural equipment wherever possible. One example is the previously mentioned FARMER program, which has funded 2,333 pieces of zero-emission equipment totaling $28.3 million, including 2020 grants of $500,000 each to Monarch and Solectrac (Green Car Congress, 2021). Both Soletrac and Monarch participated in the California Air Resources Board’s off-road incentive project CORE in 2022 and their combined category secured $10.75 million, demonstrating a significant market interest in zero-emission technologies in agricultural applications. As these companies grow and become more successful, not only will California’s agricultural sector decarbonize, but the state will also increase its clean energy jobs and its tax base by hosting these clean tractor manufacturers.

Small tractors can be complemented by cross application of a number of compact construction equipment types into the agricultural space particularly in the animal care area (where they can be particularly beneficial since quiet battery-electric machines do not disturb livestock) (cze seed, 2021), as well as for work in greenhouses and produce packing operations. Such equipment can include wheel loaders, skid-steers, and multipurpose small telehandlers. There are also European examples of battery-electric self-propelled feed processing and dispensing equipment.

FORKLIFTS

The forklift sector has been electrified for decades. Regular deployment of forklifts in enclosed environments pushed lead-acid technology in this domain. Meanwhile, the arrival on the scene of the lithium-ion (Li-ion) battery is a technological step up from lead-acid batteries. Li-ion batteries still have a large price premium compared with their lead-acid counterparts, and the latter is a well-proven technology, but-lead acid requires regular maintenance, and does not last as long. Li-ion batteries require no maintenance, have a longer lifespan, are more efficient, and the battery chemistry accepts a higher rate of current, meaning batteries can be charged faster. Forklifts powered by lead-acid cells currently occupy roughly 80% of the electrified market but they will be gradually displaced by their Li-ion equivalent, with the current 80/20 ratio in favor of lead-acid reversing to 30/70 by 2030.

In the North American market, the development of Li-ion forklift technology is relatively stable, increasingly focusing on control, quality, and service. According to feedback from the American market, the price of lithium batteries for forklifts in North America is generally two to three times higher than that in China. North America also has stricter battery structure and safety protection measures. But the boom in warehousing in particular will drive the battery-electric forklift market in North America. Bloomberg reported in January 2022 that e-commerce sales surged to a record 15.7% of total retail sales in 2020 (Monteiro, 2022), and there appears to be very little let-up at the time of writing this paper. The need for speed and efficiency on the warehouse floor will continue to fuel the demand for electrified forklift solutions, of both the manned and automated varieties.

PORTS

The EPA estimates that emissions from port operations expose the millions of people living in close proximity to harmful levels of air pollution associated with diesel engines. This pollution includes particulate matter, nitrogen oxides, ozone, and air toxics which can cause serious health problems, including those related to heart and lung disease and cancer and can also cause respiratory problems, particularly among young children, the elderly, and those exposed directly to the emissions. For example, in 2013, a study by the Just Health Action and Duwamish River Clean-up Coalition revealed that some residential neighborhoods near Seattle's port had a 13-year shorter life expectancy than areas farther from the port (Stand.earth, 2022). A more recent 2019 study by the International Council on Clean Transportation (ICCT) also found that "the ports of Seattle/Tacoma and San Francisco have the highest rates in the U.S. of early deaths per 100,000 residents from port pollution, more than double the global average" (Stand.earth, 2022a). Port-related diesel emissions such as CO_2 also contribute to climate change.

Ports present a range of relatively straightforward electrification options. One of the most effective in terms of reducing emissions is a system known as cold ironing, where docked ships are powered "shore-to-ship" by an electrical power source mounted on the quayside, thereby eliminating the need to keep the ship's diesel engines running. CARB is currently working to extend cold ironing to nearby anchorages. Other options include electrifying port cranes, cargo-handling equipment, and drayage trucks. The ports of Los Angeles and Long Beach have given themselves a target of emission-free goods movement by the 2030s as mentioned earlier. The infrastructure and equipment associated with this project is expected to cost up to $14 billion, an investment that is being made across multiple partners and involved parties.

