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Stakeholder perspectives on the transition to zero emission off-road equipment

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Stakeholder Perspectives on the Transition to Zero Emission Off-Road Equipment

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16. Abstract

California has set an ambitious target to transition 100% of off-road vehicles and equipment to zero-emission (ZE) alternatives by 2035 "where feasible," as outlined in Executive Order N-79-20. Interviews were conducted with 16 stakeholders—contractors, manufacturers, rental firms, researchers, nonprofits, and public agencies. Interviewees acknowledged positive attributes of ZE equipment, but barriers were more numerous and included inadequate charging infrastructure, limited grid access at job sites, high upfront equipment costs, limited ZE model availability, and complications with rental-based procurement models. Social and organizational barriers such as operator resistance, climate skepticism, and inequities faced by smaller firms were also noted. Most interviewees expressed skepticism that the 2035 ZE off-road goal is realistically achievable without significant policy and infrastructure support. Commonly recommended interventions included strengthening site-level grid capacity, expanding financial incentives and public investment, aligning regulations with market realities, and improving policymakers' understanding of construction practices.

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Executive Summary

The State of California is pursuing various electrification goals, including 100% of new car sales being zero-emission vehicles (ZEVs) by 2035. Similarly, a 2020 executive order from Governor Newsom (Executive Order N-79-20. 2020) stated the goal for "the State to transition to 100 percent zero-emission off-road vehicles and equipment by 2035 where feasible." Light duty vehicle electrification is progressing with 25% of new car sales being electric and the increasing deployment of charging infrastructure. However, less progress has been made on the electrification of off-road equipment.

In this report we explore barriers and enablers to the transition to zero-emission (ZE) off-road equipment. To meet this aim we conducted interviews with stakeholders in off-road equipment and explore their perception of off-road vehicle electrification, its challenges, feasibility, and actions needed to meet the State's goal.

Off-road equipment is essential to industries such as construction, agriculture, and mining. The equipment includes excavators, bulldozers, and forklifts—most of which are traditionally powered by internal combustion engines (ICEs). These machines are significant contributors to greenhouse gas and air pollutant emissions. The sector is beginning to transition to zero-emission (ZE) alternatives, particularly for compact and mid-sized equipment such as mini excavators, scissor lifts, and small loaders, which are commercially available in ZE varies. However, larger, power-intensive machines, such as bulldozers and large excavators remain less available in ZE variants, with the exception of some niche applications and in prototypes.

This study used a qualitative, inductive research approach to explore real-world barriers and opportunities for zero-emission (ZE) off-road equipment adoption in California, addressing a gap in social science research on this topic. Semi-structured interviews were conducted with 16 stakeholders—including people working in construction firms, equipment manufacturers, rental companies, public agencies, researchers, and nonprofits. They were selected to reflect diverse perspectives across roles, geographies, and organizational sizes. Interview protocols were tailored by stakeholder type and covered equipment use, procurement, policy familiarity, and other relevant themes. Insights were derived through thematic analysis of the transcripts, enabling researchers to identify key challenges, opportunities, and perceptions around ZE off-road equipment implementation.

While positive and negative perceptions were reported, negative themes were more numerous (27 total) and more frequently cited per interviewee (10 on average) than positive themes (12 total, 4 on average), suggesting significant perceived challenges in the transition to ZE off-road equipment.

The most cited advantages were reduced emissions, improved public health, reduced fuel and operating costs, and lower noise—especially important in residential or sensitive locations. Economic benefits included fuel and maintenance cost savings, while technical advantages focused on the availability and viability of compact electric equipment. Social benefits, such as ease of use and improved performance in specific applications, were mentioned, though less frequently.

Participants identified many challenges to adopting zero-emission (ZE) off-road equipment, with the most common concerns related to charging infrastructure and site-level power access, both posing major logistical and technical barriers. High equipment costs and difficulty electrifying heavy machinery were also frequently cited, alongside broader economic and operational issues such as increased construction costs, limited equipment range, and dependence on diesel generators at remote sites. Additional concerns included procurement challenges, distorted investment incentives due to widespread equipment rental, and social barriers such as operator resistance, climate skepticism, and equity impacts on smaller firms.

Most interviewees expressed skepticism that California's 2035 zero-emission (ZE) off-road equipment target is achievable, citing the sector's complexity and persistent barriers such as grid limitations, high costs, and equipment suitability. Interviewees suggested interventions to improve feasibility. The most common suggestions included addressing grid constraints and improving power access, increasing financial incentives such as tax credits, and boosting investment in technology and infrastructure. Other key recommendations included improving policymakers' understanding of construction operations, aligning regulations with market readiness, and ensuring equitable access to incentives. Additional ideas included mobile and standardized charging solutions, reframing ZE policy as a public health initiative, and enhancing client education.

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Introduction

The state of California is pursuing various regulations aimed at reducing emissions from transportation. Many of these policies, including Advanced Clean Car 2 (ACC2) and Advanced Clean Trucks (ACT) were initiated in a 2020 executive order from Governor Newsom (Executive Order N-79-20. 2020). The executive order also stated the goal of “the State to transition to 100 percent zero-emission off-road vehicles and equipment by 2035 where feasible.” This goal has yet to be enshrined in a regulation like ACC2 or ACT but remains a goal of California. Progress towards this goal is also less than that towards on-road vehicle electrification: notably 25% of new car sales are ZEVs and about 5% of all light duty vehicles in California are ZEVs. In addition, there is less progress on research that could inform the transition to off-road equipment compared to research on light- and heavy-duty vehicles. In this paper we aim to contribute to the nascent literature on off-road vehicle electrification.

The aim of this project is to understand barriers and solutions to the implementation of zero-emission (ZE) off-highway equipment and infrastructure in California. To meet this aim we conducted interviews with stakeholders in off-road equipment and explored the following research questions:

- How do stakeholders perceive electrification and what challenges exist in electrifying off-road equipment?
- Is California’s off-road electrification goal achievable and what actions are needed to meet this goal?

The interviewed stakeholders included policymakers, operators, building contractors, rental fleets, academics, and vehicle manufacturers. The interviews explored various topics related to off-road equipment use and each interviewee’s role in relation to the equipment. Questions covered barriers to using off ZE off-road equipment, ways to address these barriers, experiences with off-road equipment, policies, including California’s ZE off-road equipment goals.

Background

Technology overview

Defining Off-Road Equipment

Off-road equipment encompasses an array of machinery designed for operations beyond public roadways, primarily used in sectors such as agriculture, construction, mining, and material handling. This category includes vehicles like tractors, excavators, bulldozers, forklifts, and airport ground support equipment. Traditionally powered by internal combustion engines (ICEs), these machines contribute significantly to greenhouse gas (GHG) emissions and air pollutants, thereby impacting air quality and climate change. For instance, in California's San Joaquin Valley, farm equipment accounted for approximately 14% of nitrogen oxide (NO_x) emissions in 2012 (California Air Resources Board, 2014).

