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Impact assessment of zero emission building processes in Oslo

SINTEF

Oslo

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Impact assessment of zero emission building processes in Oslo

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Preface

The City of Oslo's Climate Agency has engaged SINTEF and TØI to carry out an impact assessment of zero emission building processes in Oslo. The goal of the City of Oslo is that building and construction activities in Oslo shall be zero emission by 2030. This impact assessment has been initiated to study the consequences of a gradual transition to zero emission implementation of building processes in Oslo. This report considers energy consumption and energy supply at, as well as to/from a building site, cost analyses and market analyses, while assessing various development scenarios. To what extent zero emission construction machinery and vehicles are available in the local market in and around Oslo is studied, while assessing whether the use of such equipment entails significant disadvantages or additional costs, and how this is expected to develop in the years approaching 2030. Future scenarios have been established for the development of zero emission concepts for building and construction sites in the years up to 2025 and 2030 to identify how the City of Oslo may effectively facilitate the desired development.

Oslo, May, 2022

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Executive Summary

The goal of the City of Oslo is that building and construction activities in Oslo shall be zero emission by 2030. From 2025, building and construction work carried out on assignment for the City of Oslo shall be zero emission. This impact assessment is based on quantitative analysis of energy and power requirements, cost increases, wealth creation and employment, as well as qualitative methods to describe the market prospects. The objective has been to examine changes in energy and power consumption, costs, and other consequences of the transition to zero emission building processes in Oslo, as well as to describe future scenarios in the period up to 2025 and 2030.

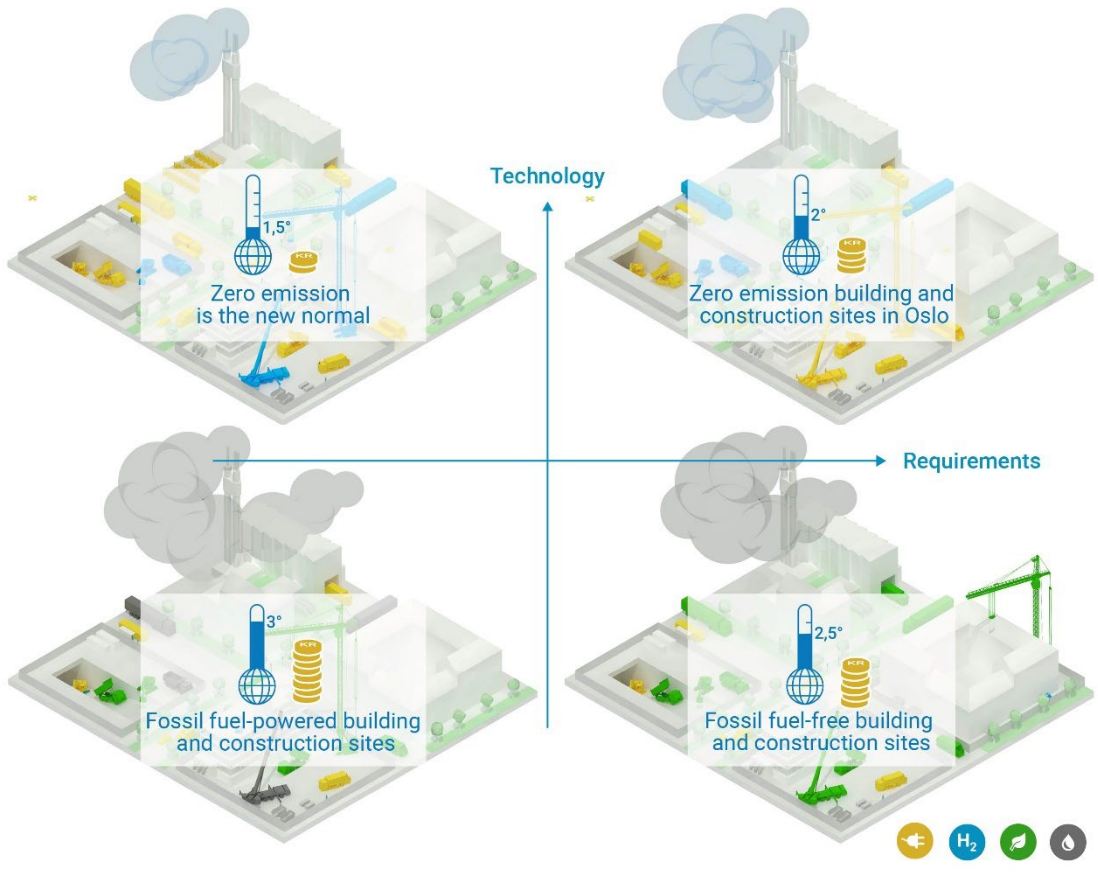
The analyses connected with energy and power consumption are based on energy consumption data from some of the first zero emission building and construction sites in Oslo. A selection of building and construction projects has been scrutinised with respect to how energy requirements vary, depending on differences in work processes and different types of construction machinery and means of transport. This has been carried out for two theoretical scenarios: a fully electrified building site and a fully electrified construction site. The results demonstrate that the most energy-demanding construction phase is groundwork, followed by superstructure and demolition. The energy consumption of construction machinery is within the available power rating, and by making some adjustments to charging breaks and technology type (battery, cable or cable/battery), the power issues presented by the construction machinery are resolved according to our calculations. This becomes a greater challenge if one is also to have enough available power for charging vehicles, since charging of external transport does not at present take place at building and construction sites, and few facilities exist for charging heavy transport vehicles. Analyses have also been carried out for three alternative scenarios: a reference, an average and an optimised scenario. The results have been used to create a projection of the energy requirements for zero emission building and construction sites in the City of Oslo in the years up to 2030 for two different scenarios (reference and development), assuming rapid and gradual implementation rates. The results show that the future energy demand for zero emission building and construction sites in the City of Oslo will be in the order of 77-97 GWh. Since at present only a small number of building and construction sites in Oslo use electricity, this can result in an increase in energy requirements of 77-97 GWh between now and 2030.

In connection with the cost analyses, estimates of lifetime costs were prepared for a small (8-16 tonne), a medium (16-23 tonne) and a large (>23 tonne) excavator, and for a tipper truck without a trailer and a tipper truck with a trailer with a maximum permitted total weight of 27 tonnes. The smallest construction machinery units (under 8 tonnes) are not included in this cost analysis. Such machines are assumed to represent a small percentage of greenhouse gas (GHG) emissions and are already more readily available in the market with approximately competitive lifetime costs. Lifetime costs have been compared for diesel, hydrotreated vegetable oil (HVO) and electric alternatives, and analyses show that the electric alternative involved higher initial investment costs but lower operating costs over its lifetime. Depending on energy prices, the lower operating costs could mean that the price of the electric alternative is competitive over an analysis period of five to six years. Based on the lifetime costs and energy requirements, an assessment was carried out of what the additional costs for a building and construction site may be in 2022, 2025 and 2030. The results indicate that additional costs will probably be accrued through a transition to zero emission building and construction sites for some time but that in some cases break-even, or even reduced costs, may be achievable, approaching 2030.

Dialogue with market operators has been carried out in the form of interviews, workshops, and questionnaires. The most positive respondents believe that the City of Oslo will achieve the goals set for 2025 and 2030, with a few exceptions. Few believe that it will be possible to achieve the 100% zero emission goal by 2030, since there are still many types of construction machines that have not yet begun the transition to zero emission operation. Several major manufacturers have commenced mass production of smaller construction machines (under 8

tonnes), but machines over 8 tonnes are only specially produced in smaller numbers. As a rule, it takes two to three years from the introduction of a machine until it is commercially available. Many models will therefore not be ready for sale in 2025. Some believe that it is within the bounds of possibility that almost the entire market share (new investments) in Oslo will be zero emission by 2030. These operators expect that even in 2030 there will be a need to use diesel-based machinery and vehicles but with sustainable biofuel (HVO100). The market dialogue also showed that there is broad agreement that the transition to zero emission building and construction sites requires expansion of the supply grid, both for district heating and for electricity, and that infrastructure for charging large vehicles must be in place.

Based on the energy and power analyses, cost analyses and market dialogue, four potential future scenarios have been drawn up for zero emission building and construction sites in Oslo in 2030. The main sources of uncertainty that form the basis of these scenarios are *the degree of technological development* and *strict/effective requirements from the City of Oslo*. Measures for achieving the various scenarios are not considered but highlight important driving forces that impact their development.



In the scenario entitled "Zero emission is the new normal", energy and concepts are available for zero emission building and construction sites, both nationally and internationally. The market has received impetus because developing zero emission building and construction sites has been given high priority both locally and in the EU. With global supply and demand for zero emission concepts and technologies in place, both costs and emissions are reduced. In the scenario "Zero emission building and construction sites in Oslo", the City of Oslo attains the goal of zero emission building and construction sites by imposing effective, strict requirements, even though the rest of Norway and the EU lag slightly behind. This is achieved because the international market has turned around and is moving in the same direction. Because of Norway's dependence on imports and limited significance in the global market, developments in Oslo will depend on developments in the global market. In the scenario "Fossil fuel-free building and construction sites", the rest of Norway and the EU lag so far behind that even Oslo does not attain the goal of zero emission building and construction sites by 2030. Because of a lack of available technology and energy supply, exemptions are granted from the requirements, and the large building and construction projects are in practice fossil fuel-free, but they are expensive. In the scenario “Fossil fuel-powered building and construction sites”, Norway and the rest of the world are so far behind in the green transition that industry segments with the highest levels of emissions are given the highest priority. This is the scenario with the highest additional costs connected with zero emission concepts and the highest level of emissions.

Development towards zero emission building and construction sites depends on technological development, which is influenced by demand. Norway is dependent on imports when it comes to construction machinery, including equipment and spare parts, and the availability of zero emission construction machinery depends on the existence of global demand for these concepts. If there is only demand for zero emission construction machinery in Norway, the country will continue to convert its fossil fuel-powered construction machinery. Mass production will not commence until there is a greater market. The interviews similarly argue that infrastructure for energy supply will be developed as the number of users increases, and that this will occur as the extent of, and access to, zero emission technologies increase. While the development of concepts for excavators has come a long way, there are still few concepts for heavy transport, dumper trucks and wheel loaders. In the case of heavy transport, funding such as road tax and tolls contributes to rapid market introduction when zero emission alternatives become available. Similar economic incentives do not exist for construction machinery, either in Norway or in the EU. This leads to increased uncertainty regarding the market prospects for zero emission machinery. Further development of battery technology is needed to achieve increased accessibility and lower unit costs.

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Introduction

The goal of the City of Oslo is for building and construction activities in Oslo to be zero emission by 2030 (1). From 2025, building and construction work carried out on assignment for the City of Oslo shall be zero emission. This impact assessment has been initiated to study the consequences of a gradual transition to zero emission implementation of building processes in Oslo. To what extent zero emission construction machinery and vehicles are available in the local market in and around Oslo will be studied, while assessing whether the use of such equipment entails significant disadvantages or additional costs, and how this is expected to develop in the years approaching 2030. The City of Oslo's Climate Agency has engaged SINTEF and TØI to carry out this impact assessment.

The objective of the impact assessment is to establish future scenarios for the development of zero emission concepts for building and construction sites in the years up to 2025 and 2030 to identify how the City of Oslo may effectively facilitate the desired development. This report will consider energy consumption and energy supply at, as well as to/from, a building site, cost analyses and market analyses, while assessing various development scenarios.

Background

This report is based on previous experience studies from the requirements for zero emission building and construction sites in Oslo with the main topics of electricity supply, zero emission construction machinery and goods vehicles, and charging logistics, as well as associated experience and barriers (2). The results indicate that the development towards zero emission building and construction sites is progressing rapidly, although some barriers and challenges remain. Since October 2019, Oslo has awarded suppliers who can provide zero emission construction machinery and transport in competitive tendering for assignments for the City of Oslo, based on standard climate and environmental requirements for the municipality's building and construction sites (3). The market has seen rapid development and an increasing number of zero emission construction machines. In 2021, numerous building and construction projects on behalf of the City of Oslo were carried out using zero emission machinery and vehicles. The City Government has previously announced its desire to gradually introduce requirements for zero emission building and construction sites.