Path Forward for Electrifying Larger Off-Road Equipment

The very largest equipment across all sectors (mining, construction, agriculture, and ports) will be the most challenging to decarbonize immediately. However, the direction for change has been set. In 2021, the International Council on Mining and Metals group of major mining companies committed to net zero carbon by 2050 (ICMM, 2021). Currently, some large haul and dump trucks used in mining have electrified drivelines with their wheels driven by electric motors. However, this is a hybrid arrangement with the power for these motors being provided by a large onboard diesel engine, connected to an inverter which generates high voltage AC power. While it is technically possible to replace these diesel engines with batteries or with a hydrogen fuel cell, the batteries or hydrogen fuel cells needed to drive large equipment with current technology would be very large. However, many zero-emission underground haul trucks in the 15-50 ton capacity are already in operation and commercially available (such as CAT's battery-electric LHD). Some such pieces of equipment use fast charging technology and others use battery swapping, while a small set use overhead power cables (catenary) to power their systems. That said, there is already one larger equipment solution in development, Sandvik's battery-electric 65-ton TH665B, which will be the largest-capacity battery-electric truck for underground mining when it enters the market (Gleeson, 2022). It will get its first trial run at AngloGold Ashanti's Sunrise Dam gold mine in Western Australia in late 2022, prior to it going into commercial production in late 2023. This truck will be available with automated battery-swap technology.

Although recharging large battery-electric mine equipment can prove challenging, there are also reports of electrification breaking out into surface mining, especially haul trucks (Moore, 2022). There is a strong push to address the challenges and realize the energy and emissions reductions available for large mining operations, and this is reflected in the progress that is being made in Asia, Africa, Australia, Canada, and Chile on using batteries or hydrogen (of both the hydrogen fuel cell and hydrogen ICE varieties) to electrify the largest mine haul trucks. Mining is an ideal place to start with electrifying heavy equipment because mines tend to be in place for years and operate continuously, meaning that the case for investing in charging infrastructure and on-site power generation is strong (unlike in agriculture which is seasonal or in construction where sites are only worked on for a short period). A number of mines are therefore converting to zero-emission or starting up as zero-emission operations. Strong support is being offered from OEMs as well (CBC news, 2021).

If battery-swap technology is not available, there are various means of achieving the significant charging that large truck batteries need while mitigating the potential productivity hit that waiting for slow charging might imply. To overcome this challenge, very large fast charging systems are being developed and operations arranged to allow opportunity charging during loading and unloading or even while underway with catenary (trolley wire/pantograph) systems. Pantographs can be prohibitively expensive unless built for mines that are planned to be in operation for decades, and they should ideally be paired with renewable generation (e.g., solar and/or wind) to ensure a green electricity supply. According to the Electric Mine Consortium, "mine scale energy storage technologies are not yet operationally or economically proven in mining," although many OEMs and large mining organizations are working to change this by funding innovation (Electric Mine Consortium, 2022). For example, the Charge On Innovation Challenge, being funded by BHP, RIO Tinto, and Vale, is a competition to encourage development of haul truck electrification systems. Meanwhile, Anglo American has unveiled a 2-MW fuel cell electric 300-ton haul truck, as well as plans for on-site renewable hydrogen generation.

Efforts to decarbonize larger agricultural equipment experience similar challenges to these efforts in the mining sector. Again, the machines are very big, meaning that the batteries that would be required to run them for extended periods are currently too large. Additionally, the chargers are also very expensive. In fact, for large machines, powerful rapid chargers costing up to $100,000 are needed. Furthermore, charging/refueling infrastructure presents difficulties; farms/fields can be remote and there is often limited access to electricity, while the transportation and storage of hydrogen can be a logistical challenge. The duty cycles of farm machines add to the complexity. Agricultural equipment often sits unused for long periods and then undergoes phases of dawn-to-dusk intensive use. There are questions about whether electrification is currently suited to this: for example, will batteries hold their charge, or would farmers need to charge up equipment immediately before use?

Also, when machines are suddenly urgently needed to harvest a large crop, requiring round-the-clock work, most farmers cannot afford the time needed to make regular recharging stops.

Another challenge for decarbonizing agricultural equipment is the fact that machines are by no means the sector's major source of GHG emissions. In fact, agricultural equipment's contribution to emissions is tiny when compared to those generated through enteric fermentation. This means that the agricultural sector generally views electrification of equipment with less urgency than other sectors. However, the presence of other greenhouse gas sources does not lessen those greenhouse gases emitted from these large pieces of equipment. The easier initial decarbonization steps are to improve hydraulics, substitute direct electric actuation, and use ancillary electrified equipment and farming implements to enable precision agriculture. These may be more attainable ways of reducing emissions in the near term.

Construction equipment was discussed at length in an earlier section. Though the zero-emission technology is already quite advanced, the construction industry would benefit from increased education, technical assistance, and funding. That said, charging downtime continues to be a major challenge, though charging technology is making significant improvements, with battery-swapping solutions and high-power charging up to 1.5 megawatts being developed (McKinsey, 2019). But there will still be some types of heavy equipment where adoption will be slow owing to the remoteness of work sites and challenges around access to electricity, or where duty cycles are not arranged for regular charging. Fuel cell electric systems may provide an opportunity for decarbonizing these applications, particularly if remote hydrogen generation can be developed. Increasing examples of larger equipment are appearing, both from OEMs (Hyundai, Komatsu, VolvoCE, Leibherr, Junttan, Dynapac) and a diverse set of third-party conversions. There is a growing cohort of fuel cell electric large equipment in demonstration, including multiple tracked and wheeled excavators, articulated haul truck, and large rock drill examples.

