

Article

The Construction Site of Tomorrow: Results of 3 Years of Field-Testing Electric Excavators

Willem Christiaens ^{1,*}, Harm Weken ¹, René van Gijlswijk ² and Michiel Zult ²¹ FIER Sustainable Mobility, 5708 JZ Helmond, The Netherlands; harmweken@fier.net² The Netherlands Organisation for Applied Scientific Research TNO, 2509 JE The Hague, The Netherlands

* Correspondence: wchristaens@fier.net

Abstract

“The Construction Site of Tomorrow” is a 3-year collaboration of a consortium of seven contractors, two knowledge institutes, and the construction machinery supplier on the deployment of heavy-duty electric excavators. The practical experiences of “The Construction Site of Tomorrow” have resulted in technical improvements of the machines, new insights about energy consumption in different use cases, experience with the deployment of the machines, and practicalities around charging the machines’ batteries in different situations. In this paper, we elaborate on the findings of the project, including the usability of the machines, their energy consumption, and total costs of ownership. This work has been coordinated by FIER Sustainable Mobility. The project was sponsored by the Netherlands Enterprise Agency.

Keywords: off-road and industrial electric vehicles; charging business models; measuring methods and equipment; climate change; electric vehicles

1. Introduction

Electric non-road mobile machinery is a relatively new development that allows construction without local pollutant emissions such as nitrogen oxides and particulate matter, for instance, in the built environment. An additional benefit of electrification is a potential reduction of CO₂ emissions per unit of work, compared to traditional diesel-engine-powered machines. However, the practical implementation of electric machinery requires machines to be available, reliable, affordable, and preferably capable of replacing diesel machines one-to-one in daily operations. Daily operations require charging, if possible, without hampering productivity.

The adoption of zero-emission mobile machinery is particularly important in the Netherlands, where the nitrogen deposition load on natural areas is high, and habitats in these areas are often marked as sensitive. Construction projects using combustion engine-powered machines may, depending on the location and the size of the project, contribute to this deposition and therefore require a Natura 2000 permit, since the exemption for construction projects was discontinued in 2022. However, due to the trend of deterioration of natural areas, there is little-to-no room to grant these permits. This, and the complexity of the procedures, lead to large delays in construction projects [1–3].

Existing research on the electrification of construction machinery is generally aimed at improving energy efficiency. This is useful because there is room for improvement, and electrification opens new ways to accomplish these improvements. Efficiency gains can be achieved by load sensing and on-demand hydraulics (e.g., [4,5]), and by energy



Academic Editors: Joeri Van Mierlo
and Peter Van den Bossche

Received: 23 October 2025

Revised: 19 January 2026

Accepted: 22 January 2026

Published: 29 January 2026

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World Electric Vehicle Association.

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recovery (e.g., [5,6]), which works well with electric powertrains. However, little research was published on the practical usability of electric equipment in day-to-day use in different kinds of construction and maintenance projects. Studies on practical usability and energy consumption are available for heavy-duty road vehicles (e.g., [7–10]), but results cannot be projected on hydraulic heavy machinery.

Due to the limited availability of real-world data and the urgency of the Dutch situation, the Dutch government was interested in having an investigation into the extent to which electric heavy machinery currently on the market is able to fulfil the above-mentioned practical requirements. If they can replace diesel machines on a day-to-day basis, they may help alleviate the process of initiating construction projects. The project “The construction Site of Tomorrow” is a demonstration project for heavy-duty electric excavators and was subsidised by the Netherlands Enterprise Agency RVO. It has been carried out by a consortium of seven front-running contractors, two knowledge institutes (TNO and FIER Sustainable Mobility), and a construction machinery supplier (Staad Group, Veghel, The Netherlands), which developed two types of electric excavators at the time of commissioning.

In a practical sense, within this project, seven battery-electric excavators have been monitored during full-time operation by the contractors. This way, new insights were gained from practical experience with these machines about their usability, energy consumption, emission savings, costs, and logistical issues regarding, for example, the charging of the batteries of these machines. The monitoring took place over a period of two years. This has advantages over short-term field studies: seasonal effects are included in the results, and the machines could be followed across multiple projects, enabling the calculation of, e.g., energy consumption by project type. Furthermore, it allows statistical analysis of battery use patterns.

