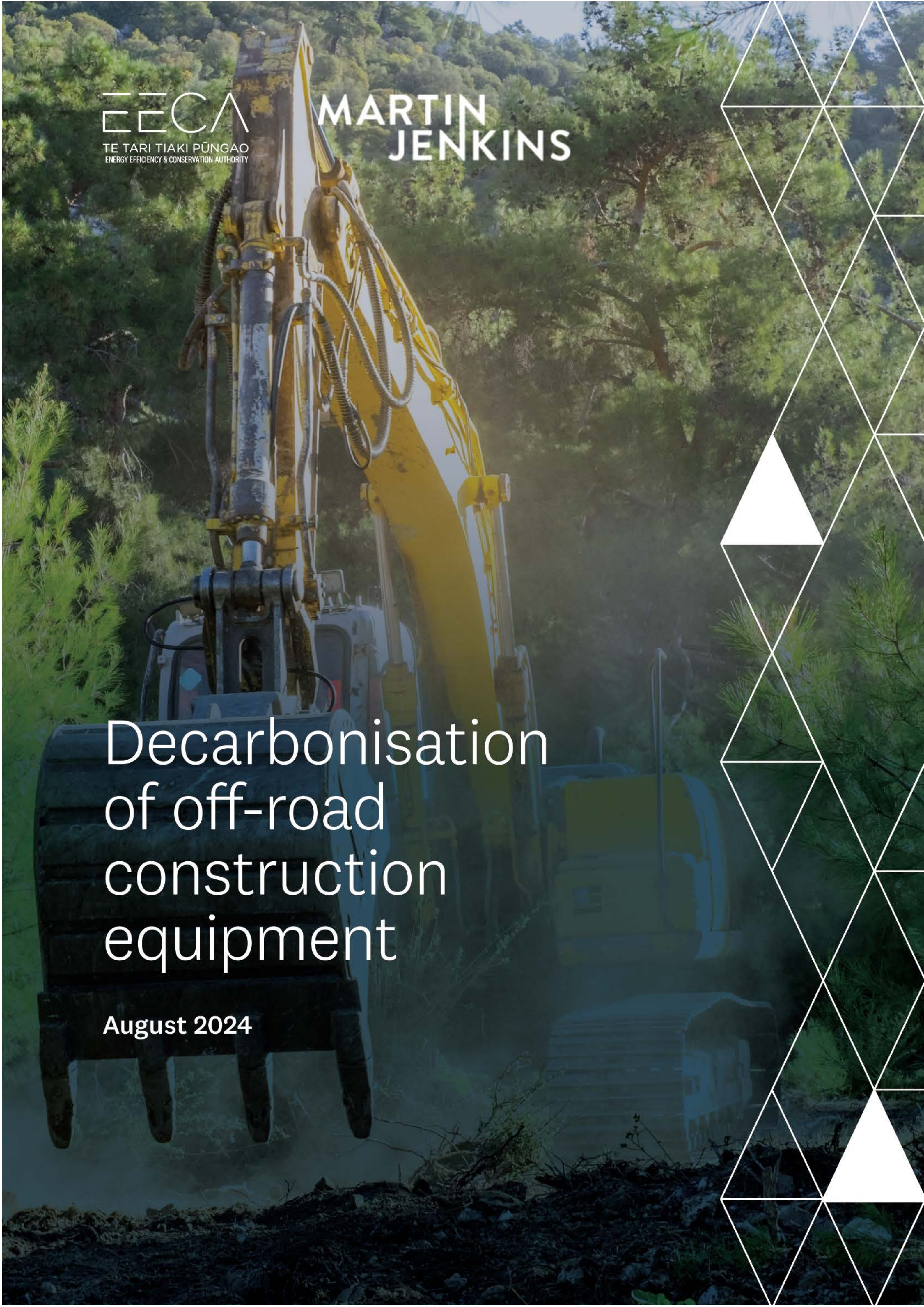


EECA
TE TARI TIAKI PŪNGAO
ENERGY EFFICIENCY & CONSERVATION AUTHORITY

MARTIN JENKINS

Decarbonisation of off-road construction equipment

August 2024

Contents

Executive Summary

Diesel is ubiquitous in the building and construction industry, powering most of its mobile equipment. Off-road building and construction activity accounts for around 5% of New Zealand's yearly diesel consumption, or around 1.7% of New Zealand's yearly energy sector CO_2 emissions in 2021. Given the industry's large volumes of off-road diesel use, and that electric and hybrid construction equipment is increasingly becoming available and matching the performance of diesel equipment, the building and construction industry is a potentially fruitful area of focus for energy conservation and greenhouse gas reduction.

In this research we aim to better understand the key opportunities for decarbonisation in the building and construction industry, and how drivers for, and barriers to, decarbonisation apply in the New Zealand context. To achieve this, we have undertaken a desk-based review of relevant literature and conducted several interviews of key stakeholders in the building and construction industry.

The literature and information from interviewees were almost unanimous in their recognition of the important drivers and barriers to construction sector decarbonisation. Drivers include:

- **National environmental policies and company pledges and public commitments** - with initiatives to decrease their carbon emissions increasingly in place, there is increased demand for low-carbon equipment in building and construction.
- **Decreased operating costs** - this is driven by the efficiency of electric motors, and maintenance savings for electric construction machines.
- **Equal or better moment-to-moment performance compared with diesel machines.**
- **Co-benefits from eliminating combustion** - this brings about more market opportunities and health and safety benefits through the elimination of fumes (or reduction in the case of hybrids), and large reductions in noise, heat, and vibration.

Barriers include:

- **High initial capital costs of electric and hybrid machines** - at present electric construction equipment costs around two to three times as much as a diesel with equivalent power output.
- **Many electric machines cannot yet match the daily duty cycles for diesel machines** - most electric machines encountered through our research were capable of fewer productive hours over an 8-hour workday, due to battery capacity and charging requirements.
- **Charging and refuelling infrastructure is still in early stages of development -** investment in charging infrastructure will increase the size of the market for electric and hybrid machines; however, technology solutions for remote charging of machines are slowly becoming available (for example, the KTEG Power Tree).
- **Uncertainties about battery longevity -** the extent to which factors like temperature, dust, humidity, and other environmental factors affect battery longevity are unknown, and will influence the lifetime costs of electric construction machines.
- **Short supply, small market, far from other markets -** there are challenges to consistently securing a supply for hybrid and electric machines in New Zealand. However, financial projections of the electric construction equipment market forecast very fast growth in the near term, so this barrier will pass with time.

Electric construction machinery and hybrids show a lot of promise for decarbonisation, and there are already dozens of high-quality electric products on the market that perform well and could be used as replacements for diesel vehicles. Fuel savings are immediate and significant and the reported co-benefits (see the "drivers" listed above) are realised in practice. However, in most cases, these benefits do not result in a more economic investment over the lifetime of the machine. At present there are only a very small number of scenarios that clearly favour electric and hybrid machines nationwide, which is reflected by the very low numbers of these machines in operation.

The two most important factors working against electric and hybrid machines are the high capital cost of machinery and practical challenges to charging machines far from an appropriate electrical supply (and little precedent regarding solutions). This means that in many cases electric and hybrid machines cannot yet adequately replace diesel machines.

At present, investment in battery powered and hybrid construction equipment is generally not economic. Even assuming intensive use over the entire working year, and with reliable access to electricity (that is, ideal conditions favouring electric machinery), the electric equivalent of the largest carbon emitting machines on aggregate internationally (excavators more than 10 tonnes) frequently cost twice as much, or more, than diesels over a machine's lifetime. Consequently, uptake of electric and hybrid construction machinery is low globally (estimated by IDTechEx to be 0.5% of construction machines) and in New Zealand (there are only a handful of electric and hybrid machines operating here).

However, this is likely to change over the medium- to long-term. Manufacturing of low-carbon machines will increase in scale, investments in charging infrastructure will increase, the price of carbon will increase, and as battery pack prices decrease, there will be many more opportunities for decarbonisation of the building and construction. While only 0.5% of the global market currently, sector experts expect almost half of all construction machinery will be fully battery powered or tethered by the year 2042.

Glossary

CO_2, CO_2e	Carbon dioxide, carbon dioxide equivalent
GHG	Greenhouse gas
ICE	Internal Combustion Engine
kW	Kilowatt
kWh	Kilowatt-hour

1. Introduction of off-road fuel use in the New Zealand construction industry

Diesel is currently the main source of energy for building and construction equipment both in New Zealand and worldwide. While it is ubiquitous today, there are several products on the market, and technological developments, that show promise for large energy savings and carbon emissions reduction.

In this report we focus on "off-road" equipment in the building and construction industry, that is, any mobile device powered by an internal combustion engine or electric motor, used primarily off public roads and highways. Given the industry's large volumes of off-road diesel use and that electric and hybrid construction equipment is increasingly becoming available and matching the performance of diesel equipment, the building and construction industry is a potentially fruitful area of focus for energy conservation and greenhouse gas reduction.

