Danish Energy Agency

Technology review on non-road machinery

Technical assessment of technologies in future construction and agriculture machinery

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1 Introduction

1.1 Introduction

Heavy construction and agricultural machines play an important role in modern society, underpinning infrastructure development and ensuring global food production. For decades, these demanding applications have been predominantly powered by internal combustion engines, with diesel engines emerging as the workhorse due to their robust performance characteristics.

However, the increasing global focus on climate change have spurred a significant re-evaluation of traditional power sources across all sectors, including heavy machinery. This growing emphasis on reducing greenhouse gas emissions is driving the exploration and adoption of alternative drivetrain technologies. The rate of this shift will likely vary considerably across different types of heavy construction equipment and agricultural machines due to their diverse operational demands and performance requirements. Heavy-duty applications like large mining trucks have vastly different energy needs and operating cycles compared to smaller agricultural tractors used for lighter tasks. This heterogeneity necessitates a detailed examination of each technology's suitability for specific applications within these industries.

1.2 Scope and target audience

The purpose of this technology review is to gauge the developments in available alternatives to diesel-driven machinery, which today dominates end uses in both agriculture and construction. In doing so, the Danish Energy Agency has relied mainly on secondary sources, and this review in turn summarizes the insights of available literature and data about development trends.

Our review covers both agriculture and construction, as the drive-train technologies are similar, but will split in separate sections, one covering agriculture and one covering construction, as there are important differences: Machinery within construction are typically used with a constant work-load throughout the year, and often in intervals within a standard work-day of 5-8 machine-hours, although this depends heavily on the task or project at hand. In agriculture, this is true only for the machines used within the confines of the farm such as telehandlers and small tractors, whereas field-machines like combine harvesters and larger tractors remain immobile for large parts of the year, with intense workloads during harvest- and planting season. While this review focuses primarily on mobile machinery, stationary equipment will be addressed where relevant. A full list of the reviewed machine types is available in the beginning of each section.

Throughout this review, focus will be on monitoring tendencies, pursuing technical advances, and describing existing technology in terms of availability, cost and potential for substitution of fossil driven machinery. In other words, the purpose is not to guide the development of new machinery, but to canvass it, and provide an overview of state-of-the art within a field of development, which is undergoing rapid change. Thus, the Danish Energy Agency aims to lay the foundation for a more comprehensible technology catalogue on the subject, which will follow when more experiences with the technologies emerge.

Being a canvass of existing development trends, this review will focus mainly on technological transformation of business as usual, and less on structural changes to the way that work in the sectors is fundamentally carried out. Thus, this review will be mainly preoccupied with technology switching, e.g. running the same process with electricity instead of diesel. Tendencies towards AI, robots and autonomous units etc. will be included somewhat where relevant. Governmental and other planning institutions have noted and are counting on some degree of technological disruption of the sectors by AI and robots (e.g. (European Comission, 2024)).

The review focuses on the technical parameters of different drive-trains, and does not seek to provide insights on the role of government policy or the role of institutions and organizations.

Target audience for this review is anyone with a system-level interest in technology-shifts for energy end-uses in the construction and agriculture sectors. Operators and developers within the sectors may likely find that the scope is too general to be useful as a guide on investment decisions. Rather, the review aims at providing foundations for assumptions on how the energy demands within sectors may develop, and what system costs this is likely to incur. These foundations will inform assumptions made in the DEAs efforts to model the long-term behavior of sectoral energy demand in Denmark.

What is a Technology Review?

The Danish Energy Agency publishes this Technology Review with the aim of communicating the latest knowledge about current and future non-road technologies in the agriculture and construction sectors.

It introduces technologies relevant for the energy transition away from fossil fuels in both sectors.

While sharing some key parameters with the technology catalogues. The format of this report will differ from a technology catalogue, as it concerns a subject of much lower empirical experience and available data. Therefore, this product does not include data sheets, unlike a technology catalogue.

1.3 Terminology

Throughout the review, the following terminology is used.

Technology review: The term places this paper in relation to the Danish Energy Agency's Technology catalogues. In contrast to these, a review is a lighter publication, reflecting that the technologies under scrutiny are less in use in the sector today. In the context of machinery for agriculture and construction, many alternative technologies for substituting diesel internal combustions engines are still prototypes. As a consequence, technical specifications such as efficiencies, OPEX, CAPEX, and expected lifetimes are highly uncertain and difficult to assess from a systems perspective. Therefore, a reader accustomed to the content of technology catalogues will find a relative overweight of qualitative over quantitative data and descriptions of technological parameters.

Machinery in the construction and agriculture sectors: We use the term machinery to refer to machines, whose main purpose is not to transport on/off site, but operate within the construction site or farm. The definition thus spans across mainly non-road machinery, but includes machines like tractors, which may be registered for driving on roads. The focus is thus not on any type of transport – e.g. delivery trucks or transport for livestock. For these end-usages, see the Technology catalogue for commercial freight and passenger transport (Danish Energy Agency, 2023).

Technology Readiness Level (TRL): The technology readiness level indicates how developed a technology is, ranging from 1, basic research, to TRL 9, commercially available. See box to the right.

Technology Readiness Level (TRL):

1. Basic principle
2. Concept formulated
3. Experimental proof
4. Lab validation
5. Simulated in relevant environment
6. Pilot demonstrated in relevant environment
7. System prototype demonstrated in operational environment
8. System complete and qualified
9. System proven in operational environment (NASA, 2023)

Segment: Refers to either the weight of machines (a metric often used in construction sector) or the engine size class in terms of kW.

Final energy: Energy consumed at end-use sectors, such as the agriculture and construction sectors. I.e. energy put into machinery is final energy.

Useful energy: The portion of final energy available at end-use point after losses. Losses could be e.g. engine losses. Useful energy is the energy that eventually gets traction or implement work in construction and agricultural machinery.

Energy service: The service provided by the machinery, e.g. the plowing of a field, harvesting of crops, excavating of soil, etc. Energy services are defined in terms of useful energy.

PTO: Power take-off is the power transferred from the engine using a gearbox through rotation to auxiliary equipment.

Traction: Is the pulling or pushing force measurement of movement for heavy machinery.

Gravimetric energy density: Amount of energy stored in a given substance, e.g. in liquid fuels, gaseous fuels or batteries, per unit of mass.

Total cost of ownership - TCO: Metric for assessing the total cost of ownership, given both up-front investments costs and operating and maintenance costs, together with costs of disposal or income by reselling.

1.4 Structure of the review

Starting with a combined introduction to drive-train technologies, this review will split into two distinct parts, focusing on the agriculture and construction sectors separately, since development trends and application demands for machinery varies fundamentally between the sectors.

For each of the sectors the review starts by exploring how machinery is currently used and then continues to evaluate the potentials of alternative technologies. Each technology will be evaluated using the same formula, were maturity and expected future development, operating hours, infrastructure needs and economy is assessed.

Furthermore, the appendix concentrates the summarized knowledge on the assessed categories (maturity, future development, operating hours, infrastructure and economy) in combined tables were available.

2 Drive-train Technologies

In this chapter follows a technical walk-through of the technologies available for providing energy services in construction and agriculture. The focus is on describing the characteristics of the drive-train technologies, e.g. the engine or fuel cell. The technology itself is first introduced, then energy efficiency, infrastructure requirements and advantages/disadvantages are discussed. The following sector-specific chapters 3 and 4 then depart from here and dive into sector-specific differences in more detail.

The first sub-chapter describes the characteristics of internal combustion engines and the fuels that can be combusted herein: diesel, biofuels, e-fuels and methane.

2.1 Internal Combustion Engines

2.1.1 Introduction

Internal combustion engines (ICEs) made their entrance in the 1920s and became the dominant engine for heavy duty transportation in the 1930s (Danish Energy Agency, 2023). ICEs, operating on the principle of compression ignition, convert chemical energy into mechanical work, providing the high power and torque necessary for demanding tasks.

These engines have been refined over decades to offer robust performance, increase efficiency and the capacity to ensure stable output for extended periods of time. Due to high volume production, production costs are low. Safety is good (high flashpoint, no sparks) and uptime is high.

The engines can use diesel, synthetic diesel made with GTL (Gas-to-Liquid), methane gas, PtX (Power-to-X) fuels, or biodiesel (FAME and HVO). Special ethanol (dual fuel, ED95) versions are also available, typically with a modified engine, i.e. to allow higher pressure (Danish Energy Agency, 2023).

We do not include hybrid machinery in this drive-train technology, as we want to secure a baseline technology as present in the sector today.

2.1.2 Diesel

The dominant fuel used in ICEs today is diesel. Diesel fuel presents a comparatively high energy density, allowing machines to operate for extended periods without needing to refuel frequently, a critical requirement for maintaining productivity in operations in agricultural fields or construction sites.

The peak efficiency of diesel combustion in an ICE is generally somewhere in the range of 40-50% (Danish Energy Agency, 2023; ICCT, 2015; Quan, et al., 2021). The efficiency includes losses in the engine itself, but not subsequent losses occurring when converting final energy to useful energy[1]. These losses include losses in gear boxes, hydraulic systems, wheels, electricity generation, etc. This overall efficiency term is sometimes referred to as brake thermal efficiency (Ashok & Nanthagopal, 2019). The overall efficiency will be different for different use patterns and will depend on the type of machinery.

For a tractor, power from the engine is lost through heat loss, friction, vibration and or noise in the different components as shown in Figure 1 (Roer Hjelkrem, et al., 2020). Efficiency of a tractor powered by an ICE depend on the power output use-pattern between Power take-off (PTO) and traction. Power take-off (PTO) being the energy used from the engine to power auxiliary equipment. While the efficiency varies between tractors and application of the machine, an average efficiency of 0.27 for diesel tractors are calculated by (Roer Hjelkrem, et al., 2020), based on a power output usage split of 70% for PTO and 30% for traction. Average efficiencies for traction alone would be 0.16 and only PTO 0.31.

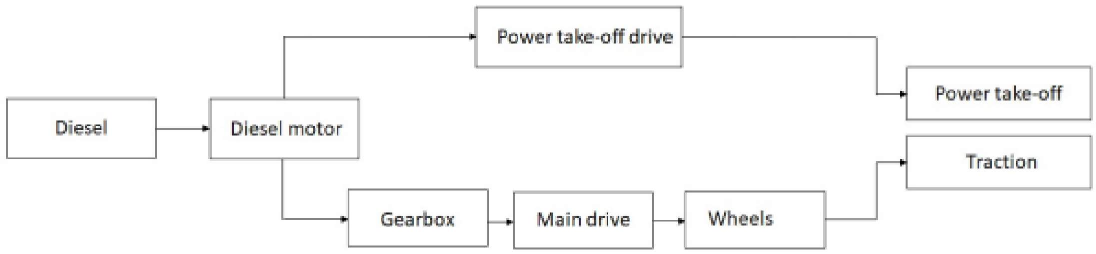

Figure 1: Schematic overview of a diesel tractor (Roer Hjelkrem, et al., 2020)

For construction machinery energy efficiency of ICEs is not able to reach the peak efficiency of a traditional ICE engine of 40-50%, as engines are not run at an even load but is fluctuating and unstable with cycling tasks (Quan, et al., 2021). Typically, efficiencies of ICE engines in construction are peaking at around or just above 40%. After losses in the ICE, the hydraulics and the pumps, only around 12% of energy inputs are actually delivered in the form of useful energy to perform work, e.g. traction or excavation, in a standard wheeled excavator (Vucovic, et al., 2017).

2.1.3 Biofuels and e-fuels

Since the default for machinery in the agriculture and construction sectors is diesel-driven internal combustion engines, a compelling solution to eliminating GHG emissions from diesel would be to introduce renewable ‘drop-in’ fuels that can use the existing infrastructure and that are compatible with the machinery. Biofuels are therefore a relevant alternative, as they are already used in many existing internal combustion engines designed for diesel or gasoline. Biofuels exist in different variants, with the most common types being HVO (Hydrotreated Vegetable Oil[2]), FAME (Fatty Acid Methyl Ester), bioethanol and biomethanol. This report will not analyze the use of bioethanol or

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[1] Useful energy is energy that end up moving the tires or performing the actual work, e.g. plowing, excavating, etc.

[2] Or hydrated, hydrogenated. Can also be produced from animal fats and other types of biomasses, including lignocellulose.

biomethanol further. While they are all made from biomass, important differences in composition and use-cases exist, and so a brief introduction follows.

Biodiesel (HVO and FAME) is made from oils and fats using different production methods and resulting in slightly different fuels with different properties. HVO and FAME are both substitutes for diesel, but with different limitations for blending. 1st generation is based on feed- and food crops such as rapeseed, soya and palm oil. 2nd generation is based on used vegetable oil and animal fats such as used cooking oil (UCO) and tallow[3]. Biodiesel have similar calorific value (GJ/l.) compared to conventional diesel.

FAME can be blended in diesel up to 7% by volume. This according to the diesel standard EN590 and the Fuel Quality Directive (FQD) in the EU. Higher concentrations normally require modifications to the engine, and the standard will no longer be fulfilled[4]. FAME has a corrosive and filter-blocking effect on engines, and deteriorates over time. Unblended FAME needs to be stored in slightly heated tanks (15-25 degrees Celsius) as it can solidify at lower temperatures. Blended within the blend wall this is only an issue when storing the blended fuel for longer periods, as it increases the risk of bacteria growth forming diesel plague which is harmful for the engine. However, some manufacturers offer modified diesel engines that can run on 100 percent FAME (i.e. Volvo) for trucks and buses, so it is likely possible also for non-road machinery (Baker, et al., 2022; PON CAT, 2025).

HVO is a drop-in fuel that can replace fossil diesel 1:1, as it is chemically very similar. A large number of non-road OEMs have declared full compatibility between their engines and HVO (Certas Energy, 2025). Compared to fossil diesel, the technical differences are that mass by volume is slightly lower for HVO compared to fossil diesel. HVO is approved with regards to a different European norm (EN15940) than diesel (EN590) if used in higher concentrations. As an environmental bonus, HVO burns cleaner due to higher cetane numbers, and lead to lower NO_x and SO emissions (PON CAT, 2025).

E-diesel is produced with the established Fisher-Tropsch process using CO_2 reacting with hydrogen to eventually produce e-diesel. For the fuel to be sustainably produced there is a need for low-emission electricity generation to produce sustainable hydrogen using an electrolyser. Furthermore, as the process requires carbon, this needs to be sustainably sourced, e.g. captured CO_2 from biomass combustion or the air (direct air capture) (Zero Carbon Shipping, 2025). E-diesel can replace fossil diesel 1:1 like HVO, but tend to be even more expensive than HVO.

Biofuels all come with a price premium compared to fossil fuels as they are more expensive to produce, but also due to demand and supply issues. The higher prices are also a result of regulations – such as blending mandates. The price tag is highly variable and is partly following the price on crude oil (with a markup) (OK, 2026; Uno-X, 2025).

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[3] Except from animal fats and used cooking oil – all waste and residue-based fuels are considered to be advanced fuels according to the Renewable Energy Directive.

[4] Can lead to the lapse of guarantees, as engines are approved according to the standards.

2.1.3.1 Climate impact of using biofuels

Biofuels are considered CO_2-neutral when used. But there are CO_2- and other GHG-emissions linked to the production of the fuels. GHG-emissions – well-to-wheel are lower compared to fossil fuels but will depend on the biomass used and the production process.

Biofuels often exist in a first and second generation. This signifies the virginity of the fuel, i.e. if it was produced directly to be used as a fuel, or produced for alternative reasons, e.g. food production, and then subsequently utilized as a fuel. First generation (1G) is based on feed- and food crops (i.e. corn, sugarcane, wheat, rapeseed and palm oil). The emissions are relatively high, as the full process from harvesting etc. is included. Second generation (A and B categories) is based on waste and residue and thus have lower emission than 1G biofuels. The “B” category consists of animal fats and used cooking oil. These residues/waste products are considered scarce and therefore limited (at least in the EU) to avoid fraud. “A” is also named “advanced” biofuels. This could be based on straw, municipal waste, manure, tall oil, bagasse etc.

E-fuels, like E-diesel, are also in many cases considered CO_2-neutral if produced from renewable electricity and renewable sourced CO_2.

2.1.4 Methane

Methane can be used in an internal combustion engine operating with spark ignition. Beside the spark plug ignition it is very similar to a diesel engine. The fuel can also be used in dual-fuel internal combustion engines thus running on a mix of diesel and methane. Methane has a higher calorific value compared to diesel but lower gravimetric energy density – calorific value per mass. Thus, methane needs more space on the vehicle, as the volumetric energy density is lower compared to diesel. The efficiency is similar to that of a conventional diesel engine, and delivers torque equivalent or just below of a diesel engine. Methane is used either as liquefied (LNG) or compressed (CNG) to improve the energy per volume. The engine is in general the same technology for both (Tripathi & Dhar, 2022).

Methane is produced from either stored naturally occurring gas underneath the earth in various rock formations or in geological storages off-shore. This methane is considered a fossil fuel. Methane can also be produced from biogas, produced using e.g. agricultural waste products like manure and straw, that is subsequently upgraded to remove excess CO_2. In this case the methane is considered as biomethane and climate neutral. Leakage of methane should be avoided as it is a very potent greenhouse gas (with a global warming potential of almost 30 times that of CO_2 (Forster, et al., 2021).

Methane can be substituted 1:1 with bio methane without any technical issues. LNG (liquefied natural gas) requires cooling for storing in tanks on the machine but can offer longer operating hours between refueling compared to CNG, as the energy density is higher.

Emissions from N_2O are around 95% lower and emissions of CO_2 (biogenic or fossil depending on the source of methane) around 25% lower compared with diesel (Jensen, et al., 2024). Noise from methane combustion is also lower compared to diesel combustion.

2.1.5 Infrastructure requirements

Diesel is normally distributed to the site where machines are located and stored in tank storage systems. A well-established global infrastructure exists for the production, distribution, and storage of diesel fuel, thus the distribution of the fuel to site is well established.

Diesel and biofuels can be distributed and stored using existing infrastructure. In some cases, a modification is required for storing biofuels. For both farm use and for construction it is possible to store the fuel in a local tank at the farm or construction site. The use of HVO requires no supplementary investments in infrastructure. Other alternative fuels have to be stored in heated tanks, and some biofuels (especially FAME) cannot be stored for extended periods due to risk of bacteria growth etc. This can be an issue in the agricultural sector, where the use of some equipment is seasonal. HVO is currently available in several Danish gas stations[5] and can be delivered by truck to a tank on the premises of the user.

Availability of biodiesel varies geographically throughout Denmark, with availability being high closer to large cities and low in rural areas. Furthermore, larger infrastructure construction projects can have difficulties getting the required amounts of HVO needed. Thus, agriculture and construction companies are not equally able to directly use biofuel as a means of converting from fossil diesel as this depends on their location and size (M. J. Eriksson A/S, 2025).