Establishing a Beachhead

While there remain a range of challenges to fully electrifying larger equipment today, CALSTART's previously mentioned beachhead model provides some of the answers. The beachhead model shows that the electrification of larger equipment can be achieved by using small equipment electrification as a starting point. We already see examples of this in the large electrified mining equipment mentioned above. The reason is that as large fleets of compact equipment are electrified, it has some key benefits that make the electrification of larger equipment more likely. These benefits include that the charging infrastructure grows, that employees and companies that were previously skeptical of electrified equipment learn to accept it in principle, and that research and development spending in the electrified segment as a whole is boosted. The result is that the technologies needed to develop larger zero-emission equipment will evolve faster.

Clean Alternatives to Battery-Electric Powertrains

Hydrogen Fuel Cells Require Additional Advancements

A key advantage of fuel cell electric technology is its high energy density, meaning it can drive large equipment for long periods with a high degree of efficiency. Fuel cell energy efficiency is around 60%, compared to 20-30% for internal combustion engines (and nearly 99% for Li-ion batteries). Fuel cells produce zero emissions when used and are practical insofar as the refueling process is quick and easy. However, there are some technological barriers which are yet to be overcome. For example, infrastructure is a major challenge to fuel cell technology, raising concerns about affordability as well as the safety and security of liquid hydrogen transportation and storage.

Additional barriers to widespread fuel cell electric equipment adoption include the cost and carbon footprint of hydrogen fuel. There are two main processes by which hydrogen is produced: Extraction from natural gas, and electrolysis. The former is a process called "Steam-methane reforming," and this procedure involves significant carbon dioxide emissions. Electrolysis, the process of extraction of hydrogen gas from water, involves the use of large quantities of electricity, which may not necessarily be sustainably generated.

That said, it is important to note that progress is being made on the generation of green hydrogen, meaning production through electrolysis using renewable energy. For example, the United States has ambitious plans for the roll-out of fuel cell technology. The Department of Energy is in the process of allocating $8 billion for the development of "Hydrogen Hubs" across the country that should transform the supply of hydrogen to a number of end use cases, including off-road equipment. Fuel cell electric equipment certainly can be a component of a push to fully transition to zero-emission equipment.

Hybrid Electric

Finally, hybrid electric technologies must be considered. Part three highlighted hybridized LHDs used in mining, where electrified wheel drives and ancillary equipment run from power generated by a diesel engine. There are various hybrid configurations which can be used in scenarios where full electrification is not or not yet an option. These technologies can be sophisticated, as seen in Volvo's EC300E hybrid electric excavator which utilizes advanced technology that stores energy generated by the downward motion of the excavator's boom and uses it to drive the hydraulic assist motor that helps power the engine system. This arrangement, according to Volvo, results in a fuel efficiency improvement of up to 17%. Hybrid electric excavator examples such as the Kobelco SK200H-10 have been on the market since 2016. The Komatsu, with its supercapacitor/swing axis approach, has been available since 2008. The durability potential of electrified drivetrains in off-road equipment is illustrated by a 20,000-hour warranty that John Deere has offered on their hybrid electric wheel loaders (Grayson, 2017).

Takeaways from the Netherlands Model

The Netherlands is substantially ahead of many other countries when it comes to decarbonizing the machines that have the most intensive duty cycles, such as construction equipment. There are four policy areas that have pushed the Netherlands into a strong position:

- The Clean and Emission-Free Construction Material Subsidy Scheme (SSEB) has made €270 million available for the purchase or retrofit of zero-emission construction machines. Under this program, companies can recoup up to half their machine cost.
- The Netherlands co-led the process and signed the Global Memorandum of Understanding on zero-emission medium- and heavy-duty equipment at COP 26. This commits them to a target of 30% of new medium- and heavy-duty equipment being zero-emission by 2030, and 100% by 2040.
- Nearly thirty cities in the comparatively small country of the Netherlands have pledged to establish zero-emission zones by 2025, which will ban most polluting equipment by 2030.
- Strong national contracting policies for public works projects were established through the Zero Emission Construction Site 2030 Program of Rijkswaterstaat, the Netherlands Ministry for Water and Infrastructure, including roads and dikes.