Overview of off-road fuel use in the construction industry

Worldwide, and in New Zealand, building and construction equipment (such as excavators, wheel loaders and off-road trucks) accounts for a large portion of diesel use and carbon emissions.[1] Off-road building and construction activity accounts for around 5% of New Zealand's yearly diesel consumption,[2] which accounts for 1.7% of New Zealand's yearly energy sector CO_2 emissions in 2021.[3]

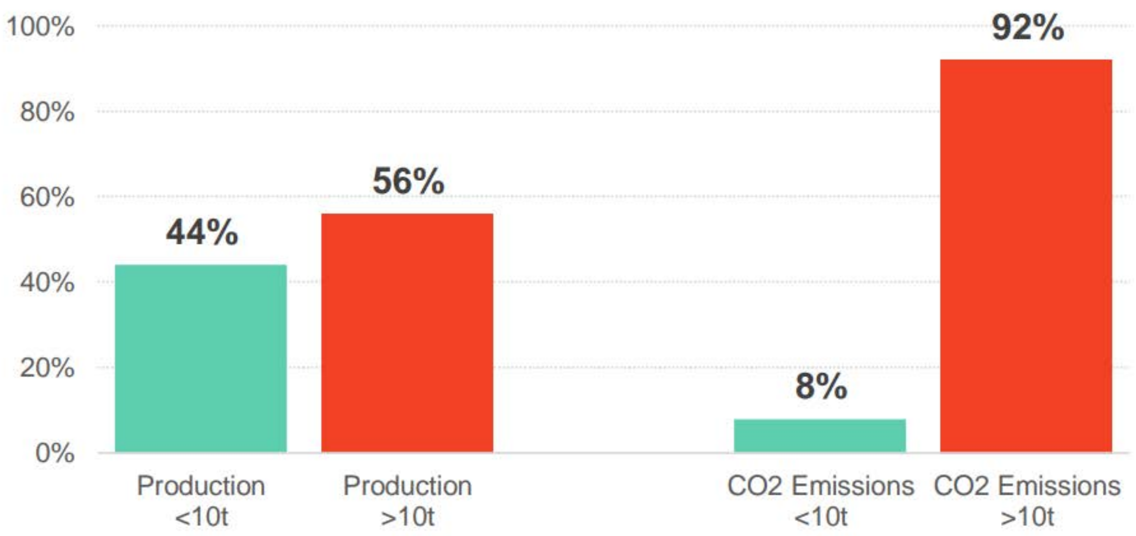
Building and construction equipment is a category that contains many types of machines that vary greatly in function and fuel consumption. Important in understanding the building and construction industry's energy footprint, and how to reduce it, is understanding the impact of different types of machinery on aggregate fuel consumption.

According to research from the Danish engineering firm Danfoss, excavators account for around half of all construction equipment CO_2 emissions worldwide (most of these emissions produced by excavators over 10 t), wheel loaders produce around 20% of all emissions, and all other machines make up the remaining 30% of emissions.[1]

The same research finds that delivering zero-emission solutions for the market of excavators, 10 tonnes and heavier, has the potential to save 184 $MtCO_2e$ emissions per year. As seen in Figure 1 below, while production of large and small excavators is similar in relative terms (that is, in terms of units manufactured), larger excavators use much more fuel; excavators exceeding 10 tonnes account for 92% of all excavators' CO_2 emissions.

[1] Danfoss Power Solutions
[2] Data from New Zealand Ministry of Business, Innovation and Employment Energy Balance tables, 2021
[3] New Zealand Ministry for the Environment's "Emissions Tracker" 2023

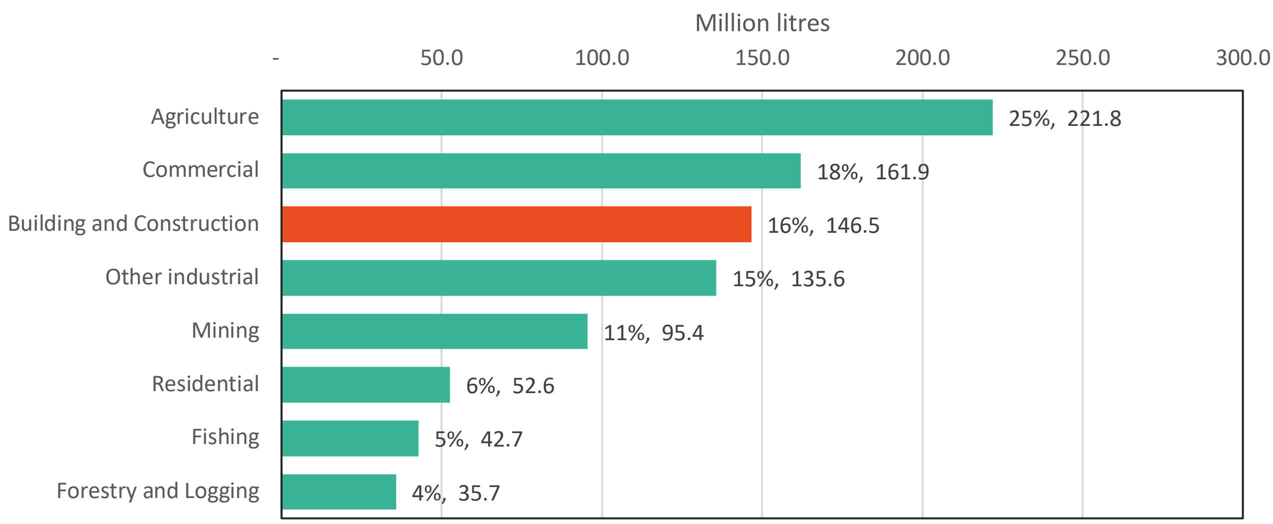
Figure 1 - Annual production volume and CO_2 contribution by Excavator Class



Construction off-road fuel use in the New Zealand

New Zealand has its own profile of off-road fuel consumption by industry, which is detailed in this section.

Figure 2 - Off-road diesel consumption in New Zealand by industry in 2022



Source: MBIE, 2023 (Energy Balance Tables)[4]

Figure 2, above, shows national off-road diesel consumption by industry. This chart shows that in 2022, the Building and Construction industry was the third largest off-road industry, accounting for 16% of off-road fuel use (147 million litres), or 5% of all diesel consumption (on-road and off-road) in 2022.

[4] MBIE, 2023. Energy in New Zealand 2023. Energy Balance Tables for 2022.

To put this in context, the off-road construction is the fourth largest category in terms of diesel consumption, after on-road domestic transport (69% of all diesel), and off-road activities in the agricultural sector (8%), and commercial sector (6%).

As is the case internationally, the New Zealand building and construction industry uses a wide range of diesel-powered equipment varying greatly by function and energy consumption. From the previous research on off-road fuels and equipment undertaken for EECA, we can provide approximate estimates of yearly fuel consumption for common off-road machines.

Table 1 - Estimates of the fuel consumption for common off-road equipment used in the construction industry

Equipment type	Average fuel consumption (litres per year per machine)
Small generator (<100 kVA)	2,000
Hydraulic excavator (Mini and Small)	2,800
Hydraulic excavator (Medium and Large)	14,800
Wheel loader (<200 kW)	6,300
Wheel loader (>200 kW)	21,200

Source: MartinJenkins survey of off-road equipment users, 2022.

Table 1 lists the categories of equipment that are likely to have the largest impact on fuel use according to this research, which surveyed owners of off-road equipment, asking "which of the following diesel using equipment do you use in your business?" and "approximately how many litres of diesel (per year) does one piece of equipment use?" According to this research, the most numerous machines are small generators, hydraulic excavators, and wheel loaders. These findings are drawn from small survey samples and should be treated as high-level approximations and interpreted with care.[5]

These findings are in line with the international inventory of construction equipment,[6] the interviews that were conducted as part of this report and supported by import data collected by Stats NZ (see Table 2 below). Import figures suggest that the quantity of excavators and loaders imported into New Zealand is much greater than any other category of construction equipment. Equipment suppliers and contractors interviewed as part of this research reported that excavators and wheel loaders were the most numerous types of equipment in the New Zealand construction industry, and that large excavators and wheel loaders used relatively large volumes of diesel.

[5] There were few responses to the survey our survey (62 agriculture, 20 building and construction, 20 mining and quarrying, 11 port industry, and no responses from the forestry industry) so uncertainties in the estimates shown are very large. These estimates should be used as a high-level indication only, to provide a sense of the relative magnitude of fuel consumption.