Methane can be stored by liquefaction using cryogenic temperature levels (as LNG) or compressed using compressors (as CNG). Both will demand different storage requirements. CNG will need compressed reinforced steel tanks and LNG demands double walled insulated tanks and cooling systems (Bassioni & Klein, 2024; Sustainable Conservation, 2005). Methane in Denmark is distributed via the gas grid, but can also be transported by truck or ship. Fueling stations can be established with direct connection to the gas grid or production facilities for biomethane. In Denmark, there exists for road vehicles around 20 publicly accessible filling stations for CNG and 7 privately owned (i.e. for bus fleets). LNG infrastructure is at present insufficient (2 stations in Denmark – Padborg and Hirtshals). Compared to storing diesel, that only requires standard tanks, CNG and especially LNG requires more equipment and maintenance making them more expensive.

2.1.6 Advantages/disadvantages

The advantage of ICEs is the high maturity of the technology with very low refueling time and thus operating reliability. The operating costs for diesel are currently lower compared to hydrogen. For bio- and e-fuels it varies a lot whether these costs are higher or lower compared to hydrogen. Energy efficiency of diesel is on par with hydrogen combusted in an ICE. Investment costs of ICEs are generally lower compared to both electric and hydrogen

[5] I.E. UNO-X and OK energi, which have gas stations with HVO, and offer the possibility for receiving the diesel alternatively in tanks on premises.

fuel-cell machines. Infrastructure requirements are simpler for diesel compared to both electric, methane and hydrogen machines.

The general disadvantages of ICEs are the low energy efficiency of the engine compared to an electric motor and a fuel cell. Furthermore, diesel combustion emits fossil CO2 which causes climatic changes. When bio- or e-fuels are used this is not the case. Biofuels have the disadvantage of needing either land use for fuel production which causes competition for land e.g. with food production, or residues and wastes, which vary in quality and quantity. Biomethane has the disadvantage of potential leaks, with methane being a potent greenhouse gas.

2.2 Electric motors & batteries

This sub-chapter describes the characteristics of electric motors relying on either batteries or direct cabling.

2.2.1 Introduction

Battery-electric or cable-electric machinery uses electric motors to convert electricity to deliver useful energy for powering a variety of services, including traction, mechanical rotation, and hydraulic systems. Most motors run on the principle of electromagnetism were the interaction between a magnetic field and an electric current generates a force that causes rotor to spin (Gobbi, et al., 2024). Millions of battery electric vehicles produced have increased the speed of development of electric motors for the transport sector (IEA, 2025).

2.2.2 Energy efficiency

Electric motors normally have higher energy efficiency compared to an internal combustion engine resulting in lower operating costs. The general efficiency of an electric motor itself is between 85-95%, depending on type of electric motor and configuration (Gobbi, et al., 2024; Ehsani, et al., 2017). Thus, electric motors are at least twice as efficient compared to ICEs. The efficiency of the electric motors does not include subsequent losses when providing power for services like hydraulics, traction or others used in the agricultural and construction sectors.

The electric motor drive-train for e.g. a battery electric tractor, similarly to the diesel norm, is required to provide both traction through the wheels, as well as output for the attachments used, through the so-called PTO (Power Take-Off). Figure 2 depicts this setup. The average efficiency of battery electric tractors is 0.53 using only traction, 0.98 using only PTO, and 0.85 assuming a 30/70 percent split between the two usages for normal tractor operation (Roer Hjelkrem, et al., 2020). Compared to the diesel standard, this would give a comparative efficiency gain of 58 percentage points for the battery electric variant.

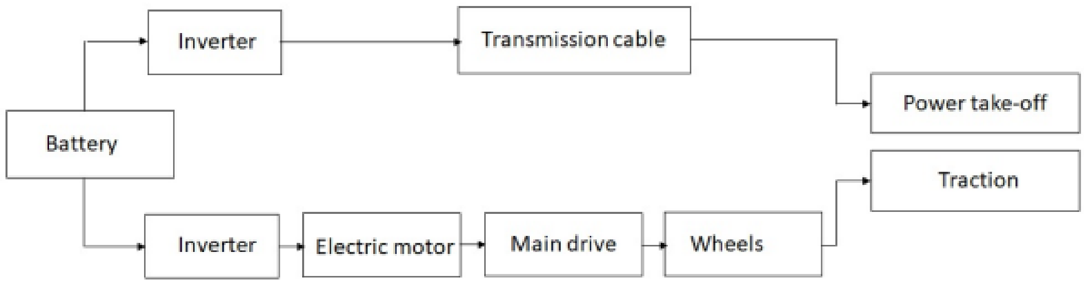


Figure 2: Schematic overview of a battery-electric tractor with PTO (Roer Hjelkrem, et al., 2020).

The architecture displayed in Figure 2 can be seen as a theoretical translation of the traditional diesel architecture to electric drives. In current and future electric agricultural machines, the layout of drivetrains varies, especially since not all electric tractors are conceptualized with a PTO, and some feature an interface for electrical implements as well (Mocera, et al., 2023).

In construction the overall system efficiency of a battery electric machine using a similar hydraulic system as a traditional ICE driven excavator is around 45% (Vucovic, et al., 2017; Minav, et al., 2017). This includes losses in the engine, the pump and the hydraulics. Compared to the system efficiency of a comparable traditional ICE excavator of around 12% this is around 2.5 times more efficient. Furthermore, a study by CO-PI and EY finds that the efficiency gains from electric machinery declines with the increasing weight and motor size. With battery electric machines in the mini segment (0-5 tons) eliciting an up to 450% increase in energy efficiency compared to diesel, which decreases to around 280% in the large segment (26-38 tons) (CO-PI & EY, 2023). This could indicate that the focus of development has been on the smaller machine segments initially, and/or it could indicate that larger machines have larger, and thus heavier, batteries, which decreases performance somewhat.

The energy efficiency of batteries is typically seen to decrease with colder climatic conditions, and thus the same battery capacity cannot deliver the expected duration of work in cold weather (Oslo Economics & Hafslund Rådgivning, 2024).

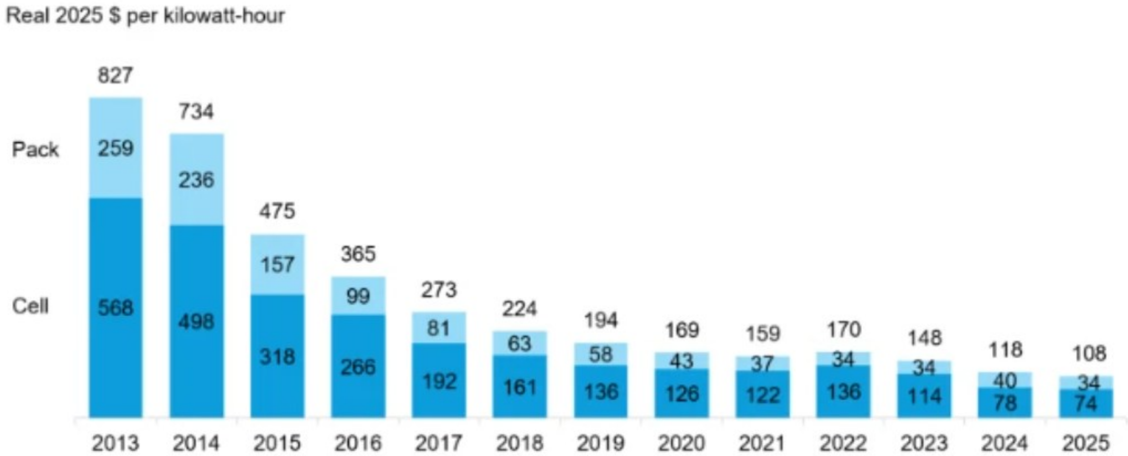
The efficiency gains of an electric drivetrain translates into a better fuel economy for electric machines compared to diesel-driven, but reduced OPEX are often the case as well due to fewer moving parts, no need for oil filters and additives, less down-time etc. (New Holland, 2025a; Un-Noor, et al., 2022). However, total machine investment costs typically are 1-3 times higher than for comparable diesel machines as discussed further in the following sector-specific chapters 3 and 4.

2.2.3 Battery technology development

The batteries that power battery-electric machinery have seen rapid advancements in the last decade. Various chemical combinations are now being used, leading to lower energy storage costs and a growing global production capacity.

In 2024 lithium iron phosphate (LFP) batteries made up almost half of global electric vehicle battery production and lithium nickel cobalt manganese oxide (NMC) batteries nearly the rest. The trend is that LFP batteries continue to increase their share, being almost 30% cheaper per kWh (CAPEX) compared to NMC batteries. However, LFP batteries suffer a one-fifth decrease in gravimetric energy density (kWh per weight) (IEA, 2025).

Bloomberg New Energy Finance reports decreasing costs of battery capacity, with the cost even dropping around 20% in 2024 compared to 2023, to further historic lows of around $\$^{2025}$108 per kWh in 2025 – as shown in Figure 3 (BloombergNEF, 2025). The decreasing cost of battery capacity is believed to continue, with Goldman Sachs reporting that prices will further drop by almost 50% by 2030 compared to 2024 (Goldman Sachs, 2024).



Source: (BloombergNEF, 2025).

Figure 3: Average lithium-ion battery pack and cell cost split, 2013-2025.

The historic and projected trend of decreasing costs of battery capacity described above is also applying to the battery packs needed in the construction and agricultural machines. It is important, though, to note that research indicates that battery packs in non-road machinery generally are around 40% more expensive compared to on-road vehicles. This is because the packaging of batteries needs to be more robust, for the environment and harsher conditions in the agriculture and construction sector. Furthermore, machines in these sectors come in a variety of types and sizes, so OEMs cannot produce just a couple of different sizes engines and battery packs to cover the whole market (Interact Analysis, 2023).

Battery innovation is underway with researchers exploring many different advanced battery technologies including solid-state, sodium-ion and lithium-sulphur batteries for future on-road and off-road application. These vary in stage of maturity (technological readiness level – TRL), and purpose of development: with sodium-ion batteries trying to reduce the reliance on lithium, solid-state and lithium-sulphur batteries focusing on greatly increasing the energy density of batteries (IEA, 2025).

Solid-state batteries are closing in on becoming commercial with major OEMs pledging large investments into prototypes and manufacturing, like Samsung SDI, NIO, CATL, BYD, SAIC and Toyota. Still, TRL remain at large pilot stage (TRL 6 out of 9). The promise of solid state is both increasing energy density of batteries and providing safety because no flammable electrolyte exists. Major OEMs like Toyota and BYD are planning to mass-produce solid state batteries beginning from around 2028. Initially, production levels will be low and a potential roll-out of the technology will take many years as solid-state production will be in competition with full-scale lithium-ion battery technologies like LFP. It remains to be seen if this timeframe will hold, as the production of solid-state batteries was initially thought to already be initiated (IEA, 2025; Goldman Sachs, 2024).

2.2.4 Infrastructure requirements

Electric machines, either cabled or battery electric, require electrical power to be able to run. This can be supplied either by utilizing existing electrical grids or if grids are not sufficient or are inaccessible by an alternative source of electricity. Alternative sources include power banks/battery containers, which can charge and store electricity. Alternatively, there is the possibility of upgrading existing grids to be able to sustain electric and/or battery electric machine operations by adding additional electrical cables and/or substations connected to nearby grid installations.

Battery electric equipment furthermore needs charging facilities in order to recharge internal batteries for further operation.

Read more about infrastructure requirements for electric and battery electric machines in the sector-specific chapters 3 and 4 below.

2.2.5 Advantages/disadvantages

Battery driven electric motors have the advantage over diesel combustion of zero emissions of any kind, significant increases in energy efficiency, lower noise and lower vibration levels. These features make for better work environment and less complaints from nearby neighbors. The high energy efficiency coupled with few mechanically moving parts facilitates low operating costs.

A disadvantage of battery electric machines to diesel ICEs is the recharging time, which takes significantly longer. Range in the form of machine operating hours are also lower compared to both diesel ICE and hydrogen fuel-cells/ICEs. But as noted above, significant progress has been made and development to come for batteries with higher energy densities, increasing machine operating hours. However, even with substantial improvements in battery technology, the gravimetric and volumetric energy density is still significantly lower compared to liquid fuels. Upfront investments costs are significantly higher for battery electric machines as a result of the additional costs of batteries compared to both ICE and fuel-cells (Danish Energy Agency, 2023).

2.3 Hydrogen fuel cell and combustion

This sub-chapter describes the characteristics of hydrogen and the drive-train technologies that can utilize this fuel for agriculture and construction machinery.

2.3.1 Introduction

Hydrogen is an energy carrier just like diesel, but contains no carbon and thus emits no carbon emissions when either run through a fuel cell or combusted in an internal combustion engine. Emissions may occur from producing hydrogen from either the production, processing or transportation processes. Hydrogen must be sourced from renewables like wind and solar in order to be classified as green. In 2023, hydrogen was primarily produced using fossil fuels through the process of steam methane reforming. Less than 1% was produced with low-emissions using electrolysers. In 2024, producing renewable hydrogen with electrolyser were 1.5-6 times more expensive compared to traditional steam methane reforming (IEA, 2024). Hydrogen at liquid stage contains only around one fourth the energy per liter (volumetric energy density) compared to diesel, and if stored as compressed gas at 700 bars around one sixth the energy per liter compared to diesel (Speight, 2011; Center for Sustainable Systems, 2025).

2.3.2 Fuel cell

Hydrogen fuel cells are commonly referenced as an alternative that is competing with battery electric drive-trains, since the hydrogen is utilized to run an electric motor. Fuel cells function much like a battery, but is able to generate electricity as long as fuel is supplied, without needing recharging. It is highly modular, and individual fuel cells can be stacked to generate high effect output.

In a fuel cell, two electrodes, a cathode and an anode, is placed around an electrolyte. A catalyst in the anode splits the hydrogen into electrons and protons, which are directed through different paths to the cathode, generating electricity, heat and water. A fuel cell could also run on methanol, methane and other hydrocarbons, but in this review, only hydrogen has been identified as a potential fuel.

Fuel cells can utilize between 40-60% of the energy in the fuel, depending on the type of cell components (Roer Hjelkrem, et al., 2020). This efficiency includes only the losses in the fuel cell itself, not upstream, when producing hydrogen, or downstream, e.g. losses in hydraulics or traction.

When used in agricultural applications, the efficiency of a fuel cell motor is set around 35% (Baker, et al., 2022) to 42% (Roer Hjelkrem, et al., 2020), depending on use patterns between power take-off and traction. In Figure 4, a schematic overview of a hydrogen fuel cell tractor is depicted, showing similarities with the battery electric layout.

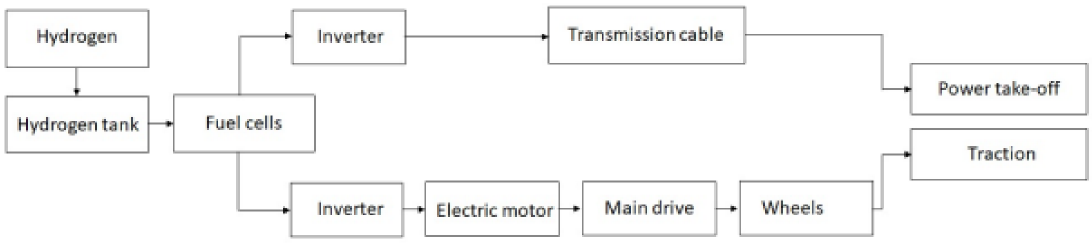


Figure 4: Schematic overview of a hydrogen fuel cell tractor (Roer Hjelkrem, et al., 2020).

In the construction sector no information was found regarding the overall efficiency of hydrogen fuel cell powered machines. Taking the somewhat increased efficiency of the fuel cell itself compared to a diesel ICE, the overall efficiency of fuel cell construction machinery can be assumed to be slightly higher than diesel ICE machines.

2.3.3 Hydrogen ICE

Hydrogen can also be used in an internal combustion engine replacing diesel. Like for methane it needs a spark plug to ignite. Furthermore, a complete re-work of the fuel-system needs to be implemented. Hydrogen burns cleaner with no CO_2-emissions, but there could be some issues with NOx-emissions, due to the high temperatures that can make nitrogen in the air to react with oxygen.

The efficiency of hydrogen ICEs are lower compared to state-of-the-art diesel engines (Sari, et al., 2024). The exact efficiency varies in literature, as the hydrogen internal combustion engine only nears commercial availability. Hydrogen ICEs deliver at efficiencies of around 30-40% (McKinsey & Company, 2021; Boretti, 2020; Baker, et al., 2022), whereas conventional diesel ICEs deliver 40-50%.

For both agriculture and construction no cases of calculated overall efficiency from well-to-wheel were identified. As a result of the lower engine efficiency itself it can be assumed that overall efficiency is likely to be lower compared to the diesel ICE.

2.3.4 Infrastructure requirements

Hydrogen can be transported to the site of use or it can be produced locally via an electrolyser and grid connection and/or local energy production (such as e.g. solar photovoltaics). In Denmark there are currently no hydrogen refueling stations and so the infrastructure of obtaining hydrogen is abysmal (FDM, 2023). Thus, producing hydrogen on-site, or alternatively obtaining it directly by truck from a national producer, both comes at great costs.

When storing and transporting hydrogen a number of safety considerations prove vital. Hydrogen is an odorless, colorless and tasteless gas that is lighter than air and diffuses rapidly. It is non-corrosive, non-toxic and non-poisonous. It combusts easily and thus ignition sources such as sparks from e.g. rapidly closing valves, electrical equipment and heating equipment should be eliminated with care. Conversely, because hydrogen in its gaseous form is very light, it diffuses quickly, and as such does not pose risks of asphyxiation in open areas. It does, however, make for difficult detection of leaks and careful design of equipment is needed. The hydrogen combustion flame is almost invisible and does not emit visible light or smoke, thus a hydrogen fire can go undetected and can spread easily even with human monitoring. Furthermore, hydrogen burns with high energy output and very fast. Explosions cannot occur in a tank or pipe containing only hydrogen, as an oxidizer is needed, such as oxygen or air in the right concentration. Since hydrogen is often pressurized there is a risk of high-pressure hazardous projectiles if a failure occurs. Furthermore, hydrogen is often stored as a cryogenic liquid which can cause burns if in contact with the human skin. With the right care taken to monitoring, detection and design of equipment, hydrogen use poses no greater danger compared to other flammable liquid fuels (SES Hydrogen, 2022; US Deparment of Energy , 2024).

Because of these safety considerations transporting and storing hydrogen is to be considered more expensive compared to traditional storing of diesel, and permits and certifications are likely required as well.

For machines using hydrogen on-board storage systems demand more space compared to diesel because, as noted earlier, the lower energy density per liter of hydrogen. This will decrease range/operating hours compared to diesel machines and increase the storage space needed for on-site hydrogen storage.

2.3.5 Advantages/disadvantages

Both fuel cell and hydrogen ICE technologies have the advantage of zero direct emissions. The fuel cell furthermore has the advantage of low noise and vibration due to fewer moving parts. Compared to a lithium-Ion battery they are more compact and lighter (U.S. Department of Energy, 2021). Refueling time is similar or slightly higher compared to diesel ICE, but is faster than battery electric recharging. Furthermore, refueling is more complex compared to diesel, as hydrogen is pressurized and diffuses rapidly. Range and thus machine operating hours are slightly lower than diesel ICEs, but higher compared to battery electric.