The definition of a zero emission building site entails the use of zero emission energy carriers (such as electricity, district heating or hydrogen) for building activities within the system boundary, while a fossil-free building site entails the use of fossil-free energy carriers (such as hydrotreated vegetable oil biodiesel (HVO), bioethanol or district heating) for building activities within the system boundary. The definition of zero emission building sites used by the City of Oslo encompasses both zero emission concepts and biogas-based concepts. The system boundary is defined according to the types of construction activities included (4).

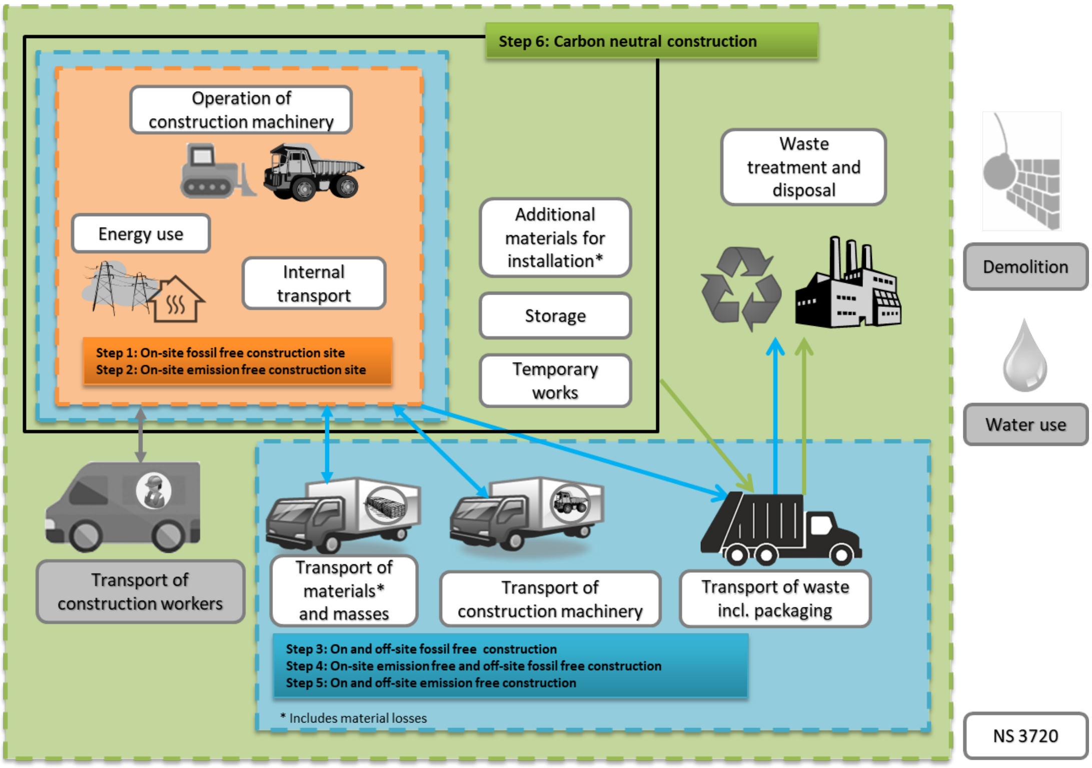


Figure 1.
Diagram showing the system boundary for all construction activities taking place in the construction phase, with a stepwise approach (2).

This report studies the consequences of a gradual transition to zero emission implementation of building processes in Oslo. To what extent zero emission construction machinery and vehicles are available in the local market in and around Oslo will be studied, while assessing whether the use of such equipment entails significant disadvantages or additional costs, and how this is expected to develop in the years approaching 2030. The report considers the consequences for industry operators of a gradually increasing proportion of zero emission energy consumption in the building phase, in step with developments in costs and the market as 100% zero emission construction activity is approached in 2030. The report includes an assessment of how this will influence foreign operators, as compared with Norwegian operators. Norway and Oslo constitute a small proportion of the global market for construction machinery and associated equipment, and by far the majority is imported from abroad. The pace of reorganisation and cost developments for zero emission building sites therefore depends on other countries also entering the market and demanding zero emission concepts. The assessment distinguishes between zero emission construction machinery at the building site (Step 2), versus zero emission transport to and from the building and construction site (Step 5). This is important because there will be differing technological developments in these areas, and as such it might be assumed that it is possible to adopt requirements for one without making demands on the other.

Maskingrossisternes Forening (MGF), a trade association for machinery wholesalers, states that more than a hundred larger electric excavators (above 8 tonnes) were available in Norway at the end of 2021. It is estimated that about 250 new electric excavators (above 8 tonnes) will emerge onto the Norwegian market in 2022. As a result, zero emission machinery will attain a market share of approximately 15% of all new construction machinery in this industry segment in Norway in 2022. This is an important parameter to measure since 40% of all medium-sized and large construction machines are excavators. In the case of battery-powered excavators over 8 tonnes, the investment costs are typically three times higher than for equivalent diesel-powered construction machines, and delivery time is around 6-12 months. For machines under 8 tonnes the additional costs are lower, and the market looks different. However, machines under 8 tonnes are not analysed in this report. At present, demand is greater than production capacity. Different machinery manufacturers tackle technological challenges in different ways. One manufacturer may convert its production lines to produce electric machinery, while another converts diesel-powered machinery to electrical operation. Some choose replaceable battery concepts, while others favour cable operation. For the majority, initial production has been of the smallest construction machines (under 8 tonnes), while others have started to electrify small (8-16 tonne), medium (16-23 tonne) and large machines (over 23 tonne). New operators are entering the market with various mobile, temporary battery concepts, energy tracking tools and power calculators. In addition, Standards Norway is developing a new standard, prNS 3770, that applies to zero emission building and construction sites.

With regards to transport, electrification has progressed farthest in construction worker cars. All models of vans from most major manufacturers are now available in battery-powered versions and most small and medium-sized vans can tow a trailer. Except in the case of the largest vans, ranges approaching 200 km are achievable even during winter. The same established charging and rapid charging technology can be used for vans as for construction worker cars. In the case of urban buses, there has also been comprehensive technological developments in recent years, and the availability of different battery-powered concepts is good. From a technical viewpoint, the electrification of buses presents few problems, but route adaptation may be necessary to provide adequate charging, especially in winter, when a lot of energy is required for interior heating. There has been less progress with other types of buses, because of more challenging patterns of use, but even here development is rapid.

In the case of lorries, there has been a trend in recent years from the conversion of diesel-powered vehicles to battery operation (individually or in small-scale production) to small-scale mass production of dedicated battery-powered vehicles. In Norway the first mass-produced, heavier, battery-powered commercial vehicles were on the road from the summer of 2020, and at present (small scale) mass-produced, battery-powered lorries and road tractors are available from several major manufacturers. These are in all size classes from under 16 tonnes and up to 44 tonnes. In practice, such vehicles are mainly used on Norwegian roads for waste transport, local and regional delivery, and construction-related transport. In the case of construction-related transport, several of the battery-powered vehicles in use in Norway are based on a delivery vehicle chassis and therefore have an articulated rear chassis. The manufacturers are launching new vehicle models, generations, and size classes. Mass-produced, long distance transport vehicles with large batteries are being developed and are expected to be available within 2-3 years.

The European Commission has established a collaborative arena to exercise public purchasing power as a strategic tool for climate-change transition, known as the EU Big Buyers for Climate and Environment initiative (7). Zero emission construction sites are one of the initiative's fields of application, and the working group for this field is coordinated by the City of Oslo. In connection with this arena, the Netherlands has reported about a 5% increase in costs for green acquisitions, while Copenhagen reports about a 2% increase in energy costs connected with transitioning from diesel to battery power. C40 cities (8) is a network consisting of 97 of the world’s largest cities that take responsibility for climate change and want to demonstrate how they can contribute to developing low- or zero-emission concepts. Oslo has acquired the status of an innovative city in C40 because it has demonstrated clear leadership in the environmental and climate change fields. In this network, Oslo also heads the C40 Clean Construction Programme (9), in which 40 cities from all continents are now participating to promote the use of climate-friendly materials and zero emission building and construction activities.

Approach

For the purposes of this study, both quantitative and qualitative methods have been used (See Figure 2). Interviews and a questionnaire were employed, and a workshop was arranged. Ten semi-structured interviews were carried out with ten different respondents from different parts of the value chain. This included construction machinery, energy supply, building dryers and heaters, and transport. The respondents were selected based on earlier projects and have experience with zero emission building and construction sites. The respondents were sent an interview guide (Appendix A) a few days before the interview containing information about which of the questions we would be focusing on. The interviews were conducted using Microsoft Teams, and each lasted about an hour. Two research scientists were involved in each interview, one leading and the other taking notes. The interviews were designed and analysed using NVivo software. Notes from the interviews were sent to the respondents afterwards, giving them the opportunity to make corrections.

A questionnaire (Appendix B) was sent out to a large group of people and 11 responses were received within a week. There were 23 participants in the workshop, in which incentives and potential scenarios related to zero emission building and construction sites in Oslo in 2030 were discussed. The Miro presentation software was used. The interviews, questionnaire and workshop formed the basis of the development of the various scenarios. Meetings were also carried out with project teams from the City of Oslo. These meetings formed the basis of data collection for the 100% electric building and construction site energy demand examples. Quantitative analyses were carried out on the energy, power and cost calculations and the method used for calculations is described in more detail under each chapter.

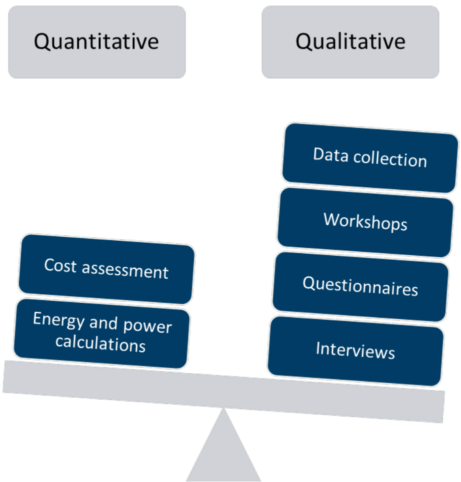


Figure 2.
Overview of quantitative and qualitative analyses.

This impact assessment includes a description of the consequences of electrifying building and construction sites in Oslo and evaluates various scenarios. Scenarios were developed showing energy and power consumption at building and construction sites, energy costs and differing development of building and construction sites in the years approaching 2030. For the energy and power calculations, a reference scenario, an average scenario, and an optimal scenario, assessing different charging cycles were developed. For the cost analyses, a reference scenario, a pessimistic scenario, and an optimistic scenario were developed. The cost analysis scenarios consider the effect of fluctuating energy prices for electricity, fossil fuel and biofuel. Finally, all these results are combined with the market analysis to establish four development scenarios. A further description of the assumptions behind the scenarios can be found in each chapter.

Energy consumption and energy supply at the building site

The chapter about energy consumption and energy supply at the building site is divided into three sections, dealing with the experience study, energy modelling and energy projection.

Experience study

A previous SINTEF report on an experience study related to the requirements for zero emission building and construction sites shows that of 35 building and construction projects in the City of Oslo, 77% have documented the proportion of zero emission construction machinery and 43% have documented the proportion of zero emission transport of masses (2). The report shows that most projects have begun to electrify construction machinery and that thirteen of them have also to a certain extent acquired both zero emission construction machines and zero emission mass transport. The experience study shows a market in rapid transition and the goal is for all public building and construction projects carried out on assignment for the City of Oslo to be zero emission by 2025. By 2030 all building and construction work in Oslo shall be zero emission (1).