[6] Electric Vehicles in Construction 2022-2024, IDTechEx

Machine type	Number of machines imported	Import value (million $NZD; Cost, Insurance and Freight, CIF)	Average CIF per machine ($NZD)
Bulldozers and angledozers; self-propelled, other than track laying	37	7.45	215,700
Bulldozers and angledozers; self-propelled, track laying	101	24.08	259,000
Graders and levellers; self-propelled, having a basic operating weight less than 10,000kg	316	0.13	43,000
Graders and levellers; self-propelled, having a basic operating weight of 10,000kg or more, but less than 16,500kg	5	2.71	542,400
Graders and levellers; self-propelled, having a basic operating weight of 16,500kg or more	35	14.31	434,700
Loaders; front-end shovel loaders, self-propelled, excluding those for excavating and underground mine use*	-	59.17	-
Loaders; front-end shovel loaders, self-propelled, for excavating	1,381	147.69	106,400
Loaders; front-end shovel loaders, self-propelled, for underground mine use*	-	2.77	-
Mechanical shovels and shovel loaders; self-propelled (excluding those for excavating), n.e.c. in in loader or mechanical shovel categories	53	1.66	36,900
Mechanical shovels, excavators and shovel loaders; self-propelled, for excavating, n.e.c. in loader or mechanical shovel categories	843	47.22	61,700
Mechanical shovels, excavators and shovel loaders; self-propelled, with a 360 degree revolving superstructure, (excluding those for excavating)*	-	0.53	-
Mechanical shovels, excavators and shovel loaders; self-propelled, with a 360 degree revolving superstructure, for excavating	5,240	442.45	84,900
Road rollers; self-propelled, other than vibratory types	140	12.90	104,800
Road rollers; self-propelled, vibratory types	272	19.98	78,400
Scrapers; self-propelled	769	6.72	86,300
Tamping machines; self-propelled	54	1.27	45,400
Total		**791.05**	

Source: StatsNZ Overseas merchandise trade data 2022

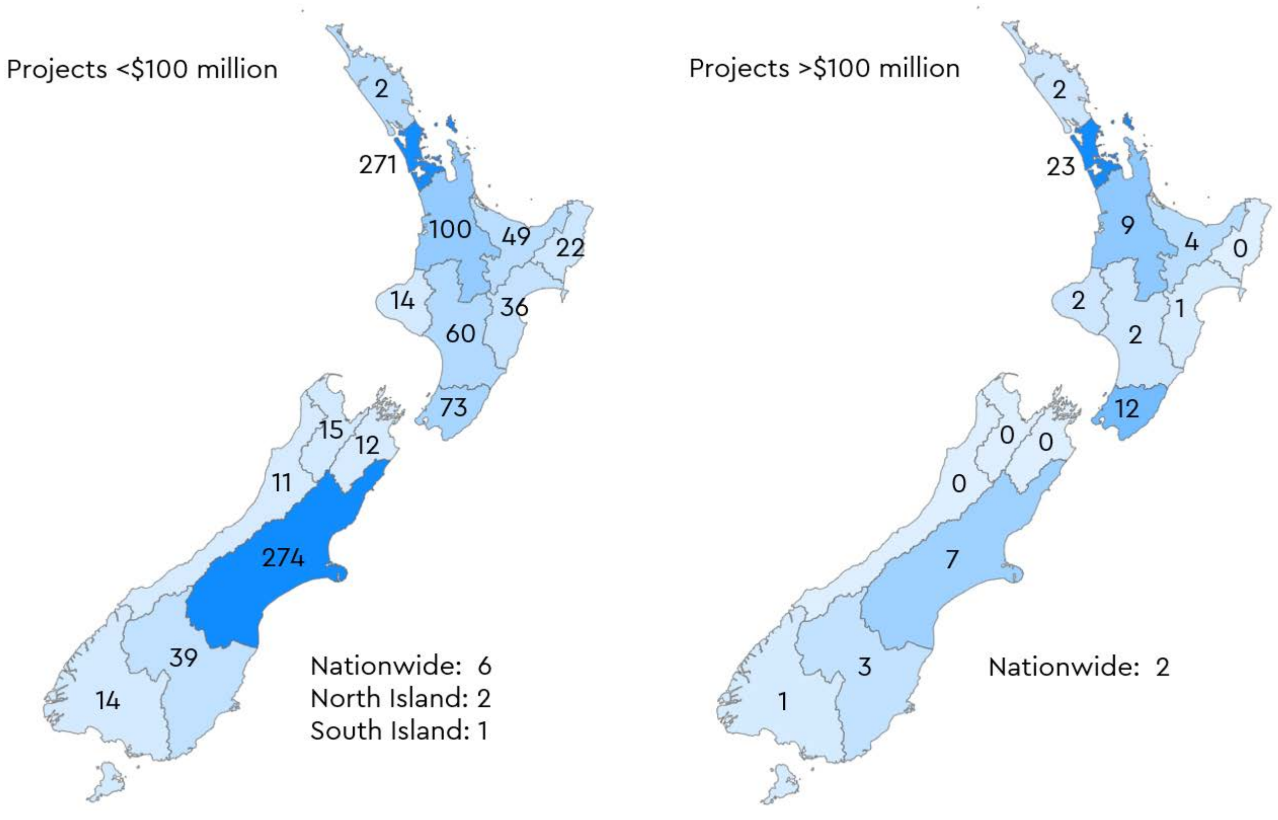
* these values were reported as kilograms in the data, and not numbers.

Geographic spread of construction activity in New Zealand

The New Zealand Infrastructure Commission keeps a public record of all publicly funded infrastructure projects planned and under construction in New Zealand,[7] in a document called the "National Infrastructure Pipeline". We searched this database for information labelled as "under construction" to get an indication of where construction activity is in the near term; and therefore, where there may be opportunities for decarbonisation.[8] This information includes the number of projects grouped into project expenditure categories and the location of each project at the regional council level.

The information available to us in the pipeline is challenging to summarise, but we can provide a few insights. Firstly, when using the mid-point of each expenditure category (and the minimum value in the case of the largest category) and multiplying these values by the corresponding numbers of projects, more than half of all project expenditure is spent on projects with lifetime costs more than $100 million.

Figure 3 - Count of public infrastructure projects under construction in New Zealand, 2023



Source: Te Waihanga, the New Zealand Infrastructure Commission Pipeline Data from June 2023

We have distinguished between "small" (<$100 million) and "large" (>$100 million) projects. Figure 3 above shows a count of all the projects under construction, shading each region according to its share of all infrastructure projects underway (a darker shade of blue corresponds to a higher proportion of the total projects). The lefthand side shows the number of small projects, and the righthand side shows large projects. We find that small projects are distributed

[7] https://tewaihanga.govt.nz/the-pipeline/downloadable-data

[8] We searched for records that were labelled as under construction as of the dates the record was last updated. This was between February and June 2023 at the time of writing this report.

proportionally to regional populations. The only large outlier being the Canterbury region, which has 26% of the small projects, compared with its 11% share of the population.[9] For large projects there was a disproportionally large amount of activity undertaken in Auckland (33% of projects compared with 26% of the population), the Waikato (13% compared with 8% of the population) and Wellington (17% compared with 9% of the population).

When investigating appropriate sources of electricity for electric machinery, we found that most electricity networks will have at least some spare capacity, particularly at off-peak times (depending on what other demand is connected at that network node). We engaged with EECA's Regional Energy Transformation Accelerator (RETA) team who have been investigating the opportunities for process heat conversions to electricity and biomass, and transport electrification opportunities, by region in New Zealand. So far, the team have published detailed studies for West Coast, Mid and South Canterbury, and Southland.[10]

These reports have highlighted specific transmission network nodes (GXPs) that have spare capacity; however, we do not have enough information to match the regional construction activity from Table 3 to specific parts of the electricity grid that have spare capacity. Furthermore, some equipment suppliers that we interviewed mentioned technology solutions that would allow charging of off-road construction on site (for example, the KTEG PowerTree[11]).

Drivers for decarbonisation

The general drivers to the decarbonisation of construction equipment are well documented[12,13], and were practically unanimously agreed through interviews. These include:

National environmental policies and commitments to international agreements (for example, the 2015 Paris Agreement) - To mitigate the effects of climate change, governments have committed to interventions such as new legislation, policies, subsidies, taxes, and cap-and-trade schemes. Regulations and price incentives can have a material impact on the adoption of low carbon alternatives to Internal Combustion Engines (ICEs).

Company pledges and public commitments - Many companies and other non-government organisations have made public commitments to decrease their carbon emissions. Examples include: the Volvo group (a large construction equipment manufacturer as a well as car manufacturer) who aim to reach net-zero emissions through their value chain by the year 2040 and for their customers' rolling fleet to have net-zero emissions by 2050. Fulton Hogan (a civil engineering contractor in New Zealand and Australia) has publicly committed to reducing its carbon emissions by 30% by 2030 and has adopted a net zero carbon target by 2050.

Decreased operating costs - Because of increased the efficiency of electric motors, and very low energy use when idling, fuel consumption savings from hybrid and electric construction machines are immediate and significant. Operating cost savings also extend to maintenance of electric motors, which require much less maintenance than a diesel engine. Decreased maintenance also results in reduced machine down time.

Equal or better moment-to-moment performance - Compared with diesel machines of the same power-rating, electric and hybrid construction equipment on the market today typically provides

[9] New Zealand Census 2018
[10] https://www.eeca.govt.nz/co-funding/regional-decarbonisation/about-reta/
[11] https://www.kteg-company.com/files/downloads/KTEG-Powertree-en.pdf
[12] Electric Vehicles in Construction 2022-2024, IDTechEx
[13] 2022 Survey undertaken for EECA investigating off-road machinery.

the same power output. In some instances, the maximum performance of the electric powertrain is reduced to fit the desired characteristics of the machine. In addition, electric motors deliver maximum torque even at very low revolutions, which can result in a performance advantage in some applications.

Elimination of harmful products of combustion - Eliminating combustion products from construction machinery (or reducing them, in the case of hybrids) has immediate health benefits to construction workers. Moreover, electric machines can more easily work indoors and underground without requirements for expensive ventilation equipment.

Additionally, electric and hybrid machinery can operate much more freely (or, without incurring a fee) in locations where construction activity is limited by air pollution regulations. For example, 36 members (including Auckland) of the "C40" Network of cities are signing up to the Zero Emission Area programme, which limits access to (or charges a fee to) fossil fuel powered vehicles wishing to enter an established Zero Emission Area.

Reduction of noise - There are clear health and safety benefits that arise from significant noise reductions from replacing diesel engines with electric motors. Not only does this improve the long-term hearing of construction workers and machine operators, but it also increases the environmental awareness of operators and people working on site.