Energy efficiency of fuel cells is somewhat higher compared to diesel ICEs, but significantly lower than battery electric motors. Hydrogen ICEs exhibit the lowest overall efficiency of all analyzed drive-train technologies. Hydrogen today is an expensive fuel, when produced with renewables, and thus operating costs are higher compared to diesel ICEs and battery electric motors. Up-front investment costs are higher compared to diesel ICEs but lower compared to battery electric (Danish Energy Agency, 2023).

It is a further barrier that hydrogen gas has a low density, which necessitates compression and makes handling more difficult and expensive. Special tanks are required, as hydrogen is prone to leaking from metal containers (Bovingdon, 2022)

3 Construction machinery

In this chapter, machinery used across construction sites will be reviewed. Subsequently, developments into alternatives to the standard diesel engine will be presented.

3.1 Use of machinery in the sector today

The Danish construction industry today relies heavily on a diverse array of construction machinery to execute various projects across residential, commercial, infrastructure, and specialized sectors. From the initial earthmoving phases to the final touches in construction, specialized machines provide the power, precision, and efficiency required to meet project demands. The types of machinery range from excavators, bulldozers, and loaders for site preparation and material handling, to cranes and lifts for building construction, and pavers and rollers for road infrastructure. Material handling equipment further streamlines the movement of goods and supplies across construction sites.

3.1.1 Energy consumption and machine segmentation

The Danish Centre for Environment and Energy at Aarhus University keeps track of the sales of construction (and agricultural) machinery in Denmark, and thus the composition of machines. Almost 100 % of energy consumption today is diesel. Table 1 provides the latest overview of the estimated energy consumption of construction machines in Denmark. Here we see that excavators and wheel loaders make up more than half of the energy consumption of all non-road machinery in the construction sector, and up to two-thirds when excluding stationary equipment like compressors and generators (Winther, 2024). This is because excavators and wheel loaders are used for a variety of different project types, including residential and industry construction, road construction, infrastructure projects (like bridges and tunnels) and demolition. Excavators especially perform numerous task such as digging foundations, basements, utility trenches, and general site preparation, drainage work and material handling, underwater work and breaking and shearing for demolition. Note that the use of a specific type of machine varies from one year to the next as investments in construction projects vary over time, e.g. investments in major infrastructure projects.

Table 1: Distribution of energy consumption across machine types in the Danish construction sector in 2023

Machine type		Typical application	Share of total non-road
Excavator		Site preparation, excavation of foundations and trenches, material handling, demolition	31 %
Wheel loaders		Digging, loading and transporting materials, grading landscapes	22 %
Dump/haul trucks		Transporting soil, gravel, demolition debris to and from sites	8 %
Roller		Compacting soil, asphalt, and gravel layers in road and foundation construction	6 %
Telehandler		Lifting and placing materials at elevated heights with extended reach	4 %
Compressors		Powering pneumatic air-powered tools, lifting and hoisting, concrete spraying, and more	14 %
Generators		Providing an electricity source where the main grid is unavailable or insufficient	6 %
Other		Bulldozers for clearing/leveling land, lifts for providing elevated platforms, cranes for lifting and moving heavy materials, and more	9 %

Source: (Winther, 2024). Numbers are rounded and thus the sum can be different from 100%.

To undertake meaningful analysis of technologies within the construction sector we break down the heterogeneous machine types into engine size segments and corresponding typical machine weight. This is done because our initial research revealed that technology readiness levels (TRLs) are similar across machine types within the same size segments, but vary across size segment: Larger equipment generally show lower technology readiness levels (TRL) compared to smaller equipment – indicating that new technologies are faster adopted for smaller machinery, possibly because of the high costs of batteries in the case of battery-electric machinery. The segmentation allows us to analyze across machine types, but at the same time include the potential barriers and differences that exists between engine size segments. Table 2 shows the breakdown in size segments.

Table 2: Distribution of energy consumption across construction machinery segments in 2023

Segment	Size (kW)	Typical weight	Share of total non-road	Share of energy consumption within segment
Mini	0-37 kW	0-5 tons	17 %	Roller (32 %) Excavator (18%) Pumps (15 %) Wheel loader (13 %)
Small	37-56 kW	5-10 tons	20 %	Compressors (63 %) Generators (25 %) Excavators/loaders (11 %)
Medium	56-130 kW	10-26 tons	23 %	Wheel loaders (27 %) Excavators (23 %) Dump/haul trucks (23 %) Telescopic loader (17%)
Large	130-200 kW	26-38 tons	18 %	Excavators (59 %) Wheel loaders (26 %) Dozers (6 %) Compressors (6 %)
Huge	>200 kW	>38 tons	22 %	Excavators (52 %) Wheel loaders (34 %) Dump/haul trucks (14 %)

Source: (Winther, 2024) updated with new numbers. Numbers are rounded and thus the sum can be different from 100%.

According to Statistics Denmark diesel consumption in the construction sector, which is mostly used for non-road machinery, is used for renovating existing buildings (34 percent), for building new buildings (28 percent) and for larger construction projects like bridges, tunnels, rail and roads (34 percent) (DST, 2025)[6].

The location of the construction site has implications on a range of things like available fuel-infrastructure, noise-requirements, pollution-requirements, safety, etc. A construction site located further away from dense housing areas, like a larger construction project of a high-way, would normally entail less noise-requirements, but also less fuel-infrastructure in the vicinity.

3.1.2 Typical use pattern

Construction machinery is used varying amounts of time depending on the given type of machinery and on the project. Some equipment is used intensively for a period of a project’s life time, and then not needed and thus off to the next project – e.g. stampers, rollers. Other machinery is used both intensively and intermittently, like excavators and wheel loaders, throughout the project horizon. The use of machinery throughout a projects horizon is varying with the project phases, with construction projects generally demanding

[6] It is important to note, though, that these shares have not changed in the last five years, which indicates that the data is uncertain.

machinery during the beginning to middle of the project, for site preparation, foundation work, material handling, etc. Road and infrastructure projects often need machinery throughout the project horizon for site preparation/foundation, material handling, paving, and heavy lifting.

The typical full-time workweek in Denmark consists, normally, of 37 hours, usually spread across five days from Monday to Friday. While office employees typically work from 8 AM to 4 PM or 9 AM to 5 PM, construction workers often have slightly different schedules, sometimes starting earlier, around 6 AM or 7 AM, and completing their workday by 2 PM or 3 PM. This earlier start can maximize daylight hours, especially during seasons with shorter days, and allows for an earlier finish, but can also be attributed with trying to skip traffic. The general workhours do not always apply, as machines are often seen working beyond the 37 hours per week and through weekends by teams working in shifts to finish projects fast.

Some projects will not need machinery continuously, if there are wait-times or other work not demanding machinery. Other projects might conversely rely heavily on machines and be running almost around the clock – e.g. if there is a planned shut-down of a road, in order to finish building a bridge. Thus, machines have to deliver on a diverse work-load, from little use per day, to almost non-stop, depending on the project at hand and the stage of the project. A study from 2024 performed by Anders Gadsbøll for Co-Pi revealed that construction machines in Denmark typically was used for 3.5 to 5.5 hours per work-day (Gadsbøll, 2024). This number vary from task to task, with parts of infrastructure projects being machine-intensive demanding machines running effectively up to 9 hours per day (M. J. Eriksson A/S, 2025).

Machines at construction sites use a varying amount of time idling with the engine turned on waiting to be able to perform a task. One article reports upwards of 40 percent idle time for a 36-tons excavator that runs around 1000 hours per year, but on average puts the idle time of all machines at between 25-30 % (Construction Equipment, 2020; Vucovic, et al., 2017). With careful management, e.g. by better controls and automated start/stop-systems, this number can be reduced for example from 31 to 14 percent in the Danish example of 10 machines laying high-voltage cables (Maskin Teknik, 2023). The actual idle time in Denmark presently is believed to be significantly below 25 % (Materielsektionen, 2025).

3.1.3 Investment costs of the diesel baseline

In the construction sector today, as noted above and in chapter 2.1, the combination of diesel and ICE is the standard for providing the energy services needed. This section shortly introduces the investment costs for the diesel baseline technology. Thus, a comparison of potential additional investment costs for alternative technologies can be made in the following sections.

Numbers provided by several retail construction machine sellers indicates that the average costs of diesel-powered construction machinery are around 1400 $€^{2025}$/kW engine or the equivalent of 12.000 €^{2025}/ton machine[7] (Volvo CE, 2025c; J-maskiner, 2025; SMF, 2025). This makes for a 20-ton excavator to cost around 240.000 €^{2025}. Furthermore, data indicates, that smaller equipment is relatively more expensive per engine power or per machine weight compared to larger machinery. This is average prices across segment size and type of machinery and in reality, prices vary quite significantly depending on type of build and type of work. Prices are '*from'* prices, and are indicative of an average price level to be compared against when looking at alternatives in the following sections on biodiesel, battery electric and hydrogen machinery.

3.2 Alternative technologies

This section identifies alternatives to diesel construction machinery, including the stage of development, the use-potential in the sector, the economic costs and barriers for adoption.

3.2.1 Relevant technologies

An initial literature review explored both the available alternatives to diesel in the construction sector currently available and currently under development. The review is based on available online information from most of the major OEMs, i.e. Volvo Construction Equipment, Caterpillar, Komatsu, Wacker Neuson, Hitachi, Bobcat, CASE CE, JCB, Liebherr, Kubota, XCMG, and more. Table 3 gives an overview of the results.

Table 3: Overview of assessed available alternatives to diesel in the construction sector

Segment	Size (kW)	Typical weight	Biodiesel	Electric	Hydrogen	Methane
Mini	0-37 kW	0-5 tons	✓	✓	(✓)	✗
Small	37-56 kW	5-10 tons	✓	✓	(✓)	✗
Medium	56-130 kW	10-26 tons	✓	(✓)	(✓)	✗
Large	130-200 kW	26-38 tons	✓	(✓)	✗	(✓)
Huge	>200 kW	>38 tons	✓	✗	✗	✗
Generators & power banks	0-56 kW	-	✓	✓	✓	✗

Source: Own literature review.

The assessment indicates that while biodiesel and electric and battery electric alternatives exists, hydrogen alternatives are scarce. Methane alternatives does not seem to be available beyond the refurbishing-stage and are not explored further in this review (Made-in-China, 2025).

Each of the technologies identified above are assessed in the following sub-sections. For each of the technologies the assessment looks at maturity, expected development,

[7] Note that these are Danish retail prices with no VAT included

operational hours, infrastructure requirements and techno-economic parameters like CAPEX and OPEX where available. The assessment of technologies does not take re-furbished or retrofitted machines, converted from diesel to e.g. battery electric, into account.

Where possible, the assessment refers to the Technology Readiness Levels (TRLs) to assess *maturity* of a technology within each segment. TRLs range from TRL 1, basic research, to TRL 9, commercially available.

3.2.2 Biodiesel

This section covers the use of biodiesel in either existing or new construction machines.

3.2.2.1 Maturity

Mainly, the drop-in fuel characteristics of biodiesel makes for a compelling pathway of mitigating greenhouse gas emissions due to the fact that the fuel can be utilized in existing engines and machinery, and using the same infrastructure as diesel. This is elaborated further in chapter 2.1.3. The maturity of biofuel use is ripe, with many examples of the use of biodiesel in the construction sector in Denmark already today.

Some issues persist regarding availability of biodiesel, as noted in chapter 2.1.3. Construction sites located far away from major cities, in rural or coastal areas, potentially have difficulties buying biodiesel. As do very large construction projects, such as infrastructure projects, where the demands exceed the supply (M. J. Eriksson A/S, 2025).

3.2.2.2 Expected development

No further development is needed since engines can utilize the fuel already. The availability of biofuels is most likely what will limit the uptake of biodiesel globally.

3.2.2.3 Machine operating hours

Provided that biofuels can be delivered on site; the operating hours will be on par with the current diesel alternative.

3.2.2.4 Infrastructure requirements

Biofuels needs to be transported to the construction site the same way diesel is currently transported to construction sites – most often by truck. On-site diesel tanks can often be used for biofuels, like HVO, instead of diesel. Thus, current diesel infrastructure will most often be enough for switching to biofuels like HVO, and no investments are needed.

Theoretically this is true, but the practical experiences with biofuels, e.g. HVO, from construction sites is that the durability of the fuel depends heavily on conditions like temperature, weather and tank material – all which are normally not optimal at traditional construction sites with exposed conditions and sometimes temporary tanks (M. J. Eriksson A/S, 2025).

3.2.2.5 Economy

Switching to biofuels will likely not require investments in new machines, new infrastructure, changes in operating and maintenance costs or changing work-patterns. The only additional cost is for the biofuel itself. Additionally, as HVO has a slightly lower energy density, as noted in chapter 2.1.3., there will be slightly higher HVO volumes consumed compared to diesel. At the time of writing the price difference between HVO and off-road diesel is that HVO comes with premium at around +30% (OK, 2026). Other sources indicate a similar number of around 10-30% (Prema Energy, 2025; Certas Energy, 2023). The variation in the price of biodiesel makes it hard for construction companies to estimate prices for construction contracts, which often rely on locked fuel prices, and thus converting to biodiesel comes with an economic risk (M. J. Eriksson A/S, 2025).

3.2.3 Electric

This section covers battery electric machines and were stated also cable electric machines.

3.2.3.1 Maturity

This section first assesses the maturity of non-stationary construction equipment, like dump/haul trucks, excavators, etc. per size segment, and then proceeds to assess the maturity of generators and power banks.

3.2.3.1.1 Non-stationary machinery

Mini equipment (0-5 tons): In this size-segment there exists a quite large variety of construction machinery based on battery electric drive-train. Examples of available equipment on the market are:

- Excavators: Bobcat E10e and E19e (Bobcat, 2025), CAT 301.9 (CAT, 2025), Volvo CE EC18, ECR18 and ECR25 (Volvo CE, 2025a), Komatsu PC20E, PC26E and PC33E-6 (Komatsu, 2025), JCB 19C-IE (JCB, 2025b), Wacker Neuson EZ17e and EZ26e (Wacker Neuson, 2025a).
- Loaders: Liebherr L507E (Liebherr, 2023b), Volvo CE L20 and L25 (Volvo CE, 2025a), Wacker Neuson WL20e and WL28e (Wacker Neuson, 2025b), Kubota RT210-2e (Kubota EU, 2025).
- Dumpers/haulers: JCB HTD-5E (JCB, 2024), Wacker Neuson DW15e (Wacker Neuson, 2025c), Kubota KC70H-4e (Kubota EU, 2025).

This non-exhaustive list indicates the availability of different battery electric machinery in the mini-segment. Almost all major manufactures have machinery either in serial production, pre-production, demonstration or under development. This indicates a high TRL, estimated to be between 7 and 9 (CARB, 2024). The variation is caused by the fact that not all major manufactures have a full-scale serial production line-up yet. This variation is expected to decrease quite rapidly, as more serial production facilities are set up at all major manufactures. Thus, the mini-segment being almost commercially available, and expected to be fully commercially available in the near future indicates a TRL closer to 9.

Our review furthermore finds that most other types of equipment in the mini category not mentioned, e.g. telehandlers, lifts, rollers and cranes, are all available in battery electric versions.

Small equipment (5-10 tons): In this segment there is less equipment available compared to the mini segment.

- Excavators: Hitachi ZE85 (Hitachi, 2022), Sunward SWE60UFED (OEG, 2025).
- Loaders: CAT 906 (CAT, 2025), Liugong 820TE (SMF, 2024).
- Dumpers/haulers: Hydrema DT6 (Hydrema, 2025), Mecalac eMDX (Mecalac, 2025a)
- Telehandlers: JCB 525-60E (JCB, 2022)

The above list suggests that the small equipment category is in a slightly earlier stage of maturity compared to the mini category. Fewer models are available in this category and not all major manufactures have machinery in production, demonstration or under development. This indicates a medium to high TRL, ranging between 6 and 8 (CARB, 2024).

Crucially, availability in the next segment, the medium sized equipment (10-26 tons), is quite high. Thus, technically it seems that no major technical barriers exist to build machines within the small size segment (5-10 tons). The observed low availability within the small segment then indicates that the small equipment segment is not as large as the mini or the medium segments, and thus manufactures might have prioritized investments in the mini and medium segments over the small segment. As no technical barriers exists TRL can quite quickly increase towards 9 in the next five years or depending on sufficient investments.

In 2023, delivery times for 5-15 tons battery electric machinery were in the range of 9-12 months for small orders, and in the magnitude of several years for larger orders (+100s of machines) (Region Hovedstaden, 2023). These delivery times are substantially higher compared to the diesel alternative. This indicates a lack of full-scale serial production facilities.

Our review furthermore finds that most other types of equipment in the small category not mentioned above, e.g. lifts, rollers and cranes, are all available in battery electric versions.

Medium equipment (10-26 tons): In this segment there seems to be a high availability of equipment, but not for all types of machinery.

- Excavators: CAT 320 (CAT, 2025), Mecalac e12 (Mecalac, 2025b), Komatsu PC138E-11 and PC210E-11 (Komatsu, 2025), SANY SY215E (Sany, 2025), Volvo CE EWR150 and EC230 (Volvo CE, 2025a) and XCMG XE215EV (XCMG, 2025a).
- Loaders: CAT 950 GC (CAT, 2025), Liugong 856HE and 870HE (Liugong Europe, 2025a), Volvo CE L90 and L120 (Volvo CE, 2025a) and XCMG XC968-EV and XC975-EV (XCMG, 2025b; XCMG, 2025c).
- Dumpers/haulers: None found.

The review of available equipment within the medium segment (10-26 tons) indicates, that excavators and loaders are available through various major manufacturers. This indicates a high TRL. Dumpers/haulers do not exhibit the same degree of availability, perhaps because dumpers/haulers in this size range are uncommon. This theory is strengthened by the fact that dumpers/haulers in smaller and larger sizes exists, thus a technical barrier does not seem to be the reason. TRL is estimated to be between 6 and 8 (CARB, 2024).

Other types of machinery in the size category, including dozers, graders and cranes, generally seems to be available (e.g. the Shantui DE26-X2 dozer (Shantui, 2025), the 4280DE grader (Liugong Europe, 2025a) and the Kalmar Forklift Truck 9-18 ton (Kalmar Global, 2025)). The medium equipment segment exhibits high availability from many manufactures, and TRL can thus reach 9 in the next five to ten years with more models entering serial production.

Volvo CE reveals that stocks of electric equipment (10-26 tons) are quite low, but being built on demand. Some of the machines are not yet readily available in Denmark, but coming by latest Q1 2026 (the EC230). Battery electric machinery have their own semi-automatic production lines at the factory and Volvo CE claims sufficient capacity to ramp up production as demand increases (Volvo CE, 2025b).

Large equipment (26-38 tons): In this segment there are some examples of excavators but not many other types of machinery.

- Excavators: Doosan DX300LC (Staad-group, 2025), Liugong 924FE (Liugong Europe, 2025a) and XCMG XE270E (XCMG, 2025d).
- Loaders: *none identified*
- Dumpers/haulers: Volvo CE A30 (Volvo CE, 2025a).

The above list indicates that availability of battery electric machinery in the large equipment segment varies quite a lot depending on machine type. Excavators exists, though not necessarily ready-to order, like the Doosan DX300LC, which is a retrofitted machine, not in serial production (E-mobility, 2025). While the Liugong 924FE is listed on the Liugong Europe main page, it does not feature on the official dealer in Denmark’s homepage. The same goes for the XCMG XE270E excavator. The A30 dumper/hauler from Volvo is listed on the official homepage, but not ready-to-order before Q1 of 2026 (Volvo CE, 2025b).