The report describes important lessons learnt, such as maintaining a battery bank as a buffer for battery-powered construction machinery to reduce power peaks. The tipping point for the electrification of construction sites will be reached when batteries can last a full working day without recharging, rather than starting up several machines to do the same job. If we think ahead a little, biogas and hydrogen may be an important solution for electrifying larger construction sites. For example, a hydrogen generator could be used to charge battery-powered construction machinery and reduce power peaks in the grid, or biogas and hydrogen vehicles could be used for external transport of goods, mass, waste, construction workers, and machinery and in areas without a grid supply. Challenges have also arisen where preparations were made for construction site electricity supply before the contractor was selected or before it was known how many electric machines would be needed or would be available at the time construction commenced. It is necessary to consider the maximum anticipated capacity for each construction site. The maximum power requirement is estimated based on experience of, for example, what volume of mass material is to be transported, what type of machine is to be used, how many operating hours and how much energy consumption is likely, as well as the layout of the construction site. This was adjusted upwards as time went by.

A commonly heard comment was that smaller electric machines and equipment presented no problems. Electric construction machinery also results in less noise and pollution and improved air quality and working environment. Project owners do not always stipulate how many electric construction machines are to be used. It is left to the contractor to decide what they can supply. It is also up to the contractor to decide whether large construction machines are to be supplied by cable, battery, or a combination of the two, but this has major impact on the planning of maximum power and current requirements, as well as charging facilities. When the municipal agencies assessed the machine lists, several commented that the points system did not reflect reality, since the lists did not consider hybrid machines, areas of use, charging arrangements, or the total operating time of the various construction machines. Several agencies recommended the use of a percent-based zero emission level, which would consider to what extent electric construction machines in different size classes are to be used in different work operations.

Shared lessons learnt involve dimensioning and ordering construction machines according to the work they do and having effective routines to adapt the power consumption to the task, rather than running at maximum output. At present, battery-powered construction machines are often used for lighter tasks because they quickly become discharged. Energy is then used optimally and there is less likelihood of energy running out. With cable-supplied electrical concepts this is not a problem, but such concepts also demand robust electrical supply, preferably backed up by battery systems to handle power peaks. It is difficult to estimate maximum power and plan for adequate electricity supply early in a project. It is therefore helpful to gather experiential data for, among other things, electricity consumption, operating hours, battery capacity, power requirements during operation, charging power and rapid charging power, subsequently identifying power peaks during the implementation of various building activities. Effective charging routines are needed if the machinery is to be used for a full working day. Part of the solution involves using battery/cable-powered construction machinery and battery containers to provide more flexibility at building and construction sites. There is also a need for energy management tools in large building and construction projects, especially where several large construction machines and vehicles are used simultaneously.

Energy modelling

SINTEF has used its own energy and power modelling tools to investigate electrical energy requirements for building and construction sites and how these requirements are distributed among various work processes and between different construction machines and transport. Calculations have been carried out for two theoretical scenarios: a fully electrified building site and a fully electrified construction site. The energy and power modelling is structured for building projects according to the following work processes in the implementation stage:

- Demolition
- Groundworks: Preparation of the site, including using mobile construction machines
- Superstructure: Construction of the building
- Façade
- Internal works: Drying and heating buildings and other internal works
- External works: Development of infrastructure such as water supply and drainage, electricity, roads, and zoning
- Internal transport: Transport of goods, masses, construction workers, waste, machinery, and suchlike within the construction site area (incorporated into the other work processes where it occurs)
- External transport: Transport of goods, masses, construction workers, waste, machinery, and suchlike to and from the construction site area

Construction site projects only have an implementation stage and are not divided up into building phases, because the work consists of a continuous cycle of excavation and removal of masses, shoring, pipe laying and replacement of masses, often working along a street. The energy and power requirements are calculated for an envisaged zero emission building and construction site. In other words, all machinery, transport, and equipment are based on a fully electrical concept. The scenario analysis takes the process one step further and considers other energy sources such as district heating, biogas, and hydrogen.

<u>Electricity supply</u>
During the establishment of a building or construction site, a contractor must often construct a transformer to convert from 230 V to 400 V, so that the larger construction machinery can be charged on site and put into use.

Based on the interviews with industry representatives it was quickly discovered that available power in *construction projects* varies from 50 to 150 kW and sometimes reaches 250 kW, depending on the existing infrastructure and how many outlets were available in the area. This is often limited for such projects since these may take place in established residential areas with existing electricity customers and limited development, triggering a need for additional capacity. In a construction project there is often no demand for additional supply capacity or power after the construction phase is completed.

Based on interviews with industry representatives it was established that available power for *building projects* is at present around 400-500 kW but building site managers envisage a future requirement for up to 1 MW when everything is to be electrified. Access to electricity is not always such a serious problem for *building projects* as for *construction projects*, since in a building project there is also an increased demand for electricity supply after the building phase.

Machine park

The energy and power modelling tool includes detailed information about a machine park that represents what is currently available on the Norwegian market for construction machinery and hypothetical average data for vehicles. Hypothetical average data for vehicles are based on converting equivalent diesel-powered vehicles to electric operation. The source of the fuel efficiency data is taken from Hovi et al. (10) and presents an overview for heavy transport vehicles from at least twenty-two companies. A factor of 10.06 kWh per litre of diesel is then used when converting to electric vehicles, assuming a conversion efficiency of 30% for diesel and 85% for electricity. Information regarding electric construction machinery was obtained from interviews with machine suppliers, technical specifications, and product data sheets, and is quality controlled by machine and equipment suppliers and with the trade associations. The machine park includes:

- Construction machinery: dumper trucks, excavators, wheel loaders, compressors, mobile cranes, demolition machines, sorting machines, stampers, tower cranes, vibration plates, boom lifts, scissor lifts, telescopic trucks, and drilling rigs.
- Energy storage: battery packs, battery containers, microgrids and hydrogen fuel cells.
- Vehicles: lorries, container trucks, special vehicles, concrete transporters, tractors, vans, and construction worker cars.

Machines and vehicles that have not been electrified at all include road graders. There is also a shortage of electrified construction machinery and vehicles in the larger classes. Observations from the machine park database indicate that there are wide variations in maximum power, depending on manufacturer and technology development. It is anticipated that this situation will be improved and standardised in the future. Figure 3 gives an overview of the machine park currently available in Norway, showing that most small machines (<8 t) have been electrified, while fewer medium-sized (8-20 t) and large (>20 t) machines are available as electric versions. The exception is excavators, which is the construction machine with the largest number of electrified models available in several sizes.

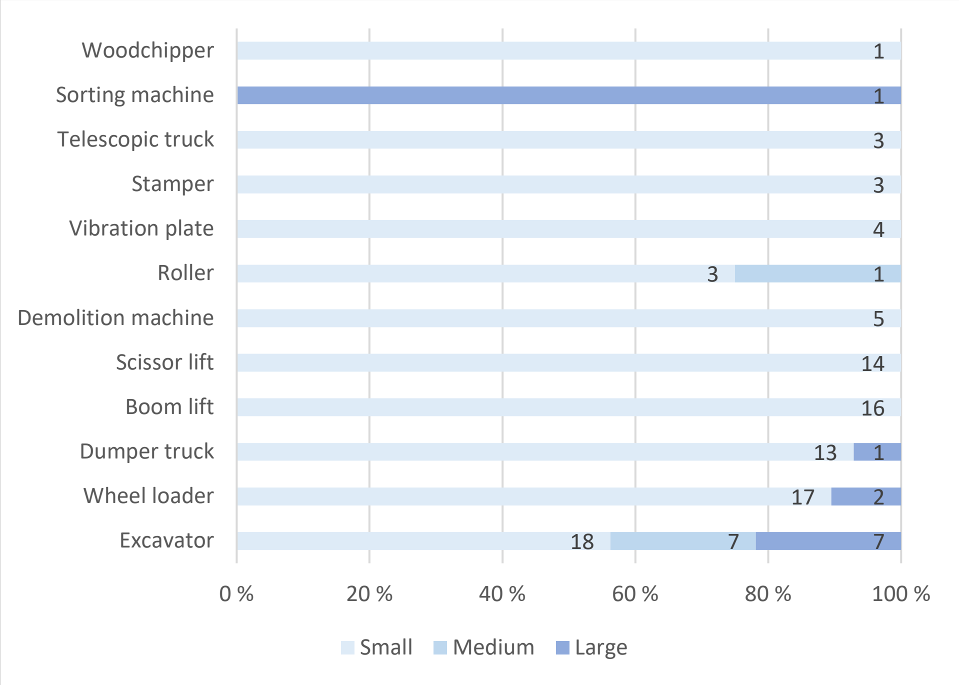


Figure 3.
Overview of the machine park available in Norway today. NB: Road vehicles are not included since these figures are based on hypothetical average data.

<u>Data acquisition</u>

From an earlier experience study of zero emission building sites in the City of Oslo, several projects were identified which possess a detailed insight into the energy consumption of machinery and vehicles at building and construction sites. These projects have been used in this analysis to ascertain what data the projects have at their disposal related to energy consumption and energy concepts at building and construction sites in different phases of construction. This has not been done previously. There is some uncertainty in the estimates since it is difficult to acquire data for a "typical" building or construction site. Electricity consumption depends strongly on the construction machinery and vehicles in use, what they are used for and how much they are operated. Data have therefore been acquired from six different building and construction sites in the Oslo area that have either been completed recently or are in progress. SINTEF also has data from two building projects that can be incorporated in the overall collection of acquired data. All this information has been used to design a hypothetical 100% electrified building site and a hypothetical 100% electrified construction site. It was decided to define separate scenarios for building and construction sites since it was quickly discovered that these operate according to different premises and have different energy and power requirements. Some of the main differences relate to working time, project phases, the proportion of mass transport and construction worker transport and building activities connected with construction machinery. The acquired data includes:

- Key information about the project, such as start date, completion date, project type, work schedule and project size.
- Construction machinery used in the building period, including internal transport, small equipment, machine type, operating time, fuel technology and the way in which all the equipment is transported to and from the site.
- Mass transport to and from the site throughout the construction period, including vehicle types, number of journeys and fuel technology.
- Goods transport to and from the site, including information about goods quantities, vehicles, and fuel technology.
- Waste treatment reports for the entire construction period, including quantities of waste per waste fraction, vehicle types, number of journeys and fuel technology.

- Average number of skilled workers and managers employed per month in the construction period, as well as information about typical travel habits of daily and weekly commuters and their working hours.
- Energy consumption for heating and drying.
- Maximum electric power available in the construction period.

Follow-up meetings were also arranged with construction managers and project managers to fill in gaps in the acquired data. One challenge connected with data acquisition was the level of data resolution, which varied widely from one project or activity to another. In some cases, the data resolution was at a high level (hourly basis) while in other cases it was less precise (monthly basis). In some cases, the data were incomplete, for example being available only for a five-month period in a project that lasted two years. It was therefore necessary to extrapolate the data to create complete sets. This was completed through conversations with construction managers to develop realistic scenarios.

It may be argued that data acquired from projects that are either recently completed or still in progress are not representative of normal project duration because of restrictions imposed during the pandemic in 2020-2022. When the construction managers were asked about the impacts of COVID during construction work, they stated that they felt that there was somewhat more transport of employees directly from their homes, instead of by public transport. They also noticed some restrictions related to entry and quarantine for foreign workers. Some construction workers were quarantined because of contact with infected persons and there were some delays caused by goods supply issues. However, these factors did not affect project duration.

Most building and construction projects last two years. The effect of holiday absence on the construction cycle is similar in building and construction projects. Most suspend operations for two weeks at Christmas and for four weeks during the summer. Working hours are from 7am to 4pm Monday to Friday, but often Monday to Thursday in the case of construction projects to allow for the transport needs of weekly commuters. In the case of such four-day weeks, work starts at 7am and ends at 7pm. Delivery and collection times for mass, goods, waste, and construction machinery transport is based on the average frequency of deliveries and collections for the entire building and construction sector for a typical working day (10). This has been adjusted slightly to consider the fact that deliveries do not take place outside of working hours. The resulting distribution of deliveries and collections throughout the working day is 27% between 7am and 9am, 62% between 9am and 3pm, 6% between 3pm and 5pm and 5% between 5pm and 7pm.

Scenario analysis

A scenario analysis was also carried out (i.e., reference, average and optimal scenarios) providing some examples calculations of high and low estimates of energy consumption and power peaks. The reference scenario is based on full electrification while the medium and optimum scenarios include other renewable energy sources such as hydrogen, biogas, and district heating.