As well as driving market penetration, these policies give a strong advantage to domestic OEMs. One example is Limach, which has developed a range of battery-electric excavators and whose efforts recently received investment from compact equipment electrification leader Volvo CE (Volvo, 2022). BAM provides another success case. It has commissioned a battery-electric asphalt paver, a 1,000-kWh full shift capable piledriver, and repowered asphalt rollers. Finally, KWS showcases this successful policy through demonstrating a commercial battery-electric asphalt paver with Dynapac and a Dutch electrification company. This level of development and activity in turn stimulates the supply chain, including companies such as Accenda, New Electric, and Urban Mobility Systems doing equipment integration work, as well as Smesh, which has developed an innovative e-axle, and DENS which is working on an off-grid battery-electric equipment charger for use in remote locations. These Dutch companies will soon be in a good position to export their products globally.

The smart partnership between public and private entities in the Netherlands is a strong case study from which to learn for U.S. states such as California.

III. Technology Readiness Levels for Zero-Emission Off-Road Equipment

An understanding of technology readiness for different segments of zero-emission off-road equipment can be obtained using the model of Technology Readiness Levels (TRLs), first applied in the aerospace industry (NASA, 2012). The TRL framework presents a picture of aggregate estimated progress, from early pilot stage to full market maturity, for an equipment platform (as opposed to different manufacturers and individual models).

This year's technology readiness analysis featured a significant expansion of the off-road categories considered for technology readiness, including additional categories in the construction, cargo-handling equipment, rail, and mining segments. In general, Figure 8 below exemplifies the great diversity in technology readiness of off-road equipment, reflecting the underlying diversity of off-road applications, technology development, and market conditions. Light off-road equipment (defined differently depending on the application) is generally already at high levels of technology readiness and entering commercial production, and in some areas heavy-duty technology is also maturing rapidly as well.

Construction and agricultural equipment have had breakout years with many major OEMs beginning production of battery-electric equipment platforms. Light battery-electric excavators (less than or equal to eight tons) are being produced by 23 OEMs internationally, including some of the largest construction equipment OEMs: Komatsu, JCB, Volvo Construction Equipment, and Bobcat. These excavators are showing an increasing ability to replace diesel excavators at job sites while reducing air pollution, carbon emissions, and cost. Skid-steers and compact loaders are entering early commercialization stages and reaching mature levels of technological readiness. One notable advancement is the battery-electric compact track loader from Bobcat, which has purchase commitments from rental company Sunbelt Rentals.

This year also featured advancements in light agricultural tractor technology, especially from OEMs such as Monarch Tractor, Hummingbird EV, and Solectrac. Now reaching the stages of early commercialization, agricultural tractor technology is moving forward and is expected to be widely commercially available in the next few years.

Another notable technological advancement is in switcher locomotives used in railyards, which will be offered vouchers through CORE for the first time this year. These locomotives, which can have batteries as large as 14.5 MWh, are primarily for use in switching shunting operations in rail yards, regional service, or for use in a diesel consist. Demonstrating the commercial readiness of switcher locomotives, freight hauler Union Pacific has committed to purchasing 20 of them, and Australian mining company Fortescue is additionally purchasing two of them, to be delivered in 2024.

Figure 8. Battery-Electric Off-Road Equipment Technology Status Snapshot - Cargo Handling