Barriers for decarbonisation

However, there are still significant barriers to the widescale adoption of electric construction equipment:

Lifetime costs of diesels, in most cases, are still lower - In most instances, the electric construction equipment currently available on the market is unlikely to return the operating savings over its lifetime to justify its initial capital cost, compared with a similar diesel machine. There are conditions where the total cost of operation is clearly in favour of an electric machine, but these conditions are usually exceptional.

Our Total Cost of Operation (TCO) calculations (see next section) found a general case in favour of electric equipment over diesels for intensively used XCMG 20 tonne wheel loaders. Electric excavators over 10 tonnes cost approximately three times as much as a diesel machine to purchase. For the large excavator case we calculated, the TCO was around two times larger than that of an equivalent diesel over the machine's lifetime. For small electric excavators, diesels are cheaper over their lifetime, but relative difference is much smaller (around 10%).

Our investigations did not attempt an exhaustive list of comparisons between diesel and electric machines, and we have not found any such list in the literature. In addition, we have not found any estimates of how much of diesel activity electric machines can reliably replace (nor did we attempt such an estimate). Therefore, we cannot say what proportion of work electric equipment can cost effectively replace. If the international market is any indication, the number is likely to be around 0.5% (the estimated market share of electric equipment within the building and construction equipment market in 2021).

Many electric machines cannot yet match the daily duty cycles for diesel machines - For the equipment that was brought to our attention through interviews, most electric machines were capable of a period of intensive use close to, but less than, that of a diesel machine (when using fast charging over break periods). Ultimately over an 8-hour workday, most electric machines would have fewer productive hours.

Charging and refuelling infrastructure still in early stages of development - One of the main concerns of potential customers of electric construction equipment is how they will reliably power the machines, including when they are far from an appropriate source of electricity. At present many construction sites are not connected to the grid in a way that would allow for charging of batteries. Alternatives such as battery swapping and mobile battery packs could reduce this barrier in some cases.

Uncertainties about battery longevity - Electric construction machinery batteries using either of the two most common cathode materials are expected to be adequate for 1,000 to 5,000 charge cycles.[14] In theory, these batteries could still be useful for less intensive applications after this period.

However, most electric construction equipment currently in use is very new to market. A full life cycle of a modern battery powered machine is yet to be seen, and the challenging conditions that off-road machine batteries are exposed to make comparisons with on-road EV batteries difficult. We cannot know the extent to which factors like temperature, dust, humidity, and other environmental factors affect battery longevity.

These uncertainties follow on to uncertainties regarding the TCO, as operators could not know if they must purchase a second battery during the machine's lifetime. An equipment supplier interviewed noted that in some cases batteries could make up as much as 40% or 50% of the capital cost of an electric machine, consistent with international reports.[15] The battery condition will also heavily influence the price they can sell the machine on the second-hand market (the "residual price").

Short supply, small market, far from other markets

With New Zealand making up a small portion of international demand for construction equipment, we have little influence on worldwide demand or international production. While electric construction equipment continues to be prototyped and produced in low quantities, there will be challenges to consistently securing a supply in New Zealand. Financial projections of the electric construction equipment market anticipate fast growth in the near-term however, so this barrier will pass with time.

Problem definition: decarbonisation drivers and barriers apply uniquely to the New Zealand context

The drivers and barriers outlined above are well documented, but there has been little research undertaken to date that investigates how they apply in the New Zealand context. Electric construction machines need the right circumstances to be used to good effect, and the investment required to give rise to these circumstances will depend on several New-Zealand-specific factors, including geography and the built environment, electricity supply and demand, and market factors.

This report summarises research, commissioned by EECA, to better understand the New Zealand context. This research begins to build an evidence base of opportunities and challenges to decarbonising electric construction equipment.

[14] Electric Vehicles in Construction 2022-2024, IDTechEx - Lithium-ferro-phosphate (LFP) batteries have a useful lifetime of around 5000 charges, and lithium-nickel-manganese-phosphate (NMP) batteries have between 1000 and 2000 charges

[15] Electric Vehicles in Construction 2022-2024, IDTechEx – This report estimates that the battery of a Caterpillar 323F Z-line (a 26 tonne electric excavator) accounts for 50% of the cost

Methods

We have undertaken a desk-based review of relevant literature and conducted several interviews. For the desk-based exercise, we have analysed the academic literature, industry reports, manufacturer data including equipment specifications, and government documents and statistics.

We interviewed representatives from construction industry bodies, civil engineering contractors, building and construction suppliers, and government agencies involved in electricity infrastructure planning as well as procurement of construction services. In these interviews we sought information about their experience with electric and hybrid construction equipment, and their perspectives on the drivers and barriers to construction sector decarbonisation. The interviewees represented the following organisations:

- The New Zealand Civil Contractors Association
- Fulton Hogan
- Construction equipment suppliers:
    - CablePrice
    - Vertu Equipment
    - eTrucks
    - TDX
- Waka Kotahi, the New Zealand Transport Authority
- EECA's Regional Energy Transition Accelerator (RETA) team.

2. Assessment of decarbonisation opportunities for New Zealand construction equipment

In this section we consider how the factors driving and hindering building and construction industry decarbonisation apply in New Zealand, and how to best take advantage of opportunities for the industry's decarbonisation.

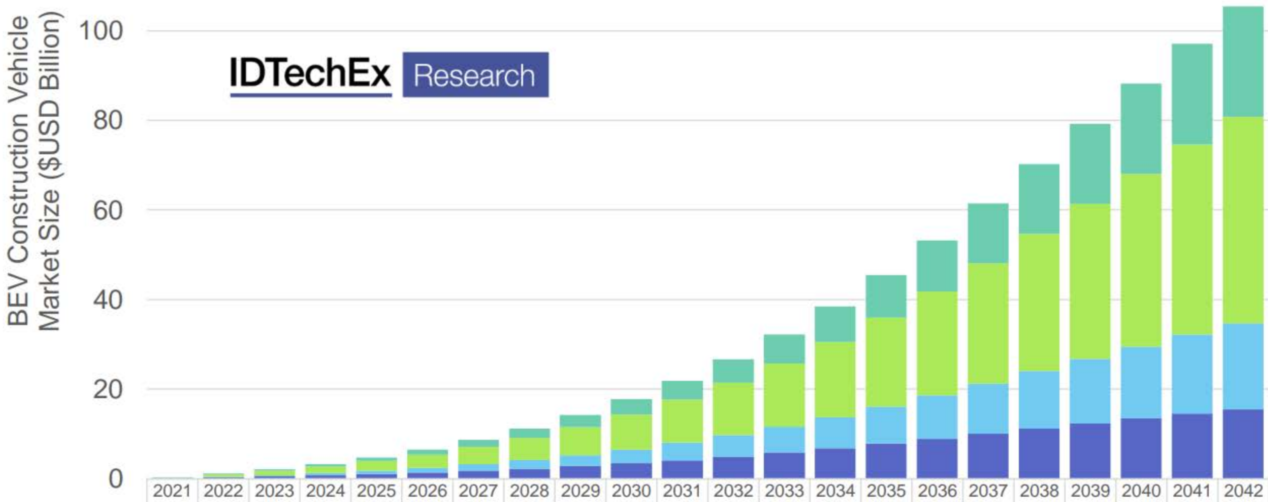
New Zealand market overview of electric and hybrid construction equipment

The interviews undertaken during this research suggest that there are few hybrids and battery powered off-road electric construction machines operating in New Zealand. Interviewees were typically aware of only a small number of electric construction machines (in most cases, fewer than 10) operating across the country.

The low number of applications for which electric machines give a lower Total Cost of Ownership (TCO) than similar diesel machines likely plays a large part in the small number of machines in use (TCOs are discussed in more detail later in this section). Short supply is a significant driver, too. In some cases, interviewees mentioned that machines are sometimes unable to be shipped to New Zealand, even where suppliers were willing to pay a manufacturer's asking price.

Short supply is a reality for most international operators as electric machines only made up 0.5% of all construction machine sales in the 2022 calendar year. This will likely not persist as a barrier in the long-term. Sector experts predict rapid growth in this industry, with 157,500 electric machines sold in 2032 (13.5% market share) and 526,700 electric machines expected in 2042 (43.5%).[16] This market growth assumes policy driven increases to the price of diesel (for example, through schemes like New Zealand's Emissions Trading Scheme), cheaper battery pack prices, and increases in the volume of electric equipment production by manufacturers.

Figure 4 - Forecast of market size of battery powered electric construction equipment



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
RoW	0.0	0.1	0.3	0.5	0.8	1.1	1.5	2.0	2.6	3.4	4.2	5.3	6.5	7.9	9.6	11.4	13.4	15.6	17.8	20.2	22.4	24.6
China	0.1	0.6	1.0	1.5	2.2	3.0	3.9	5.0	6.3	7.8	9.6	11.7	14.1	16.8	19.9	23.2	26.8	30.6	34.6	38.6	42.4	46.1
US	0.0	0.1	0.3	0.5	0.8	1.1	1.4	1.9	2.4	3.1	3.9	4.8	5.8	7.0	8.3	9.7	11.2	12.8	14.5	16.1	17.6	19.1
EU+EFTA+UK	0.1	0.3	0.5	0.7	1.0	1.4	1.8	2.3	2.8	3.4	4.1	4.9	5.8	6.8	7.8	8.9	10.0	11.2	12.3	13.4	14.5	15.5
Total BEV-CE	0.2	1.1	2.1	3.3	4.8	6.5	8.6	11.2	14.2	17.7	21.9	26.7	32.2	38.5	45.5	53.2	61.5	70.2	79.2	88.2	97.0	105.4

[16] Electric Vehicles in Construction 2022-2024, IDTechEx

From our interviews, and from interviewee's sales catalogues, we found the following equipment on offer in New Zealand:

- Battery powered excavators (between 1 tonne and 30 tonnes)
- Tethered excavators (greater than 9 tonnes)
- Large hybrid excavators (39 tonnes to 50 tonnes)
- Battery powered rollers (4 tonnes)
- Battery powered skid steers (3 tonnes)
- Battery powered wheel loaders (6 tonnes to 23 tonnes)
- Telehandlers (5 tonnes)
- Crawler canes
- Hybrid mining shovels and electric rope shovels
- Electric Mining Trucks
- DC Fast chargers, AC charging equipment, and large battery packs (125 kWh).