Other types of equipment include the Sennebogen 30 tons material handler (Sennebogen, 2025) and XCMGs GR350EP motor grader (XCMG, 2025e).

The above assessment suggests that the TRL of the large equipment category is not as high compared to the lower weight categories. This would indicate machines being at the demonstration or pre-production stage, with a TRL varying between 5-8 (CARB, 2024). The large equipment segment would need higher investments in the coming years to move into the commercial stage.

Huge equipment (>38 tons): Available battery electric machinery within the huge category tends to be mining-focused, with mainly dumpers/haulers and one loader identified.

- Excavators: *none identified*

- Loaders: Sandvik Toro LH518iB (Sandvik, 2025a).
- Dumpers/haulers: Liebherr T264 (Liebherr, 2025a), Liugong DR50CE (Liugong Europe, 2025b), Sandvik TH550B (Sandvik, 2025b), Volvo CE A40 (Volvo CE, 2025a).

The assessment shows that the huge equipment category is notably characterized by the mining and demolition industry. Huge dumpers/haulers and loaders are available from major manufacturing companies catering to these industries.

No battery electric excavators of this size were found during the review. This might be due to demands for mobile machinery within the huge equipment category being low, and/or that demand is low in general within this size category. Excavators do exist with tethered electric cable, like the 91-103 tons CAT395 Tethered Electric excavator (CAT, 2025) and the R992-E from Liebherr (Liebherr, 2022a). Other tethered machine types include the Sany SCE1350A-EV crawler crane (Sany, 2023).

For non-mining machinery it is difficult to find battery electric machinery. Examples do exist including Liebherrs Unplugged series of crawler cranes (Liebherr, 2025b), with the LR 1300.2 SX unplugged able to lift 300 tons (Liebherr, 2025c).

The assessment indicates, that TRL is high for mining machinery, crawler cranes and dumpers/haulers, with TRLs between 7-9, but quite low for the remaining part of the machines in the huge category, with TRL around 5-7.

3.2.3.1.2 Stationary equipment

Compressors, generators & battery packs: Numerous electric compressors exists and many alternative power generation solutions, such as battery electric packs, are readily available with more being developed.

- Compressors: Common on the market, numerous major manufactures like Rentair, Atlascopco, Bosch, Hyundai, Sullair, Fusheng, Kaeser, Hitachi, Boge, Gardner Denver and more.
- Generators/battery packs: Volvo CEs PU40 and PU500 (Volvo CE, 2025a), Infinity Cube (Infinity, 2025), Bredenoords battery boxes 30 to 600 (Bredenoord, 2025), KTEGs PowerTree (KTEG, 2025).

Electric compressors are used in the construction sector today together with its diesel counterpart. We haven’t been able to locate data indicating the split between the two. Diesel compressors have the advantage that they offer mobility and thus are the obvious choice for remote and/or non-powered sites (Rentair, 2025). Electric compressors conversely are more efficient and often have lower running costs (Atlas Copco, 2025).

Generators can be replaced with battery packs, often referred to as battery electric storage systems (BESS). They vary in energy storage capacity and thus in the amount of charge they can deliver to construction site machinery and equipment. They are not meant to just replace generators, but as charging capacity for battery electric machines and backup power capacity for weak or unavailable grid-access. KTEGs Powertree has 126 kWh (KTEG, 2025), The Infinity Cube ranges from 82 to 300 kWh (Infinity, 2025), Volvos PU systems from 40 to 500 kWh (Volvo CE, 2025a) and Bredenoords from 34 to 600 kWh energy stored (Bredenoord, 2025). The power output most often follows the amount of stored energy, with smaller battery packs delivering lower output watts compared to larger ones. This of course impacts the charge time of machinery and equipment. Most battery solutions can either be charged off-site and transported back and forth to the construction site or be directly connected to on-site electrical grid, thus providing higher output power in peak demand while slowly re-charging from the electrical grid throughout the day and night.

The combination of battery electric storage systems with electric compressors offers the same services as a diesel driven compressor. This combination can deliver in remote and/or non-powered construction sites, and is also able to deliver electricity to other machines and tools.

The assessment indicates that TRL of electric compressors and battery electric storage systems are quite high, with TRLs around 8-9.

3.2.3.2 Expected development

The above assessment of maturity found that smaller machinery and generator and power banks generally are available, or exhibit a high technology readiness level. Larger machines (above 56 kW, but especially above 130 kW) have lower maturity, but are currently being deployed indicating that TRL's are increasing in the coming years.

The expected market maturity development is presented in Table 4 with colors indicating the expected year of full market maturity, equivalent to 9 on the scale of TRL. This assessment is done qualitatively based on the above review of technological maturity per segment, and is to be considered highly uncertain.

Table 4: Expected market maturity development of electric construction machines

Segment	Size (kW)	Typical weight	2025	2030	2035	2040
Mini	0-37 kW	0-5 tons				
Small	37-56 kW	5-10 tons				
Medium	56-130 kW	10-26 tons				
Large	130-200 kW	26-38 tons				
Huge	>200 kW	>38 tons				
Generators & power banks	0-56 kW	-				

Source: Based on own literature review. Red: Low availability, Yellow: medium availability, Green: Fully available.

3.2.3.3 Machine operating hours

The desirability of battery electric machinery is significantly impacted by the effective operating time between charging sessions. We have collected operating hours and charging times from a selection of battery electric machinery currently on the market. Often one or the other is not available as the machinery are new on the market or the data just not presented on the webpage. Furthermore, charge times vary depending on which size of charger is used, with ultra-fast chargers providing as much, or more than, 350 kW. Operating hours also vary significantly depending on the use of the machinery, with heavy use and operation leading to lower operating hours, and light usage with many stops leads to more operating hours.

These factors all contribute to operating hours and charge time being uncertain and thus direct comparisons between segments and battery-electric and diesel is not a simple task. Here we provide the overall trends in operating hours and charge time, together with current battery capacity per size segment. Table 5 provides this overview based on the more detailed assessment in Table 16 in annex chapter 5.1. The overview indicates that operating hours and charging times vary significantly, even within segments and type of machinery.

Table 5: Current trends in battery capacity, operating hours and charging time per size segment

Segment	**Size (kW)**	**Typical weight**	**Type**	**Battery capacity** (kWh)	**Operating hours**	**Charging time** (1)
Mini	0-37 kW	0-5 tons	Excavator	10 – 40	4 – 8h	1 – 4h
			Wheel loader	10 – 40	7 – 8h	1 – 3h
			Dumper	4 – 5	3 – 7h	3 – 8h
Small	37-56 kW	5-10 tons	Excavator	100	5 – 6h	1h
			Wheel loader	20 – 70	7 – 8h	1 – 2h
			Dumper	60 - 80	7 – 8h	3 – 5h
Medium	56-130 kW	10-26 tons	Excavator	100 – 500	4 – 8h	1.5 – 9h
			Wheel loader	150 – 350	4 – 11h	1 – 2h
Large	130-200 kW	26-38 tons	Excavator	350 - 550	6 – 8h	1.5 – 9h
			Dumper	200 – 300	-	-
Huge	>200 kW	>38 tons	Wheel loader	450 - 500	-	1 – 2h
			Dumper	350 - 3200	-	1 – 2h

Note: 1) charging time is reported as lowest possible found from manufacture (highest charging speed).
Source: Own analyses from Danish Energy Agency. For more detail see Table 16 in annex chapter 5.1.

The overview above indicates operating hours of all types of machinery and size-segments of between 4 to 8 hours – with some variations to this. The findings are largely confirmed in actual practical use cases of battery electric machinery in Denmark (GSV A/S, 2025). The larger the segment the lesser amount of data was available and thus numbers are associated with higher uncertainty. The data indicates that battery electric machines can at the very least operate during a normal work day, with a mid-day charging session (fast-charging). Some machines can operate longer hours with bigger batteries, and some use-cases with lower utilization again decreasing the need for a mid-day charging session. All machines would need an overnight charging session to be available for tasks the following day. Furthermore, some machines are fitted with the ability to change or swap battery, eliminating the need for charging. These include the Sandvik Toro LH518iB (Sandvik, 2025a) and select machines from XCMG that have partnered with BYD for a battery swap-technology (Electrek, 2025). As presented in chapter 2.2.3 on battery electric machinery the rapid development of battery technology will further increase battery capacity by falling costs and higher energy intensities thus leading to higher operating hours.

In Table 5 charging times vary significantly with some manufactures providing charge-time considering fast-charging and thus present low charging times. Others present only charging times with the on-board charger at lower output – thus a direct comparison is invalid. This is often the difference between AC-charging and DC-charging, with DC-charging obtaining higher output wattages compared to AC-charging. We can observe, though, that fast-charging typically takes just around or above 1 hour, indicating that the machinery can quite quickly get back to work. The longer charging times presented are often associated with machines expected to charge overnight.

Other factors such as temperature affects the efficiency of the battery and thus result in reduced operational hours (Oslo Economics & Hafslund Rådgivning, 2024). Colder temperatures also affect battery containers and power banks, and thus reduce their availability.

3.2.3.4 Infrastructure requirements

Battery electric construction machinery requires access to some type of charging-infrastructure to be able to operate. Machines can be charged either on-site or off-site and transported back to site by truck. For prolonged use of machinery on-site charging is often cheaper and thus preferable. On-site charging can be provided either using power from connected electrical grid or by using power banks/battery containers or generators, or a combination of the two. Power banks/battery containers can then be powered off-site and transported back and forth using trucks, or with on-site grid power (or alternatively using solar photovoltaic panels). Excavators use too much of their stored battery capacity if driving to and from charging options far away, thus many utilize transportable charging systems to charge excavators directly where they operate (Volvo CE, 2025d).

Construction sites normally use multiple power cabinets, often from several existing substations, to provide adequate power (Hafslund Rådgivning, 2025). With the introduction of battery electric construction machinery this may not be enough to provide the needed power. Whether or not sufficient power is available depends on available capacity in the local grid, voltage levels and available connection points, were several can be connected in parallel. Typically, if power demand exceeds 500 kW there is a need for a new temporary or permanent substation, which is a somewhat bigger task as it most often requires the grid operator to provide this. This task can take weeks or months and should be initiated as soon as possible if there is insufficient power available (Hafslund Rådgivning, 2025).

Planning becomes of the upmost importance, as a project can eliminate or alleviate some of the issues mentioned above by mapping available power capacity, access to new power through grid operator, mapping of charging needs, and future demand for power in the area of the project (CO-PI, 2024b; Hafslund Rådgivning, 2025; Region Hovedstaden, 2023; CO-PI, 2024a). For example, a building project for a new housing area might install charging capacity that can both be used by battery electric construction machinery during the construction phase and by home owners charging their electric cars in the future (CO-PI, 2024a).

Unfortunately, no analyses or reports exist indicating to which extent the necessary power for a fully battery-electric construction site is available. This will vary significantly depending on available existing grid capacity, grid-operator responsiveness in installing new capacity and how machine-intensive the project is. Many sources indicate that today there is limited power capacity available for battery electric machinery, and that this problem will only get bigger as more and more machines get electrified[8]. This is an issue both for construction sites in cities and for construction sites located further away, such as larger infrastructure projects. In a Danish context there are more examples of battery-electric machinery utilized for construction projects in close vicinity of cities compared to remote infrastructure projects, as power infrastructure is scarcer in more remote areas (GSV A/S, 2025). Projects in the vicinity of towns and cities will often be closer to power capacity compared to remote projects. For more remote projects new (often temporary) power capacity will need to be established, or the use of power banks/battery containers or generators is necessary in order to utilize battery electric machinery. Hybrid systems, combining solar PV with battery capacity can also be utilized, especially in areas with no existing grid infrastructure. Furthermore, some construction projects are scattered over a larger area making centralized charging infrastructure problematic (CO-PI, 2024a). Here, a centralized charging solution won't work as experience with a 25-ton excavator showed that a just 300 meters drive to the charging station came with a 10% decrease in battery power (M. J. Eriksson A/S, 2025). Early experiences indicate that larger battery electric machines will most likely need additional electrical capacity on-site, in the form of battery/charging capacity and/or substations. Smaller projects using smaller machinery might be able to use existing local on-site grid (Oslo Economics & Hafslund Rådgivning, 2024).

The needed infrastructure will depend heavily on the existing infrastructure, the site-location and the type of work – i.e. site size: building site versus infrastructure site. All these comes in variations: existing grid capacity can be plentiful, low or inaccessible, the site can be remote, close to city or within city, and the size can be small, medium or huge. The work done can be building-related with low need for heavy construction equipment for long durations, all the way to infrastructure-related with high need for heavy construction equipment for long durations. These elements will determine the need for infrastructure

[8] (Region Hovedstaden, 2023) and (CO-PI, 2024a) both collect testimonials on the barriers perceived when doing projects that include battery-electric machinery. These testimonials include from public property developers such as municipalities, regions and state, together with contracting firms

investments in additional grid capacity, chargers, power banks, battery containers, hybrid systems with solar PV and batteries, etc.

Additionally, when finding the right amount of infrastructure needed for using battery electric machinery, comes the in-optimal reality of construction work. Often there are pauses in work caused by unforeseen issues. This causes machines to be used in-optimally and thus may need to run for longer or shorter amounts of times, and thus do not follow optimal charging schedules. Furthermore, machines may be needed at other sites, and need to change site within the construction projects time-horizon, causing the optimization of infrastructure to be even more complicated.

3.2.3.5 Economy

The economy of battery electric machinery is complex and consists of the initial investment costs, operating and maintenance costs, with additional costs associated with power capacity at site as explored in the previous section. This makes it difficult to compare the costs of operating battery electric machines to that of conventional diesel machines. Furthermore, the technology is in early commercial stage and the cost estimates obtained are thus more uncertain compared to already established conventional diesel machines.

Investment and operational costs

The initial investment costs of battery electric construction machines are reported to be around 1.5-3 times higher than that of an equivalent diesel machine (Region Hovedstaden, 2023; Hafslund Rådgivning, 2025; Volvo CE, 2025c; J-maskiner, 2025; GSV A/S, 2025; SMF, 2025). This number varies between size-segment and also type of construction machinery (CO-PI, 2023; Volvo CE, 2025c). Table 6 provides an overview of the expected difference in investment and operating costs in battery electric machinery compared to diesel machinery. Not depicted in the table it seems that cable-electric equipment is somewhat cheaper than presented in the table (SWECO, 2025).

Table 6: Expected investment cost difference compared to equivalent diesel machine

Segment	Size (kW)	Typical weight	Investment costs compared to diesel	Operating costs compared to diesel
Mini	0-37 kW	0-5 tons	+0 to +150%	-10%
Small	37-56 kW	5-10 tons	+10 to +200%	-30%
Medium	56-130 kW	10-26 tons	+80 to +300%	-50%
Large	130-200 kW	26-38 tons	+100 to +300%	-50%
Huge	>200 kW	>38 tons	-	-

Source: Based on (CO-PI, 2023; Region Hovedstaden, 2023; SWECO, 2025; Volvo CE, 2025c; Oslo Economics & Hafslund Rådgivning, 2024; J-maskiner, 2025; CO-PI & EY, 2023; SMF, 2025).

Note: Not enough data for indications in the “Huge” category. The cost differences are obtained as of 2025. Please note that these costs include, were possible, just the base machine, no additional or extra equipment, to be able to compare with the base diesel baseline machine.

Operation and maintenance costs associated with operating battery electric machines are lower than equivalent diesel machines. This is because electric motors induce significantly higher energy efficiency, as further elaborated in chapter 2.2.

On top of efficiency gains of electric motors, it seems that battery electric machines have lower operating and maintenance costs compared to diesel machines, as there are fewer moving parts. Table 6 indicates lower overall operating costs of 10-50 percent compared to diesel machines. This will vary depending on the price of diesel and electricity, and with the segment size, as noted previously.

The cost of infrastructure

As noted above battery electric machinery often require the purchase of power infrastructure entails considerations regarding: power banks/battery containers, power generators, substations, cables and altercations to existing electrical high- or low voltage substations. The cost of these varies quite substantially depending on the specification of the project, the distance to existing power grid and the amount of available power capacity in the existing installations. Furthermore, it depends on the specifications of the power bank/battery container: the power output (kW) and the amount of stored energy (kWh). Power generators also vary in price, depending on the fuel input and the power output demand (kW) – with hydrogen being more expensive compared to diesel, although likely a greener solution.

A study based on Norwegian experiences finds that infrastructure costs increase the overall investment costs of using battery electric machinery compared to diesel machinery. The investment cost presented in Table 6 increases by 20-30 percentage points in areas with decent grids and 30-80 percentage points in areas with limited available grid capacity (Oslo Economics & Hafslund Rådgivning, 2024).

Battery containers, or power banks, are decreasing in costs as battery cells decrease in costs. A Norwegian example is a battery container containing 200 kWh battery capacity that can charge and discharge itself using both 230V (32A to 63A) and 400V (63A to 125A) at up to 150 kW. The cost of the battery container was around 0.32 million €^{2025} in 2022. The general costs of battery containers including energy management systems (but excluding charging systems) are in the range of 0.35-0.7 million €^{2025} per 1 MWh. A fast charger (>100 kW) costs around 43,000 €^{2025} (SWECO, 2025).

Total cost of ownership

Battery electric machines have higher initial investment costs, lower operational and maintenance costs and additional costs associated with infrastructure as noted above compared to diesel machines. Calculating total cost of ownership (TCO), where the total costs of using a machine over a proposed time of ownership is calculated e.g. per hour of use, makes it easier to compare the economics of battery electric machines with its diesel counterpart.

Studies show that battery electric machines in the mini and small segments (0-10 tons) have lower TCOs compared to equivalent diesel machines. The picture is blurrier when entering the medium and large segments (10-38 tons), where battery electric is somewhat more expensive compared to diesel. In the huge category (> 38 tons) the TCO becomes cheaper for cable electric machines but not for battery electric machines (CO-PI, 2023; CO-PI & EY, 2023). Other studies report consistently that battery electric machines outperform their diesel counterpart in all size segments (Lendlease & University of Queensland, 2022).

The TCO calculations above does not include costs for power banks/battery containers, chargers, substations and cables (CO-PI & EY, 2023; Lendlease & University of Queensland, 2022). These infrastructure costs are very uncertain and ranges significantly as introduced above. Thus, it is uncertain to which extent these costs could tip the TCO balance in favor of diesel.

Although TCOs of battery electric machines are possibly lower compared to diesel machines the construction sector tends to focus on the up-front investment costs. This is because of many factors, including e.g. lack of access to capital and uncertain end-of-life value of battery electric machines. Thus, the additional up-front investment costs, as presented in Table 6, weigh heavier than the lower operational costs (SWECO, 2025). A battery electric machine with lower TCO then might be seen as an economic disadvantage compared to an equivalent diesel machine.