Off-Road Construction Equipment and Zero-Emission Alternatives

The transition toward zero-emission (ZE) alternatives in the off-road construction sector is underway, though progress varies significantly by equipment type. Compact electric machinery—such as mini and mid-size excavators, wheel loaders, and scissor lifts—is already commercially available and in use. These machines are well-suited for electrification due to lower power demands and the ability to return to a central charging location between shifts. However, for larger and more power-intensive equipment—such as bulldozers, large excavators, and telehandlers—zero-emission models remain largely in development or are only available in hybrid form. These categories face greater technical challenges related to power delivery, battery size, and energy density.

Table 1 outlines the types of construction equipment evaluated in this study, their typical uses, and the current availability of electric or hybrid versions. Manufacturers such as Volvo, JCB, and Bobcat are leading the commercialization of electric models in smaller equipment categories, while companies such as Komatsu and Liebherr are piloting hybrid solutions for heavier-duty applications. Current trends suggest that electrification is most advanced in compact and mid-sized equipment categories, with aerial lifts and small loaders seeing the widest adoption of fully electric models. In contrast, road construction machinery—including pavers and rollers—and heavy earthmoving equipment still face technical limitations, making zero-emission alternatives unavailable or impractical at present. Aerial equipment, in particular, has demonstrated strong alignment with electrification due to urban noise restrictions and the availability of electric scissor and boom lifts. Nevertheless, many interviewees noted that charging infrastructure and battery performance continue to constrain broader deployment, especially on larger or remote job sites.

Table 1. Off-Road Construction Equipment and Zero-Emission Alternatives.

Equipment Type	Category	Typical Use	Zero-Emission Alternatives Available?	Examples of Manufacturers/Models
Excavators (Mini & Mid-Size)	Earthmoving	Digging, trenching, demolition	✓ Available (Electric)	Volvo EC230 Electric, CAT 301.9E
Excavators (Large)	Earthmoving	Heavy-duty excavation for large construction sites	✕ Not widely available	Prototypes in development
Wheel Loaders	Material Handling	Lifting and transporting materials	✓ Available (Electric)	Volvo L25 Electric, CASE 580 EV
Bulldozers	Earthmoving	Earthmoving, grading, land clearing	✕ Not widely available	Research in early stages
Backhoe Loaders	Earthmoving	Digging and loading materials	✓ Limited Availability (Electric)	CASE 580 EV
Cranes (Mobile & Tower)	Lifting	Lifting and moving heavy materials	✓ Hybrid versions available	Liebherr Hybrid, Kalmar Electric
Dump Trucks	Hauling	Transporting soil, gravel, and debris	✓ Limited Availability (Hybrid/Electric)	Komatsu Electric Dump Truck
Pavers & Road Rollers	Road Construction	Road paving, asphalt compaction	✕ Not widely available	Research in early stages
Skid Steer Loaders	Compact Equipment	Light construction, material handling	✓ Available (Electric)	Bobcat T7X Electric
Telehandlers	Lifting	Lifting and placing heavy materials at height	✓ Limited Availability (Hybrid)	JCB 505-20E Electric Telehandler

Equipment Type	Category	Typical Use	Zero-Emission Alternatives Available?	Examples of Manufacturers/Models
Scissor Lifts	Aerial Work	Vertical lifting for indoor/outdoor work	✓ Available (Electric)	JLG ES Series, Genie GS E-Drive
Boom Lifts (Articulating & Telescopic)	Aerial Work	Lifting workers to elevated areas	✓ Available (Electric & Hybrid)	JLG EC600, Genie Z-45 FE Hybrid
Mast Lifts	Aerial Work	Compact vertical access for tight spaces	✓ Available (Electric)	JLG 1230ES, Genie GR-20
Truck-Mounted Lifts	Aerial Work	Elevated work for utilities & maintenance	✕ Not widely available	Research in early stages

Literature Review

Zero-Emission Off-Road Equipment Policies Worldwide

Globally, several jurisdictions have taken concrete steps to encourage the adoption of ZE off-road equipment. The European Union has adopted Stage V emission standards, mandating the use of particulate filters and more stringent emission controls on non-road mobile machinery (European Commission, 2016). These regulations have helped spur innovation and reduce diesel reliance across European markets. China and Chile have set some of the most ambitious global targets, committing to 100% zero-emission sales for new equipment over 560 kW by 2035 and for mid-sized equipment (19–560 kW) by 2040 (International Council on Clean Transportation, 2021). These timelines have influenced global manufacturers and helped align supply chains around the development of ZE technology.

Zero-Emission Off-Road Equipment Policies in California

California has emerged as a leader in advancing policies to reduce emissions from off-road construction equipment. Executive Order N-79-20, signed in 2020, directs the California Air Resources Board (CARB) to develop strategies for achieving 100% zero-emission off-road equipment operations by 2035, where feasible (Office of Governor Gavin Newsom, 2020). CARB has also adopted zero-emission standards for small off-road engines (SORE), with phased requirements beginning in 2024 (California Air Resources Board, 2021). To support industry compliance, California has implemented several incentive programs, most notably the Clean Off-Road Equipment Voucher Incentive Project (CORE), which offers point-of-sale discounts on eligible ZE equipment. These policy mechanisms not only encourage early adoption but also provide a testing ground for scaling ZE technology in real-world construction settings.

Zero-Emission Off-Road Equipment Commercialization

Commercialization of ZE off-road equipment continues to accelerate, propelled by both market demand and public investment. As of 2023, the global off-highway electric vehicle market was valued at $5.85 billion and is projected to grow to $63.86 billion by 2032—an annual compound growth rate of more than 30% (Precedence Research, 2023). This growth is fueled by expanding product availability, increasing environmental regulations, and rising investor interest in clean technologies. Manufacturers are responding to this momentum. For example, Fortescue Metals Group has committed $2.8 billion toward building a large-scale zero-emission fleet, including 360 autonomous battery-electric trucks, 55 electric excavators, and 60 battery-powered dozers as part of a major procurement partnership with Liebherr (Fortescue Metals Group, 2023).