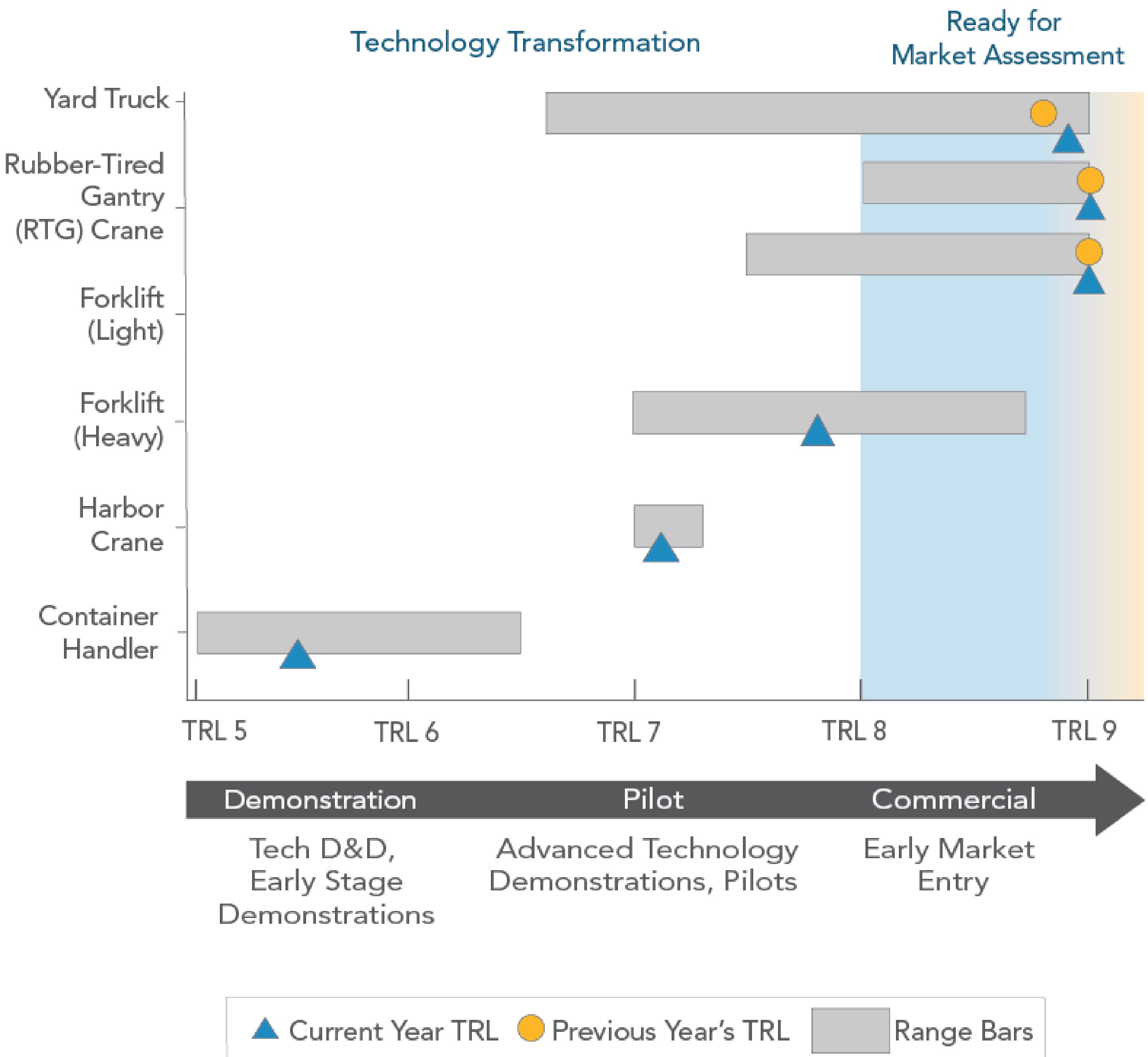


Figure 9. Battery-Electric Off-Road Equipment Technology Status Snapshot - Construction