This paper summarises the results of the project. The first part describes the findings in terms of usability, electricity consumption, and its dependence on the type of activities, and the avoided emissions compared to a diesel machine. The second part is an analysis of the Total Cost of Ownership (TCO) of the excavators in the project, and the sensitivity of the TCO to several factors, such as the electricity price.

2. Materials and Methods

Six 17-ton mobile excavators and a single 35-ton tracked excavator were monitored, as shown in Figure 1. All machines are converted diesel machines and are fitted with a swappable battery box system. The 17-ton machines had two 114 kWh (usable) powerboxes at delivery; some were later upgraded to a single battery of 385 kWh usable. The tracked machine had 2 packs of 385 kWh from the start.

The powerboxes contain batteries, HVAC, control electronics, an AC inverter, and a cloud module with a GPS sensor, and can be charged on the excavator (AC 44 kW max.) and off the excavator (AC 44 kW max. and DC 140 kW max.). They can be exchanged with a loader crane. More information about the machines can be found here: <https://www.staad-group.com/electric/electric-machines> (accessed on 16 August 2025).

The data from the machines was categorised by type of operations, named “use cases”, as indicated per working day by the respective contractors. The use cases distinguished are as follows:

- Residential construction;
- Civil engineering;
- Forestry;
- Demolition works;
- Railway maintenance.

For the day-to-day monitoring of the machines, data was requested from the existing cloud modules. Those were fitted on the machine and on each powerbox by the manufacturer, and they collect data from sensors through CAN. Data frequency is generally 1/60th Hz (1 averaged sample per minute), although some signals are event-driven (e.g., diagnostics codes). Data was stored in a and checked and filtered in code.



Figure 1. (a) 17-ton mobile excavator (type DX165W); (b) 35-ton tracked excavator (type DX355LC); (c) 114 kWh powerbox.

A separate comparative test programme was conducted to determine the emission and energy savings by an electric machine. Two sets of machines were tested side by side: diesel vs. electric, 17-ton and 35-ton machines. The machines were kindly made available by Staad and some of their customers, and closely matched in terms of specifications between diesel and electric variants. The test days were kindly hosted by the SOMA vocational school for infrastructure in Harderwijk, the Netherlands. The electric machines were fitted with additional 1 Hz data loggers. Emission measurement equipment and data loggers (1 Hz) were fitted to the diesel-powered machines, see Figure 2. The two leftmost systems were developed in-house by TNO. For NO_x , ZrO_2 -based automotive sensors were used, with an accuracy of $\pm 10\%$ [11,12].

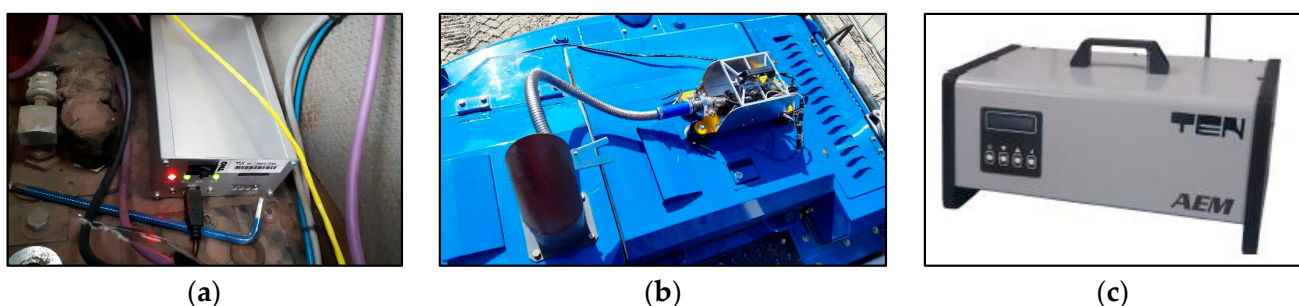


Figure 2. Measurement equipment: (a) SEMS CAN/sensor data logger; (b) portable NO_x emission measurement system; (c) portable particulate matter measurement system.

The machines were operated according to a test programme, consisting of cold idle, loading a dumper, digging a ditch and closing it (25 m), levelling a square of 25×25 m, driving in second gear (only mobile excavator), and warm idle.

3. Results

3.1. Energy Consumption

The activities during a total of 2300 working days (≥ 1.5 h) were monitored. Average hourly consumption of the 17-ton mobile excavator was 28 kWh; the 35-ton machine required 52 kWh per hour on average, which corresponds to 25% load; both numbers are exclusive of charging losses. Idle share was 30% and 29%, respectively.