1. The reference scenario

Charging of external transport does not at present take place on building and construction sites, and few facilities exist for charging heavy transport vehicles. We therefore had no choice but to construct a hypothetical scenario for charging of external transport vehicles. Dialogue with contractors revealed that transport suppliers expect to be able to charge vehicles at the building or construction site on arrival and that this shall be arranged for. We therefore assume that charging requirements are met on each visit to the construction site, and that charging is possible at the other end of the journey. Where possible, collection and delivery are coordinated and are covered by a single charge, for example with the delivery of empty containers and collection of waste. External transport is defined as “last mile” or in other words the closest leg of transport.

In this scenario, all rapid charging takes place at the construction site. Overnight charging of construction machinery and equipment takes place at the construction site, while overnight charging of vehicles takes place at the transport provider's premises. No optimisation of energy consumption or power peaks takes place. There is no energy flexibility or energy storage. It is assumed that construction machinery is operated continuously at maximum power. Electric construction machines for heavy work and whose batteries quickly become discharged have long charging times and this may delay project progress. It is assumed that overnight charging takes place between 10pm and 6am. The operating time of cable-powered construction machinery is set at ten hours, corresponding to a working day without breaks. The first work break is common to all machines and is set at 11am, except for the machines that have a shorter operating time than four hours. Machines with a shorter operating time than four hours are subjected to several breaks for rapid charging.

Mass transport

Rapid charging sessions are based on 1.2 kWh/km for tipper trucks, for which 35% of journeys involve a complete two-way journey. This is calculated based on disaggregated journey rate data available for a five-month period for a hypothetical construction project. For the construction project, the journey distance to the mass disposal site was between 8 and 30 kilometres, while for the building project the assumed journey distance was calculated as the average from 1) disposal site for soft clay mass and lightly contaminated mass at about 40 km per load and 2) disposal site for clean, solid mass at about 15 km. Delivery and collection are carried out daily using tipper trucks of maximum gross weight of 13 t (electric) and 27.7 t (diesel). However, with full electrification the load capacity of the electric truck was used in the analysis.

Goods transport

For construction projects, transport of asphalt is often included in mass and waste transport, while transport of smaller-volume components is often included in construction worker transport. The model takes this into account. For the building site, other goods are often delivered, such as concrete, lumber, pipes, electrical components, gravel, and ventilation components. These deliveries are associated with the project phase it occurs in, for example lumber during the superstructure construction and heating, ventilation, and air-conditioning (HVAC) components during internal works construction. Rapid charging sessions for these are based on the use of a small truck (0.75 kWh/km) or van (0.2 kWh/km) and a journey distance of 7-31 km.

Waste transport

Waste transport is calculated based on the amount of waste per month, the capacity of the tipper truck or skip truck and the number of journeys. Delivery of skips and collection of waste are also included. In the case of the construction project, the waste collection data were also available with a resolution of one day, so that the number of journeys is calculated directly. For the building site it is assumed that two skips can be delivered together on one truck, but when they are full, they must be collected individually. In connection with emptying, a truck can contain waste from approximately two containers. Collection was completed in connection with deliveries wherever possible. Where waste was collected that was not put in a skip (demolition waste), the number of journeys was calculated using the total amount of waste transported to each registered destination. Rapid charging sessions are based on either 1.2 kWh/km for demolition waste or 1.33 kWh/km for waste in a skip truck for short distances (6-10 km) from the site to the disposal destination.

Construction machinery transport

Transport of construction machinery is based on information about delivery and collection dates, distance to/from the machine contractor's premises or the distance to the next job (on average 25 km). It is assumed that all transport is carried out using flat-bed lorries whose energy consumption is 1.16 kWh/km. There is no optimisation of transport of construction machinery and each machine is transported individually since they often come from different machine suppliers.

Construction worker transport

For construction projects there are often about five skilled workers who work their way along a street, because the site is often constricted and there is no room for more personnel. At a building site there are often many more hired skilled workers or sub-contractors (especially in connection with the phase involving internal works, such as on ventilation systems, plumbing and electrical installation). At times there may be as many as a hundred employees in the most demanding building periods. Construction worker transport is divided between skilled workers and production workers who are often weekly commuters from, for example, Telemark, central parts of Norway or Sweden and drive their own cars, and office personnel who are often daily commuters using a combination of private cars, public transport, and walking/cycling, depending on the location of the construction site in Oslo. Sub-contractors and hired personnel often have their own transport (vans). Transport of waste is often combined with mass transport in construction projects. It is assumed that weekly commuters drive 120 km without sharing vehicles and daily commuters drive 10 km to the construction site. The energy consumption of vans is 0.15 kWh/km and it is assumed that they recharge on arrival.

2. The average scenario

The average scenario is constructed based on the reference scenario, but some optimisation is performed for the most demanding building operations and project phases. Some examples are the use of construction machinery with different technology solutions (cable and battery powered) and staggered lunch breaks to avoid charging all machinery at the same time. There is also some optimisation of transport logistics, for example for the delivery of construction machinery or building materials. In this scenario, 50% of mass transport is combined with outward and return journeys and 50% does not need charging at the construction site. In the case of goods and waste transport, only lorries need charging at the site, and we assume that this applies to half of them. Vans can manage without charging. In the case of construction worker transport, we assume that half of weekly commuters make use of car sharing and that half of daily commuters use public transport, walk or cycle.

3. The optimal scenario

The optimal scenario is developed from the average scenario, with a high degree of optimisation of operations at the construction site. The contractor has created a mass plan and an energy plan for the site to reduce transport and energy requirements, as well as power peaks. The contractor also uses energy-flexible concepts as required, such as district heating for ground thawing, heating, and drying; the use of hydrogen and biofuel for transport; and battery containers for energy storage. All heavy transport can charge batteries outside the construction site. Transport deliveries of masses, goods and waste are optimised, and the vehicles charge at their respective depots. Increased battery capacity, better technology and available charging infrastructure are assumed, so that vehicles can travel longer distances. Alternatively, other energy sources, such as hydrogen or biofuel, are adopted. All construction worker transport is carried out using either public or active transport, except for 3-4 electric-powered vans on the construction site for the use of construction workers.

Results

The tables and figures below show energy consumption, weekly power consumption curves and daily power consumption curves for a sample building site and a sample construction site for the three scenarios.

Table 1.
Total energy consumption (kWh) for the entire building period for a sample building project.

	Reference			Average			Optimised		
Construction machinery	**1st year**	**2nd year**	**TOTAL**	**1st year**	**2nd year**	**TOTAL**	**1st year**	**2nd year**	**TOTAL**
– Demolition	60,667	0	60,667	60,667	0	60,667	60,667	0	60,667
– Groundworks	64,657	0	64,657	64,657	0	64,657	68,818	0	68,818
– Superstructure	96,952	0	96,952	96,952	0	96,952	96,952	0	96,952
– Façade	11,587	0	11,587	11,587	0	11,587	11,587	0	11,587
– Internal works	21,579	65,503	87,082	21,579	65,503	87,082	21,579	65,503	87,082
– External works	0	49,920	49,920	0	49,920	49,920	0	49,920	49,920
Construction worker transport	78,465	72,789	151,254	40,369	37,960	78,329	3,363	3,442	6,804
Mass transport	14,564	330	14,894	7,282	165	7,447	-	-	-
Waste transport	1,050	463	1,513	757	525	1,282	-	-	-
Goods transport	5,236	9,670	14,933	6,091	2,356	8,447	-	-	-
Construction site transport	897	318	1,215	608	449	1,057	-	-	-
TOTAL	333,906	188,212	522,118	295,810	153,383	449,193	262,965	118,865	381,830
Average annual energy consumption			261,059			224,596			190,915

In Table 1 it is assumed that the construction phase lasts for two years. Therefore, the total energy consumption per year is based on the average energy consumption over two years. The results show a 14% reduction in total energy consumption when transitioning from the reference scenario to the average scenario, a reduction of 15% from the average scenario to the optimal scenario, and a reduction of 27% from the reference scenario to the optimal scenario. The use of construction machinery constitutes 71% of the total energy consumption in the reference scenario, while transport to and from the building site constitutes 29% in the building phase. The largest share of energy consumption of construction machinery in the reference scenario relates to the demolition and groundworks phase (34%) followed by superstructure (26%), internal works (23%), external works (13%) and the façade (3%).

Table 2.
Total energy consumption (kWh) for the entire construction period for a sample construction project.

	Reference	**Average**	**Optimised**
Groundworks	140,439	140,439	144,699
Construction worker transport	35,618	19,311	2,470
Mass transport	86,430	36,383	-
Waste transport	223	111	-
Goods transport	449	225	-
Construction site transport	6,557	3,279	-
TOTAL	269,715	199,778	147,194

We assume that the construction project also lasts for two years. The work consists of a continuous cycle of excavation and removal of mass, shoring, pipe laying and replacement of mass, often working along a street. This means that the activities and hence the energy consumption are similar from year to year. The results (see Table 2) for one year show a 25% reduction in total energy consumption when transitioning from the reference scenario to the average scenario, a reduction of 26% from the average scenario to the optimal scenario, and a reduction of 55% from the reference scenario to the optimal scenario. The use of construction machinery constitutes 52% of the total energy consumption in the reference scenario, while transport to and from the construction site constitutes 32% in the construction phase. In the reference scenario, most of the energy consumption is from mass transport (57%) followed by construction worker transport (28%), construction transport (5%), goods transport (0.3%) and waste transport (0.2%). The reason for the increase in energy consumption in groundworks between the reference/average scenarios and the optimal scenario is that the processes are optimised regarding power. This applies both to building projects and construction projects and means that an excavator with a large battery and high-power rating during rapid charging is replaced with a large battery/cable-powered excavator with slightly higher energy consumption but lower power. The reason why there is no difference in energy consumption for groundworks between the reference and average scenario is also due to optimisation regarding power. Moreover, lunch breaks are staggered to reduce the power demand when several electric construction machines are rapid charged simultaneously.

Figure 4 shows the weekly peak load and available power for the three different scenarios and for the different phases of the building period. “Peak load” refers to the hour with the highest power demand per week. The results show that there is some overlap in building activities between the building phases, such as groundworks and superstructure, and that the most energy-demanding building phase is groundworks, followed by superstructure and demolition. The energy consumption of construction machinery is within the available power rating, and by making some adjustments to lunch breaks and technology type (battery, cable, or a combination of the two), the power issues presented by the construction machinery are resolved according to our calculations. This becomes a greater challenge if there is also to be enough power available for vehicle charging. In the average scenario and optimal scenario, it is assumed that this load is moved to a different part of Oslo, for example to the premises of the transport contractor or a central charging depot. Figure 5 shows corresponding results for the construction site.

Figures 4 and 5 show weeks where there is no activity, this is due to holiday. The results for both the building and construction site are sensitive to data resolution. For example, estimates for construction worker transport on the construction site are based on aggregated data for the entire construction period, while for the building site the data are stated per month. In contrast, figures for mass transport are reported daily, and in some cases hourly for the construction site. Figures 6 and 7 show daily load profiles with hourly resolution for one of the most energy-demanding weeks at the building site (week 23) and the construction site (week 25) for the three different scenarios. For the building site in the reference scenario, the greatest power requirement occurs when construction workers arrive at the site and all want to charge electric vehicles simultaneously, followed by the lunch break, when all battery-powered construction machines are charged simultaneously. For the construction site in the reference scenario, the power requirement is steady during the working day because of the continuous delivery and collection of masses, which calls for the charging of mass transport vehicles. The figures also show to what degree overnight charging of construction machinery can be used. Stationary energy consumption is incorporated into the various construction activities where it occurs. Examples are ground thawing in the groundworks phase and heating and drying in the building phase when internal works is in progress.