The additional investment costs of running construction sites with only battery electric machines vary in the range of 2-3 % of the total cost of the project (Oslo Economics & Hafslund Rådgivning, 2024). A report from 2023 furthermore concluded, that transitioning from diesel machines to battery electric would cost society around 200€^{2025} per ton CO_2 saved, with larger machines exhibiting much higher shadow prices of 690-1650€^{2025} per ton CO_2 saved (CO-PI & EY, 2023).

Expected development of costs

The costs associated with battery electric machines are expected to fall as a result of several expected technological developments. Investments costs will decrease, as more OEMs start serial production and competition picks up. Furthermore, the future development of battery technologies, as noted in chapter 2.2.3, will decrease prices, and thus investment costs of battery electric machines (SWECO, 2025).

3.2.4 Hydrogen

This section covers machinery that runs on hydrogen – either directly combusted in an internal combustion engine or used in a fuel cell combined with an electric motor.

3.2.4.1 Maturity

This section first assesses the maturity of non-stationary construction equipment, like dump/haul trucks, excavators, etc., and then moves on to assess the maturity of power generators.

3.2.4.1.1 Non-stationary machinery

JCB started by introducing a prototype 220X 20-ton excavator running on hydrogen fuel cells back in 2020, but seems to have since stopped development on fuel cells (JCB, 2020). JCB have since been investing heavily in the development of a hydrogen internal combustion engine, and in 2023 showcased the first example (JCB, 2023). Prototypes of a backhoe loader and telescopic handlers was revealed in 2021 (JCB, 2021). By 2025 the hydrogen engine has been cleared for commercial use in Europe (EV Infrastructure News, 2025). This indicates the continued commitment from JCB to develop hydrogen machinery for the construction sector. JCB research concluded that the use of fuel cells was too expensive, complicated and not robust enough for the construction sector and thus developed the internal combustion engine instead (JCB, 2023). Other major engine manufactures, like Perkins and Cummins, are also actively developing hydrogen internal combustion engines (Construction briefing, 2023).

Hitachi has partnered with KTEG to produce a 30-ton (200kW) excavator with a hydrogen internal combustion engine (KTEG Hitachi, 2025). Generally, Hitachi sees that battery electric machines will cover the small to medium machine size segments, while hydrogen will cover the large to huge segments (above 26 tons) (Hitachi, 2025). Likewise in the huge size segment the Liebherr prototype hydrogen excavator R 9XX H2 was introduced in 2022 running the Liebherr-produced H966 internal combustion engine (Liebherr, 2022b).

Conversely to JCB, Hitachi and Liebherr focusing on hydrogen combustion in internal combustion engines, Hyundai Construction Equipment is set to develop machinery with hydrogen fuel cells. The 2-ton HW155H wheeled excavator was presented at the Bauma construction equipment convention latest in 2025, supposedly nears the production stage (Hyundai Construction Equipment, 2025; Hyundai Construction Equipment, 2024). Furthermore, forklifts running on hydrogen fuel cells seems to be market ready, albeit in the low to medium size forklifts, with the first 5-ton forklifts supplied by HD Hyundai XiteSolution in 2024 (HD Hyundai Xitesolution, 2024).

Other OEMs working on fuel cells include Volvo CE, Komatsu and Kobelco. Volvo CE began testing a hydrogen fuel cell dump/haul truck in 2022, the HX04. The project began development back in 2018, and was successful in developing a prototype (Volvo CE, 2022). Komatsu, working with Toyota Motor Corporation, announced a concept medium-sized excavator in 2023, with Komatsu aiming at hydrogen fuel cells for the medium to large construction machinery segments (Komatsu, 2023). Likewise did Kobelco, also working with Toyota, finishing a prototype hydrogen fuel cell in 2023 (Kobelco, 2023).

The findings indicate that most hydrogen powered construction machinery are at the prototype stage, or in early development – and not commercially available at present. This indicates a low TRL of around 5-7, with prototype testing in relevant operational environment. Fork lifts are the exception with TRL levels at around 8.

3.2.4.1.2 Stationary equipment

Power generators using hydrogen fuel to make electricity for on-site demands, sometimes including battery-electric systems, are numerous and can as of 2025 be rented and bought in many European countries. They all work using fuel cells producing electricity from hydrogen. Major manufactures include Intelligent Energy, HYTOR, HYGRO, JCB, Hitachi Energy and Hexagon Purus (Intelligent Energy, 2023; HYTOR, 2025; HYGRO, 2025; JCB, 2025d; Hitachi Energy, 2025; Hexagon Purus, 2025). The TRL level of hydrogen generators is high, around 9 – with many products already commercially available for rent or purchase.

3.2.4.2 Expected development

Several large OEMs have activities in developing hydrogen machinery. Few have reached higher technology readiness levels yet and thus the future pathway of expected development is highly uncertain. Only stationary equipment and fork lifts inhabit higher TRL.

It is likely, that hydrogen will come to be attractive for specific size segments, larger machines, and for specific project-types, were little to no direct grid access exists. Although refueling infrastructure will still be an issue for these niche usages, there are likely places in the world where larger hydrogen powered machinery will come into play. Thus, availability will likely be small, and possibly custom-made machinery for the exact purpose could be the case.

This review concludes, that while technically possible to build construction machinery based on hydrogen fuel (ICE or fuel-cell), it is extremely uncertain when or if the investments into the technology will result in maturity. Thus, thus report makes no assumptions on if or when hydrogen will become a mature technology for the construction sector.

3.2.4.3 Machine operating hours

The hydrogen machines presented in the previous sub-chapter on maturity all have operating hours slightly below usual diesel machinery. Fueling takes somewhere between 5-20 minutes depending on size segment, with larger machines taking longer to refuel (KTEG Hitachi, 2025; Hyundai Construction Equipment, 2025).

3.2.4.4 Infrastructure requirements

As noted in chapter 2.3.4 hydrogen infrastructure is close to non-existing in Denmark, and thus there is a large initial hurdle if the construction sector is to invest in hydrogen machinery.

Hydrogen powered construction equipment will need daily refueling like its diesel counterpart. This can be provided in a number of ways. As with the current diesel machinery, trucks can deliver the hydrogen fuel to the construction site – either to pressurized storage tanks or directly to awaiting hydrogen powered construction machines or generators. Refueling machinery can drive to central storage tanks or for ease of operation construction sites can rely on mobile refueling machines, like the JCB hydrogen refueller (JCB, 2025c). The hydrogen infrastructure is likely more costly compared to the existing diesel infrastructure due to pressure-requirements and safety regulations. For more on the requirements and safety regarding storing and transporting hydrogen see section 2.3.

3.2.4.5 Economy

It has not been possible to locate data on the economic costs of hydrogen construction machinery. This is likely because of the low technology readiness levels observed above, and thus no commercially available products exist.

3.3 Wrap-up

In this section we compare the reviewed technologies in the previous section to each other in terms of what general characteristics that can be deduced. We do not seek to provide a conclusion crowning a ‘best’ technology, as this will depend heavily on future development trends, and on the specific construction project at hand as previously noted.

3.3.1 Comparing technologies on key aspects

In the following four figures we score conventional diesel machines relative to the use of biodiesel, battery electric and hydrogen machines. We do this on seven parameters of great importance to the investment decision in new construction machinery: Maturity, investment costs (CAPEX), operational costs including fuel costs (OPEX), energy efficiency of operation, machine operating hours, infrastructure requirements and costs, greenhouse gas emissions, particle and NOx emissions, and lastly safety considerations. These ratings indicate the efficiency of each variable – meaning a higher rating represents a higher efficiency.

3.3.1.1 Conventional diesel machines

These machines have the power of being the proven technology, the baseline, and thus the safe choice of any construction project type. This is also why; we compare the three emerging technologies to this technology in the following. Diesel machines are fully market mature in all kinds of machines and project types, have relatively low investment costs, with very rapid refueling making way for high operating hours. The technology has low infrastructure requirements (for tanks, transport of fuel) and thus low infrastructure costs. Conversely, conventional diesel machines have somewhat high operating costs, especially fuel and maintenance costs, resulting from low energy efficiency. Diesel combustion results in emissions of both greenhouse gases and particles and NOx.

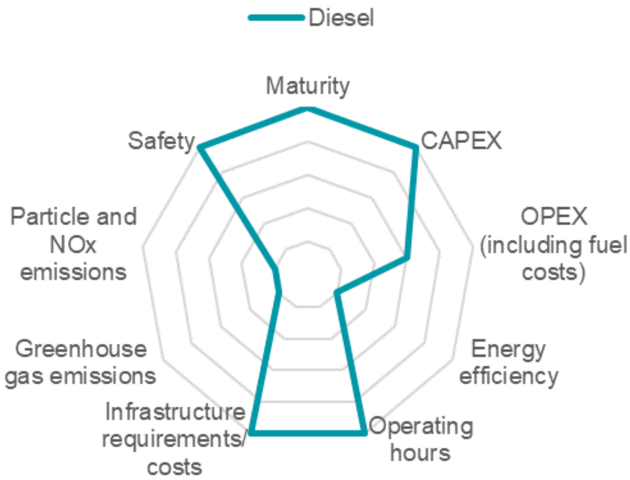


Figure 5: Conventional diesel machine score

3.3.1.2 Biodiesel

Machines powered by biodiesel fuels have much of the same advantages and disadvantages as conventional diesel machines as the fuel can be utilized in the same machines and engines. They differ slightly in terms of operating costs, where biodiesel is more expensive compared to diesel. Conversely machines running on biodiesel emit less greenhouse gas emissions and sometimes less particles and NOx.

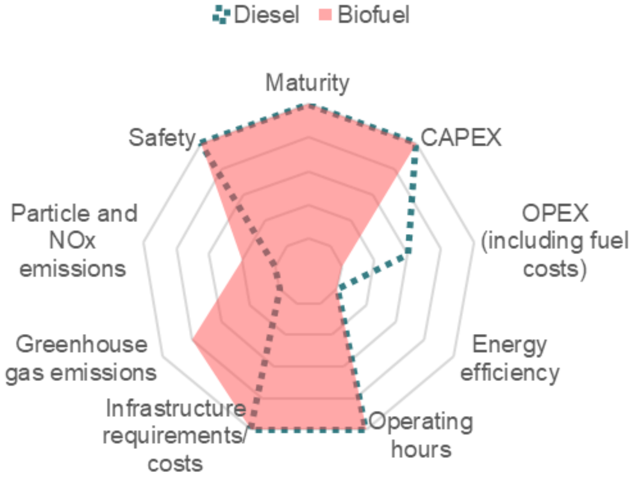


Figure 6: Biodiesel machine score

3.3.1.3 Battery electric

Battery electric machines are seeing increasing maturity with major OEMs investing heavily in production capacity in almost all machine types and at least the mini, small and medium size segments. However, not many machines are readily available on the market and as a result maturity of battery electric machines are judged to be medium. The energy efficiency of battery electric machines is the highest of the technologies compared, and together with low maintenance costs this results in low operating costs. Electric motors emit no greenhouse gases or particles, and as a results score high on these parameters. Safety score is high, as no explicit concern exits, especially compared to other technologies like hydrogen. Investment costs are higher than conventional diesel machines, sometimes 1-3 times higher. Machine operating hours, while increasing with recent developments, are lower compared to diesel machines. Switching to battery electric machines requires changes to work-patterns, which is often cited as a barrier for adoption throughout the value chain. Furthermore, battery electric machinery often require investment in infrastructure on-site, e.g. charger, battery containers, substations, cables, etc.

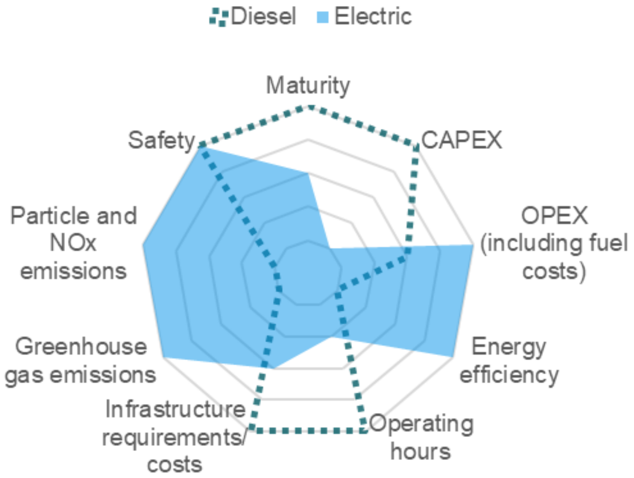


Figure 7: Battery electric machine score

3.3.1.4 Hydrogen

Hydrogen powered construction machinery, both internal combustion engines and fuel cells, exhibit quite low maturity levels, as no major OEM has commercially available machinery. The next 5-10 years will reveal if OEMs manage to get from the demonstration stage to the commercialization stage. Investment costs for hydrogen machines are very uncertain given the maturity level, but are likely more expensive compared to diesel machines, as on-board hydrogen storage increases complexity. Hydrogen as a fuel, both fossil and especially fossil-free in origin, is much more expensive compared to conventional diesel. Furthermore, while energy efficiency of hydrogen ICEs is lower compared to diesel ICEs, fuel cells are somewhat higher but significantly lower than electric motors. As a result, operating costs are high compared to both diesel and electric machines. Machine operating hours are on par or just below diesel, and above that of battery electric machines. Infrastructure requirements for hydrogen machinery are higher compared to both diesel and electric machines. Safety surrounding hydrogen storage tanks on-site and in the machines themselves is of more concern compared to both diesel and electric machine operations. Emissions of greenhouse gases and particles are zero in both the ICE and fuel cell operations.

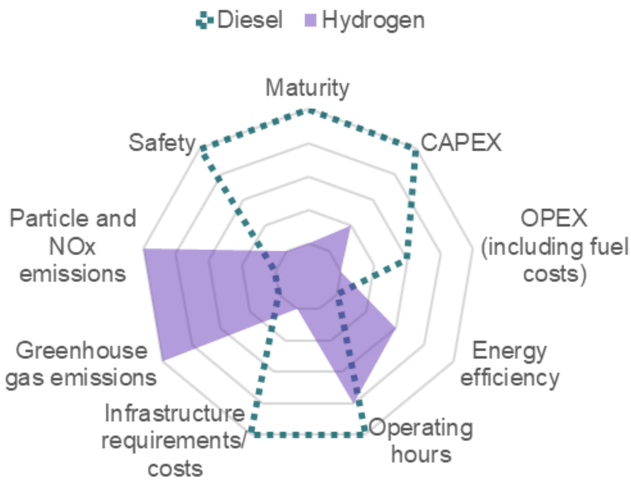


Figure 8: Hydrogen machine score

3.3.2 Comparing expected developments

In this section follows a comparison of the expected developments of the reviewed technologies in the previous sections. Uncertainty is prevalent for all technologies, but especially surrounding hydrogen machine development.

In the near future, battery electric machines will likely be commercially available in most size segments. The issue for these machines will be in the available grid-infrastructure, and as a consequence the cost of operations including additional investments into chargers, batteries, substations, cables, etc. In the meantime, hydrogen is also likely to come into the market in some segments, and for some specific use-cases – e.g. construction projects with little to no grid available and/or with high demands for power output. The availability of hydrogen machines will be much lower compared to battery electric machinery, as very few major OEMs bet on this technology. Biodiesel will possibly be used in the short- to mid-term as an easy way to live up to growing environmental demands while utilizing existing machinery. In the long-term biodiesel might be outperformed by both battery electric and hydrogen machines.

The barrier of lower machine operating hours for battery electric construction machines can supposedly be eliminated in the future, if or when solid state batteries see their penetration to the market. The promise of this technology is to contain much more energy per weight/volume, and thus increasing the amount of work hours per battery weight/volume. It is *likely* that this technology will reduce the need for hydrogen powered machines in the mid- to long-term.

4 Agricultural machinery

In this chapter, machinery used across agricultural sites and machine pools will be reviewed. Subsequently, developments into alternatives to the standard diesel engine will be presented.

4.1 Use of machinery within the sector today

Within agriculture, the use of non-road machinery varies between types and sizes of farms. The activities, or energy services, that machinery is required to perform, is dependent on whether animals are reared, crops grown or a mix of these. The energy services can be defined simply in terms of hauling, sowing, plowing, harvesting etc., but for each of these services, there may be several machine-types and motor sizes able to deliver the energy service.

Knowing the patterns of different agricultural activities between field and farm, as well as the corresponding demands with regards to operational hours and machine power needed from non-road machines, is essential in order to estimate the relevance of alternative drives in agricultural machinery. This point will be unfolded in chapter 4.1.1.

As will be shown in chapter 4.1.2, several size classes of the same machine-type currently exist, reflecting 1) that the agricultural sector is highly diverse regarding activities across farm types, and 2) economic differences between farms of varying sizes and types. These two underlying factors are not explored for the Danish context in this review, but are considered elsewhere in reviewed literature[9].

With the above distinctions in mind, the following chapters present development trends within alternative technologies in agriculture and their suitability for common use-cases today and in the future.

4.1.1 Use patterns: Distinction between fieldwork and farmwork

The tasks that agricultural machinery is used for can be divided into *fieldwork* and *farmwork.* Fieldwork, as the name suggests, takes place away from the farm complex, and involves activities such as plowing, seeding and harvesting. Farmwork on the other hand is performed inside or in the immediate surroundings of the farm buildings and can be activities such as feeding or sweeping. Some tasks in both the field and on the farm can be accomplished with the same machine, e.g. a tractor, while other machines are only useful in one of the two situations. Examples of the latter include harvesters that are only used in the field. Several types of machines like scrapers, bedding machines or sweepers are only

[9] For these points, see sources (Baker, et al., 2022) for the Scottish context and (Roer Hjelkrem, et al., 2020) for a Norwegian perspective.

used on farm, either in a self-propelled or tractor-pulled design. Use patterns between these general types of work put different demands on non-road machinery.

Fieldwork will often require machines to haul heavy loads, drive auxiliary machinery through PTO-coupling, and importantly work for an extended number of consecutive hours in season. Outside of seasonal work periods, however, there may be no work except for the occasional fertilizing or pesticide treatment, and the yearly work hours of a machine for field operations may be anywhere between 300 and 2000 hours[10]. Machines that are dimensioned for the heaviest tasks, may therefore stand completely still for most of the year, or work at loads considerably lower than their most efficient configuration. Working hours are concentrated and highly dependent on weather conditions. Within the season for seeding and harvest, this type of work requires the machinery to be operational in shifts of at least 12 hours before refueling, matching the work-shift of drivers. Therefore, machines working in the field are reliant on large amounts of available energy, and the largest motor sizes currently in use are designed for fieldwork. The most important machines for fieldwork are tractors, combine harvesters and self-propelled forage harvesters. Motor sizes vary greatly for tractors, depending on size and economic considerations of the farm, while harvesting is commonly undertaken by contracting parties such as machine pools. For both tractors and harvesters, there has been a steady trend of decreasing numbers and increasing motor sizes over the years on record (Winther, 2024).

Farmwork, conversely, is typically characterized by use patterns following a set weekly or daily schedule. For this type of work, use cases can be subdivided into typical patterns by motor size. Machines > 50kW are typically in use 2-6 hours daily and smaller machines are typically in use 1-3 hours daily. While the all-round tractor is a staple within farmwork, machines such as telehandlers and loaders are important as well. Although motor sizes are increasing for larger farms, machines dimensioned for farmwork generally does not exceed sizes of 225 kW / 300 hp.