The variation in the hourly energy demand for the different use cases is 33%, with forestry being the most energy-intensive and railroad maintenance the least. Table 1 shows the details per use case. On average, the machines were used for 7.9 h per working day (a working day has at least 90 min of usage). Differences in average motor power are related to idle share (see Table 1) and to the use of specialised hydraulic tools for forestry. Idle running is necessary to maintain hydraulic pressure, a consequence of the design (conversion of a diesel machine). The share in total energy consumption is below 10% for each of the use cases.

It is clear that each use case has different operating hours and different average motor power, leading to a variation in energy consumption per working day. Demolition works require 156 kWh/day, while civil projects use 227 kWh/day. This has consequences for the need for charging and/or battery swapping, as explained in the next paragraph.

Table 1. Use cases and averages from monitoring mobile excavators.

DX165W	Unit	Civil	Residential	Forestry	Railway Maintenance	Demolition Works
Average motor power during use	kW	28.2	24.2	31.5	23.6	25.2
Operating hours per working day	Hours	8.1	8.0	6.6	8.3	6.6
kWh/working day	kWh	227	193	208	208	156
Number of working days monitored	-	1036	159	202	27	30

3.2. Usability

From a usability point of view, it is crucial to know whether the machines can operate until the end of the working day with the onboard battery, possibly factoring in a battery swap and/or opportunity charging. A histogram was made of the total energy consumption per working day. It is worth noting that on a few occasions, the machines performed working days of 20 h or more; hence, some very high numbers were seen. Figure 3 shows the cumulative histogram of the daily energy consumption (blue line) for the six 17-ton machines. The share of working days that can be attained with several configurations is depicted by the light orange boxes. The standard two battery boxes with a joint 228 kWh were sufficient for 56% of the working days. A 45 min 40 kW DC charge increased this to 73%. A battery swap, for instance, during a lunch break, enables over 90% of the days. The upgraded battery hardly ever requires swapping or opportunity charging. A similar graph was made for the DX355 tracked excavator, summarising that the 2×385 kWh battery is sufficient for >99% of the working days (graph not included here). More results can be found in the monitoring report [13] (in Dutch).

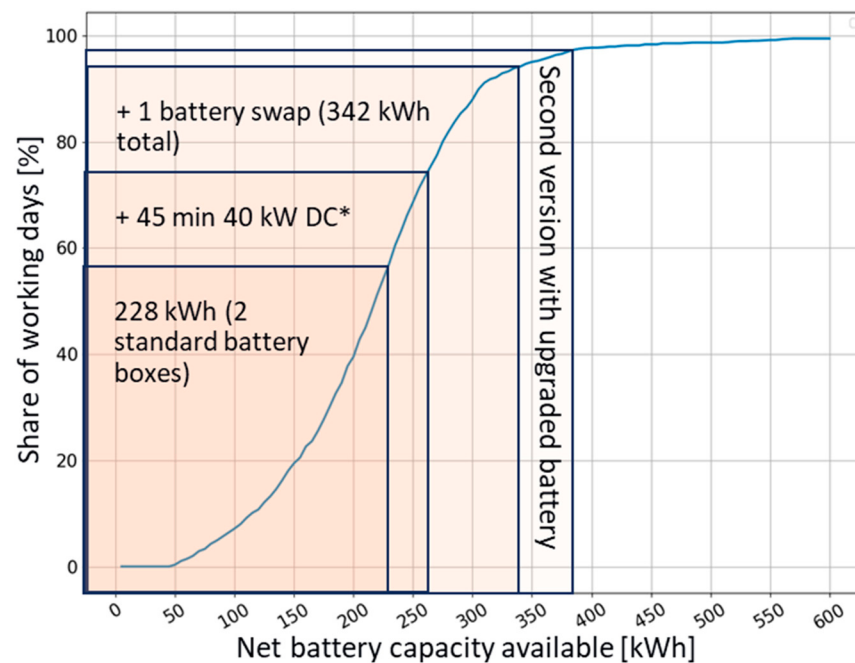


Figure 3. The relation between the available energy in kWh and the share of working days during monitoring that could be fulfilled with this amount of energy.