Most of the equipment we were made aware of was fully battery powered, with interviewees aware of few hybrid machines operating in New Zealand. Most large machines (for example, wheel loaders more than 20 tonnes, excavators more than 30 tonnes) do not yet have battery powered options available, mainly due to the challenges of producing a battery large enough to match diesel machines' duty cycles. Manufacturers of hybrid vehicles appear to focus on this market for large machines, providing a partly battery powered solution to drive energy savings. Examples of hybrid construction equipment available internationally include the 50 tonne Volvo EC530E and EC550E excavators and the Caterpillar 988k XE, and a 52 tonne wheel loader.

All stakeholders interviewed noted that electric machines had either equivalent or improved performance from moment-to-moment. What's more, interviewees reported that the theoretical benefits of battery powered and hybrid machines (outlined in the previous section) were realised:

- Fuel savings from battery powered machines and hybrids are significant.
- For each of the machines listed above, all of them roughly match the power of their diesel equivalents with the same weight (and vice versa).
- For each machine, noise is significantly reduced, in the case of small excavators, operators remark that they are essentially "silent".
- The harmful products of combustion are reduced (in the case of hybrids) or eliminated (for fully-battery powered machines), opening opportunities for indoor and underground work to take place without the requirement for expensive ventilation equipment.

Commercial readiness

Commercial readiness of new technologies is often indicated using a Commercial Readiness Level (sometimes referred to as a Commercial Readiness Index). This is a subjective scale from 1–9 that indicates the commercial readiness of a particular technology (the higher the number the more commercially ready the technology is).[17]

Generally, the electric building and construction equipment in operation in New Zealand have been introduced to the market already. They comply with international standards and local

[17] https://grantedltd.co.uk/funding-blog/what-is-crl/

regulations with few or no modifications and are available for purchase by ordinary retailers of construction equipment.

Most of these electric machines are identical to their diesel counterparts except for the electric motor, and parts and expertise for maintenance are relatively easy to come by. At present, electric machines mainly aim to replace diesel equipment, so their market value is already well established, and the revenue model and supply chain arrangements are not drastically different from those that manufacturers already have in place for more established products.

From a strictly financial point of view, electric machines are less commercially viable for most applications, but there are circumstances that favour electric machines economically, and very clear non-financial benefits (for example, emissions reduction and noise reduction). There is a small international market currently (estimated at $2.1 billion[18]) which is forecast to grow as technology improves and manufacturing increases scale.[13] All things considered, the electric construction machines we are aware of operating in New Zealand today have a commercial readiness level (CRL) of 8 (market introduction).

It is important to note that while there are already a broad range of market-ready of electric construction products, the size of the market is highly contingent on the infrastructure being available to put them to good use.

Assessment of Total Costs of Ownership (TCO) for low-carbon construction equipment

Most electric construction equipment has a higher TCO than diesel equivalents, mainly due to their large initial capital costs. However, some electric equipment that is even twice as expensive to purchase, can have a lower TCO compared with a diesel machine where they can match the diesel work cycles, consume a lot of electricity, and are highly utilised.

We have undertaken TCO comparisons for some of the electric and diesel machines for each of the following categories: 20 tonne wheel loaders; 9 tonne excavators; and 2 tonne excavators. We have chosen these examples, as they represent machinery that is common in the building and construction industry, and because they can illustrate the effects of variation in the key drivers of cost – namely, the price of purchase and energy use.

In each category, TCOs have been calculated for full utilisation (eight hours a day, 260 days a year), and half utilisation (four hours a day, 260 days a year).

These calculations assume:

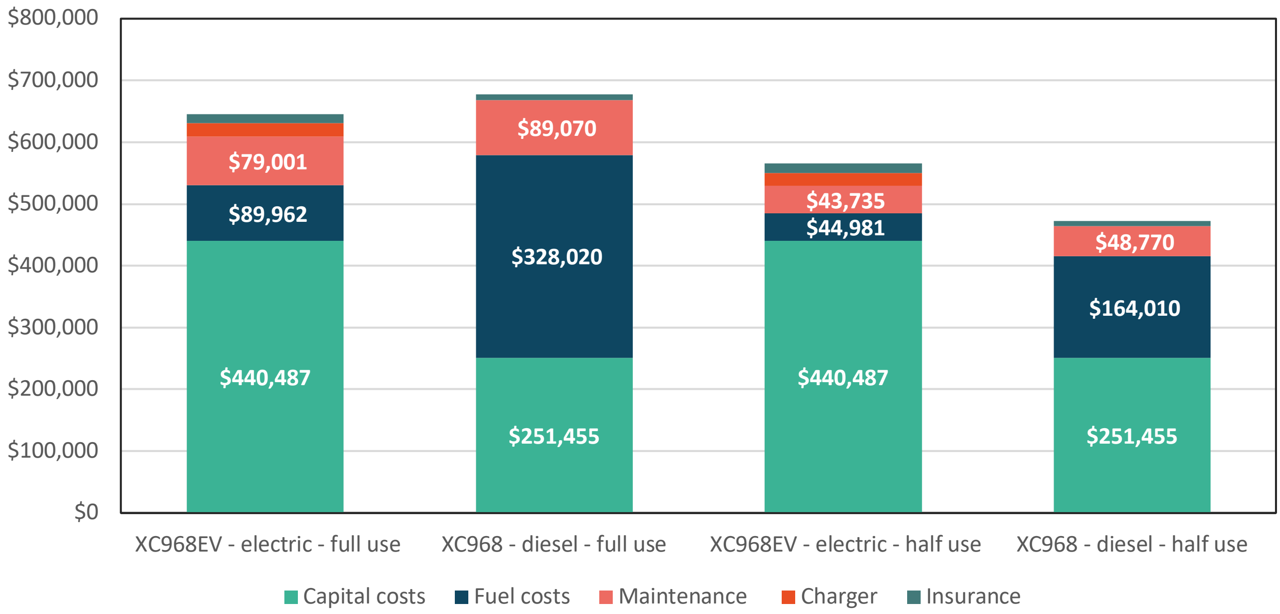
- a machine lifetime of eight years
- an 8% cost of capital
- equal payments for the initial capital cost over the machine's lifetime, with full payment received at the end of year 8
- a 0.6% annual premium on the initial capital cost for insurance
- a fast charger shared between 2.5 electric machines
- maintenance savings in line with manufacturer estimates (for example, XCMG sales brochure) if available, or using maintenance labour and parts estimates based on the TCO calculator on the Case website (construction equipment manufacturer) for similar, power equivalent equipment

[18] Electric Vehicles in Construction 2022-2024, IDTechEx

- current fuel and industrial electricity (variable rates) costs as per the most recent MBIE energy statistics
- supplier quotes for capital costs, and supplier/contractor estimates of fuel consumption, and
- no battery replacement over the lifetime of an electric machine.

XCMG XC968EV vs. XC968

Figure 5 - TCO of diesel and electric wheel loaders, 20 tonnes



	XC968EV - electric - full use	XC968 - diesel - full use	XC968EV - electric - half use	XC968 - diesel - half use
Capital costs	$440,487	$251,455	$440,487	$251,455
Insurance	$15,188	$8,670	$15,188	$8,670
Maintenance	$79,001	$89,070	$43,735	$48,770
Charger	$21,115	-	$21,115	-
Fuel costs	$89,962	$328,020	$44,981	$164,010
Total	**$645,752**	**$677,215**	**$565,505**	**$472,905**