Zero-Emission Off-Road Equipment Availability

The availability of ZE off-road equipment varies widely by sector. In the construction industry, many manufacturers have introduced electric compact machinery suited for urban work zones and short duty cycles. This includes mini excavators, electric wheel loaders, and various types of aerial work platforms, which are now commercially available through manufacturers like Volvo Construction Equipment and JLG (Volvo Construction Equipment, 2021). In agriculture, electric tractors are emerging but remain limited in size and capability due to battery weight and range constraints (John Deere, 2022). In contrast, the material handling sector has made significant strides, with electric forklifts now dominating indoor warehouse operations due to their zero-emission profiles and lower operating costs (Toyota Material Handling, 2020).

Zero-Emission Off-Road Equipment Barriers

Despite this progress, multiple barriers hinder the widespread adoption of ZE off-road equipment. Technical challenges remain at the forefront, particularly around battery energy density and the limitations of current technology in supporting high-power, long-duration applications (Fleming et al., 2021). For heavy-duty or continuous-use equipment, battery limitations reduce productivity and require larger, more expensive charging infrastructure. Economic barriers are equally pressing. Higher upfront capital costs coupled with uncertainties around long-term maintenance and resale value make ZE equipment a difficult investment for many contractors (Pamidimukkala et al., 2024). Operational barriers—including limited availability of compatible equipment, range constraints, and performance variability—also contribute to user skepticism and slow adoption (Fleming et al., 2021).

Zero-Emission Off-Road Equipment Incentives

To overcome these challenges, a variety of financial and regulatory supports have been implemented. Incentives such as subsidies, rebates, and tax credits help offset the initial cost differential between ZE and diesel-powered equipment. Programs like California's CORE initiative aim to reduce this gap at the point of sale, increasing accessibility for smaller firms.

Regulatory strategies, including emissions caps and purchase mandates, further shape market behavior by creating clear adoption targets. Public investment in research and development continues to play a role in reducing battery costs, improving equipment design, and expanding the range of commercially viable ZE machinery (Fleming et al., 2021). Together, these measures are helping to create the conditions for a more sustainable and widespread shift toward zero-emission construction equipment.

Addressing the Research Gap: Understanding Operational Barriers to Zero-Emission Off-Road Equipment Adoption

Despite significant advancements in the electrification of off-road construction equipment, a critical gap remains in understanding the operational barriers that hinder widespread adoption. Existing studies largely focus on technological feasibility, market readiness, policy incentives, and environmental benefits, yet real-world challenges that impact day-to-day operations receive comparatively little attention. For instance, while research highlights the environmental benefits and cost savings associated with zero-emission equipment (Un-Noor et al., 2022), there is limited empirical evidence on how these machines perform under actual construction site conditions. Understanding the practical constraints of using electric off-road equipment is essential to developing targeted solutions that address industry concerns.

One major operational barrier is performance and reliability concerns. Construction firms are hesitant to invest in zero-emission equipment due to uncertainties surrounding battery performance, power output, and durability in demanding work environments (Kim & Park, 2023). Unlike passenger EVs, construction machinery operates under high load conditions, prolonged usage cycles, and extreme weather, raising concerns about whether electric models can match the productivity and robustness of their diesel-powered counterparts. Additionally, charging infrastructure and logistics present another significant challenge. Many construction projects are in remote areas or dynamic, temporary work zones where access to charging infrastructure is limited or non-existent. This creates logistical hurdles for fleet operators, as the need for on-site charging stations, mobile charging solutions, or battery-swapping capabilities is still poorly understood and underdeveloped (CALSTART, 2022).

Another pressing concern is equipment downtime and productivity losses. Unlike diesel-powered machines, which can be refueled quickly, electric construction equipment requires extended charging times, potentially leading to delays in project timelines and increased labor costs. For industries working under tight deadlines, unplanned downtime could significantly impact overall productivity (EECA, 2023). Furthermore, while studies have examined financial incentives for electrification, they often overlook the total cost of ownership, including maintenance costs, depreciation, and resale value. Although electric equipment has lower operational costs, the high initial capital investment and uncertainties about long-term cost savings continue to deter adoption among fleet owners (Shao & Li, 2023).

Our research directly addresses these gaps by investigating the real-world operational barriers to zero-emission off-road construction equipment adoption. We sought this information through in-depth interviews with equipment owners, operators, manufacturers, suppliers, policymakers, public agencies, and utilities.

Method

Light-duty vehicle electrification and to a lesser extent, heavy-duty vehicle electrification benefits from a rich and growing body of literature. In contrast, there is less research on off-road equipment electrification, particularly social science-based studies that examine the implementation of electric off-road equipment. Therefore, we decided to use qualitative and inductive research methods to explore these issues. We did this rather than conducting a survey because we did not have enough information to inform the development of a questionnaire survey, for example we did not know which attributes of off-road equipment we should ask participants to evaluate.

Prior to conducting any interviews, we drafted a semi-structured interview protocol. We developed a semi-structured protocol because we knew some topics that we wanted to discuss (e.g., barriers to electrification and solutions to these barriers), but we also wanted to permit digressions and allow interviewees to share knowledge with us. The interview protocol covered the following broad categories:

- general background,
- equipment use,
- equipment procurement,
- familiarity with technology,
- fossil fuel phase out,
- familiarity with policy, and
- any other topics the interviewee wanted to share.

Since we planned to interview different stakeholder types, we drafted more specific protocols for each type of stakeholder. For example, we asked vehicle manufacturers about barriers to production of ZE off-road equipment and asked construction contractors about barriers to the use of ZE off-road equipment. Questions were asked in an open and non-leading way as much as possible, and the interviews were intended to be conversational. Interviews were all conducted by video making rapport building more difficult than in person, but we were able to at least progress to the exploration stage of rapport building.

Most interviews were conducted by two researchers, with one researcher leading the interview and the other listening and asking follow-up or probing questions where possible. After each interview, the interviewers drafted memos capturing the key takeaways from the interviews based on their recollection. All interviews were also recorded, with the consent of interviewees, and recordings were transcribed. The results in this report come from listening to the recordings, reading the transcripts, and extracting key themes from the interviews. This process allowed the researchers to better immerse themselves in the interviews as compared to post interview memos alone and identify themes they may not have recalled.

Table 2 provides an overview of the stakeholders included in this study. The table includes 16 interviewees representing a range of organization types: four universities, four government agencies, three construction companies, two equipment rental companies, one equipment manufacturer, one power producer, and one non-profit organization. Experience with zero-emission equipment varies, with several interviewees having direct involvement in electric vehicle programs, particularly those from government agencies (G1, G3, G4) and certain universities (R3, R4). The geographic distribution shows a concentration in California (10 participants) with additional perspectives from international locations (Australia, Norway) and broader regions in North America. Organization sizes range from smaller entities (PP1 with 655 employees) to very large corporations (RC2 with over 27,900 employees), providing viewpoints across different operational scales. Interviewees in leadership and technical positions offer firsthand accounts of their experiences with zero-emission equipment implementation, while those without direct experience contribute perceptions based on industry knowledge and projections.