For machines running long hours, there is less time left to charge overnight. Figure 4 illustrates this. After an average working day, the DX165W needs approximately 12 h to charge back to 100% state of charge, when connected to a 22 kW AC charger. After a 10 h working day, this is 15 h, which is, in other words, impossible to sustain in a 24 h day. On a side note, the machines can be charged using two 22 kW plugs simultaneously.

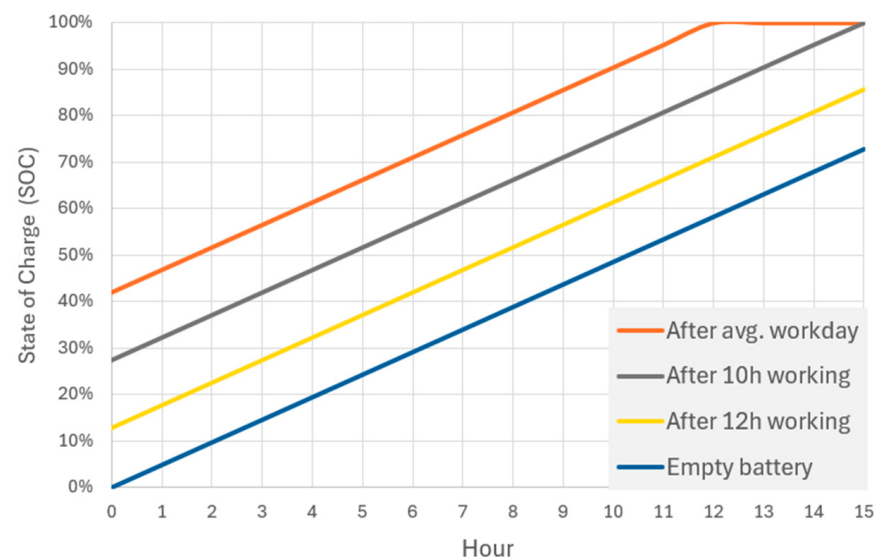


Figure 4. State of charge during charging overnight as a function of the depth of discharge at the start (22 kW AC).

3.3. Avoided Emissions

Based on the test days where diesel and electric machines were examined side by side, we observed the following. For each litre of diesel consumed, both electric machines required approximately 4.1 kWh of electricity at the plug (AC charging losses are estimated at 15%). The NO_x emissions of the Stage IV diesel machines tested were approximately 0.5 and 1.5 g/kWh for the 17-ton and 35-ton machines. Note that this is heavily influenced by

the exhaust gas temperature and, consequently, by the duration of the test; therefore, it is not representative of an entire working day.

The tests were useful to confirm the practical usability, regardless of the powertrain, and to establish the energy consumption under controlled and equal conditions. However, the NO_x emissions are dependent on many factors (engine load, ambient temperature, engine and exhaust gas treatment technology, etc. [14]), and for a fair assessment of avoided emissions, it was decided to use a model instead. The model is able to predict Stage V tailpipe emissions using the load profile from the monitoring data and the EMMA-MEPHISTO model [15], which in turn is based on emission factors per load bin that were determined from measurement data for many hours of operation [14,16]. The outcome of the model shows that the contractors have avoided an emission of approximately 115 kg of NO_x per machine per year, as well as 31 tons of CO₂ per machine per year (assuming Dutch average electricity mix 2023).

3.4. Total Cost of Ownership (TCO)

The purpose of this analysis is, on the one hand, to increase understanding for policy-makers and construction companies, as the potential end user, about the costs of deploying electric construction equipment. On the other hand, it provides insight for entrepreneurs considering the purchase of an electric excavator.

The cost analysis was first published in a report [17] and updated for this paper, reflecting the 2024 situation in terms of purchase price and subsidies.

The analysis shows that currently, the TCO of electric excavators is still significantly higher than that of a comparable diesel. For the DX165 mobile excavator, the electric version turned out 195 kEUR (42%) higher, and for the DX300 tracked excavator, it was 252 kEUR (34%) higher. See Figure 5 for the TCO comparison for both machine types. These electric machines, including existing purchase subsidies and investment deduction schemes in the Netherlands, are still far from competitive. If incentive schemes are excluded from the analysis, the gap between diesel machines rises to 58% for the tracked and 69% for the mobile machine. This means that the deployment of electric construction equipment requires additional financing from clients. In the Netherlands, we see a rise in the willingness for this additional financing in projects where the environmental benefits, like the avoidance of NO_x emissions, are key.