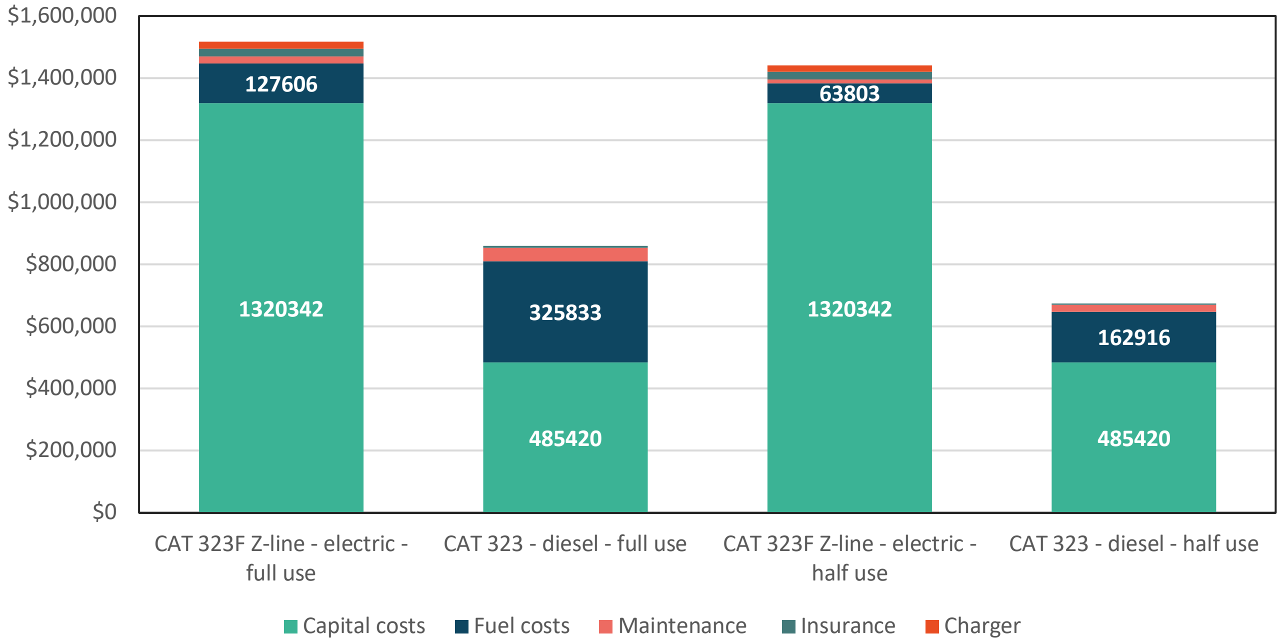
These are power equivalent 20 tonne wheel loaders, both manufactured by XCMG. Even though the electric machine costs around twice as much to purchase, it offers a 5% lower TCO when fully utilised (8 hours a day, 260 days a year). When operating at half capacity (4 hours a day), the electric machine has a 20% more expensive TCO.

According to one interview, there are many plant and site-based wheel loaders that are constantly in operation, and very frequently idling. These machines take heavy loads, and so use a lot of energy. Together, these factors result in one of the better economic cases for electric construction machinery. Many interviewees saw wheel loaders based in a single location with a reliable energy supply as a first logical step for electric construction machine adoption.

CAT 323F Z-line vs. CAT 323

These are power equivalent Caterpillar 26 tonne excavators. Although savings in fuel over the electric machine's lifetime are substantial, they're not sufficient to justify the purchase (at around three times the initial capital cost) from a purely economic point of view. Fully utilised, the 323F Z-line has a TCO 76% higher than its diesel counterpart.

Figure 6 - TCO of diesel and electric excavators, 26 tonnes



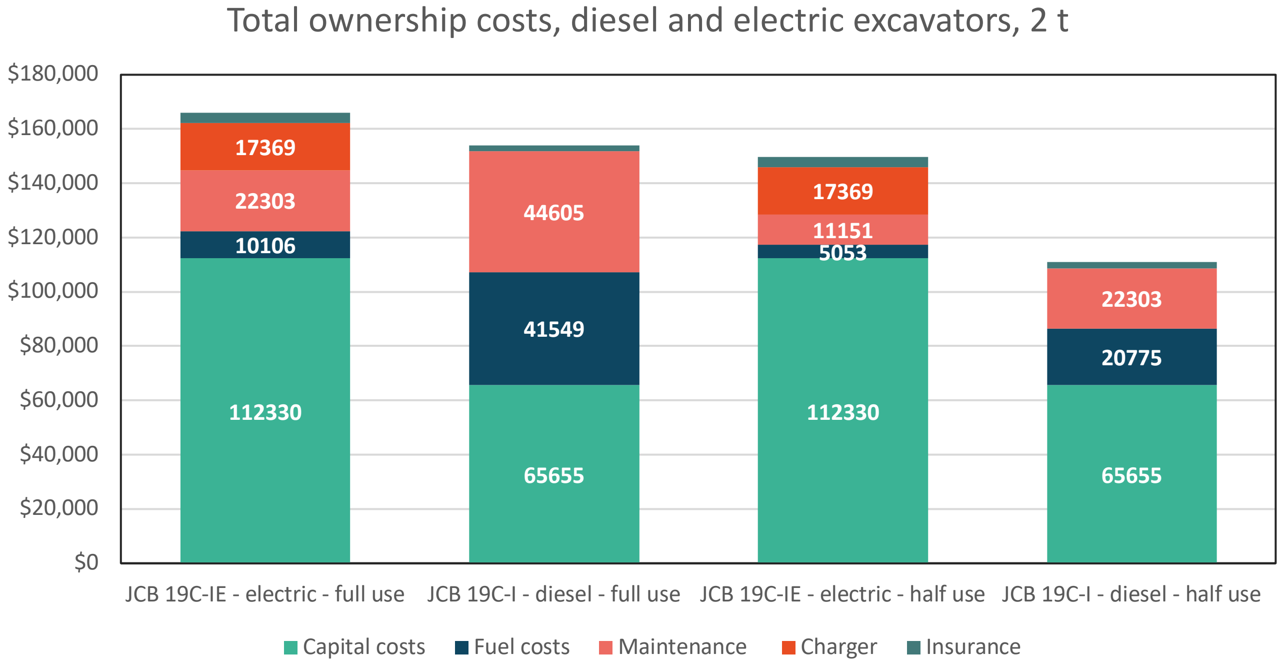
	CAT 323F Z-line - electric - full use	CAT 323 - diesel - full use	CAT 323F Z-line - electric - half use	CAT 323 - diesel - half use
Capital costs	$1,320,342	$485,420	$1,320,342	$485,420
Insurance	$25,652	$5,293	$25,652	$5,293
Maintenance	$21,716	$43,433	$10,858	$21,716
Charger	$21,115	-	$21,115	-
Fuel costs	$127,606	$325,833	$63,803	$162,916
Total	**$1,516,431**	**$859,979**	**$1,441,770**	**$675,346**

JCB 19C-1E vs. JCB 19C-1

These are lower equivalent 1.9 tonne mini excavators, both manufactured by JCB. The electric machine costs around twice the price of the diesel. Over its lifetime, the electric machine has an 8% higher TCO when fully utilised, and at half-utilisation, the electric machine has a 34.9% higher TCO.

For this class of machine, operator benefits such as safety, noise, ease of use, and versatility (both inside and underground operations) are important (depending on the application). These benefits are not costed in our calculations, so where there is only a small TCO disadvantage, we might expect to see uptake of this type of machine even where the TCO for a diesel is lower.

Figure 7 - TCO of diesel and electric excavators, 2 tonnes



	JCB 19C-IE – electric – full use	JCB 19C-I – diesel – full use	JCB 19C-IE – electric – half use	JCB 19C-I – diesel – half use
Capital costs	$112,330	$65,655	$112,330	$65,655
Insurance	$3,873	$2,264	$3,873	$2,264
Maintenance	$22,303	$44,605	$11,151	$22,303
Charger	$17,369	-	$17,369	-
Fuel costs	$10,106	$41,549	$5,053	$20,775
Total	**$165,981**	**$154,073**	**$149,777**	**$131,771**

As shown by the figures above, the main TCO disadvantage for electric equipment is the initial price, mainly driven by the cost of manufacture. Note also that these calculations assume that electric equipment operates in an environment where they have ready access to an appropriate electricity supply and can be used as intensively as diesel machines. This is likely not the case for most applications of electric equipment at present (as discussed elsewhere in this report).

IDTechEx, a market research company with expertise in emerging technologies, are expecting cost reductions over the near-term however, both through economies of scale as production increases and cost reduction in battery manufacture.[19] Over the past decade the automotive industry has been establishing a reliable and effective supply chain for electric components, and prices of lithium-ion batteries have been decreasing. By contrast, Manufacturers of building and construction equipment have only recently been developing their first generation of equipment. That is, while the construction industry will benefit from work the automotive industry has done to

[19] Electric Vehicles in Construction 2022-2024, IDTechEx

organise supply chains (and the corresponding decreases in prices of batteries), it will take time before they can take advantage of this to decrease prices for the consumer.

Figure 8 - TCO breakeven point (in years) for electric wheel loaders compared with diesel machines

Caption	Time in years until break-even TCO versus a diesel equivalent for wheel loaders of various sizes and a range of battery pricing. This is the time taken for fuel and maintenance savings compared to diesel to equal the additional cost of the battery.				
Battery pricing ($/kWh)	Machine weight (1,000kg) — IDTechEx Research				
	5	10	15	20	25
100	2.2	2.8	2.3	2.6	2.8
200	4.3	5.5	4.7	5.2	5.5
300	6.5	8.3	7	7.7	8.3
400	8.7	11.1	9.3	10.3	11
500	10.8	13.8	11.7	12.9	13.8
600	13	16.6	14	15.5	16.6

Source: IDTechEx

IDTechEx suggests that the cost of manufacture will decrease such that TCOs will be compelling for electric machines, with battery pricing potentially falling as low as automotive levels. If batteries are produced at the current costs per kWh as electric car batteries (a little more than USD 100 per kWh), owners could see a return on their investment in as little as 2-3 years (see Figure 8 above).

In short, we should expect to see some reduction in TCO for in electric equipment in the future.