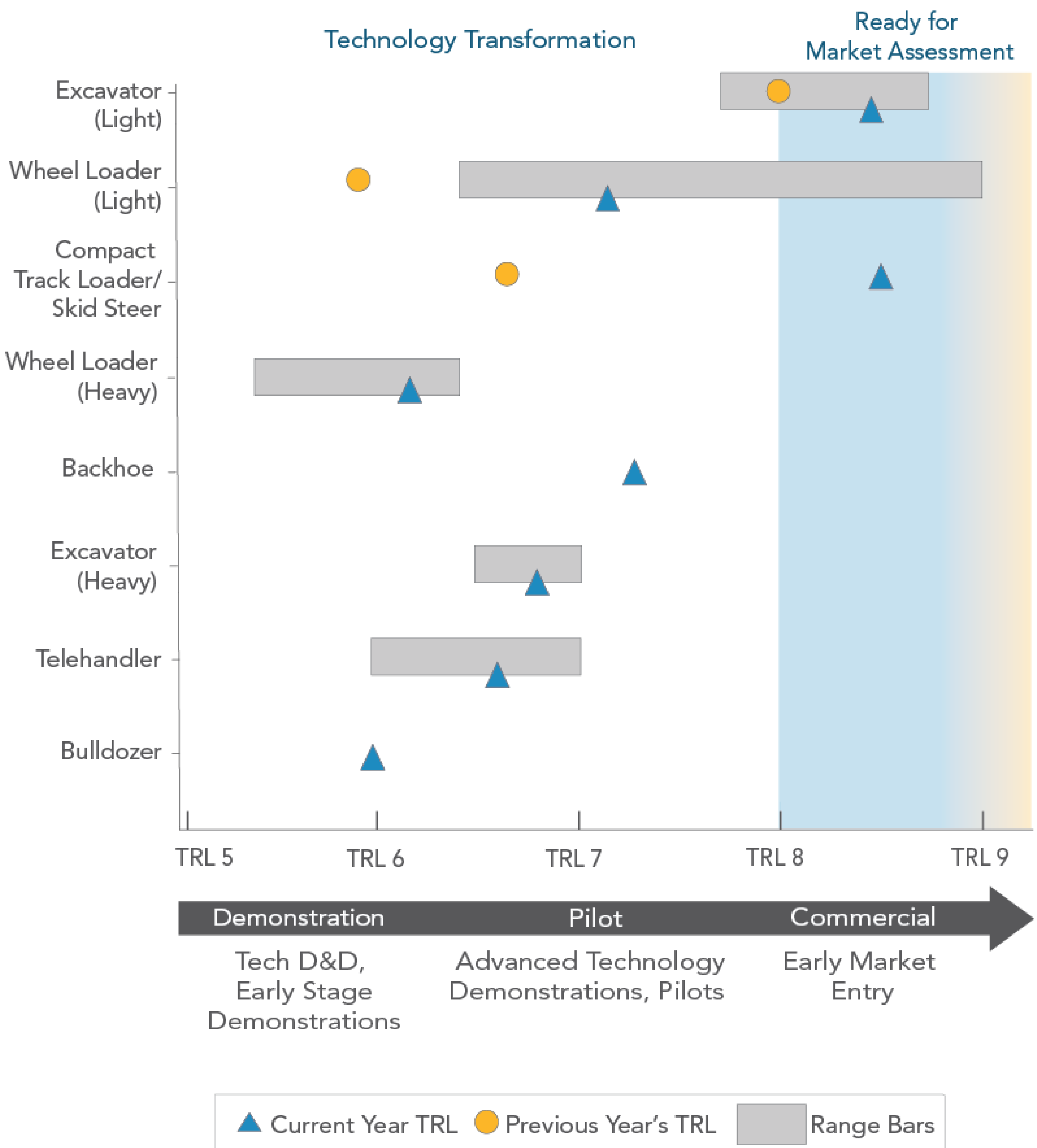


Figure 10. Battery-Electric Off-Road Equipment Technology Status Snapshot - Other