The reason for this large difference in TCO can largely be explained by the early stage that the market for electric construction equipment is currently in, especially internationally. It is expected that the scaling up of production capacity and further development of machines in the longer term will have a downward effect on the TCO of the electric machine, narrowing the gap with diesel.

The procurement prices, utilisation, and the total costs of charging are important factors that make up the TCO of these machines. The utilisation of the machines affects the TCO of both electric and diesel. The larger the deployment, the smaller the difference between the two becomes, but even when tripling the standard deployment, the TCO of the electric machine remains higher. Looking at Dutch incentives, the subsidy on the purchase of electric machines is significantly reduced compared to 2023. With purchase costs of the machine certainly not reduced, this means a significant deterioration in TCO compared to 2023. The analysis shows that the combined subsidy rate (MIA and SSEB purchase, available in The Netherlands) needs to increase by a factor of 2.5 for a competitive TCO for electric machines.

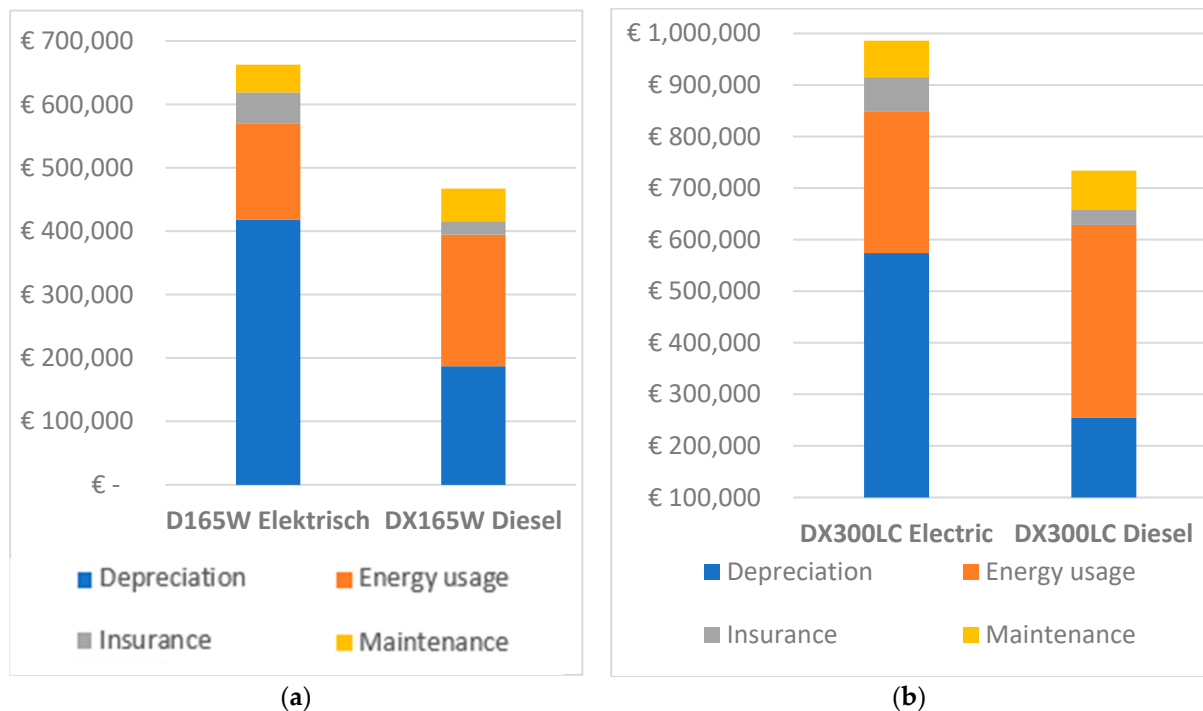


Figure 5. TCO comparison of diesel and electric variants for two types of excavators: (a) 17-ton mobile excavator; (b) 35-ton tracked excavator.

The impact of the total costs of charging on the TCO is illustrated in Figure 6. The TCO takes into account 0.35 EUR/kWh. The total costs of charging not only include the cost price of electricity in the Netherlands, but also the additional (capacity) charges from the DSO, the depreciation of needed charging infrastructure, possible costs of additional energy storage, and logistical changes to transport energy storage units from and to the construction site. For the latter, this can be about transporting swappable battery packs to the construction site or about organising large (2.4 MWh) mobile energy container units in remote locations. A variety of examples have been encountered in the project and described in an earlier report [17]. This shows that the cost of charging varies across the different charging methods applied, and it has a significant impact on the overall TCO of electric machinery.