Table 2. Stakeholder Profile and Organizational Demographics (stakeholder IDs listed here are used to identify fleets throughout the paper).

Stakeholder ID	Organization Type	Organization Size	Equipment Applications	Equipment Types	Location (Region)	Job Classification
R1	University	Over 55,000 students, 2,500 faculty	Research	Construction equipment, cranes, excavators, road equipment	Australia	Researcher
RC1	Equipment Rental	Over 18,000 employees	Various rental applications	1/3 aerial equipment, earth moving fleet, power generation, pumps	North America & UK	Senior Director
RC2	Equipment Rental	Over 27,900 employees	Various rental applications	6,000 equipment types including aerial, dirt engagement, water trucks	North America, Europe, Australia, NZ	Market Sales Manager

Stakeholder ID	Organization Type	Organization Size	Equipment Applications	Equipment Types	Location (Region)	Job Classification
G1	Government Agency	Over 50,000 employees	Municipal operations	20K on-road electric equipment, limited off-road	California, USA	Deputy Director of Vehicle Electrification
R2	University	Over 22,000 students, 1,400 faculty	Research	Construction Equipment	California, USA	Senior Project Researcher
G2	Government Agency	Over 20,000 employees	Transportation projects	Construction Equipment	California, USA	Assistant Director, Construction Division
PP1	Power Producer	655 employees	Energy production	Construction Equipment	Norway	Electrification Advisor
R3	University	Over 40,000 students, 2,500 faculty	Research	Hybrid off-road equipment	California, USA	Researcher
C1	Construction Company	Over 11,000 employees	Construction	Construction Equipment	International	Regional Sustainability Manager
OEM1	Equipment Manufacturer	Over 16,000 employees	Manufacturing	Construction Equipment	International	VP Sustainability
C2	Construction Company	Over 23,000 employees	Construction	Construction Equipment	USA	National Carbon Manager
G3	Government Agency	Over 1,700 employees	Regulatory	Off-road Equipment	California, USA	Tech Advisor for Heavy Duty Technologies
R4	University	Over 26,000 students, 1,100 faculty	Research	Off-road Equipment	California, USA	Research Engineer
C3	Construction Company	Over 9,000 employees	Construction	Construction Equipment	International	Global Sustainability Leader

Stakeholder ID	Organization Type	Organization Size	Equipment Applications	Equipment Types	Location (Region)	Job Classification
NP1	Non-profit Organization	Over 200 employees	Clean transportation	Off-road Equipment	California, USA	Project Manager - Clean Off-road Equipment
G4	Government Agency	Over 50,000 employees	Municipal operations	On-road Equipment	Norway	Electric Mobility Manager

Results

First, we explore first positive and then negative perceptions and sentiment towards ZE off-road equipment. We identified more negative themes (27 in total) compared to positive themes (12 in total) and on average more negative themes per interviewee (10 on average) compared to positive themes (4 on average). While the positive and negative themes cannot be precisely weighted, counted, and summed to determine a viability score for ZE equipment, the negative themes highlight challenges that the transition to ZE off-road equipment may face. All interviewees also reported some "hands on" experience with ZE off-road equipment, whether by operating the equipment, conducting research on it, procuring it, or working on related ZE policy.

Positive Perceptions

Each perception was classified based on how it was described by interviewees, rather than how the researcher viewed it. The positive perceptions were extracted from memos written following interviews and reflect how participants themselves described benefits associated with ZE off-road equipment. Each perception was coded based on whether it was explicitly raised during an interview, with frequency counts indicating how widespread a particular view was among participants.

Table 3 defines the positive perceptions identified in this study and categorizes each as technical, environmental, economic, or social. **Figure 1** shows a count of themes identified related to positive perceptions and sentiment towards ZE off-road equipment. The most frequently mentioned benefits were economic, environmental, and the availability of small off-road equipment. Environmental benefits such as reduced emissions (15 interviews), less noise (6), and improved public health (7) were commonly recognized, especially by stakeholders operating in or near residential areas or vulnerable communities. Public health benefits also included those to operators who are directly exposed to emissions on job sites. Several interviewees emphasized the health and environmental advantages of eliminating diesel emissions, particularly in urban areas. One participant noted:

> Maybe one possible good application would be in, basically, high-density, urban areas that have high air pollution. They are areas that usually with like low-income people living in high density and high pollution, and having a construction zone near them can be rough because these diesel machines, they would emit emissions. Like, tailpipe emissions that can have like health hazards. Using electric machines in those environments reduces both the noise pollution and like the toxic health problems. (Interviewee R3).

Another interviewee reflected on how air quality messaging can resonate with workers and communities, stating:

> But if I can talk to them [operators] about how they've been operating an excavator for 20 years, and if they start using this battery one, it's going to, it's going to be better on their body. They're not going to be as tired at the end of the day. (Interviewee C1).

Multiple participants also pointed out the improved working conditions for operators:

> People are actually happier operating them. That's because of the exhaust. Because there are no tailpipe emissions on construction sites., (Interviewee R1).

Operational or fuel cost savings were cited as benefits of ZE equipment in eight interviews, and maintenance cost advantages in four—reflecting broad interest in the long-term cost competitiveness of ZE equipment. Several interviewees emphasized that lower fuel costs were a key driver of economic value, especially when diesel prices were high. One participant observed:

> The diesel prices were quite high and energy prices were quite low, so the operational costs were... about a 50% reduction in the operational cost. (Interviewee R1).

Another noted:

> "These [ZE equipment] machines also have less rotating parts so they need less maintenance and less downtime." (Interviewee OEM 1)

Participants also emphasized indirect cost savings, such as avoiding on-site fuel storage risks:

> "People are also happy that they don't have to store diesel on site because storing diesel onsite sometimes can be dangerous" (Interviewee R1).

On the technical side, availability of small electric machinery was discussed in 12 interviews, indicating strong awareness of compact equipment options on the market. This includes light towers, small lifts, material handling equipment, and small excavators. Some interviewees reported electrification of equipment less than 150 HP was viable, whereas others perceived that electrification of equipment up to 350 HP as being viable. Others reported equipment less than 5 tons was a good candidate for electrification.

One participant stated plainly:

> "In a very non-technical manner, the smaller the piece of equipment the easier it is to electrify... A lot of smaller equipment—like Dumb buggies, concrete wheel buggies, ATV's—a lot of those can be done battery electric." (Interviewee C2)

Another highlighted real-world deployment, sharing:

> "We did a pilot here in Queensland. And then, we did another one in Parramatta in New South Wales where we had whatever we could find electric. So the smaller excavators, the spider cranes, the tower cranes, whatever we could find electric." (Interviewee R1).