Case study – New electric shovel at Macraes gold mine

Oceana Gold has been given co-funding for a technology demonstration partnership with EECA to partially fund the replacement of a diesel excavator with an electric powered shovel for use in Macraes gold mine, in Otago. OceanaGold have pledged to reduce emissions across its operations for an interim 2030 target of 30 per cent per ounce of gold produced. A total of 13 diesel excavators are currently in operation at the Macraes site, another of which will be requiring replacement by 2025. Some electric equipment still needs to be installed before the electric shovel can being operating.

The shovel is a Komatsu electric powered "super-giant" class mining excavator unit tethered to, and powered by, the national grid. Hitachi's super-giant excavators begin at 190 tonnes and reach up to 808 tonnes, with power outputs ranging from 610 kW (using a single motor), up to 2,400 kW (using two 1,200kW motors).

It will be the first example of an electric shovel for open cast mining operations in New Zealand. Shovel type mining excavators dig material at and above the loading level they sit on. This machine can dig up to 12 meters along the bench (the characteristic narrow terraces of open cast mines) before they need to advance along it. This mode of operation covers a lot of ground, and a large volume of earth is moved while the shovel effectively stays in place. The current backhoe type diesel excavators in operation work slightly differently, digging below their operating bench level which requires them to retreat along the bench after digging for 4 meters.

The shovel effectively remains in place for long period, needing to relocate less frequently than other excavators in operation, while moving just as much earth. Oceana Gold expect that the shovel’s slow and predictable movement will be ideally suited to cable connected operation.

Tethered electric machines, where able to be used effectively, have two significant advantages over completely battery powered machines. They can be used continuously, without needing to stop for charging, and they do not need to carry heavy batteries. The main challenge with tethered machines is the physical limits set by the length of the cable, and the management of cables on sites, especially when shared with other heavy machinery and personnel. In the right circumstances, good management and planning can overcome these challenges.

Introducing the shovel will come with safety risks. Within the mine, people will be at increased risk of contact with high-voltage electricity. This has been mitigated by developing training plans and safe operating procedures with overseas experts. It is also likely the power cable will be buried along most of its length instead of overhead routing to minimise exposure.

Oceana Gold estimates that from use of the shovel alone, carbon emissions would be reduced by around 3,600 tCO_2e per year. In addition, long-term savings are expected from decreased energy costs and less required maintenance from the electric motor (which will also result in less down time compared with diesel machines).

This project introduces a new technology not previously used in mining in New Zealand. EECA expects that this technology demonstration has much to teach not only other mining sites, but also operators in other sectors, about the energy, emissions and other savings that can be gained from electrification, and about the operation of tethered mobile equipment.

3. Construction industry perspectives on decarbonisation opportunities and challenges

We interviewed representatives from construction industry bodies, civil engineering contractors, building and construction suppliers, and government agencies involved in electricity infrastructure planning as well as procurement of construction services. In these interviews, we sought information about interviewees' experience with electric and hybrid construction equipment, aspects of performance relative to common, comparable diesel machines, and their perspectives on the drivers and barriers to construction sector decarbonisation.

The key findings from those interviews are documented in this section. Most of the insights covered here align very closely with those documented in academic and industry literature and are discussed in earlier sections of this report. We have not distinguished between the perspectives of suppliers, contactors, or other industry representatives, as there was almost unanimous agreement on the issues discussed.

Key barriers to adoption

Infrastructure

Infrastructure was a key barrier identified by all interviewees. Essentially, these concerns reflected challenges in securing a reliable power supply to recharge or replace a depleted battery. These challenges differ according to the wide variety of locations where construction equipment is operating.

In some instances, the infrastructure challenges will be minor, particularly in established or permanent sites close to an appropriate power supply. Interviewees were also aware of equipment engaged in work at the other extreme, remote work in difficult terrain. In this case the challenges are so great that interviewees saw no medium-term solution that enables battery powered or hybrid construction equipment to function reliably. Construction equipment is in operation in both extremes, as well as the many situations lying in between them.

Interviewees reported that some power suppliers say they have the electricity, and the challenge for charging batteries will relate to the method of delivery.

Solutions that lie outside of the national grid were also mentioned. These included temporary energy infrastructure, like solar panels, battery swapping (the practice of carrying another fully charged battery nearby, and replacing batteries when needed), large battery packs, and (when feasible) low carbon solutions from alternative energy sources (for example, from a fuel cell engine powered by hydrogen).

Interviewees said that these options for charging machines off the grid all have pros and cons that depend a lot on the situation in which they are used. For example, solar power installed at a site provides a long-term power source but incurs costs from setting up and packing away and would usually only be able to power machines using relatively small amounts of energy, particularly given the large area of most construction sites. By contrast, some large battery packs can charge energy intensive machines two full times before their energy is spent, but this can only be a temporary solution as it will need to be transported to a power supply once depleted. Most of these alternative charging methods appear to have unique utility, and operators of electric machinery will likely use a mix of these to make the best use of electric construction machinery.

Duty cycle

For the equipment that was brought to our attention through interviews, most electric machines were capable of a period of intensive use close to, but less than, that of a diesel machine (when using fast charging over break periods). Ultimately over an 8-hour workday, most electric machines would have fewer productive hours.

There were some exceptions to this, for example, some 20 tonne wheel loaders can undertake an 8-hour day of work with no breaks for charging. As machines get larger, weight distribution frequently becomes an issue, and this issue can be addressed using a large battery to balance weight as well as provide power to the machine.

Of course, tethered electric machines can be used essentially continuously, assuming a three-phase electricity connection is available. Three-phase AC tethers are used for the electric machines offered, or in use, by our interviewees. They noted that the management of tethers, and the limited mobility of tethered machines limits their use for general tasks, but otherwise tethered machines are a very attractive investment given there is no need for batteries (which are expensive) and they can work continuously without charging.

Availability of parts, and expertise for maintenance is a concern for electric machine owners

As with most new equipment, owners and prospective buyers of electric machines like to be assured that they can easily purchase parts and expertise for their maintenance and repair.

Electric motors generally require little maintenance and have been widely used in industry for more than 100 years. On-road electric motors are becoming increasing widespread so relative expertise should not be difficult to find and most other components of electric construction machines requiring maintenance are very similar, or identical to diesel components (for example, maintaining hydraulic systems). What is unique for electric machines, or potentially unfamiliar to mechanics or electricians, are the large batteries that electric machines and hybrids use.

As a battery can be up to 40 to 60 percent of the total cost of an electric machine, interviewees informed us that owners of electric equipment are often anxious that these are well maintained.

Interviewees have been impressed with the support that manufacturers have offered to date regarding maintenance and safety (which typically relates to the electric components of the machine).

Price

Interviewees' saw the initial capital cost of electric consumption equipment as a large barrier to adoption. In short, while many companies have pledged to reduce their carbon emissions, large scale efforts to decarbonise construction fleets are much more likely to be successful if the TCOs of electric machines are less than diesels for most applications. In some cases, particularly for smaller and less diversified building and construction firms, access to finance (and the cost of lending) will mean that high initial capital costs cause firms to not invest, even if the TCO looks be lower than alternatives.

Interviewees' observations of prices generally align with other information available to EECA. There was general agreement that electric construction equipment (able to complete most of a full day's worth of work) is around two to three times the price of similar diesel machines operating at around the same power. In a few instances electric machines are as much as five times the usual price of a similar diesel machines. More details are available in the total cost of operation section above.

Suppliers noted that production is low worldwide, and that they would expect to see prices fall as production increases in scale. One interviewee noted that a XCMG 20 tonne electric wheel loader (a flagship product of the company and so produced in relatively large volumes) was able to be price competitive with diesels from competing companies. However, at present, cases like this are the exception.

According to interviewees, residual value of an electric vehicle (that is, the price of a machine on the second-hand market) is another important factor for prospective buyers. Much of an electric machines' residual value will depend on long-term battery life. As described below, there are clear expectations about battery longevity, but this can be influenced by environmental factors which introduces uncertainty when used in new situations. This uncertainty does not favour electric machines when calculating the costs and benefits of replacing a diesel machine.

Priorities

Many corporates have made a pledge to reduce emissions, but see other investments (that is, outside of new investments in their fleet) as more pressing or higher impact per dollar spent. For example, one interviewee told us that some civil engineering contractors' best investment in decarbonisation could be to make the production of asphalt more energy efficient.

Some interviewees also mentioned that there were still opportunities for decarbonisation for internal combustion engines, for example, improvements brought about through new diesel engine standards and exhaust gas recycling.

The costs of operation too being too uncertain

One interviewee noted that while there is good information on which to base how long batteries last in ideal conditions, we won't know how long batteries in local conditions tend to last until we have experienced the full lifecycle of a battery. Humidity, dust, and variation in temperature all influence battery life and the conditions in New Zealand differ from other parts of the world.

Extreme temperatures are usually the main environmental factors associated affecting battery performance, which should not be a big concern in New Zealand's mild climate. However, potential customers are still conscious that the off-road conditions are typically much more extreme than on-road conditions (for which there is good data about battery longevity), and uncomfortable with the fact that estimated battery life, at this point, is largely based on laboratory data.

Related to this point, is that potential customers of electric machines don't know whether they can believe manufacturers' promotional material or not.

Some interviewees shared their expectations of battery life, which was generally around 10 to 11 years. There is also an expectation is also that, at the end of their life as a construction machine power source, batteries can have a second life with less intensive use, for example, for energy storage for solar power generation. But battery longevity for these machines mostly hasn't been tested in New Zealand yet, as no production battery powered electric machine has been in operation for its full lifecycle.