Figure 7 shows some practical examples of charging methods used in the project, and the results of the analysis on the total costs per kWh. No conclusions can be drawn from these as to the most appropriate or average cost per charging method. This depends very much on the specific situation of the work and underlying factors. However, the examples do show that there is a large variation in charging costs between different methods. Here, proximity to a grid connection is an important factor in keeping costs down. In cases where no grid connection is available near the site, solutions such as swappable batteries or mobile energy storage containers are used. The purchase costs of these assets and the logistics costs add up significantly to the total costs of charging. For larger, long-term projects, this can be organised in a way that the additional cost of charging remains relatively low. For shorter-term projects, i.e., if swappable batteries or mobile energy storage containers are only used for a few weeks, the costs of charging will be significantly higher.

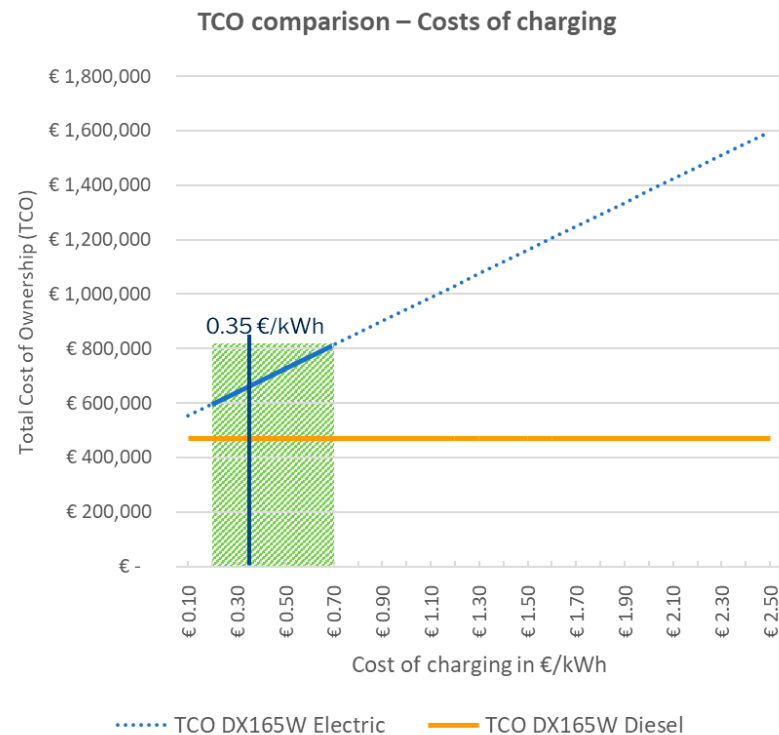


Figure 6. TCO comparison of diesel and electric machines, and the influence of deployment.