The distinction between the two types of usage is not a perfect typology, as a tractor may be used both in the field and on the farm as all-rounders. This distinction, however, yields the advantage of being able to access differences within useability for alternative drivetrains depending on other energy carriers than diesel, such as electricity or methane. For example, as machines in the field are further away from the farm, they require a different infrastructure for refueling than machines that work on-farm, where energy-infrastructure is commonly more available. The demand for fast refueling to make the most of stable weather conditions further puts pressure on the refueling events to be quick. Machinery for farmwork on the other hand have work patterns which are less reliant on fast refueling or –charging.

4.1.2 Energy consumption and machine segmentation

In the following, data from the latest inventory by Department of Environmental Science (DCE) is used to showcase the various dimensions that are relevant for machines

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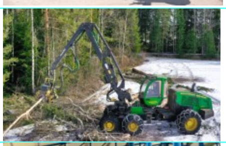
[10] Range provided by Spiras consulting.

registered in agricultural use, forestry and machine pools in Denmark. DCE data combines stock and sales data based on the Danish Motor Register as well as expert interpolation to account for non-road machinery (Winther, 2023). It is worth noting that energy usage of machine types is difficult to assess, and highly dependent on assumptions.

Table 7: Distribution of energy consumption across machine type in the Danish agricultural sector in 2023.

Machine type		**Typical applications**	**Share of total non-road**
Tractors		All-round workhorse. Hauling and driving other applications for plowing, sowing, fertilizing etc.	66 %
Combine Harvesters		Reaping, threshing and winnowing. Intensive field-usage during harvest season.	17 %
Self-propelled forage harvesters		Harvesters for fine-cutting produce into silage.	6 %
Telescopic loaders		Handling of haybales, materials, fodder etc.	5 %
Chippers		Grinding branches and timber into smaller pieces of wood.	2 %
All-Terrain Vehicles (ATV)		Lighter field and farm work including feeding, mowing, inspection etc.	1%
Forestry-machines		Felling and transporting timber	1 %
Chainsaws, fodder trucks, sweepers, other machines		Machines for specific and smaller operations on or outside of the farm and in the forest.	1 %

Source: (Winther, 2023)

Data for Forestry, Agriculture and Machine pools in DK. “Other machines” include scrapers and bedding machines.

Tractors is a composite category across agriculture and forestry, including forwarders and silvicultural tractors.

Percentages are rounded and does not sum to 100%.

As can be seen from Table 7, agricultural machines have a wide range of end-usages. Tractors are by far the most typical machine type, and 66% of energy usage for machinery within the sector can be attributed to these. Combine harvesters make up the second largest part of energy usage within the sector, 17%, while the self-propelled forage harvesters account for 6%. A diverse mix of machines make up the remaining demand for energy.

Within the categories of machines, further subdivision can be made into motor sizes. As shown in Table 8, machines with motor size below 57 kW up to 560 kW nominal effect are seen in the sector[11]. We divide DCE data into four motor size classes, A – D, based on nominal kW effect and typical use-cases. The largest range of machine types are found in the smaller category A, where compact and specialized tractors, all-terrain vehicles (ATV), sweepers, fodder machines, chainsaws, bedders and scrapers etc. are found. Although diverse, the lowest class until 56 kW, only account for roughly 5% of energy usage in the sector. In the intermediate classes B and C, tractors are the main machine types, and used primarily within the premises of the farm, or for all-round purposes on mixed farms with both crops and livestock. In class B, telescopic loaders are an important on-farm asset as well. Size class C introduces lighter harvesters as well. Generally, equipment above 225 kW should not be expected to perform farmwork, but only work in the field, which is mirrored in the large fractions of harvest equipment in the class.

Drawing upon the evidence from these data-tables, the most relevant technologies in an energy-perspective seem to be tractors and combine harvesters as well as forage harvesters and telehandlers, as these stand for the largest percentages of energy-consumption within the sector. Further, it is evident that not only the larger motor sizes are relevant in an emissions perspective since energy usage is spread out across size-classes. The findings from the review of alternatives to diesel will be structured with reference to the size-classes presented in Table 8.

[11] Based on insights from Spiras, we expect that this range is too low, since especially forage harvesters and some large tractors have surpassed 560 kW in recent years. The market for pre-owned agricultural machines shows motor sizes above this threshold as well. Still, DCE data is our best available source of insights into machine types and shares.

Table 8: Distribution of energy consumption across agricultural machinery size segments in 2023.

Segment	Motor size (kW)	Machine type	Share of total non-road
A – Specialized tractors and hobby equipment	< 57	Compact tractors, landscaping and municipal machines, specialized orchard or horticultural tractors, ATVs and other smaller equipment.	5%
B – light farmwork	57 - 130	Tractors	24%
		Telescopic loaders	5%
C – heavy farmwork, light fieldwork	131 – 225	Tractors	26%
		Forage harvesters	3%
		Combine harvesters	4%
		Forestry machines	3%
D – heavy field equipment	226 – 560	Tractors	13%
		Combine harvesters	14%
		Forage harvesters	3%
		Forestry machines	1%

Source: Own calculations based on (Winther, 2023), with qualitative input on classification from Spiras.

Note 1: Data for Forestry, Agriculture and Machine pools in DK, diesel-driven. Nominal effect.

Note 2: Sum of shares may be different to 100 due to rounding.

4.1.3 Investment costs of the diesel baseline

In the agriculture sector today, as noted above and in chapter 2.1, the combination of diesel and ICE is the standard for providing the energy services needed. This section shortly introduces the investment costs per segment and machine type for the diesel baseline technology. Thus, a comparison of potential additional investment costs for alternative technologies can be made in the following section.

Costs of agricultural machines vary depending on type, motor size and other configurations. In Table 9, mean investment costs for agricultural diesel machinery based on realized trades are listed. As can be seen, the cost per kW effect increases with motor size for tractors and combine harvesters, whereas the largest forage harvesters are the cheapest per kW effect.

Table 9: Mean investment costs for new agricultural diesel machinery in Denmark

<table>
<tr><th rowspan="2">Motor size</th><th colspan="4">Mean investment cost by machine type (DKK per kW)</th></tr>
<tr><th>Tractor</th><th>Combine Harvester</th><th>Forage Harvester</th><th>Telescopic loader</th></tr>
<tr><td>< 37 kW</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td><td rowspan="5">N/A</td><td>N/A</td></tr>
<tr><td>38-56 kW</td><td>8000</td></tr>
<tr><td>57-130 kW</td><td>6000</td><td>5500</td><td>8000</td></tr>
<tr><td>131-200 kW</td><td>8000</td><td>6000</td><td rowspan="5">N/A</td></tr>
<tr><td>200-300 kW</td><td>8000</td><td>8000</td></tr>
<tr><td>300-400 kW</td><td>8000</td><td>8500</td><td>7200</td></tr>
<tr><td>400-500 kW</td><td rowspan="2">N/A</td><td>10000</td><td>6500</td></tr>
<tr><td>>500 kW</td><td>10000</td><td>6000</td></tr>
</table>

Note: Mean investment cost in DKK per kW. Based on realized trades on the Danish market. N/A indicates no trades were recorded for this segment, or too few for an estimate. Data from 2023.
Source: (DME, 2025).

4.2 Alternative technologies

This section identifies alternatives to diesel construction machinery, including the stage of development, the use-potential in the sector, the economic costs and barriers for adoption.

4.2.1 Relevant technologies

Based on media coverage, grey literature, OEM promotion and open-access academic sources, this review explores several alternatives to the current diesel-driven machines within agriculture as listed in Table 7. The technologies deemed relevant for this review are listed in Table 10, where emphasis is on highlighting which size-classes of existing machinery can be interchanged with an alternative energy source or drivetrain. Here, the existence of machines within size-classes is presented. In the corresponding technology chapters the suitability for field- and farmwork is considered.

Table 10: Overview of assessed alternative technologies to diesel in the agriculture sector

<table>
<tr><th>Segment</th><th>Size (kW)</th><th>Machine Type</th><th>Biofuels</th><th>Electric</th><th>Hydrogen</th><th>Methane</th></tr>
<tr><td>A</td><td>< 56 kW</td><td>Compact tractors, ATV, etc.</td><td>✓</td><td>✓</td><td>✗</td><td>(✓)</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">57-130 kW</td><td>Tractors</td><td rowspan="2">✓</td><td>(✓)</td><td>(✓)</td><td>(✓)</td></tr>
<tr><td>Other</td><td>(✓)</td><td>(✓)</td><td>✗</td></tr>
<tr><td rowspan="3">C</td><td rowspan="3">131-225 kW</td><td>Tractors</td><td rowspan="3">✓</td><td>(✓)</td><td>✗</td><td>(✓)</td></tr>
<tr><td>Harvesters</td><td>✗</td><td>✗</td><td>✗</td></tr>
<tr><td>Other</td><td>✗</td><td>✗</td><td>✗</td></tr>
<tr><td rowspan="3">D</td><td rowspan="3">>226 kW</td><td>Tractors</td><td rowspan="3">✓</td><td>(✓)</td><td>✗</td><td>✗</td></tr>
<tr><td>Harvesters</td><td>(✓)</td><td>✗</td><td>(✓)</td></tr>
<tr><td>Other</td><td>✗</td><td>✗</td><td>✗</td></tr>
</table>

Source: Own literature review.

For many of the technologies, the possibility of creating engines fitting with the sizes described in Table 10 technically exist. For example, Fiat Powertrain Technologies have developed a 500 kW engine, which can be modified to run on hydrogen, diesel, methane or biofuels, depending on the infrastructure available to the user (FPT, 2023b). Similarly, it is conceptually possible to stack enough batteries to power a machine at any motor size currently in use today. This would suggest that this type of technology would be able to fit any of the size ranges currently found within agricultural machinery in Denmark at the time. However, the theoretical concept does not allow for farmers to buy the machine, nor does it imply that such a machine would be practical for use, barring a fundamental change of infrastructure or work-pattern for the farmer. In other words, the effect output of a motor does not alone determine useability in the field, even if it is a good proxy. For these reasons, only machines created with the distinct purpose to deliver on one of the relevant energy services in agriculture within the specified motor size intervals will be considered.

The review will focus mainly on providing evidence of relevance and associated costs where possible. Analyses of potentials for replacing diesel consumption on farms would require assumptions of existing farm types and sizes, machine use-patterns in terms of the effect-requirements, timing of use, as well as distance to fueling or charging stations and the farmer’s potential for on-site production of energy, as suggested in academic literature and case studies (Baker, et al., 2022; Roer Hjelkrem, et al., 2020). It might be added that disruptions to the agricultural sector such as trends towards regenerative farming or taxes on emissions may change the way machinery is currently being used with the predominance of diesel. This in turn could affect the potential of alternative drivetrain technologies to deliver on farmers’ demand for energy services, e.g. through use of autonomous drive (Ghobadpour, et al., 2022), no or reduced tillage practices (Baker, et al., 2022), and agriphotovoltaics (Schneider, et al., 2023). That being said, this review focuses on describing technologies that can replace existing farming machinery.

In the following chapters, selected alternatives are described. For each of the technologies the assessment looks at maturity, expected development, operational hours, infrastructure requirements and techno-economic parameters like CAPEX and OPEX where available.

4.2.2 Biodiesel

This section covers the use of biodiesel in either existing or new agriculture machines.

4.2.2.1 Maturity

For newer machinery, HVO should be able to substitute diesel on a drop-by-drop basis, making considerations of price and availability of certifiable biofuels the main concern for reaching emissions reduction through biodiesel. The capability of motors to run on HVO can be influenced by motor type (Baker, et al., 2022), but typically, ICE motors currently in use are expected to be able to substitute diesel for HVO on a drop-by-drop basis.

4.2.2.2 Expected development

Some OEMs claim to be making HVO the new standard fuel, with e.g. Claas offering deliveries of all new machines with a tank full of HVO (Claas, 2024). Others seem to be mainly looking at biodiesel as a short- term solution while working on other decarbonisation technologies (Koerhuis, 2020). The actual uptake will depend on the costs of HVO relative to using fossil diesel, but no further development to machinery is needed for the fuel to supply the different demands for either farm- or fieldwork.

4.2.2.3 Infrastructure requirements

Since HVO can use the same infrastructure as diesel, there are no additional infrastructure costs associated with a change. HVO and fossil diesel can even be mixed at any ratio in the same tank. According to OEM Claas, an average farmer in Britain would have to invest 8000 € in a fuel storage tank to effectively shift to HVO (Claas, 2023).

4.2.2.4 Economy

Operation and maintenance costs are equal to diesel machinery if HVO is used. In case FAME is used, there may be detrimental effects to machine parts as discussed in 2.1.3 This means that the main cost-difference between HVO and fossil diesel is the purchase price of the fuel itself.

4.2.3 Electric

This section covers battery electric machines and were stated also cable electric machines.

4.2.3.1 Maturity

Electric machines for agricultural application are seen mainly in the form of battery-electric vehicles. Only one example of a cable-electric machine concept was found during the literature review but the concept was referenced frequently in academic assessments of electrification potentials. Fuel cell electric tractors are often referenced in research within this category as well, but since costs, infrastructure and performance vary considerably, these are evaluated separately in chapter 4.2.5. This section will go through the size segments, and provide, were possible, examples of concepts, prototypes, refurbishments, or OEM-produced machines, per machine type.

Size-segment A (< 57 kW / < 76 hp): In this size-segment there exists a quite large variety of agriculture machinery based on battery electric drive-train. Examples of available equipment on the market are:

- Compact tractors: FT25G (Kubota, 2024). Kubota Lxe-261 (Kubota, 2022). Knegt 304G2E, 404G2E and 504G2E (Knegt, 2025). Avenger-26 hp (DK-TEC, 2025).
- ATV: Bernards EATV4X4-S (RCholm, 2025), Powerland Tachyon (Powerland, 2025).
- Telehandler: Kramer KT144e (Kramer, 2025a), JCB 525-60e (JCB, 2025a), Dieci MINI AGRI-e SMART 20.4 and 26.6 (Dieci, 2025), Merlo eWorker 25.5-90 (Merlo, 2025) and Manitou MT625E (Scantruck, 2025).
- Specialized tractors: New Holland T4 (New Holland, 2025a), Fendt e107/100 V Vario (Fendt, 2024a), Rigitrac SKE 40 (Rigitrac, 2025) and ONOX (ONOX, 2025).

Machines of most types are ready for purchase from major OEMs to the European market, with for example the Fendt e-107 bought for use on a dairy farm in Denmark in 2025 (Tjell, 2025). On the other hand, there are also machines at prototype stage, such as the German startup ONOX electric tractor, are also being developed in this size range, focusing on delivering non-stop operation through battery swap.

Both tractors and telehandlers exist in this size segment, with tractors for municipal and orchard work being in focus for development efforts in the high end of the scale. Most OEMs have only one or two models for the segment, showing that battery-electric machines are not yet commonplace or ready to take over the primary market share from diesel. This signifies a TRL between medium and high, varying between machine types.

Operating hours top at 9 hours for tractors and 8 hours for telehandlers, with lower available hours for the larger tractors, especially dependent on work-load.

Size-segment B (57-130 kW / 77-177 hp): This size segment shows limited examples of agriculture machinery based on battery electric drive trains:

- Tractors: TADUS (TADUS, 2023), ZSHX Advanced Tractors E904i (ZSHX, 2024), Seederal (Guillaumot, 2024) and John Deere (John Deere, 2025)

Mainly prototype tractors were found in this size-range, with some OEMs hoping for market ready machines soon, like the TADUS. News on the status of development and when to expect market commercialization is limited. No harvesters were found in this size-segment. TRL is considered low.

Size-segment C and D (130-225 kW & >225 kW, 178-300 hp & >225 hp): Only concepts, prototypes and retrofits are available in these size segments. Examples are:

- Tractors: Agromec Fendt 700 (Agromec , 2025)
- Combine harvesters: Linttas (Linttas, 2025) and Terafield (Terafield, 2025).

In theory the technology to power stronger machinery through batteries is available. But practical applications are limited to a prototype and concept, suggesting infeasibilities or practical limitations to develop larger battery-electric tractors. Two startups, Linttas and Terafield, were identified to be researching the concept of battery powered combine harvesters. They are both in concept stage, with very limited information on technical details and expected timeline. No concepts for forage harvesters were identified. In reviewed academic literature, no concepts of battery driven harvesters were identified, and some studies dismissed the idea as infeasible due to the implied weight of a harvester with enough capacity to be practically useful (Schneider, et al., 2023), (Scolaro, 2023). The findings indicate a very low TRL for this size-segment.

Summary of available machines

Summing up available and conceptual electric machines for agricultural applications Table 11 shows the extent to which diesel machinery can be replaced with electric, using motor size and operation hours as a key. Electric machinery exists up to size-segment A (below 56 kW), while the larger size-segments only see concepts, prototypes and retrofits. It is worth keeping in mind that the largest percentage of machinery currently in use in Danish agriculture features motor sizes of the largest categories. Looking at available operating hours for electric equipment, the use cases for replacing diesel driven machines in a 1:1 manner therefore seem limited to farmwork, barring improvements in energy density to power larger machines.

Table 11: Available battery-electric machines for within-farm and on field operations in 2025

Size-segment	Motor size	Extensive farmwork (1-3 hours)	Intensive farmwork (4-6 hours)	Fieldwork (>10 hours)
A	< 57 kW			
B	57-130 kW			
C	131-225 kW			
D	>225 kW			

Source: Based on own literature review. Red: Low availability, Yellow: medium availability, Green: Fully available.

4.2.3.2 Expected development

Seeing as battery-electric machinery is beginning to show signs of availability in smaller machines for farmwork, the question is whether development of larger machines for fieldwork can be expected as well.

OEMs like German CLAAS cite the potential of arraying battery packs as a limited method for increasing capacity for field equipment, since the implied weight of stacking a tractor with enough battery-electric power for running the required hours and workloads could ruin the soil due to compaction (Claas, 2023). On the other hand, John Deere is working together with publicly funded German research project GridCON on powering a 1MW grid connected machine for field operations. The American OEM is cited for stating that these electrified solutions hold promise of reducing the pressure on soil in the context of autonomous, electrified machines, that would be available from 2030 onwards (Koerhuis, 2020). Finally, some sources cite doubts over how batteries would handle the variable use-cycles of farm-equipment, while others declare tractors to be the perfect fit for electrification, considering the potential for using the large batteries for balancing the power supply or even providing services to the grid (Hayfield, 2023).

The issue of weight-to-power is raised within scientific literature as well, with some dismissing the thought of electrifying machines larger than 120 hp (Scolaro, 2023), and others citing automatization as a potential way of solving the issue through substitution of large machines for several smaller (Ghobadpour, et al., 2022). Trends in battery development for on-road electrification points towards higher gravimetric efficiencies (Schneider, et al., 2023), which is likely to be applicable to battery technology for agricultural machines as well, and could change the thresholds for 1:1 electrification of current diesel driven operations. The adoption is, however, likely dependent on associated costs of new types of batteries (Jeffs, 2024).