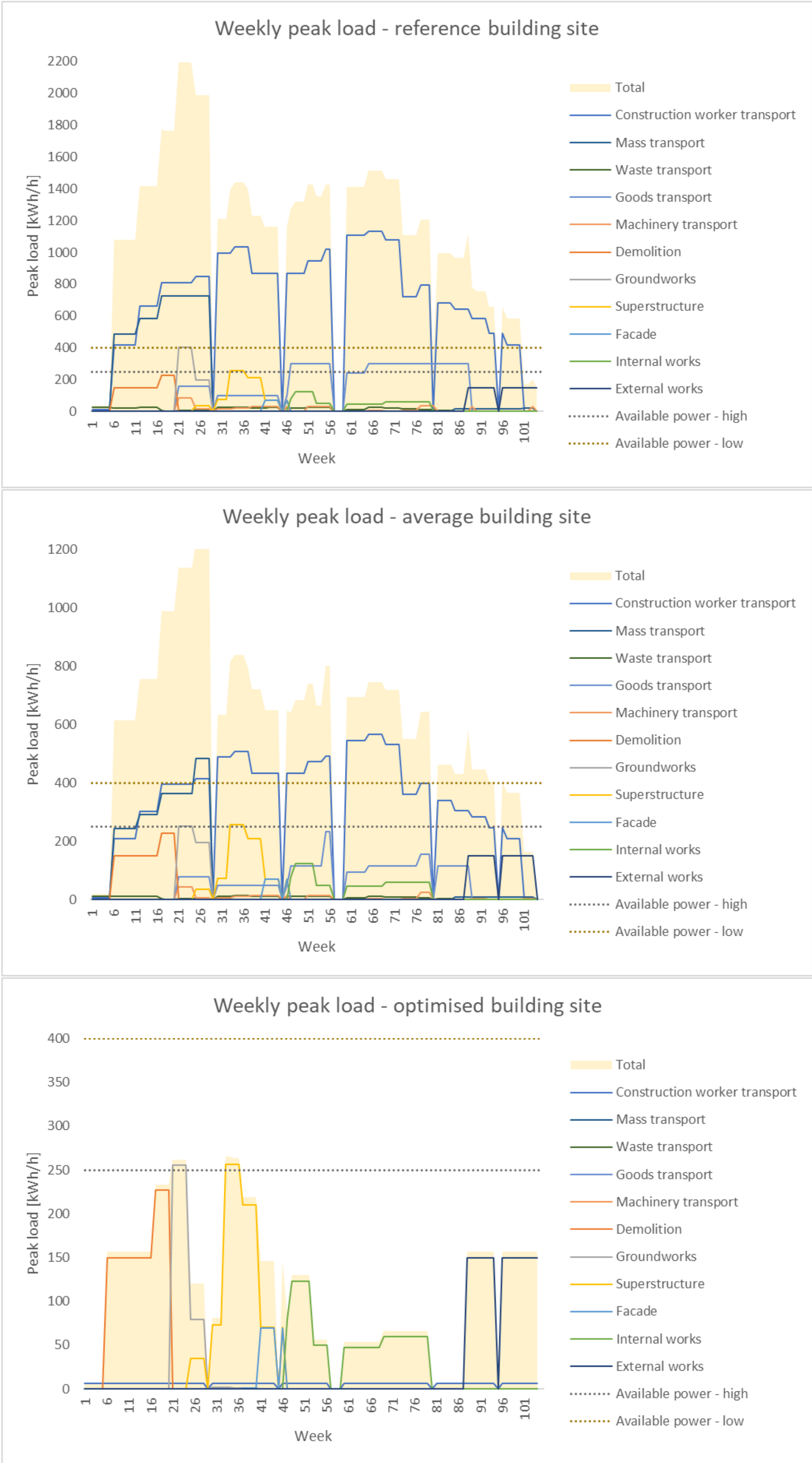


Figure 4.
Weekly peak load and available power for the three different scenarios and for the different building activities of the building site.

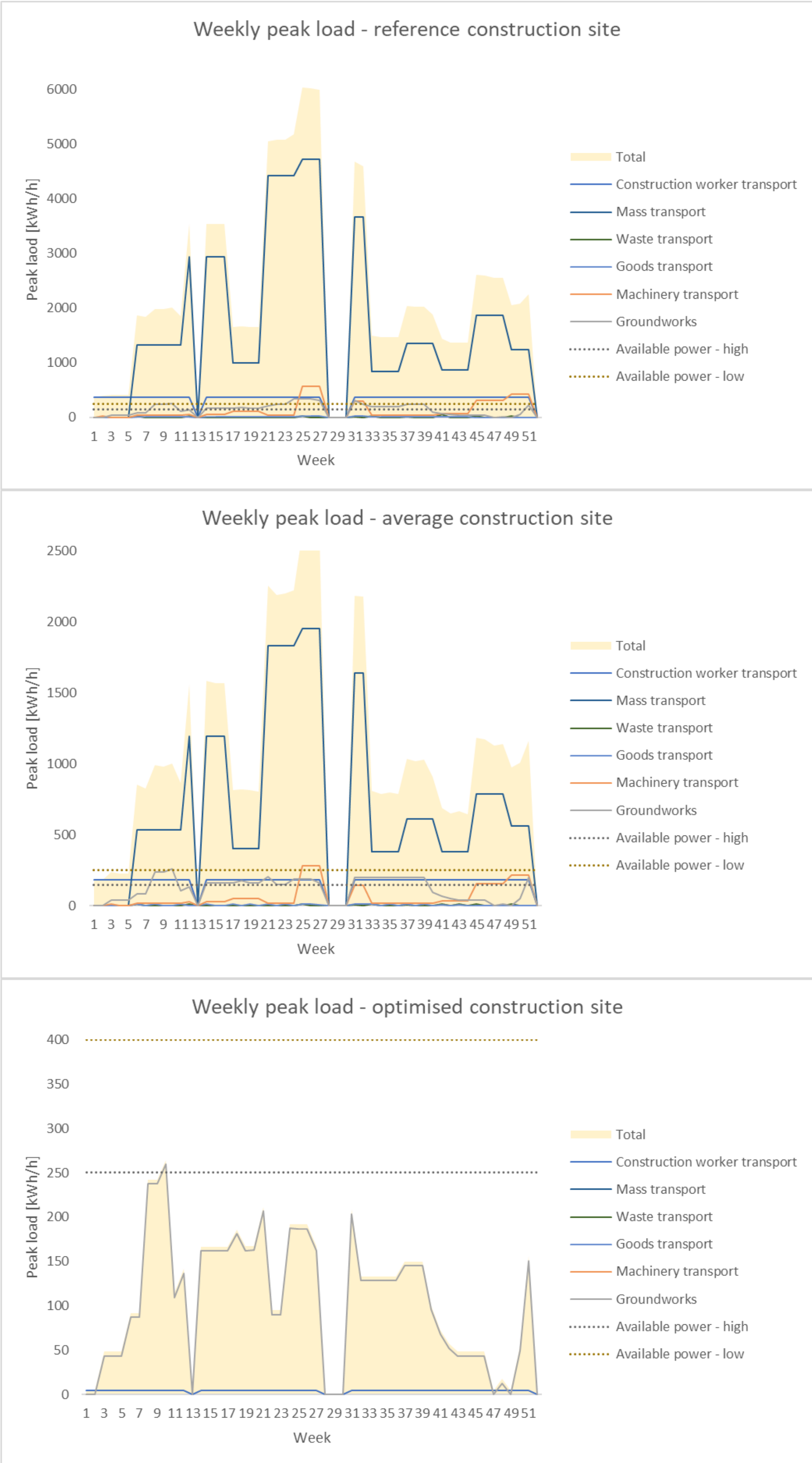


Figure 5.
Weekly peak load and available power for the three different scenarios during the construction period for a sample construction site.

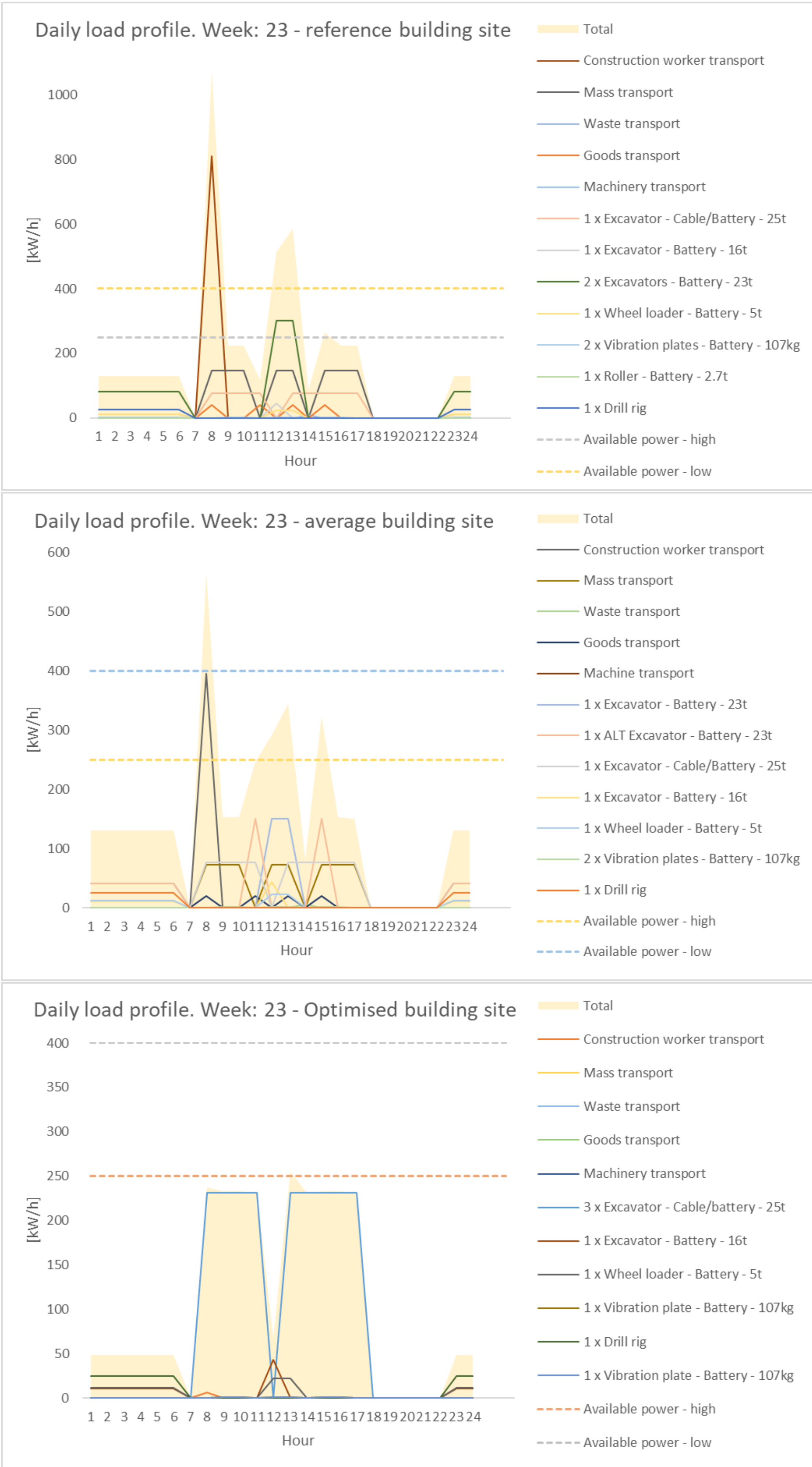


Figure 6.
Typical daily load profile with maximum energy consumption (hourly resolution): Week 23 - building site.