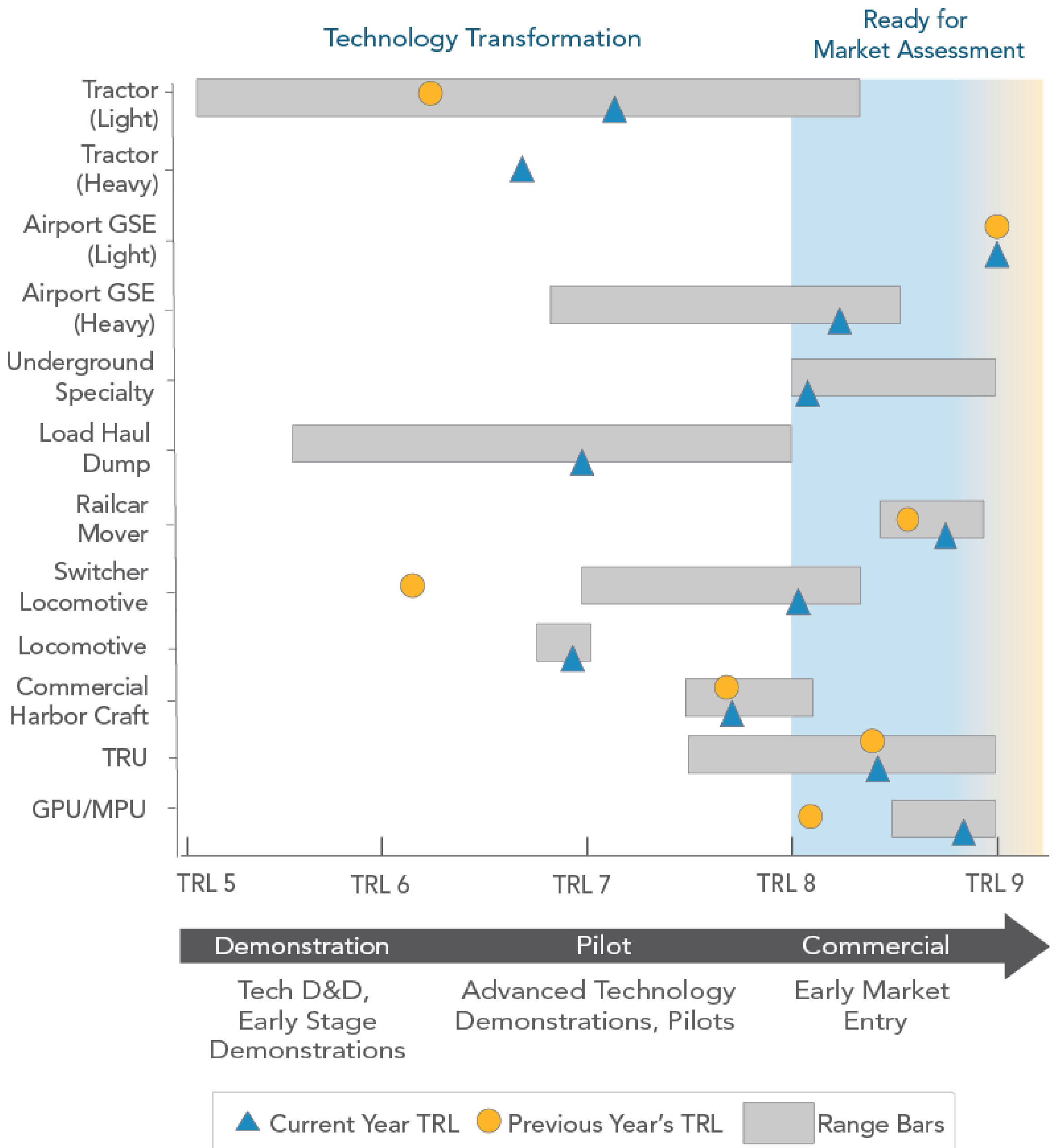
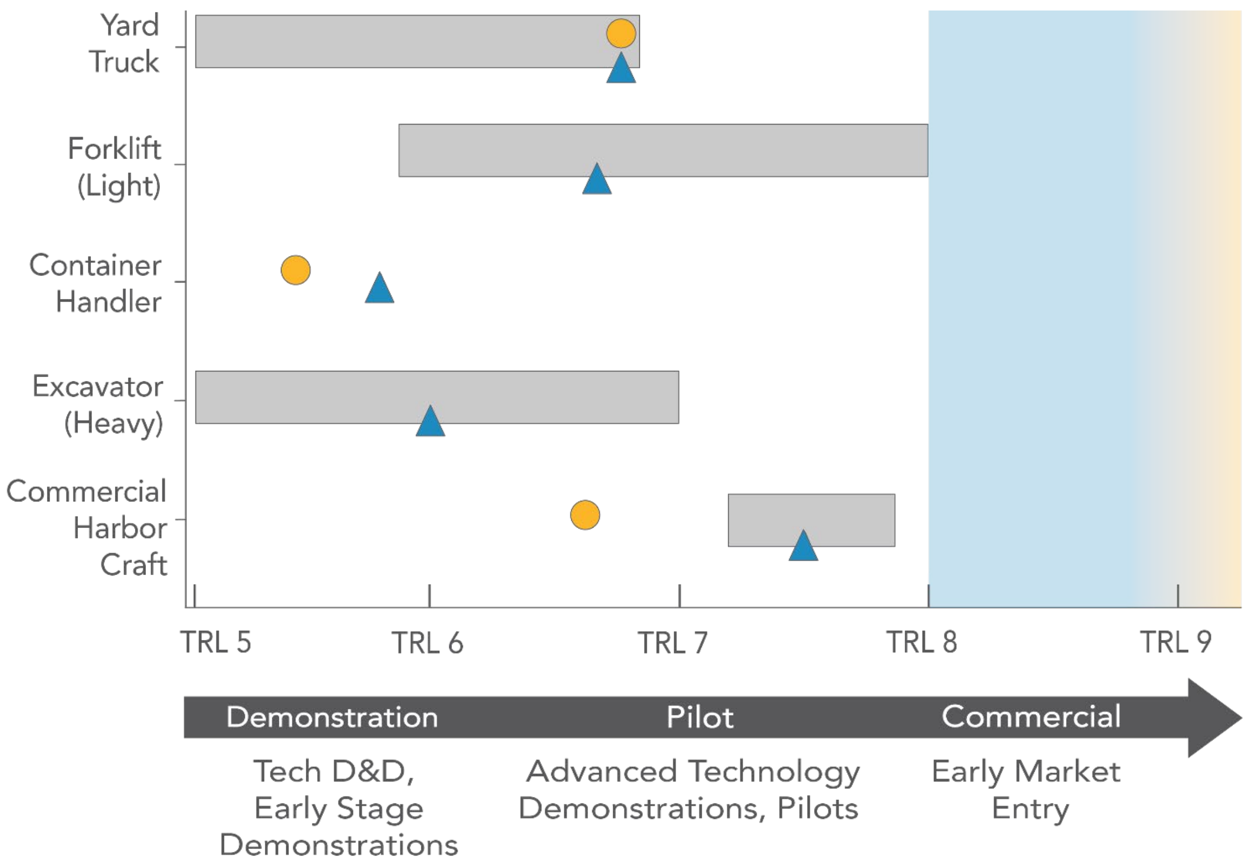


Figure 11. Hydrogen Fuel Cell Electric Off-Road Equipment Technology Status Snapshot



As illustrated in Figure 11 above, the off-road fuel cell equipment models tracked here sustained minimal movement over the past year, with the exception of the commercial harbor craft vessel segment, which has seen increasing demonstration projects seeking to prove out fuel cell technology for typical harbor duty cycles.