Consequently, some development trends in agricultural decarbonization challenge the premise of evaluating electrification potentials through a 1:1 substitution of diesel driven fieldwork. The potential of battery swap, among other development pathways like autonomous drive, swarm technology, no-till agriculture and agrivoltaics remain uncertain. The fact that current technology is not ready to drive heavy tractors for field work at the same work-hours as diesel driven equivalents should not imply that the application of electric drivetrains for fieldwork is infeasible. Rather, electrification might require, and allow, new machine concepts to be developed for farming usage, which would change operational patterns, rather than substitute current machines on a 1:1 manner. Technology-driven disruptive changes to how fieldwork is conducted cannot be expected with current technology levels, as discussed in Roer-Hjelkrem et al. 2020. For the short-medium term, a 1:1 replacement of diesel machinery might be more realistic, as using smaller tractors would incur the need for equipment with adapted working width, implying high costs. Whether and when such concepts would evolve and become marketable, is hard to gauge, but should be watched as the technologies mature and advance.

Based on this review of limited current technologies and trends, a possible trajectory for market availability of electrical machines per size class is presented in Table 12.

Table 12: Expected market-availability of electric equipment by size-class

Size-segment	Size (kW)	Type of work	2025	2030	2035	2040	2050
A	< 57 kW	Farmwork					
B	57-130 kW	Farmwork					
B	57-130 kW	Fieldwork					
C	131-225 kW	Fieldwork					
D	>225 kW	Fieldwork					

Source: Based on own literature review. Red: Low availability, Yellow: medium availability, Green: Fully available.

Electric equipment for delivering on energy-services in size-segment A already exist, while a number of current prototype technologies in size-segment B are claimed by manufacturers to be marketable by 2025 onwards. In the overview, these claims are translated conservatively to be available for early adoption in the late 2020’s and gradually becoming commonly available through the 2030’s on par with the lower size-classes. Developments for size-classes C and D are more uncertain, although with sparse evidence of concepts being developed.

Whether this availability of motor sizes will translate into actual products is uncertain. Use of machinery is only a small part of emissions from the sector, and therefore other types of emissions reduction projects may be first in line for investments and development. Some market analysts suggest a global uptake of electrified tractors as small as 5% of tractors sold in 2030, due to the more cost-effective decarbonization actions within manure- and livestock-reduction as well as mitigating enteric fermentation (Hayfield, 2023).

Changing the drivetrain to electric will incur changes to cost-compositions, and infrastructure of the farm. In simple terms, investment prices increase, while operations and maintenance costs decrease, and the necessity for drawing increased amounts of power from the grid, or producing some on-site is a large factor in this. Infrastructure requirements are considered in the following chapter 4.2.3.3, and economy in chapter 4.2.2.4.

4.2.3.3 Infrastructure requirements

In order to electrify machines in agriculture access to sufficient charging capacity is required. This raises questions of whether the existing grid connection is sufficient across farmland to facilitate charging at the right time and place. If farm site upgrades are required, the existence of transformer stations to facilitate an upgrade becomes important. Given sufficient grid connectivity, electrification would require one or more charging stations, depending on size of the farm and number of machines that would require charging at the same time (Lagnelöv, et al., 2021). Depending on the design of machines, investments in battery exchange systems might be required as well.

For the battery-electric machines identified in this review, the assumed charging capacity for realizing charging hours vary greatly. In the smaller scale, the battery of 21.6 kWh on the Farmtrac 25G only needs a standard household outlet of 220/240V with 10-16A to reach the charging time of 6-8 hours (2.7 – 3.6 kW required). This might be sufficient for farms only electrifying smaller parts of the machine fleet. In the large end of the scale, the Agromec Fendt 700 would need a 140 kW charger to reach the promised charging time of an hour for the 140 kWh battery. This would require dedicated charging sockets and -stations on site or portable generator concepts (Agromec , 2025).

Cabled machine concepts are dimensioned with 1-3 km cables of either 8 kV (Schneider, et al., 2023), or 2,5 kV (Pickel, 2019). Either dimension would require an adjacent electrical substation to secure connection to the farm.

Potential combination with agriphotovoltaics could lessen the reliance on grid connection in the field, but simulation studies suggest that own

Box 1: Simulated infrastructure requirements for electrification of field operations

A simulation study of total electrification through mixed concepts of battery-electric tractors, cabled harvesters, own production through agriphotovoltaics and additional feed-in from grid, showed a requirement of 183 kW grid connection power for a 12.1 ha farm in Lower Saxony, Germany, in the case of an agriphotovoltaic system with a production capacity of 252 kWp.

Source: (Schneider, et al., 2023).

production of electric power would not suffice for heavy and intensive fieldwork, especially when it takes place outside of peak solar production hours. See Box 1 for an example. Grid connection could in any case be beneficial for farmers with own production of power, since electric machinery could potentially provide grid flexibility services when not in use (Duarte, 2023).

The required infrastructure for either battery or cabled connection would depend on the existing grid connection, fleet size, workload intensity and requirement for fast charging across vehicle types to deliver energy services in a timely manner. It might be assumed that farmwork generally requires a smaller connection than fieldwork, due to considerations of charging time, but there are simply too many variables to draw any conclusion.

4.2.3.4 Economy

Machines for farming are chosen based on a consideration of their suitability to the specific tasks undertaken on the farm, and their associated costs of performing these. This means that rate of return on the investment in machines is important, and key factors to gauge this are investment cost and operation and maintenance, which again is dependent on the amount of yearly working hours, fuel efficiency and the associated costs of fuel. While the tendency of higher investment costs and lower operating and maintenance costs for electric drivetrains compared to diesel is similar to the trend in other sectors such as on-road vehicles, the specifics for agricultural use-cases are likely to differ. Compared to on-road, investment costs per kW are likely to be higher, since many of the agricultural machines are not yet mass produced. The operating and maintenance cost reductions are also likely to differ from on-road (Interact Analysis, 2023), especially between field- and farmwork since the use patterns of heavy farmwork is likely to be more detrimental to batteries than stable patterned farmwork.

Due to low maturity and lack of mass production, analysis of associated costs for electrical machines is uncertain, and largely based on assumptions, either of cost or usage patterns or both. This means that the numbers presented here should be interpreted conservatively and as indicative only. Within existing literature on the subject, simulation based assessments are most common (Schneider, et al., 2023; Lagnelöv, et al., 2021) with only a single study referring actual performance of (very small) electric tractors in the field (Proctor, 2022). Across the reviewed content, it appears clear that investment costs are higher for electric equipment, but that these costs could be countered by lower operation and maintenance costs. This, however, depends on specific use case, where the number of yearly operating hours is most significant, since more use-hours exacerbates the higher efficiencies of electric equipment, pulling the business case in a favorable direction. Factors such as whether the electric tractor is used alongside other machines or is performing all main tasks; whether the farm is large or small and to what extent sufficient electric power is already available on the farm, are important to the total costs of electrifying operations.

Examples of cost assumptions

One line of simulation studies assumes practical changes to the way agriculture operations are conducted today in order to enable the use of electric tractors at low motor sizes, reflecting available size-classes. One example being to electrify the fieldwork of one regular size diesel tractor (160 kW) with two smaller (36kW) autonomous tractors (Engström & Lagnelöv, 2018). Here, 15% cost reductions are achieved, along with 58% energy savings. An important assumption for the results however is the cost of an operator for the diesel case, and the fact that diesel tractors were assumed 10 hours of working time vs 24 hours for the electric tractors. A similar study with two electric 50 kW tractors substituting a 250 kW diesel, finds that the total costs of electric field tractors are roughly equal to diesel, when costs of necessary infrastructure is covered as well (Lagnelöv, et al., 2021).

In a total cost of ownership (TCO) calculation of small compact tractors, an interest rate (4 % p.a.) for purchasing new equipment from an unestablished manufacturer vis a vis the possibility of zero interest financing from established OEMs of diesel machines, was put forward as an additional monetary hurdle to electrify (Proctor, 2022). The results are, however, similar TCO for ICE and eTractors in the 30 hp size range. The TCO for electric tractors lowers with increasing number of working hours due to higher energy efficiency and lower maintenance.

The reviewed literature thus points towards electrification of operations being cost-competitive. It is worth noting the scarcity of available references and more data is generally needed to gauge to which extent electrification of field-operations is manageable in a foreseeable future. No studies were found that considered the economy of electrifying farmwork, although this would seem to be a lower hanging fruit.

Operation and maintenance costs (OPEX)

Electric machinery has a simpler motor design, better energy efficiency, fewer moving parts and less maintenance compared to ICE, which results in lower OPEX (Un-Noor, et al., 2022). An important issue for electric vehicles is battery degradation or ageing, which might require replacement before the expected lifetime of the vehicle, but it does not seem to tip the scale out of favor for electric compared to diesel in simulations (Lagnelöv, et al., 2021).

In reviewed literature, the savings in OPEX from diesel to electric drive is around 30% (Lagnelöv, et al., 2021) or 40% looking at maintenance alone (Proctor, 2022). Cases from prototype-developers provide some key figures into expected economic performance of electric agricultural equipment. Specifically, some OEMs report operation cost savings of 56% compared to diesel (New Holland, 2025a), while others estimate a flat 50% (TADUS, 2023).

Investment costs

Investment costs are mainly associated with the requisition of the vehicle, although most farmers will need to invest in some level of infrastructure as well, as presented chapter 4.2.3.3. Depending on the use case, the electric tractors might need additional investments in batteries for fast swapping, turbo chargers, or autonomous drive.

In Table 13, price comparisons on the base investment between diesel and electric machines are made for different sizes found in this review. The diesel benchmark is chosen based on comparisons with the electric models on e.g. engine output, or through dialogue with dealers. The comparisons show a mixed picture, with a premium on electric machines ranging from 40-50% for telehandlers and 87-120% for the tractors. As is the case for construction machinery, agriculture machines show increasing costs with the size-segment. Again, note that very few examples of investment costs persist for agriculture electric machinery, especially with increasing engine size.

Table 13: Expected investment cost difference compared to equivalent diesel machine

Size-segment	Machine type	Comparison	Investment costs compared to diesel
A (<57 kW)	Tractor	Fendt e107 Vario vs Fendt 207	+90%
	Telehandler	Merlo Eworker vs Merlo P27.6 & Dieci MINI AGRI-e 20.4 vs Dieci Apollo Smart 20.4 & Dieci MINI AGRI-e 26.6 vs Dieci Apollo 26.6	+40 to +50%
C (131-225 kW)	Tractor	Retrofit Fendt 720 vs Fendt 720 Gen6	+120%

Source: Own review, including correspondence with dealers to the Danish market.

4.2.4 Methane

As an alternative to diesel, methane is an interesting solution within agriculture, due to the potential of own-production of the fuel and quick refueling. New Holland's methane tractors are sold in Sweden, but issues persist with the infrastructure of delivering methane for the farms. Also, refueling events may occur more often due to less energy density of methane compared to diesel, which reduces the working hours of the machines and may make their use less efficient, especially in the field (Jensen, et al., 2024; New Holland, 2025c). Valtra has reportedly been making dual fuel diesel/methane powered tractors since the early 2010's, aimed at primarily the northern and eastern European markets (Valtra, 2015), but sources on the actual machines are sparse.

Our review found only four examples of methane machines across three OEMs, where one was a prototype, another not available for purchase and two still being manufactured. One was explicitly targeting the European market.

4.2.4.1 Maturity

The examples of methane powered machines are centered around the larger size-classes.

Size-segment A (< 57 kW / < 76 hp): Only features an academic study of a 47.5 kW retrofitted New Holland crawler tractor not marketed outside of this theoretical purpose. Small tank, possible only relevant for wine farming.

- Tractors: Retrofit New Holland prototype (Assandri, et al., 2025).

Size-segment B (57-130 kW / 77-177 hp): This segment features one tractor from a major OEM and one dual fuel tractor, which is not available for purchase.

- Tractors: New Holland T6.180 (New Holland , 2024), Valtra N101 (Valtra, 2015; AGWEB, 2020).

New Holland T6.180 methane power with 185-liter capacity and an optional range extender with 270 liters, occupying the front hitch (New Holland , 2024). According to OEM, this enables 8 hours of intensive usage or 14 hours for extensive use cases between refueling events (Elmore, 2021). It runs on compressed natural gas (CNG) or methane. It was not available for purchase in Denmark at the time of writing.

Valtra N101 is a 110 HP all-purpose tractor with dual-fuel engine to utilize a mix of diesel and methane, reaching up to 90% methane in the mix (Valtra, 2015), (AGWEB, 2020). While not currently available for purchase, the company behind is still looking into biogas as a potential fuel of the future (Valtra, 2022).

Size-segment C and D (130-225 kW & >225 kW, 178-300 hp & >225 hp): One tractor from major OEM New Holland is going for sale from 2026 onwards, and one combine harvester from Belarussian company Gomselmash which was not available for purchase in the Denmark.

- Tractors: New Holland T7.270 (New Holland, 2025b)
- Combine harvesters: Gomselmash Palesse GS 4118 K (Gomselmash, 2019).

New Holland T7.270 methane power, with a tank capacity of 660 litres CNG and, according to OEM, same performance characteristics as diesel equivalents, including operation times, but lower running costs (New Holland, 2025b). The CNG model can be equipped with a range extender to reach 1265 litres. According the New Holland the machines will start shipments from 2026 (New Holland, 2026).

The Gomselmash Palesse GS 4118 K, with 257 kW /350 hp engine, features a capacity of 1816 liters of compressed gas, allowing for 8-10 operating hours between refueling (Gomselmash, 2019). At the time of writing, it was not possible to identify sellers of the harvester within the EU.

The review indicates a very small supply of methane machines, with basically only New Holland selling tractors based on methane. Currently available methane machinery is centered around the medium to heavier tasks for agricultural end-uses, which is displayed in Table 14. These results indicate that the maturity of methane machines are uncertain as the market is currently very small.

Table 14: Available methane machines for within-farm and on field operations in 2025

Size-segment	Motor size	Extensive farmwork (1-3 hours)	Intensive farmwork (4-6 hours)	Fieldwork (>10 hours)
A	< 57 kW			
B	57-130 kW			
C	131-225 kW			
D	>225 kW			

Source: Based on own literature review. Red: Low availability, Yellow: medium availability, Green: Fully available.

4.2.4.2 Expected development

With the limited array of OEMs engaged in methane technology, it would seem a niche alternative, and thus very dependent on investment decisions of these few OEMs. Judging by financial reports from CNHI, the company behind New Holland, methane is a prioritized alternative technology with dedicated R&D facilities in Europe (CNH Industrial N.V., 2024). In any case, the segments covered by methane alternatives accumulate approximately 50% of the overall energy consumption within Danish agriculture (c.f. Table 7). This means that the potentials of methane to replace current technology are large, and mainly dependent on accessibility of methane infrastructure in the rural areas, availability of methane machinery, as well as vehicle design in terms of fuel storage for the machines to be practical in the field.

The expected development is shown in Table 15. The smaller size A-category is initially red, signifying that OEMs have not focused on methane machinery for this size-segment. Size-segment B could potentially be ready for full commercialization by the mid-2030s for both farm and field work, with machines already on the way in the coming years. Size-segments C, and especially D, are further away from commercialization, and much more investments are needed from major OEMs with a focus on sales in Europe. Tractors could be the exception with OEM New Holland bringing in C size-segment tractors in 2026.

Table 15: Expected market-availability of methane equipment by size-class

Size-segment	Size (kW)	Type of work	2025	2030	2035	2040	2050
A	< 57 kW	Farmwork					
B	57-130 kW	Farmwork					
B	57-130 kW	Fieldwork					
C	131-225 kW	Fieldwork					
D	>225 kW	Fieldwork					

Source: Based on own literature review. Red: Low availability, Yellow: medium availability, Green: Fully available.

4.2.4.3 Infrastructure

Methane-powered machines require access to refueling infrastructure for methane, necessitating either delivery from an upgrade-station, or that the farm upgrades its own organic waste for this purpose. Companies supporting this infrastructure already exist[12], allowing farmers to invest in small scale biogas plants for their own energy purposes. This requires significant up-front investment costs and expertise in running the type of equipment in the form of additional skilled labor. Central biogas production facilities exist to a large extent in Denmark already, meaning competition for the bio-residues from farms. This limits the solution of own-production, also because of economies of scale from the larger biogas reactors. Conversely, getting methane delivered by truck to an on-site tank do not require significant changes to infrastructure, only a new tank system on-site.

4.2.4.4 Economy

Across examples of methane-driven machines, claims of reduced operating costs are echoed. The specific level ranges from 30-50% compared to conventional diesel engines (CNG, 2022; New Holland , 2024). Some OEMs highlight longer engine life due to cleaner burning of the fuel. The cleaner burning also means less costs to reach environmental requirements vis a vis diesel since Adblue or filters are not necessary (Gomselmash, 2019). Lack of peer-reviewed literature makes it difficult to assess the claims of OEMs, and the subject should be monitored for operational evaluations.

Unfortunately, investment costs of methane machines have not been available at the time of writing.

Costs of establishing on-farm upgrade of biogas are likely to be farm specific, as no clear cost estimates were found. Both suppliers and academic studies suggest multiple co-benefits of upgrading biogas on farm, meaning that the specific costs related to the production of fuel is difficult to assess directly (Bennamann, 2025; Yiridoe, et al., 2009). As noted earlier regarding infrastructure, the cost of establishing on-site biogas production facilities are likely very capital intensive.

4.2.5 Hydrogen

This section covers machinery that runs on hydrogen – either directly combusted in an internal combustion engine or used in a fuel cell combined with an electric motor.

4.2.5.1 Maturity

Many OEMs have a history with prototype hydrogen machines or engines for agricultural applications, however, none are currently commercially available according to our review. This is likely due to limitations in the market for hydrogen as a fuel, the complex nature of hydrogen especially regarding the infrastructure, safety concerns, and price of hydrogen itself.

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[12] An example being Bennamann, a British company cooperating with New Holland (Bennamann, 2025)

Despite no current machines exist outside of the concept or prototype stage, case-farms already have gathered experience with retrofitted hydrogen machinery like telehandlers and tractors (SRUC, 2020). Several larger OEMs creating tractor engines have made developments into hydrogen ICE, with current strategies aimed at finding the niche for hydrogen within the machine-pool of agriculture (Hill, 2024). The sizes range from 85 kW in the Kubota WG3800 engine (Kubota, 2025a), to 340 kW in the FPT XC13 H2 engine targeted at harvesters and larger tractors (Hill, 2024). Hydrogen driven machinery is thus in the sights of many developers, but only two concept tractors could be placed in the size-categories of our review:

Size-segment B (57-130 kW / 77-177 hp): This segment features two prototypes, indicating a low to non-existing supply available:

- Tractors: Steyr FCTRAC (CNH, 2024), Fendt Helios (Fendt, 2024b)

Steyr FCTRAC is a retrofitted concept tractor with a nominal 96 kW fuel cell drivetrain (CNH, 2024). The Fendt Helios is a prototype fuel cell tractor with a 25 kWh battery buffer supplying 100 kW power. Delivers 5-8 hours operating time on a 21 kg tank full. It is currently under testing in the German funded H2Agrar project (Fendt, 2024b).