Participants also referenced the historical availability of certain types of electric equipment in indoor or material handling applications. As one explained:

> "About a third of our fleet is aerial equipment and of that, about a third of that is indoor electric products… the technology has advanced to the point where… you can now put [batteries] in earthmoving products, more on-road applications—you can do a lot more with it." (Interviewee G1).

Another interviewee emphasized the maturity of smaller equipment markets, particularly in light-duty categories:

> "I think the greatest promise is in… the light-duty truck fleet and areas that have already had… large-scale successes" (Interviewee G2).

Participants also raised niche but noteworthy benefits, such as regenerative braking (1 interviewee) and the superior performance of electric equipment in specific applications (3 interviewees). Social benefits were raised less frequently, though ease of use (2 interviewees) was appreciated by a few interviewees who had hands-on experience with electric models.

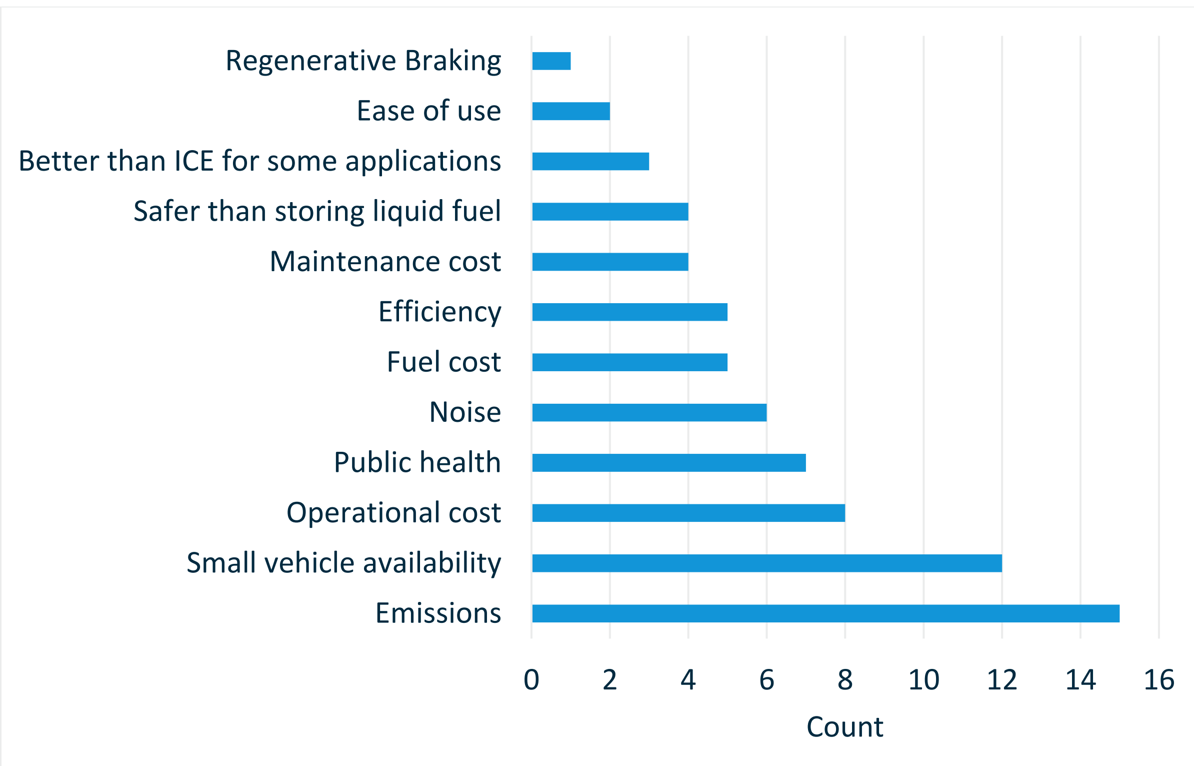

Figure 1. Count of number of interviews discussing positive perceptions and sentiment of issues related to ZE off-road equipment.

Table 3. Positive Perceptions Toward Zero-Emission Off-Road Equipment.

Positive Perception	Category	# of Interviews	Definition
Small vehicle availability	Technical	12	The availability of small, alternative fuel construction equipment options in the market, including compact machinery suitable for various job sites.
Emissions	Environmental	15	The reduction or elimination of exhaust emissions from equipment operation, resulting in decreased air pollution and carbon footprint.
Public health	Environmental	7	The positive impact on human health due to reduced exposure to harmful exhaust emissions, particulates, and other pollutants from construction equipment.
Operational/Fuel cost	Economic	8	The comparative cost advantage of electricity or alternative fuels over traditional fossil fuels, including potential savings on fuel expenses.
Maintenance cost	Economic	4	Reduced maintenance requirements and associated costs due to fewer moving parts, elimination of oil changes, and simplified mechanical systems.
Noise	Environmental	6	The significantly lower noise levels produced by alternative fuel equipment, reducing noise on job sites and in surrounding areas.
Safer than storing liquid fuel	Environmental	4	Improved safety due to elimination of hazardous fuel storage requirements, reducing risks of spills, fire, and environmental contamination.
Efficiency	Technical	5	Improved energy efficiency of alternative fuel equipment, converting more of the input energy into useful work compared to traditional equipment.
Ease of use	Social	2	The simplicity of operation, including easier startups, fewer controls, and more intuitive interfaces compared to traditional equipment.
Better than ICE counterpart for some apps	Technical	3	Specific applications where alternative fuel equipment outperforms internal combustion engine equipment in functionality, performance, or suitability.
Regenerative braking	Technical	1	The ability to recover and store energy during deceleration or downhill operation, extending battery life and operational time between charges.
Hybrids more efficient than ICE	Technical	4	The improved fuel efficiency of hybrid systems compared to pure internal combustion engines, offering a transitional technology with some benefits of both.

Negative Perceptions

Table 4 summarizes negative perceptions, the category under which each was discussed, and the number of interviews in which it was raised. **Figure 2** shows a count of themes identified and related to positive perceptions and sentiment towards ZE off-road equipment.

Several challenges emerged repeatedly, particularly around technical and logistical feasibility. The most common barriers were charging infrastructure (16 interviews) and grid or power access (15 interviews)—highlighting that site-level power constraints remain a central obstacle. Interviewees reported it would be costly, difficult, or not possible to deliver power to some sites to charge ZE off-road equipment. The concern was reported for various sites including in urban and rural areas.