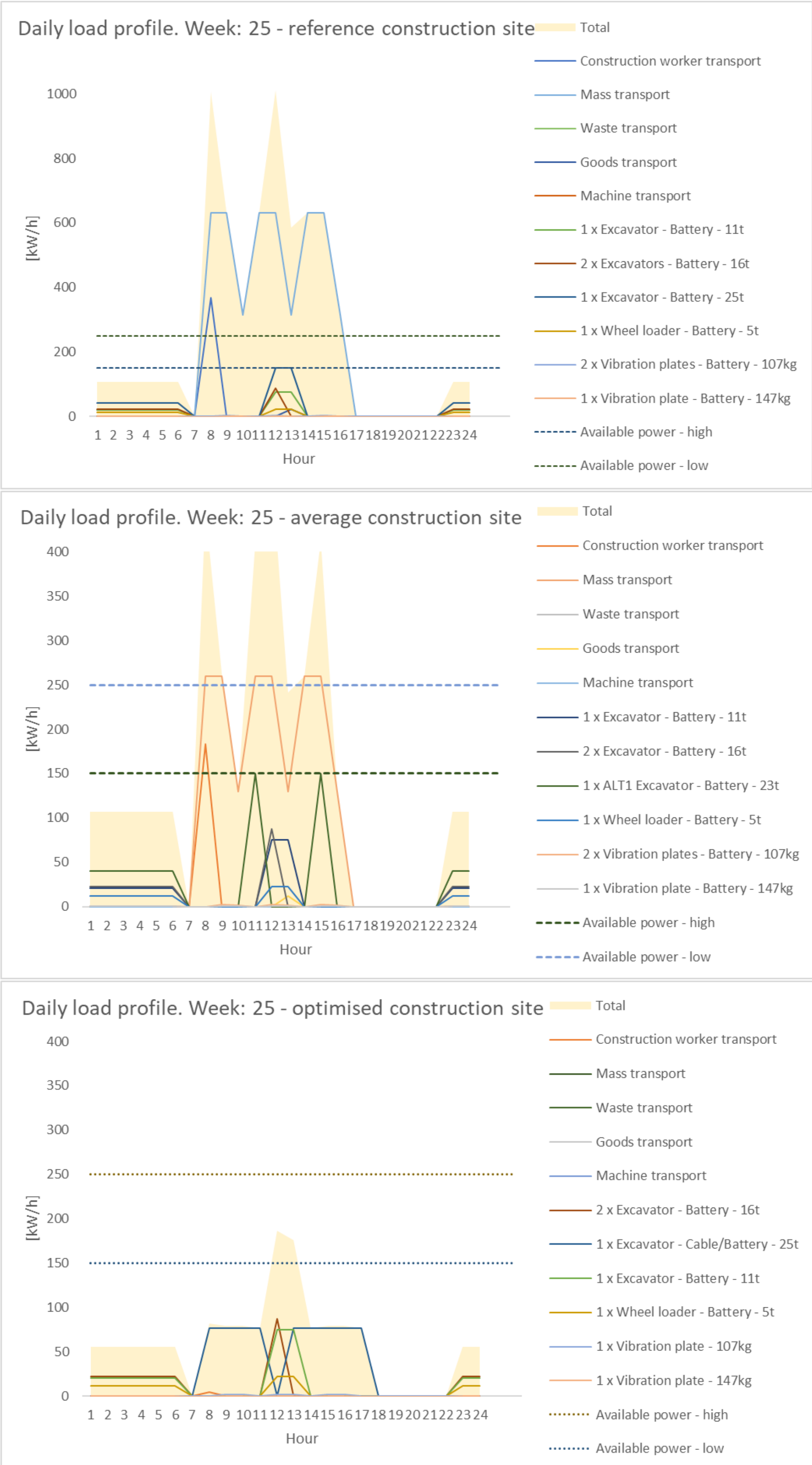


Figure 7.
Typical daily load profile with maximum energy consumption (hourly resolution): Week 25 - construction site.

When the results from Table 1 and 2 are harmonised per completed square metre of building per year for the building site and per million kroner contract amount per year for the construction site per scenario, the energy requirement for a hypothetical fully electrified building site is 38 - 52 kWh/m²/year and the energy requirement for a hypothetical fully electrified construction site is 1,780 - 2,129 kWh/MNOK/year. A 2018 report from DNV GL on the potential for emission reduction at fossil-free and zero emission building and construction sites estimated the effects of fossil fuel for heating and construction machinery, as well as corresponding emissions from building and construction sites in the City of Oslo (11). Our results correspond to the DNV GL report, which shows that energy requirements can vary considerably in the building phase, depending on the type of project, and establishes that an electric building site has an energy requirement of 77 - 92 kWh/m² and an electric construction has an energy requirement of 700 - 5,300 kW/MNOK. The DNV GL report does not consider the fact that the building phase often lasts for two years, so one needs to compensate for this by halving the results, resulting in an energy requirement of 38.5 - 46 kWh/m². It should also be noted that the DNV GL report was written in 2018, at a time when zero emission building and construction sites did not exist.

<u>Uncertainties and assumptions</u>

There is uncertainty connected with these energy and power calculations. One may discuss how representative the modelled building and construction sites are, compared with real projects. There have been challenges connected with data access, data acquisition, data gaps and data resolution. It is only possible to model the building and construction sites based on reported and documented information about machinery, building activities and transport in the various projects. Moreover, it is possible that some less significant activities are missing in the data acquisition and are therefore unknown. The acquired data provides limited information about the technical specifications of some machines and vehicles. Published technical specifications for vehicles are often based on measurements of empty vehicles, while data would be more valuable if it were based on vehicles that were tested with loads and actual conditions on the road. There are also differences in data resolution for the machine park, since average data for different vehicle categories is used for transport, while data from manufacturers' specifications is used for construction machinery. With regards to data acquisition from the building activities and two-way transport, there was considerable variation in how this was reported. Some construction managers and contractors used monthly estimates for a limited part of the building phase, while others used detailed hourly resolution for the entire phase. The acquired data is therefore extrapolated to cover all project phases and activities during the building phase to provide a complete picture of a hypothetical fully electrified building site and a hypothetical fully electrified construction site. It was also necessary to make some assumptions, such as that all transport of construction machinery to and from a building site takes place using flat-bed lorries. This is because no better information was available at the time to model transport of each type of construction machinery. The energy and power model also makes some assumptions, such as that all construction machinery is in continuous operation when determining the maximum available power.

We have based the reference scenario on the transport contractors' expectation that charging is possible at the building or construction site and that this shall be arranged for, but the results show that if everybody is to do this it will be both costly and impractical for the building contractor to provide enough power for all construction and transport needs. We therefore chose to provide transport charging in other locations in the city, spreading the power requirement while facilitating effective logistical concepts for the average and optimised scenarios. This will reflect what is more likely to happen in connection with the operation of fully electrified building and construction sites. To electrify building and construction sites as successfully and efficiently as possible, it is necessary to make use of several different strategies. This means both good planning and, for example, the establishment of associated public charging infrastructure.

Energy and power requirement calculations have highlighted some important measures which can be taken to reduce energy use and peak power:

- Early planning and identification of power supply and energy flexibility potential.
- Creation of an energy plan (prNS 3770).
- Avoid overlapping demanding building activities or phases, such as demolition and groundworks.
- Plan the use and charging of construction machinery to alternate between short, intermittent low-energy use and continuous high-energy use.
- Plan lunch breaks so that all construction machinery is not being rapidly charged simultaneously.
- Avoid charging external transport vehicles at the same time as construction machinery.
- Optimise transport logistics, for example for the delivery of construction machinery or building materials.
- Arrange for off-site charging of heavy transport vehicles at designated charging centres.
- Reduce the working week to four days, with longer working days.
- Skilled and office workers should be encouraged to use public transport, cycle, walk, or use car sharing.
- Create a “NO DIG”, mass-balance strategy to reduce unnecessary movement of mass and mass transport needs.
- Use district heating concepts for heating and drying to ease power demands.
- Use battery containers for increased energy flexibility and cost optimisation.
- Use battery exchange stations.
- In the longer term, hydrogen generators can be used to charge battery containers.
- Use peak shaving and improved battery technology to provide higher battery capacity for more efficient and long-lasting operation.
- Arrange reuse of masses, efficient transport logistics organised for two-way journeys and a local rock-crushing plant to reduce the need for mass transport.

Projection

The City of Oslo's Planning and Building Services agency has prepared an annual development projection for buildings (residential and commercial) based on their building project and planning portfolio (12). This projection considers building planning times and building development rates to spread the portfolio's operations over time. Current building projects are used to extrapolate the first two years, after which the “zoning reserve”, that is, approved building projects minus completed buildings, is used. Planning proposals are often established after about four years (up to 2025) and the potential of the city plan and regional plan plays a larger role after 7-8 years (up to 2030). Uncertainty increases with increasing projection into the future. Not all buildings with framework permits or implementation permits are developed, not all approved zoning plans become reality, and plans where work has commenced may be withdrawn, not approved, or approved with an amended number of buildings. It is possible that the pandemic has had a greater effect on businesses than on households, because of uncertainty connected with the economy and jobs. We assume that 80% of building projects are private and 20% are municipal. Unfortunately, the Planning and Building Services agency does not have corresponding figures for construction projects. We have therefore used the market report of the Federation of Norwegian Construction Industries (BNL) for the first quarter of 2021, which sums up the building and construction market for the whole of Norway in 2021-2023 and estimates investment in construction in 2020 at 130 billion Norwegian kroner (NOK) (13). This figure has been adjusted for Oslo based on the city report for 2019, issued by *Byggfakta* (a marketing channel for the Norwegian building trade), in which Oslo stands for 14.43% of the country’s building and construction investment (14). Projection of volume changes from BNL’s market report is used up to 2023, after which a growth of 5% is assumed, based on figures from Statistics Norway (SSB) (15). For simplification, we have assumed that all construction projects are municipal, even though some construction activity may take place on behalf of private and government developers.

Energy and power needs will vary between construction areas, depending on the size and scope of what is to be built and the zero emission level of construction machinery and transport. The projection assumes that all public construction sites will be zero emission by 2025 and that all construction sites (including private ones) will be zero emission by 2030. The projection is performed for the reference scenario (based on the results of the energy requirement estimates for the hypothetical building and construction site) and a development scenario that considers technology and skills development in comparison with the average and optimal scenario, and for a rapid and a gradual implementation of goals regarding zero emission building and construction sites in the private market. The projection applies only to energy needs, and not power needs. This is because the power requirement depends on a particular building or construction site, as well as the development rate for different urban districts. Hence determining the power requirement for Oslo as a whole is of little value. The results of the projections are shown in Figure 8 for building and construction projects and for a combination of both. The projection of energy needs will change in step with the development rate, goal achievement for private and municipal building and construction sites, increase in zero emission level and technological improvements. A previous DNV GL report estimated the energy requirement of building and construction activity in the City of Oslo at approximately 133 GWh (16). The result from this study is between 77 - 97 GWh. These results should not be compared directly, since different approaches have been used for the projections, with different assumptions regarding development rate and for different time scales.

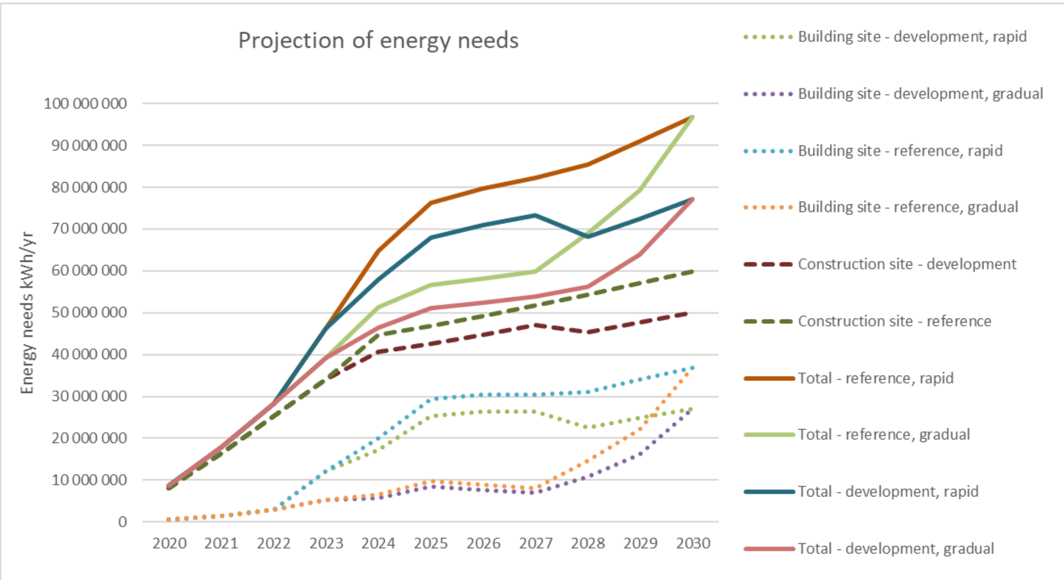


Figure 8.
Projection of energy needs for building and construction sites in the City of Oslo up to 2030.