FCEVs (fuel cell electric vehicles) have had their most successful break-out application to date with industrial forklifts. This core capability is exploring scaling to higher fuel use and weight applications, including potentially heavy lifts, cargo handling equipment, and the marine sector. Such applications could make strong use of centralized fuel production and fueling infrastructure in locations such as port sites and off-grid work sites.

IV. Roadmap/Recommendations

While all off-road equipment is expected to ultimately move to zero-emission technology, it is important to begin with high potential categories. Broadly speaking, the starting point is with smaller off-road vehicles. Focusing on this segment enables rapid immediate progress because many smaller vehicle categories across all segments, from agriculture to construction to mining, are already well-suited to electrification. In fact, zero-emission models are already commercially available for many of these segments. Large scale deployment of zero-emission technology across these equipment categories will likely result in significant research and development spend from OEMs, leading to rapid technology developments that will enable the electrification of large vehicles and equipment as well, as outlined in CALSTART's beachhead strategy (CALSTART, 2022).

While these larger vehicles and equipment tend to be more difficult to electrify, doing so is critical to decarbonizing the off-road sector as a whole. In fact, is it vitally important to reduce emissions from this larger equipment because of its comparably high fuel consumption. As such, equipment manufacturers, end users, and policymakers will need to strike a delicate balance between addressing today's "low hanging fruit" and pushing for urgency around developing heavier-duty solutions.

Governments in particular can make a sizeable contribution to the electrification of both small and large off-road vehicle and equipment types by setting aggressive policies that develop smart partnerships with the private sector (as detailed above in the Netherlands case) and, crucially, by providing significant funding or other incentives to accelerate deployments.

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Appendix

Table 11. Off-Road Equipment Categories Captured in CARB GHG Emission Inventories

Agricultural	Airport Ground Support	Cargo Handling Equipment	Construction and Mining	Locomotive
Agricultural Tractors	A/C Tug Narrow Body	Port Construction Equipment	Bore/Drill Rigs	Line Haul
Bale Wagons (Self Propelled)	A/C Tug Wide Body	Port Container Handling Equipment	Cranes	Passenger
Balers (Self Propelled)	Baggage Tug	Port Forklift	Crawler Tractors	Short Line
Combine Harvesters	Belt Loader	Port Other General Industrial Equipment	Excavators	Switcher
Construction Equipment	Bobtail	Port RTG Crane	Graders	-
Cotton Pickers	Cargo Loader	Port Yard Tractor	Asphalt Pavers	-
Forage & Silage Harvesters	Cargo Tractor	Rail Construction Equipment		-
Forklifts	Forklift	Rail Container Handling Equipment	Cement And Mortar Mixers	-
Hay Squeeze/Stack Retriever	Lift	Rail Forklift	Concrete/Industrial Saws	-
Nut Harvester	A/C Tug Narrow Body	Rail Other General Industrial Equipment		-
Other	A/C Tug Wide Body	Rail Rtg Crane	Crushing/Proc. Equipment	-
Other Harvesters	Air Conditioner	Rail Yard Tractor	Dumpers/Tenders	-
Sprayers/Spray Rigs	Air Start Unit	-	Plate Compactors	-
Swathers/Windrowers/ Hay Conditioners	Cart	-	Signal Boards	-
-	Catering Truck	-	Tampers/Rammers	-

Agricultural	Airport Ground Support	Cargo Handling Equipment	Construction and Mining	Loco motive
-	Deicer	-	Highway Tractors	-
-	Fuel Truck	-	Highway Trucks	-
-	Generator	-	Other	-
-	Ground Power Unit	-	Pavers	-
-	Hydrant Truck	-	Paving Equipment	-
-	Lav Cart	-	Rollers	-
-	Lav Truck	-	Rough Terrain Forklifts	-
-	Maint. Truck	-	Rubber Tired Dozers	-
-	Other	-	Rubber Tired Loaders	-
-	Passenger Stand	-	Scrapers	-
-	Service Truck	-	Skid Steer Loaders	-
-	Sweeper	-	Surfacing Equipment	-