One participant explained:

> "I mean like one of these huge excavators… that'll use up… four to 500 gallons of diesel a day. So, like, the grid can't necessarily support that." (Interviewer R3).

Another added:

> "Light duty vehicles, they have higher mobility and people usually have chargers in their house and at work. But for construction machines, you would move it to a construction site when electricity even like for a level one, regular charger might not be available. For those machines, you have to come up with innovative solutions, how to provide charging for them." (Interviewer OEM1).

A third interviewee underscored this point, emphasizing the regulatory and infrastructural complexity of powering large ZE equipment as follows:

> "They always need either permission or approval from the council to use that much power. When a tower client is being used, they need a huge amount of power when the crane is going up and if you're plugging into the grid that time depending on the time, you need approval from the council to use that much power." (Interviewer R1)

High equipment costs (14 interviews) and difficulty electrifying heavy equipment (13 interviews) were also cited with high frequency, suggesting that market limitations remain pronounced—particularly for larger machinery categories that require high power and longer runtimes. Several interviewees pointed to the significantly higher upfront cost of ZE models as a central deterrent. One participant explained:

> "Say for example, a spider crane—it's maybe double the price, at least one and a half to double the price upfront cost for a battery electric model compared to a diesel one." (Interviewer R1).

Another added the following, emphasizing both cost and supply-side limitations:

> "Now, one of the hurdles with setting zero-emission construction sites is just general availability of equipment… there's just the scale of things that are available that are zero-emission or battery." (Interviewer G1).

Economic and logistical constraints were frequently raised in tandem. Increased construction costs, noted in 8 interviews, were identified as a potential barrier to project delivery and client acceptance. One participant pointed out the misalignment between construction firms' sustainability goals and client priorities:

> "Whenever construction companies get a project, it's their client who has to bear the cost. The client might not even agree to the extra cost, and then it becomes difficult for the construction companies, which have targets to maintain that target" (Interviewer R1).

Another interviewee reflected on how higher capital costs may ripple through the broader development ecosystem, stating:

> "Buildings are an expensive investment. They don't ever really get cheaper to build… I think a lot of building owners would be concerned about already expensive buildings getting more expensive" (Interviewer C1).

A number of interviewees raised issues related to equipment procurement (5) and the fact that many companies rent rather than own equipment (5), which can distort investment incentives. While social barriers were less frequently mentioned overall, several participants did raise concerns such as operator resistance (5 interviews), climate-change skepticism (1), and a perceived disadvantage for small firms (3)—the latter pointing to potential equity concerns in technology adoption.

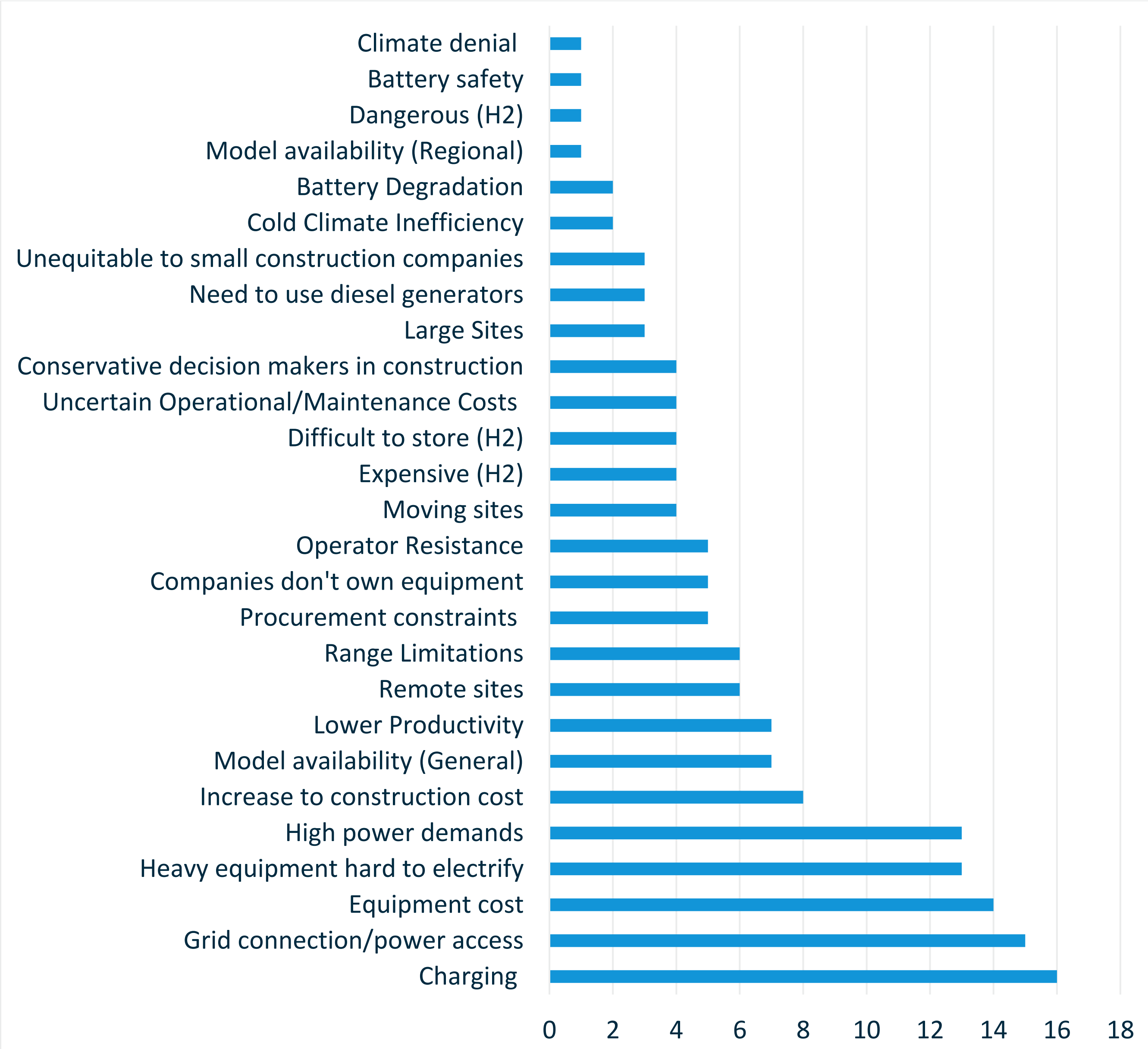

Figure 2. Count of number of interviews discussing negative perception and sentiment of issues related to ZE off-road equipment.

Table 4. Negative Perceptions Toward Zero-Emission Off-Road Equipment.