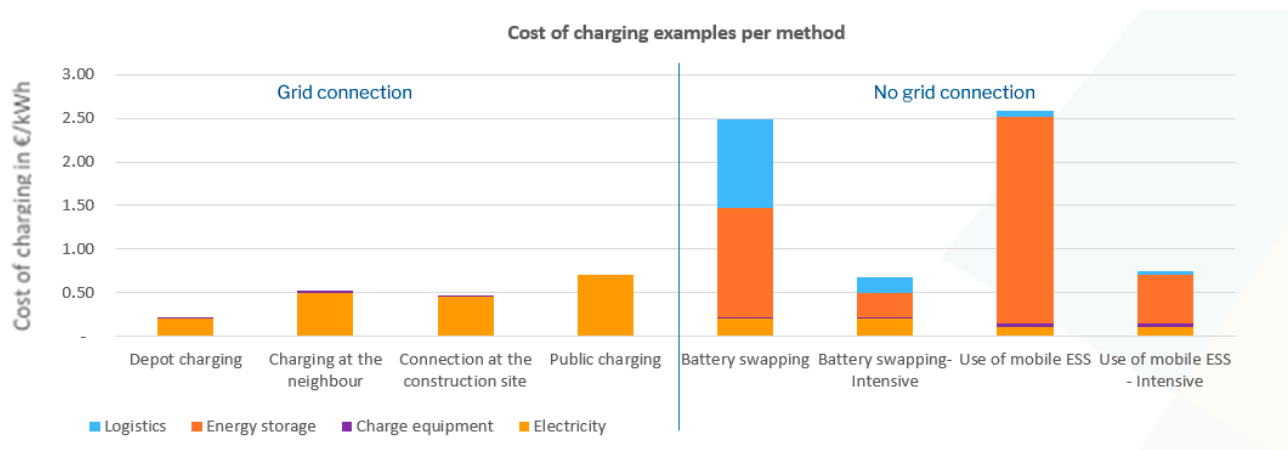


Figure 7. This comparison of costs by charging methods is based on examples. The final cost per charging method is highly dependent on the specific circumstances and thus may vary.

Another important aspect to highlight is that the higher power demand and the relative immobility of tracked excavators require different charging solutions than those employed for wheeled excavators.

To conclude, we see that the TCO for the electric excavators is still substantially higher (including incentives 34–42%, excluding incentives 58–69%) compared to its diesel counterpart. These electric machines are still far from competitive, including existing purchase subsidies. The reason for this large difference in TCO can largely be explained by the early phase in which the market for electric construction equipment currently finds itself, especially internationally. It is expected that the scaling up of production capacity and further development of electric machines will have a significant impact on lowering the TCO of the electric machine in the long run. In terms of technological developments, there are still opportunities to advance in the energy efficiency of the machines. This can be achieved by implementing and improving measures like load sensing, on-demand

hydraulics, and energy recovery. Besides lowering energy costs, improving efficiency will reduce the need for large battery capacities, hence reducing the overall machine costs. In order to justify the required investments by OEMs in technological developments, the international market demand for electric excavators needs to grow substantially. Looking at the Netherlands, we see government incentives schemes on purchasing, innovations, and the inclusion of zero-emission machines in public procurement of construction projects. This is mainly driven by the nitrogen deposition problems, something that few other countries experience. Although this creates a relatively small market in which technological developments and experimentation can happen in the short run, the international growth in market demand is needed to create sufficient scale for the market to fully mature.

4. Conclusions

The following conclusions can be drawn:

- The electric excavators have been successfully used in the project “The Construction Site of Tomorrow”.
- The energy consumption per hour is reasonably comparable among the different use cases.
- The number of operating hours per day varies widely. It has been proven to be possible to run double shifts, even with the limited battery capacity of the first-generation batteries, when making use of the battery swap system (and good planning). Using the upgraded batteries of 380 kWh makes this even easier.
- The grid connection on the construction site has to have sufficient capacity to be able to charge the machines overnight, and if necessary, separate swapped-out batteries during the daytime. In the case of long working hours, it can become critical even with 2×22 kW (3-phase 64 A per machine).
- The comparative emission measurements point at expected emissions reductions of around 21 tons of CO₂ and 114 kg of NO_x per year for the mobile excavator, and 34 tons of CO₂ and 202 kg of NO_x per year for the larger tracked machine.
- When replacing a diesel machine with an electric one, it can be expected that 4 kWh from the grid is needed for every litre of diesel consumed.
- The TCO of electric excavators is considerably higher (34–42%) than that of comparable diesel excavators, given the Dutch situation and the assumptions made.
- Upscaling and technological developments will have a positive impact on the TCO of electric machines in the long term. In this, there is the potential to improve efficiency and therefore reduce the need for large battery capacities. This will result in lower overall machine costs.
- The costs of charging are very much dependent on the local situation. A grid connection is the most cost-effective. If not available, energy storage and/or logistics give rise to higher costs.
- Charging requires organisation and planning. It is attractive in the case of long-running projects and the use of multiple machines.

Author Contributions: Investigation, M.Z.; Writing—original draft, W.C. and R.v.G.; Writing—review & editing, H.W. All authors have read and agreed to the published version of the manuscript.

Funding: The Construction Site of Tomorrow (translated from Bouwplaats van Morgen)) project and the research described in this paper received financial support from the Dutch Ministry of Infrastructure and Water Management for projects focusing on low or zero-emission, innovative transport solutions (DKTI).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Willem Christiaens and Harm Weken are employees of FIER Sustainable Mobility. René van Gijlswijk and Michiel Zult are employees of The Netherlands Organisation for Applied Scientific Research TNO. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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