Cost analyses

Previous analyses performed for the industry by SINTEF and the Norwegian Institute of Transport Economics (TØI) show that the investment costs for zero emission alternatives for construction machinery and heavy vehicles are higher than for fossil fuel alternatives. These studies also show that zero emission alternatives often have lower operating costs. To assess the effect of reduced operating costs in comparison with higher investment costs, life-cycle cost (LCC) analyses have been carried out for excavators and tipper trucks using diesel, HVO and electric power. Analyses have also been carried out on the additional cost of using zero emission alternatives at the building and construction sites outlined in the previous chapter. A qualitative assessment is provided for the scale of additional costs at zero emission construction sites, compared with fossil-free and traditional sites, for cost elements which LCC has not been carried out.

Life-cycle costs (LCC)

Life-cycle cost analysis has been carried out for a small (8-16 tonne), medium (16-23 tonne) and large (>23 tonne) excavator, for a tipper truck with a maximum permitted total weight of 27 tonnes, and for a tipper truck with a trailer. The method from NS 3454 for estimating life-cycle costs was used (18). This includes investment costs, operating and maintenance costs and energy costs, as well as any additional equipment needed to operate the machinery (such as charging installations and cable drums). A comparison was also carried out between traditional machinery and tipper trucks run on fossil fuels and biofuels.

Projected costs in 2025 and 2030

Calculations have been performed for the current situation (2022) and for the years 2025 and 2030. The analysis assumes a discount factor (the factor used to compute the present value of future cash flow values) of 4%, applied for a period of six years for excavators and five years for tipper trucks. The analysis period is based on the average time the machines are in the market, after which they are sold on the used machinery market. It is difficult to define energy prices and their development. The authorities are currently working on a compilation of price assumptions which will make it possible to use up-to-date assumptions on the Norwegian government's Climate Cure 2030 (*Klimakur* 2030) study. At present (31st March 2022), this compilation was not complete or publicly available. Developments following the publishing of the Climate Cure 2030 study indicate that price projections may be raised. In the spring of 2022, prices for electricity, diesel and HVO are historically very high. In the case of electric and diesel operation, this is generally allowed for within the limits set in our sensitivity analysis, while the increase in HVO prices is relatively greater, assuming that the high price level is maintained. This means that electric, diesel and HVO operation have all increased costs in comparison with the assumptions of the Climate Cure study, but relative price changes and energy consumption among the three energy sources favour electric operation (whose competitiveness increases relative to both diesel and HVO operation), with HVO operation being the least attractive. Table 3 shows the energy prices used in the basic scenario for both excavators and tipper trucks. A sensitivity analysis has been carried out to study the effect of higher electricity prices in 2030 and lower diesel and HVO prices, as well as lower electricity prices and higher diesel and HVO prices.

With regards to investment costs for machines in 2025 and 2030, it is assumed that prices in general will increase by 2% by 2025 and by 5% by 2030 (19). This will be reflected in the cost of acquiring machinery.

Table 3.
Assumed energy prices in 2022, 2025 and 2030*

	2022	2025	2030
Diesel price in NOK per litre, exclusive of taxes	6.86	6.96	7.08
HVO price in NOK per litre, exclusive of taxes	12.24	12.96	13.75
Electricity price in NOK per kWh, exclusive of taxes	0.744	0.81	0.77
Rapid charging price in NOK per kWh, exclusive of taxes	3.2	3.48	3.31
Carbon tax in NOK per litre	2.05	3.28	5.32
Road tax in NOK per litre	3.52	2.91	1.88
Electrical energy tax in NOK per kWh	0.1541	0.1583	0.1541

* Energy prices are based on the price projections of the Climate Cure 2030 study (Attachment II – Guidelines). Assumed energy prices connected with rapid charging are based on feedback from the market (and their level corresponds to that of several other analyses). The rapid charging prices for future years are scaled according to development in the price of electricity. Developments in carbon tax and road tax are based on current rates. The carbon tax is assumed to increase linearly up to the announced rate of about NOK 2000 per tonne in 2030, while the road tax is assumed to be reduced at half the rate of the annual carbon tax increase. In other words, the tax per litre of diesel will increase, but for HVO (which is only subject to road tax), the tax will be eased. The electrical energy tax follows the trend defined in the Climate Cure 2030 study.

Cost analyses, transport

Background and insights from cost analyses for battery-powered lorries

In the case of construction site transport, calculations have been prepared for the total cost of ownership (TCO) connected to diesel-, HVO- and battery-powered operation. The calculations were performed for the current situation and for 2025 and 2030 for two classes of vehicles: tipper trucks with maximum permitted total weight of 27 tonnes and tipper trucks with a trailer. Because the calculations are based on a framework developed by TØI over a period of several years and for several projects, the background and general insights from these analyses are first presented.

The TØI report “Green lorry transport?” (*Grønn lastebil transport?*) (20) presents calculations of TCO for various size classes of lorries and road tractors, for the entire depreciation period. The starting point of the calculations is a detailed breakdown of time- and distance-dependent costs and cost drivers. They were carried out for standard vehicles with (where relevant) the simplest bodywork, to make the cost estimates as comparable as possible. In practice, most heavy commercial vehicles are custom-built, considering, for example, the customer's preferences regarding engine size, total weight, bodywork, and driver’s cab. Hence in contrast with construction worker cars and vans, no standard price list exists. For battery-powered concepts, the customer's requirements regarding range, and therefore battery capacity, will also be an important factor affecting the price.

Table 4 has been obtained from (20) and shows that battery-powered heavy vehicles are currently subject to particularly high additional investment costs, compared with diesel-powered vehicles. Relative price differences are somewhat smaller in the case of larger vehicles, while road tractors show larger price differences than lorries do when the trailer is excluded.

Table 4.
Price differences compared with diesel power for different propulsion technologies and total weight classes for lorries and road tractors. Trailers are not included in the cost of road tractors **(20)**.

Total weight in tonnes	Axles	Diesel	Compressed gas	Liquefied gas	Normal hybrid	Plug-in hybrid	Battery-powered	FCEV estimate
Lorry:								
<16	2	100%	120%	130%	150%	160%	325%	400%
< 27	3	100%	115%	125%	145%	155%	300%	375%
> 27	3	100%	110%	120%	140%	150%	275%	350%
Road tractor:								
< 27	2	100%	120%	140%	170%	180%	375%	500%
> 27	3	100%	115%	130%	150%	160%	300%	400%

TØI has broken down current costs for diesel- and battery-powered heavy commercial vehicles into the cost of the chassis, battery, powertrain, electric motor, and a range of other components, as well as projecting these costs for 2025 and 2030, based on price prognoses from several sources to consider in more detail competitiveness in years to come. A challenge and source of uncertainty in this approach is that in the case of battery-powered vehicles, using current component prices, a major "residual cost" emerges; in other words, a cost difference compared with diesel-powered vehicles that cannot be explained by differences in components and component prices alone. Feedback from manufacturers and other sources indicates that this is a result of development costs that the manufacturer is trying to recoup, as well as high unit costs in current, relatively low-scale production. Although it can be assumed that this residual cost will moderate in time, as observed in the case of construction worker cars and vans, and through price reductions from first to second generation battery-powered lorries, the development of this cost will be a significant source of uncertainty, with considerable effect on the ownership costs of battery-powered vehicles. Another source of uncertainty in addition to actual battery price development, is to what extent price trends and technology development will affect the size of battery packs in future vehicles. Feedback from manufacturers indicates that because of customers' requirements, the range of battery-powered lorries is expected to increase in the years to come. This means that reductions in price per kWh are expected, and at the same time manufacturers expect an increase in battery capacity (in kWh), compared with the current situation.

In terms of TCO, the difference between battery-powered vehicles and diesel vehicles becomes significantly smaller than the difference in initial purchase price. This is because battery-powered vehicles have significantly lower energy/fuel costs than diesel vehicles, as well as being subject to lower road toll charges. In the case of many other cost drivers (such as the cost of tyres or annual taxes), cost differences are relatively small or negligible. An important factor with the opposite effect is the uncertainty connected with the resale value of battery-powered vehicles. This is not only because of lack of experience of the residual lifetime of such vehicles, but also the fact that many of the diesel vehicles currently in use in Norway are exported to countries in eastern Europe. In view of the infrastructure needed for battery-powered vehicles and the purchasing power of countries to which Norwegian used vehicles are normally exported, there is uncertainty as to whether it will be possible to sell used battery-powered vehicles in the same way as diesel vehicles, and whether they will have the same resale value. However, one truck manufacturer states that it assumes that battery-powered lorries will have a decent resale value, since it is expected that zero-emission zones will be introduced both in Norway and in other (western European) countries.

In general, the competitiveness of battery-powered vehicles depends strongly on the intensity of use and the frequency of (relatively expensive) rapid charging. The cost elements that result in the largest savings are distance dependent. In other words, the competitiveness increases with increasing annual driving distance. At the same time, it is the annual driving distance itself that is restricted by the limited daily range of the currently available battery-powered vehicles. In addition, framework requirements such as the continuation or elimination of road toll concessions, ENOVA grants, incentives included in tender announcements, charging situations (availability and use of infrastructure) and charging costs, will seriously affect the competitiveness of battery-powered vehicles.

Specific cost estimates for construction vehicles

This section describes the most important conditions used as a basis for cost estimates and comparisons of the costs of construction vehicles with diesel-, HVO- and battery-powered operation.

Capital costs

Battery-powered construction vehicles already in use in Norway are claimed to have been about 3 - 3.5 times more expensive than equivalent diesel-powered vehicles. The additional cost of the latter has fallen between the first and second generation of mass production. There is considerable uncertainty about the additional costs in 2025 and 2030, as has also been pointed out by market operators. The additional costs used in our calculations are therefore based on estimated price differences and projections from TØI's detailed breakdown and projection work, as described above. This means that battery-powered tipper trucks are assumed to be around 2.25 times as expensive as diesel-powered vehicles in 2025 and around 1.9 times as expensive in 2030. In the case of battery-powered tipper trucks with a trailer, the corresponding figures are assumed to be around 2.1 and 1.8 times.

These estimates are based on the fact that 40% of investment costs for battery-powered vehicles are covered by a subsidy from ENOVA. In view of the uncertainty connected with residual values, two sets of TCO estimates have been prepared for each class of vehicles. The first assumes a service life of five years, with depreciation according to the declining balance method for diesel vehicles (and a residual value after five years of approximately 28% of the price when new), consistent with methods used in earlier analyses and the Norwegian National Goods Transport Model (20). The same residual value proportion has been used for battery-powered vehicles as for diesel vehicles but adjusted downwards by 50% in 2022 and 25% in 2025, to consider market uncertainty. For the other estimates a service life of seven years is assumed, with the residual value of both diesel and battery-powered vehicles being set at zero. To calculate and be able to compare ownership costs per kilometre, capital costs over the analysis period are discounted to 2022 kroner and divided by the distance driven in kilometres in the same period. The background of the two sets of estimates is based on feedback from the market to the effect that diesel- and battery-powered vehicles in some cases are approached differently, for example with regards to service life before resale (or when a re-purchase agreement) becomes applicable, or to what extent the choice is made to "use up" vehicles under the original ownership.

Usage and driving patterns

Literature, workshops, interviews, and background information indicate that the usage and driving pattern of construction vehicles can vary considerably. This applies both generally (diesel-powered vehicles may have significantly different usage patterns) and with respect to differences between diesel-powered vehicles and the use of the (relatively few) existing battery-powered vehicles. The latter is the result of range limitations and the need for charging, as well as the kind of projects the battery-powered construction vehicles are used for and the modifications this may entail in transport arrangements. One such modification may be that instead of transporting masses out of the city, battery-powered vehicles are used to transport it to interim storage depots on the outskirts of Oslo, while vehicles with internal combustion engines transport it to the final destination. It may be possible to improve this situation if arrangements can be found to recycle more of the material for use near building and construction sites, thereby reducing the need for long-distance transport.