Negative Perception	Category	# of Interviews	Definition
Model availability	Technical	7	Limited range of alternative fuel equipment models available on the market, especially for specialized applications or larger equipment types.
Heavy equipment hard to electrify	Technical	13	Technical challenges in electrifying large construction equipment due to power requirements, battery capacity limitations, and design constraints.
High power demands	Technical	13	The significant energy requirements of construction equipment that exceed what current battery or alternative fuel technologies can efficiently provide.
Large sites	Logistical	3	Difficulties in implementing alternative fuel equipment on expansive construction sites where mobility and extended operation are required.
Remote sites	Logistical	6	Challenges in operating alternative fuel equipment at sites without reliable access to power sources, refueling, or charging infrastructure.
Moving sites	Logistical	4	Complications in managing alternative fuel equipment needs when relocating between multiple job sites, including transport of equipment and energy access.
Grid connection/power access	Technical / Logistical	15	Limitations in accessing sufficient electrical power at job sites, including insufficient grid connections or capacity constraints.
Charging	Technical / Logistical	16	Issues related to charging equipment, including time required, availability of chargers, and integration into work schedules.
Need to use diesel generators	Technical / Logistical	3	The ironic reliance on diesel generators to charge or power alternative fuel equipment in locations without adequate grid access.
Equipment cost	Economic	14	Higher upfront capital costs of alternative fuel equipment compared to traditional internal combustion engine options.
Increase to construction cost	Economic	8	The overall increase in project costs resulting from the use of alternative fuel equipment, potentially affecting competitive bidding.

Negative Perception	Category	# of Interviews	Definition
Procurement constraints	Tech / Log / Economic	5	Restrictions or complications in purchasing or acquiring alternative fuel equipment due to budget, supplier, or financing limitations.
Companies don't own equipment	Logistical	5	Rental or leasing business models that complicate adoption due to split incentives between equipment owners and users.
Cold climate inefficiency	Technical	2	Reduced performance, battery capacity, and operational capability of alternative fuel equipment in cold weather conditions.
Operator resistance	Social	5	Reluctance or opposition from equipment operators to adopt new technologies due to unfamiliarity, skepticism, or personal preferences.
Range limitations	Technical / Logistical	6	Restricted operational duration or distance capability between refueling/recharging, limiting productivity and usability.
Lower productivity	Logistical / Economic	7	Perceived or actual reduction in work output or efficiency compared to traditional equipment, affecting project timelines and costs.
Uncertain operational/maintenance costs	Economic	4	Lack of established cost history and unpredictability regarding long-term operational and maintenance expenses.
Inequitable to small construction companies	Social	3	Disproportionate burden on smaller companies that may lack capital resources or scale to absorb transition costs.
Battery degradation	Technical	2	Concerns about the decline in battery performance and capacity over time, affecting equipment value and operational lifespan.
Battery safety	Technical	1	Safety risks associated with battery systems, including potential for fires, thermal runaway, or damage in harsh construction environments.
Climate denial	Social	1	Rejection of the environmental rationale for alternative fuels based on skepticism about climate change or its causes.

Negative Perception	Category	# of Interviews	Definition
Construction sector → conservative decision makers	Social	4	The construction industry's conservative approach to new technology adoption, favoring proven solutions and showing resistance to change.

Interviewee Policy Perceptions and Recommendations

Here we explore interviewees perceptions of the goal that 100% of off-road equipment will be zero emission by 2035. Seven interviewees thought that this target would not be met. The reasons for this included the issues explored above and because interviewees reported the off-road equipment sector is very complex. One participant questioned the feasibility of applying the "where feasible" clause in California's Executive Order N-79-20, stating:

> "I think the first reaction would be to get a lot of clarity on how they can use the 'where feasible' language of that executive order. What is feasible? Is it feasible if it's technologically possible [but] comes at a 50% cost premium?" (Interviewer R3).

Another framed it more bluntly:

> "[California's Executive Order N-79-20] is not possible. I mean, to be honest—like the logistics? I mean, if you think 10 years—the logistics of the power grid supply, the willingness of people to use it." (Interviewer C2).

These comments underscore the sentiment that a uniform compliance deadline may not adequately reflect the diversity of operating conditions across construction sectors and regions.

After exploring perceptions of this goal, we asked interviewees what interventions may make reaching this rule more feasible. The recommendations below are derived from each interview and reflect participant-driven ideas for enabling or accelerating the adoption of ZE off-road construction equipment. In most cases these recommendations relate to the negative perceptions and sentiments reported above. For example, the most common recommendation related to charging as a barrier addressed grid constraints and power availability.

One participant illustrated this challenge with a site-level example:

> "Some projects are really far from a transmission line… do you really want to invest $80,000 in charging infrastructure when it's not going to be needed two years later and needs to be torn out?" (Interviewer C2).

Another emphasized:

> "If we don't have reliable charging stations, hydrogen fueling stations… then people won't have confidence in them. They're not going to take this risk of switching to a new technology" (Interviewer OEM1).

Table 5 defines the recommendations raised in this study and groups them by thematic category. The most frequently mentioned recommendation was the need to consider grid constraints (8 interviews), underscoring that many participants view power availability as a limiting factor that must be addressed through policy and infrastructure planning. Similarly, financial incentives and investment support were repeatedly emphasized: 6 interviewees called for tax incentives, and another 6 urged for increased investment in both technology and infrastructure.

One participant explained:

> "A little contractor can't run the risk of… maybe this is going to pan out a million bucks… but a company like Granite Construction, sure—$10 million, why not? Tax write-off. So yeah, we're trying to balance all that and make it fair and equitable" (Interviewer C2).

Another highlighted the transitional role of incentives in building market confidence:

> "In my opinion, funding and incentives, by definition, are not sustainable practices… but eventually you will come to a tipping point. People realize and enough people realize and enough infrastructure is built up that the economics start to make sense and people start to accept it as being a viable alternative… China is well beyond that point and you're seeing [China with] upwards of 50% now in EV adoption and EV new sales… So the incentives are very important to get people to that point. But sooner or later, it's going to make economic sense." (Interviewer G3).

One interviewee advocated for direct deployment support, stating,

> "Some coordinated efforts or programming around helping OEMs deploy prototypes in the real world would be hugely beneficial" (Interviewer C1).

Several interviewees also recommended that policymakers improve their understanding of the construction industry's operational needs (mentioned in six interviews), calling for better alignment between regulations and real-world implementation challenges.

One participant explained:

> "The technology is less mature compared to the on-road, heavy-duty sector. The implementation will be even more challenging… new types of products need to be developed and broadly deployed to make it possible" (Interviewer R4).