However, there are overseas examples, XCMG has 20 tonne wheel loaders in China that have been operating on the same battery more than 10,000 hours.

Other market factors

Interviewees mentioned that small production volumes also impact electric machine adoption. That is, low volume production means that these products are simply difficult to purchase. We have heard that that if a supplier or contractor would like to purchase several machines, these would likely not be available within a reasonable time frame.

Key factors driving electrification

Electric machines have several economic advantages

All interviewees noted that fuel savings for hybrid and electric machines were significant. One interviewee reported a 25–30% saving on fuel consumption for a 50 tonne hybrid excavator, and TCO calculations using fuel consumption and energy consumption numbers that interviewees provided us show a 73% reduction in the price of energy when replacing a diesel 20 tonne wheel loader with an electric machine, and similar reductions for small and medium excavators.

Maintenance savings, while much less than fuel savings, were reported to be significant too. Interviewees described maintenance of electric motors as simply greasing the motor every six months. Interviewees noted that other maintenance required for electric machines (apart from servicing the electric motor) would to be the same as for power-equivalent diesels (for example, maintaining the hydraulic system).

One interviewee mentioned that a factor that is often not considered (but ought to be) is that decreased maintenance amounts to a reduction in down time.

Benefits other than energy efficiency and carbon emissions reduction

Interviewees unanimously acknowledged electric vehicles' noise, heat, and vibration reduction, and the benefits of electrification including increased environmental awareness on work sites, long-term hearing benefits for machine operators, and the health benefits of reducing combustion fumes.

Another slight benefit, but significant from an operator's point of view, is the benefit of having access to an electricity supply, for example, batteries enable operators to have hot food and drinks during breaks, in situations where they otherwise wouldn't be able to.

Equivalent or better moment-to-moment performance.

Interviewees noted that operators found no performance difference, or improvement in performance, when comparing electric machines with diesels. Some interviewees mentioned a noticeably smoother and more responsive operation in battery powered machines.

Interviewees also noted that while battery weight would usually be expected to penalise performance (especially as it relates to energy efficiency), many machines need counterbalances so large batteries aren't necessarily a disadvantage (for example, heavy batteries could be used as counterbalances on a crane).

Corporate pledges to reduce emissions

Interviewees mentioned that civil engineering contractors and vehicle manufacturers are increasingly committed to carbon emissions reductions, and that economic factors are not the only consideration taken when investing in low-carbon machinery.

Demand from purchasers of building and construction services

Interviewees expected that, as very large purchasers of building and construction services, local and central government requirements and preferences for fuel or energy efficiency would be, and likely will be, very effective in driving adoption of low-carbon construction machinery.

Interviewee perspectives of potential buyers of low carbon construction equipment

We asked equipment suppliers about their customers' views on electric and hybrid machines. They described those customers as curious and eager to understand how they can derive value out of an investment in an electric or hybrid machine, and how that equipment can help them meet their emissions goals.

The most common concerns of customers related to the following:

> *"Customers want to know what infrastructure is available for charging, and what complementary equipment (such as fast chargers) is required for equipment to work well."*
>
> *"Customers want assurance that the services and products were available for equipment maintenance, and want to know how much maintenance costs, and how much down time to expect from regular servicing."*

One interviewee mentioned that as electric cars are becoming more common on our roads, public consciousness of electric and hybrid machines is high. This consciousness extended to new market leaders, for example BYD[20] for car manufacture. These interviewees supposed that legacy manufacturers would not necessarily be able to transfer their reputation for quality to their electric and hybrid offerings, making room for new competitors to enter the market.

Perception of best opportunities for decarbonisation

Interviewees agreed that the focus for economy-wide opportunities for decarbonisation should depend on diesel consumption, and the numbers of machines that can adequately undertake tasks with electric and hybrid motors. The most common equipment was seen to be excavators,

[20] BYD is an electric car manufacturer from China. https://www.byd.com/nz

particularly small excavators, and wheel loaders. Among these, wheel loaders and large excavators were seen to have particularly high fuel consumption.

Infrastructure was considered to mostly already be in place for many applications of urban small excavators (standard electric vehicle charging stations), and for most applications for wheel loaders and telehandlers (electricity supplies in plants and yards). For these reasons, many interviewees expected that a focus on wheel loaders and small excavators would be sensible to direct decarbonisation efforts.

There were conflicting views on small excavators because of their versatility. That is, while they are very common, they are often put to work where it's difficult to deliver electricity, so the economy-wide fuel savings might not be as great as initially anticipated.

Interviewees reported that in many cases, the economics will depend on the tasks required of a machine. In some special cases, electric machinery might be overwhelmingly advantageous, for example, where heavy loads are put into a machine at the top of a hill and transported downhill (that is, where the gravity is exploited to charge the machines' battery).

One interviewee commented that at this point, having a repeatable task is one of the most important factors to getting value for money from an investment in electric machine. Another interviewee approached the issue from the opposite perspective: electric machines will become more broadly economical, when they are able to be applied to a variety of tasks. In both cases, we see that the longer electric and hybrid machinery is in operation over its lifetime, the greater the economic benefits.

4. Conclusion

While electric construction machinery and hybrids show a lot of promise to address decarbonisation for New Zealand's third largest diesel consuming off-road sectors, they are not ready to economically replace diesel machines for most applications. Fuel savings are immediate and significant, and electric and hybrid vehicles have several other significant benefits, including noise and heat reduction, reduction or elimination of harmful fumes, and more responsive control. However, in most cases, these benefits do not result in a more economical investment over the lifetime of the machine.

The two most important factors working against electric and hybrid machines are: the high capital cost of machinery (often between two and three times the price of diesel equipment) and; practical challenges to charging machines far from an appropriate electrical supply.

There are, however, a small number of scenarios that clearly favour electric and hybrid machines already. Over the medium- to long-term, as production increases in scale, investments in charging infrastructure increase, price of carbon increases (through the ETS), and as battery pack prices decrease, there will be many more opportunities for decarbonisation of the building and construction industry. While only 0.5% of the market currently, sector experts expect almost half of all construction machinery will be fully battery powered or tethered by the year 2042.[21] In addition, improvements in technology in electric equipment continues to develop rapidly.[22]

[21] Electric Vehicles in Construction 2022-2024, IDTechEx
[22] To provide just one example, *Jessie E. Harlow et al 2019 J. Electrochem. Soc. 166 A3031* - lab-based research has already more than doubled the lifetime of commonly used battery cathodes through their use of electrolyte additives, an improvement we could eventually expect to see in larger scale production

Summary of low-carbon building and construction machinery

There is a broad range of electric and hybrid construction equipment that is market ready and available for purchase worldwide. However, the international scale of production is low, which gives rise to high prices and difficulties securing supply in small markets such as New Zealand. Fully battery powered equipment is available for many common types of small- and medium-sized equipment, and hybrid equipment is available for larger machines (usually more than 20 tonnes).

All low-carbon machinery that we researched is made as a direct replacement for diesel machinery, with power output generally matching diesel equipment of the same weight. They use many, or most, of the same parts as their diesel equivalents, and moment-to-moment performance is the same or better than similar diesel machines. Like the diesel machines they are made to replace, different types of machines vary widely by the energy they consume, and the numbers of machines in operation.

An estimate for the emissions impact of diesel machines can be computed by multiplying the number of machines by their estimated fuel consumption. Estimating in this way, we would find that excavators and wheel loaders, in aggregate, have the largest emissions compared with other building and construction equipment. This kind of analysis can highlight important areas for further investigation. However, this does not directly relate to an estimate of emissions reductions, as the complete replacement of diesels by electric machines is not possible. Electric machines need access to a reliable supply of electricity to be used to good effect, and equipment like excavators can be used in locations close to, and far from, the electricity grid. However, technology solutions for remote charging of machines are available (for example, the KTEG Power Tree).

Opportunities for contruction sector decarbonisation

Adoption of electric machines will depend greatly on the extent to which our current infrastructure (or other charging solutions) allows electric machines to operate to their full potential. Another important limitation is the practical challenge of creating certain types of electric machines. For example, at present there are challenges to creating batteries for heavy construction equipment (in general, above 20 tonnes). However, there are hybrid alternatives to heavy diesel wheel loaders and excavators.

In the medium-term, there will remain some applications that will likely not be adequately met by either hybrid or battery powered machines. These applications require equipment to be used far from established electricity supplies, or in difficult terrain. Low carbon options for these situations may need to come from future developments in alternative energy production, for example through fuel cells, or biofuels.

Through this research, we cannot give explicit recommendations about categories of machines or sub-sectors within the building and construction industry on which decarbonisation can focus. The literature, findings from interviews, and TCO calculations indicate several key factors that strongly influence the decision of whether to invest in electric equipment, and these may be relevant to policy setting.

The case for decarbonisation for construction equipment is currently dependent on each machine's situation and characteristics. We expect that over the next five years, electric machinery will likely be prioritised when one of, or a combination of, the conditions below are met:

- Electricity and charging infrastructure is accessible when and where it is needed (through the grid, or by using battery packs or battery swapping).
- The equipment consumes a lot of energy.
- Electric machines can be used as intensively as their diesel equivalents, for example, performing a full day's worth or work, with or without charging.
- Applications uniquely benefit electric machines, for example, demolition, inside/underground operation, carrying heavy loads downhill, lots of idling.
- Electric or hybrid machines are being manufactured at scale and supplied in the numbers that we need.