4.2.5.2 Expected development

Several OEMs and European governmental agencies are investing in tests of hydrogen machinery for agricultural appliances. Besides the actual testing, claims about technological potentials have surfaced in recent years, without reaching fruition. Examples include pledges from a large OEM from 2019 of a fuel cell harvester being ready for 2025 (Christensen, 2019), no further trace of this harvester concept was found in this review. This showcases that while the technology can be used for concepts, the date for actual applications is contingent on permitting factors. Pending developments are both practical in terms of storage capacity on the machine as well as on the farm, and financial in terms of the market for hydrogen, which cannot currently supply large quantities of green hydrogen at a low price.

As part of a project funded by the French Agency for ecological transition, OEM AGCO's branch company Massey Ferguson is scheduled to prototype a hydrogen powered ICE-tractor in the 'mid horse-power' range in 2026 (Abbott, 2025). The main aim for the project is to engineer an onboard tank system for the tractor, which will allow compressed hydrogen to be effectively stored, thus providing autonomy for more working hours between refueling events than has been possible previously (Cetim engineering, 2025).

JCB has already invested heavily in hydrogen engines, and have telescopic loaders as well as power stations underway. Read more in the construction chapter about JCBs hydrogen developments in section 3.2.4.

This review concludes, that while technically possible to build agriculture machinery based on hydrogen fuel (ICE or fuel-cell), there are no major developments pointing towards this technology commercializing any time soon and thus this report makes no assumptions on when or if the technology will mature.

4.2.5.3 Infrastructure

A main finding of the review on hydrogen has been that the main issue with hydrogen is not the engine, but sourcing, storage and handling of the fuel. Difficulties arise with both the value chain of producing green hydrogen, and technologically with keeping the gas from leaking, requiring expensive tanks (Baker, et al., 2022; Bovingdon, 2022).

CNH affiliate company Steyr have developed the BioH2Module specifically for refueling hydrogen tractors through biomass. The solution produces hydrogen from biogenic raw material and can transform 15-16 kg of dry biomass into the hydrogen equivalent of 3,5 liters of diesel (CNH, 2024).

Read more about the infrastructure requirements for hydrogen machinery in section 2.3.4.

4.2.5.4 Economy

With the current level of technology being on concept stage, no data on the costs of either machinery or infrastructure have been found.

4.3 Wrap up

4.3.1 Comparing technologies on key aspects

In the following four figures we score conventional diesel machines relative to the use of biodiesel, battery electric and hydrogen machines. We do this on seven parameters of great importance to the investment decision in new agriculture machinery: Maturity, investment costs (CAPEX), operational costs including fuel costs (OPEX), energy efficiency of operation, machine operating hours, infrastructure requirements and costs, greenhouse gas emissions, particle and NOx emissions, and lastly safety considerations. These ratings indicate the efficiency of each variable – meaning a higher rating represents a higher efficiency.

4.3.1.1 Conventional diesel machines

These machines have the power of being the proven technology, the baseline, and thus the safe choice of any agriculture type. This is also why; we compare the three emerging technologies to this technology in the following. Diesel machines are fully market mature in all kinds of machines and farming types, have relatively low investment costs, with very rapid refueling making way for high operating hours. The technology has low infrastructure requirements (for tanks, transport of fuel) and thus low infrastructure costs. Conversely, conventional diesel machines have somewhat high operating costs, especially fuel and maintenance costs, resulting from low energy efficiency. Diesel combustion results in emissions of both greenhouse gases and particles and NOx.

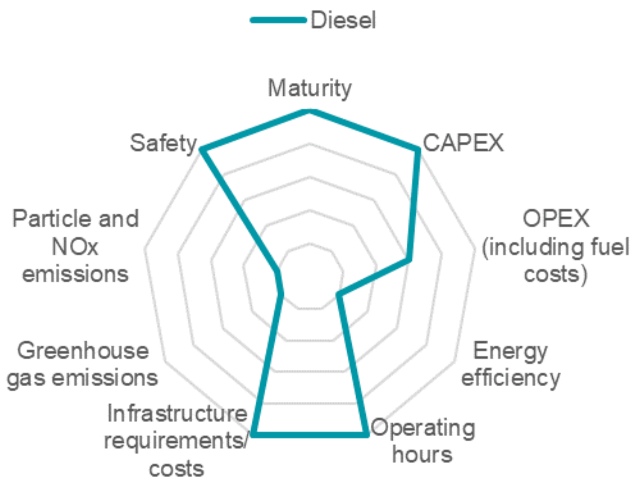

Figure 9: Conventional diesel machine score

4.3.1.2 Biodiesel

Machines powered by biodiesel fuels have much of the same advantages and disadvantages as conventional diesel machines as the fuel can be utilized in the same machines and engines. They differ slightly in terms of operating costs, where biodiesel is more expensive compared to diesel. Conversely machines running on biodiesel emit less greenhouse gas emissions and sometimes less particles and NOx.

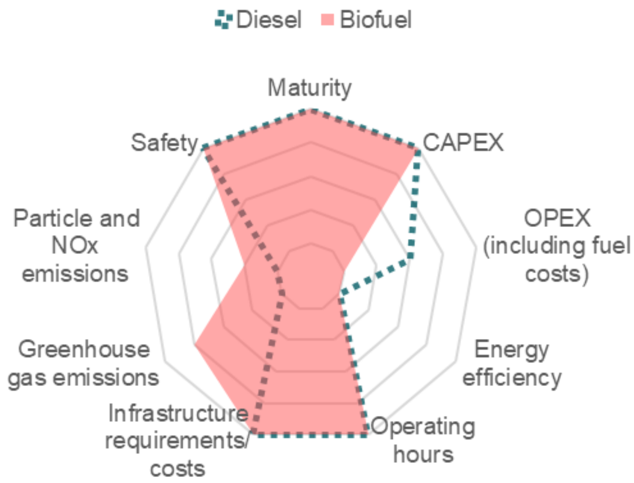

Figure 10: Biodiesel machine score

4.3.1.3 Battery electric

Battery electric machines are seeing increasing maturity, although only in the smaller A size-segment. Supply is low, and with larger size-segments seeing low to non-existing battery electric machines, maturity is rated low. The energy efficiency of battery electric machines is the highest of the technologies compared, and together with low maintenance costs this results in low operating costs. Electric motors emit no greenhouse gases or particles, and as a results score high on these parameters. Safety score is high, as no explicit concern exits, especially compared to other technologies like hydrogen. Investment costs are higher than conventional diesel machines, sometimes 1-2 times higher. Machine operating hours, while increasing with recent developments, are lower compared to diesel machines. Switching to battery electric machines requires changes to work-patterns, which is often cited as a barrier for adoption especially for field work. Furthermore, battery electric machinery often require investment in infrastructure on-site, e.g. charger, substations, cables, etc.

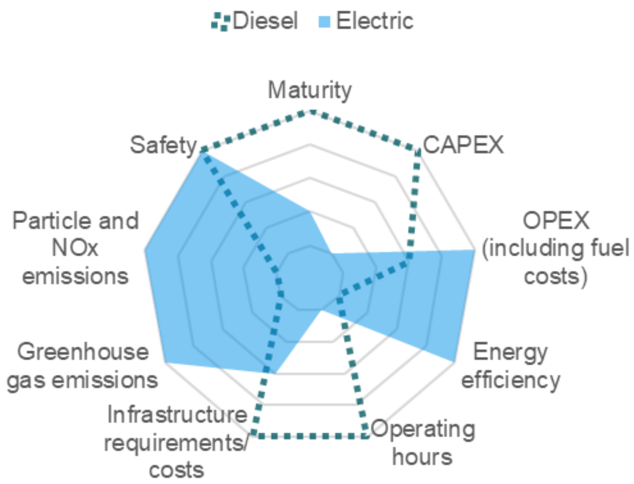

Figure 11: Battery electric machine score

4.3.1.4 Methane

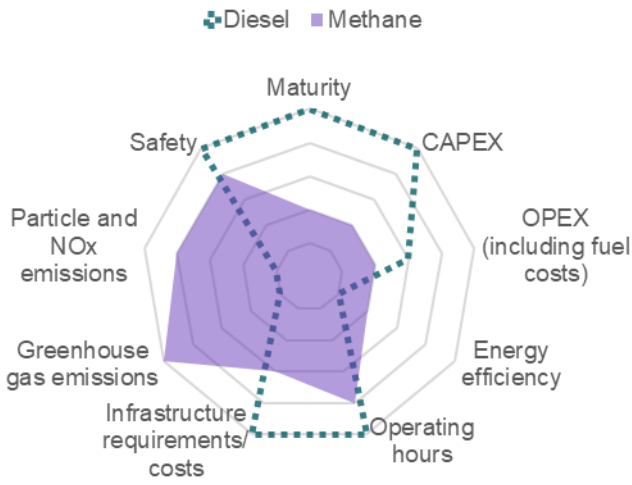

Figure 12: Methane machine score

Methane powered agriculture machinery, both internal combustion engines and fuel cells, exhibit very low maturity levels, as only one major OEM has commercially available machinery. The next 10-20 years will reveal if OEMs manage to invest further into methane drive-train. Investment costs for methane machines are very uncertain given the maturity level, but are likely more expensive compared to diesel machines, as on-board methane storage increases complexity. Methane as a fuel is likely more expensive compared to diesel if biogenic in origin, and with efficiencies slightly below that of diesel, operating costs are higher for methane machinery. Machine operating hours are on par or just below diesel, and above that of battery electric machines. Infrastructure requirements for methane machinery are higher compared to diesel, but not much if methane is delivered by truck to on-site tank. If own-production is to be utilized infrastructure costs are likely very much higher, with possibly a lower biogas fuel price to counter. Safety surrounding methane tanks and infrastructure is similar to diesel, with the added risk of gaseous leaks. Emissions of greenhouse gases and particles are lower compared to diesel, but higher compared to electric and hydrogen.

4.3.1.5 Hydrogen

Hydrogen powered agriculture machinery, both internal combustion engines and fuel cells, exhibit very low maturity levels, as no major OEM has commercially available machinery. The next 10-20 years will reveal if OEMs manage to get from the demonstration stage to the commercialization stage. Because of the small number of machines identified, and thus the low maturity of hydrogen, this review cannot rate the drive-train on the selected parameters. For telehandlers, and other machinery that agriculture shared with the construction sector, see section 3.3.1.4 of the construction chapter.

4.3.2 Comparing expected developments

In this section follows a comparison of the expected developments of the reviewed technologies in the previous sections. Uncertainty is very prevalent for all technologies, but especially surrounding hydrogen machine development.

The way towards choosing between different drive-trains for switching from diesel machinery is not very clear. Most alternatives to diesel are not commercial ready and thus development could go in all directions. Furthermore, many sources talk about fundamental changes in how agriculture machinery is used, e.g. with autonomous machinery under remote monitoring being one of the hottest (Kubota, 2025b).

Most OEMs expect that agricultural machinery will take a variety of drive-trains, depending on the end-use, i.e. size-segment and energy-service: farm work vs field work. Battery electric machines have their advantage in the smaller size-segments, and especially for farm work, with the high efficiency and low to medium operating hours. For the larger size-segments, biodiesel is a go-to, with methane emerging as a distant possibility. Hydrogen seems to be the least developed drive-train technology for agricultural machines, and will likely need massive investments to see any uptake in the sector in the future. Thus, battery-electric, or hybrid diesel and battery electric machines, for the small size-segments and farm work, with biodiesel, possibly methane, and a weak probability of hydrogen, for the larger size-segments and field work will likely be the development going forward (Kubota, 2025b; Olkkonen, et al., 2023; Lajunen, et al., 2024; FutureFarming, 2024). This is extremely uncertain, and based on the information know at the time of writing. The landscape might look quite different in the coming few years.

5 Annex

5.1 Assessed construction sector machines

Table 16: Detailed overview of assessed battery electric construction machinery, split into size segments, type, and were available presenting battery capacity, operating hours and charging time.

Segment	Size (kW)	Model	Type	Battery capacity (kWh)	Operating hours	Charging time (1)
Mini	0-37 kW (typical weight of 0-5 tons)	Volvo EC18	Excavator	20	6h	1h15m
		Volvo ECR18		16	5h	1h
		Volvo ECR25		20	4h	1h15m
		Bobcat E10e		11.5	4h	1h30m
		Bobcat E19e		17.28	4h	1h30m
		CAT 301.9		32	6-8h	4h
		Komatsu PC20E		23.2	-	1h40m
		Komatsu PC26E		23.2	-	1h50m
		Komatsu PC33E-6		35	-	1h50m
		JCB 19C-IE		19.8	5h	-
		Wacker Neuson EZ17e		23.4	-	-
		Wacker Neuson EZ26e		30 or 40	6-8h	-
		Liebherr L507E	Wheel loader	32 or 64	8h or 16h	1-2h
		Volvo CE L20		40 or 56	8h	1h20m
		Volvo CE L25		40 or 56	8h	1h20m
		Wacker Neuson WL20e		14.1-23.4	7h30m	3h
		and WL28e		14.1-23.4	7h30m	3h
		Kubota RT210-2e		12.5-25	-	1h30m
		JCB HTD-5E	Dumper/ hauler	4.9	-	-
		Wacker Neuson DW15e		-	3h30m-7h	8h
		Kubota KC70H-4e		4.4	-	3h
Small	37-56 kW (typical weight of 5-10 tons)	Hitachi ZE85	Excavator	100	5h30m	45m
		CAT 906	Wheel loader	64	8h	-
		Liugong 820TE		70.5	-	1h10m
		Hydrema DT6	Dumper/ hauler	63	-	-
		Mecalac eMDX		75	8h	4h
		JCB 525-60E	Telehandler	24	-	1h
Medium	56-130 kW (typical weight of 10-26 tons)	CAT 320	Excavator	387	8h	-
		Mecalac e12		146	8h	6h
		Komatsu PC138E-11		225.6	-	-
		Komatsu PC210E-11		451	8h	9h

		SANY SY215E		422	5h - 7h	-
		Volvo EWR150		-	-	-
		Volvo EC230		264	4h - 5h	-
		XCMG XE215EV		400	8h(2)	1h30m-2h
		CAT 950 GC	Wheel loader	256	4h	-
		Liugong 856HE		423	8h - 12h	1h45m
		Liugong 870HE		423	-	1h20m
		Volvo L90		180	4h - 6h	55m
		Volvo L120		282	5h - 9h	2h
		XCMG XC968-EV		282	5h - 10h	-
		XCMG XC975-EV		423	5h - 8h	-
Large	130-200 kW (typical weight of 25-38 tons)	Doosan DX300LC	Excavator	390	8h	9h
		Liugong 924FE		423	-	1h20m
		XCMG XE270E		525.1	6h	2h
		Volvo CE A30	Dumper/ hauler	245	-	-
Huge	>200 kW (typical weight above 38 tons)	Sandvik Toro LH518iB	Wheel loader	482	- (2)	1h - 2h
		Liebherr T264	Dumper/ hauler	3200	-	1h
		Liugong DR50CE		423	-	1h
		Sandvik TH550B		354	- (2)	-
		Volvo CE A40		350	-	-

1) Fast charging if possible.

2) Supports battery swap technology to continue working without charging.

Sources for:

Mini: Excavators: Bobcat E10e and E19e (Bobcat, 2025), CAT 301.9 (CAT, 2025), Volvo CE EC18, ECR18 and ECR25 (Volvo CE, 2025a), Komatsu PC20E, PC26E and PC33E-6 (Komatsu, 2025), JCB 19C-IE (JCB, 2025b), Wacker Neuson EZ17e and EZ26e (Wacker Neuson, 2025a). Loaders: Liebherr L507E (Liebherr, 2023b), Volvo CE L20 and L25 (Volvo CE, 2025a), Wacker Neuson WL20e and WL28e (Wacker Neuson, 2025b), Kubota RT210-2e (Kubota EU, 2025). Dumpers/haulers: JCB HTD-5E (JCB, 2024), Wacker Neuson DW15e (Wacker Neuson, 2025c), Kubota KC70H-4e (Kubota EU, 2025).

Small: Excavators: Hitachi ZE85 (Hitachi, 2022), Loaders: CAT 906 (CAT, 2025), Liugong 820TE (SMF, 2024) and XCMG XC968-EV and XC975-EV (XCMG, 2025b; XCMG, 2025c). Dumpers/haulers: Hydrema DT6 (Hydrema, 2025), Mecalac eMDX (Mecalac, 2025a). Telehandlers: JCB 525-60E (JCB, 2022)

Medium: Excavators: CAT 320 (CAT, 2025), Mecalac e12 (Mecalac, 2025b), Komatsu PC138E-11 and PC210E-11 (Komatsu, 2025), SANY SY215E (Sany, 2025), Volvo CE EWR150 and EC230 (Volvo CE, 2025a) and XCMG XE215EV (XCMG, 2025a). Loaders: CAT 950 GC (CAT, 2025), Liugong 856HE and 870HE (Liugong Europe, 2025a), Volvo CE L90 and L120 (Volvo CE, 2025a). Dumpers/haulers: None found.

Large: Excavators: Doosan DX300LC (Staad-group, 2025), Liugong 924FE (Liugong Europe, 2025a) and XCMG XE270E (XCMG, 2025d; Machmall.com, 2022). Loaders: None found. Dumpers/haulers: Volvo CE A30 (Volvo CE, 2025a).

Huge: Excavators: Loaders: Sandvik Toro LH518iB (Sandvik, 2025a). Dumpers/haulers: Liebherr T264 (Liebherr, 2025a), Liugong DR50CE (Liugong Europe, 2025b), Sandvik TH550B (Sandvik, 2025b), Volvo CE A40 (Volvo CE, 2025a).

5.2 Assessed agriculture sector machines

Table 17: appendix data for electric agricultural equipment

Size (kW) [(1)]	Type	Battery capacity (kWh)	Weight (kg)	Operating hours	Charging time (h)	Investment cost (DKK)	Source(s)
0-37 kW 0-50 hp	Tractor	23,4	1070 – 1208	3 - 4	1,5 - 8	185.000	(Danish Agro, 2025), (Kubota, 2022), (Kubota, 2025c)
	ATV	9	300	6	4-5	142.500	(RCholm, 2025)
	Tele-handler/wheel loader	18 – 37,5	3050 - 5200	4	4-6	800.000 - 1.300.000	(Kramer, 2025a), (JCB, 2025a)
38-56 kW 52-76 hp	Tractor	100	3500 - 4500	4 - 7	-	1.850.000	(Tjell, 2025) (Fendt, 2024a)
	Tele-handler	46	4950	7,5 - 8	9 [(2)]		(Merlo, 2025)
57-130 kW 77 – 177 hp	Tractor	105 - 180	4000 - 7000	5 – 8	1 –		(ZSHX, 2024), (TADUS, 2023) (John Deere, 2025)
	Tele-handler	46	4950	8	9 [(2)]	869.000	(Merlo, 2025)
131-200 kW 178 – 272 hp	Tractor	140	7980	3,5	- [(2)]	4.612.500	(Hekkert, 2023) (Trekker, 2023)
	Other						
>200 kW >272 hp	Tractor						
	Harvester	-	-	30 ha	2,5 h	-	(Terafield, 2025)

1) Machines are rated by peak motor power.

2) Battery swap possible.

Note: The table is based on a mix of academic review literature, word press, OEM spreadsheets and distributor websites. Thus, the data should be interpreted as a representative value depicting current trends and availabilities, and not authoritative datasheets.

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