Others emphasized the cultural and behavioral elements:

"We've recognized long ago that the journey to more sustainable product is not only about the product design. It's also about the culture of the people using it... their habits and their practices." (Interview OEM1)

Related suggestions included aligning regulatory timelines with actual model availability (3 interviews) and ensuring that financial incentives are equitably distributed (3), especially to support small- and medium-sized firms that may face the highest barriers to adoption. Participants also suggested that policymakers draw from international models, such as those in Norway and China, which were seen as more advanced in scaling ZE adoption and creating market-enabling conditions.

Finally, less frequent but meaningful recommendations addressed technical and implementation details, such as developing standardized charging protocols (1 interview) and expanding mobile charging solutions (4 interviews) to support equipment use at remote or temporary sites. A few participants raised messaging-related recommendations as well, including the importance of framing ZE policies in terms of public health benefits, which may resonate more broadly than abstract climate targets. One interviewee said:

"If you talk about dust control, noise, silica dust—those are things people understand because they've lived it. But if you start talking about climate change, there's a lot of people who aren't going to connect with that" (Interviewer C1).

Table 5. Recommendations and Policy Insights Related to ZE Off-Road Equipment.

Recommendation	Category	# of Interviews	Definition
Need official targets/regs from government	Policy	4	Clear governmental targets and regulations to drive the transition to zero-emissions construction equipment, providing industry with definitive timelines and requirements.
Follow Norway or China model	Policy	3	Adoption of proven regulatory frameworks from countries such as Norway and China that have successfully incentivized and mandated alternative fuel equipment adoption.
Increase investments	Economic	6	Greater financial investment in alternative fuel technology development, manufacturing capacity, and supporting infrastructure from public and private sectors.
Credits or mandates for fuel use	Policy / Economic	1	Implementation of credit systems or mandates that reward or require the use of alternative fuels in construction equipment.

Recommendation	Category	# of Interviews	Definition
Tax benefits/incentives to purchase ZE equipment	Economic	6	Tax credits, rebates, subsidies, or other financial incentives designed to offset the higher upfront costs of zero-emission equipment purchases.
Minimize cost increases from ZE transition	Economic	3	Strategic approaches to implement the transition while minimizing financial impacts on construction companies and project costs.
Policymakers should better understand construction industry needs	Policy / Social	6	Improved dialogue and knowledge exchange between regulators and the construction industry to ensure policies reflect operational realities.
Consider political shifts	Policy	2	Policy design that accounts for potential changes in political leadership and ensures continuity of support across administrations.
Consider equitable distribution of incentives	Economic / Social	3	Ensuring that financial support and incentives are accessible to companies of all sizes, particularly small and medium enterprises.
Policy based on model availability	Policy / Technical	3	Regulation timelines and requirements that align with the actual market availability of suitable alternative fuel equipment models.
Consider grid constraints for power availability	Technical / Logistical	8	Policy development that accounts for local electrical grid capacity and the infrastructure needed to support widespread equipment electrification.
Consider charger equipment compatibility	Technical	1	Development of standardized charging interfaces and protocols to ensure interoperability across equipment brands and types.
Batteries need to be cheaper and more energy dense	Technical	2	Continued research and development focused on reducing battery costs while increasing energy density to improve equipment performance and affordability.
Mobile battery solutions for charging	Technical / Logistical	4	Development of portable charging solutions to address charging needs at remote sites or locations without grid access.

Recommendation	Category	# of Interviews	Definition
Frame policy as public health benefit rather than climate mitigation	Policy / Social	1	Strategic messaging that emphasizes the immediate public health benefits of reduced emissions rather than focusing solely on climate change benefits.
Educate clients about model availability and expectations	Social	1	Programs to inform construction clients about alternative fuel equipment options, capabilities, and realistic performance expectations.
Do not rush implementation	Policy / Logistical	1	A measured, phased approach to alternative fuel equipment adoption that allows the industry time to adapt and technology to mature.

Conclusion

This research highlights both the perceived benefits and significant challenges associated with the adoption of ZE off-road equipment in California. While interviewees identified a number of promising advantages—particularly environmental, economic, and operational—most also emphasized persistent, multi-dimensional barriers to widespread deployment. Key positive perceptions included reduced tailpipe emissions, improved public and operator health, quieter worksites, and the potential for lower operating and maintenance costs over time. Interviewees consistently noted that smaller, lighter-duty equipment represents the most feasible entry point for ZE technology, with existing models already demonstrating commercial viability and functional advantages.

However, the overall sentiment among participants reflected a cautious or skeptical outlook on the pace and scale of transition. A broad array of technical, logistical, and financial challenges were reported, with inadequate charging infrastructure, power grid limitations, and high upfront costs emerging as particularly significant barriers. In many cases, these challenges were compounded by the temporary or remote nature of construction sites, the limited availability of ZE models for larger equipment classes, and the fragmented structure of the construction sector—where ownership and use of equipment are often separated. These realities led many interviewees to question the feasibility of achieving California's goal of 100% ZE off-road equipment by 2035, especially without major systemic and policy shifts.

To address these concerns, participants emphasized the need for targeted and coordinated policy interventions. Chief among the recommendations was a call for greater investment in grid infrastructure, mobile and flexible charging solutions, and supportive technologies that can meet the high energy demands of construction operations. Financial strategies such as tax incentives, subsidies, and public-private investment programs were seen as essential to reduce cost barriers and lower the risks of early adoption. In addition, interviewees called for regulations that reflect real-world conditions, including phased timelines based on model availability and use cases, and improved engagement between policymakers and industry stakeholders to ensure that policy design aligns with operational realities.

This study highlights that many of the barriers to ZE off-road equipment adoption are not solely technical—they are also institutional, economic, and cultural. Therefore, an integrated approach that addresses the technological development and the human systems surrounding equipment procurement, usage, and training will be critical. Several interviewees pointed to the need for cultural shifts within the industry, such as normalizing requests for hybrid or electric alternatives during procurement and educating clients on the performance and benefits of ZE options.

The electrification of off-road equipment remains in its early stages, especially when compared to the light-duty vehicle market, which itself is still transitioning out of the early adopter phase. As such, the perspectives captured in this study reflect a moment in time—one where experience with ZE equipment is still limited and uncertainty remains high. These views will likely evolve as technology matures, infrastructure expands, and the broader vehicle and construction environment adapts. However, the barriers identified here are real and pressing. Addressing them will require concerted action from policymakers, industry leaders, utilities, technology developers, and other stakeholders involved in the off-road equipment value chain.

Ultimately, this research underscores the urgency of building a supportive, flexible, and inclusive policy and market framework that can accelerate the ZE transition—starting with equipment that is ready today, while laying the groundwork for the electrification of the broader off-road equipment fleet in the years ahead.

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