In general, the driving distances of vehicles are often limited by the fact that they spend a lot of time stationary at construction sites, where time spent on loading and unloading is significant. This affects the competitiveness of battery-powered vehicles, since savings and additional costs connected with investment must be compensated for during their service life. Figures obtained from periodic inspections of construction vehicles in the Oslo area indicate that newer vehicles are driven on average from 35,000 to 50,000 kilometres per year. To reflect the large variation in usage and driving patterns and to illustrate the importance of intensity of use for the competitiveness of battery-powered vehicles, we present TCO estimates for annual driving distances of 20,000, 30,000, 40,000, 50,000 and 60,000 km.

Fuel and energy costs

Energy costs represent an important part of ownership costs. The analyses are based on the development of energy prices as summarised in Table 3. The cost of establishing a depot charger is included in the estimates as capital costs (NOK 100,000 and NOK 150,000 for tipper trucks, without and with a trailer, respectively). Apart from a (significantly) higher price per kWh for rapid charging, the costs of establishing rapid charging facilities and the cost of time spent charging have not been considered. Including costs for establishing rapid charging infrastructure by the operator is challenging and entails a good deal of uncertainty, since such costs depend strongly on the need for grid upgrades and on the number of vehicles served by each rapid charger. The extent to which time spent charging represents a cost, depends on how much of the charging takes place during breaks, in which the vehicles would not be in use anyway.

Operators state that the fuel consumption of construction vehicles varies considerably, depending on the type of driving and usage patterns. In our estimates, the diesel consumption of tipper trucks is assumed to be 0.4 litres/km, and 0.475 litres/km for tipper trucks with a trailer. These figures are based on feedback from operators and fleet management data for actual driving connected with building and construction transport, acquired through TØI's LIMCO project (10). It is also stated that the energy consumption of battery-powered vehicles can vary considerably, depending on the type of driving, as well as if second-generation vehicles have shown a significant improvement in energy efficiency. Therefore, in our estimates, energy consumption from battery-powered operation is based on the relative energy efficiency of diesel- and battery-powered powertrains, scaled according to the energy content of diesel. The resulting electricity consumption (1.4-1.7 kWh/km) is of the same order of magnitude as estimates provided by operators. The fuel consumption for HVO operation is based on the diesel consumption but adjusted for the relative energy content.

Energy costs in battery-powered operation are also dependent on how much the batteries are charged by charging at a depot (at a relatively low electricity price) and how much rapid charging is used, at a significantly higher cost per kWh. As mentioned above, TCO estimates are carried out at differing usage intensity (annual driving distances). Dividing by 250 operating days, this results in an average daily driving distance. Based on the range of the vehicles, we have defined proportions of rapid charging that increase with the daily driving distance. This assumes that with low daily driving distance there will be little need for rapid charging during the daytime, while in the case of intensive use, the need for rapid charging will be significant. Approaching 2025 and 2030, the proportion of rapid charging is adjusted downwards somewhat to reflect expected increases in battery capacity.

Road tolls

With regards to road tolls, we have assumed an average fee of 1.35 NOK per kilometre for diesel- and HVO-powered vehicles (based on figures from the National Goods Transport Model, adjusted for the Oslo area), and that battery-powered heavy vehicles will remain exempt from road tolls until after 2030.

Maintenance

Costs for general maintenance are based on the National Goods Transport Model (21), with some minor adjustments to reflect feedback from the market and assumptions in the corresponding analyses. Maintenance costs for diesel- (HVO-) and battery-powered vehicles are assumed to be approximately equal, based on feedback from the market. There are some indications that maintenance may be somewhat more expensive for battery-powered vehicles, but there are also signs that this cost may fall significantly, since battery-powered vehicles have fewer (moving) parts needing maintenance and are less subject to vibration. Moreover, technology-independent expenses for tyres and washing have been considered, also based on the cost assumptions of the National Goods Transport Model.

Other cost drivers

The TCO estimates also include annual expenses for insurance and management (obtained from the cost model in the National Goods Transport Model for equivalent vehicles), which are assumed to be the same for diesel- and battery-powered vehicles. The estimates also include the weight-dependent annual road tax, which is marginally higher for diesel-powered vehicles because of a small environmental differentiation in the tax.

Results of the cost analysis, transport

As previously mentioned, cost analyses have been carried out for a tipper truck with a maximum permitted total weight of 27 tonnes and a tipper truck with a trailer. The analyses are based on the current cost situation for diesel-, HVO- and battery-powered operation and on assumptions regarding cost developments up to 2025 and 2030. In addition, a sensitivity analysis has been carried out for the reduction or increase in energy costs, to study the effect of increased/reduced electricity prices and fuel prices.

The results presented are based on average annual driving distances of 40,000 km for tipper trucks, and 50,000 km for tipper trucks with trailers, and on the estimates for 5-year service lives (with associated assumptions regarding residual value, as discussed above). There are two exceptions, which are clearly defined: An illustration of the effect of lower/higher usage intensity (annual driving distance) and an illustration of the effect of ownership costs when a 7-year service life is stipulated with zero residual value for both diesel- and battery-powered vehicles.

Figure 9 shows the distribution of lifetime costs (in 2022) for the various cost categories: The investment cost (considering subsidies and included capital costs), operating costs (energy/fuel), maintenance costs, road tolls, other costs, and residual value after five years for the two categories of vehicle. The figure clearly shows that the acquisition costs and energy/fuel costs are the most important cost drivers. Acquisition costs are highest for battery-powered vehicles, which at the same time have significantly lower operating costs than diesel- and HVO-powered tipper trucks. There is also a saving because of the road toll exemption. It is assumed that standard energy prices as shown in Table 3 “Maintenance costs” represent a slightly less important cost driver, and any differences between vehicles with internal combustion engines and battery-powered powertrains will have less effect. Other costs have little cost driving effect. The figure also shows the effect of uncertainty regarding the residual value of battery-powered tipper lorries, which amounts to a smaller proportion of the (higher) investment costs than for diesel- and HVO-powered vehicles.

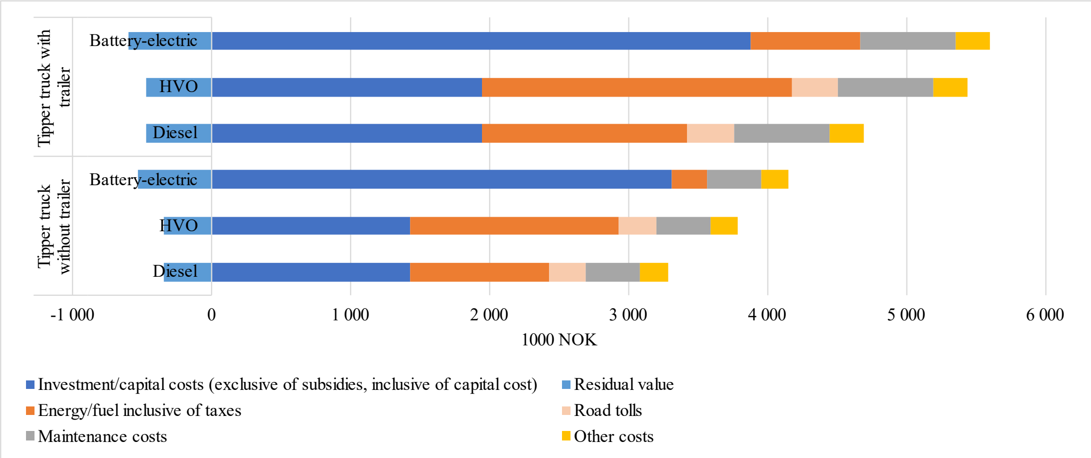


Figure 9.
Lifetime costs of a tipper truck without a trailer and a tipper truck with a trailer divided into various cost categories in 2022.

The development of total lifetime costs for tipper trucks with and without a trailer using different energy technologies is shown in Figure 10.

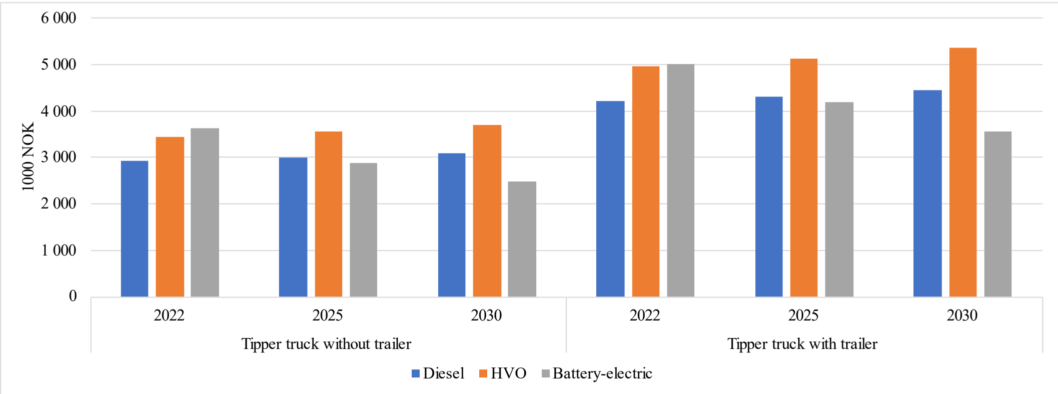


Figure 10.
The development of total lifetime costs in the years 2022, 2025 and 2030 for tipper trucks with and without a trailer using different energy technologies.

The lifetime costs for battery-powered tipper trucks are at present higher than for both diesel and HVO operation, but the difference (particularly for HVO) is smaller for tipper trucks. This is because of higher energy consumption per kilometre (and therefore higher savings on transitioning to electrical operation), as well as the higher annual driving distance assumed when using trucks with a trailer. With the assumptions regarding particularly the development of investment costs and energy prices specified here, battery-powered operation is expected to have lower lifetime costs than both HVO and diesel operation in 2025, for both tipper trucks with and without a trailer. With regards to 2030, the figure shows significant cost savings connected with battery-powered operation, largely because of expected major reductions in additional capital costs.

Figure 11 shows ownership costs for tipper trucks today, per km for varying annual driving distances.

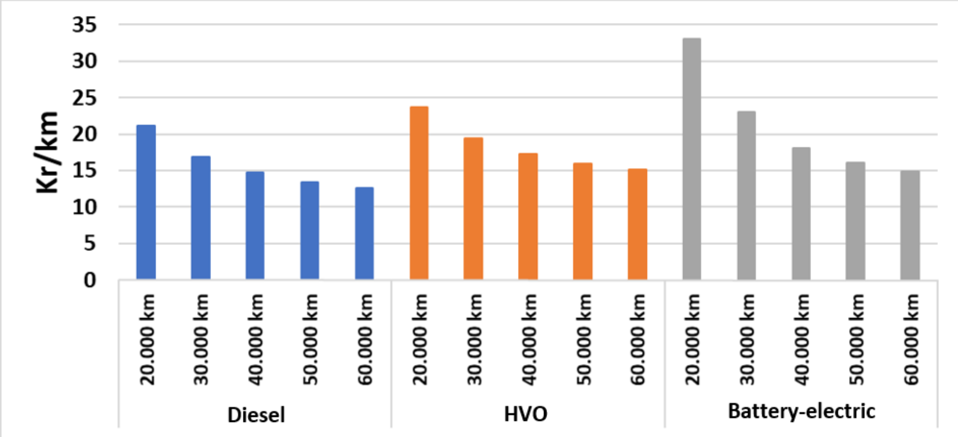


Figure 11.
Lifetime costs in NOK/km for tipper trucks in 2022, for different energy technologies and for varying annual driving distances.

The figure clearly illustrates the effect of intensity of use on the competitiveness of the different energy technologies. In the case of all the energy technologies, the costs per km fall, the more the vehicles are used since fixed costs are distributed over a longer distance. In the case of battery-powered vehicles, this reduction is greater because of the particularly high investment cost and the significant savings per kilometre driven. The figure illustrates, for example, that with high annual driving distances, battery-powered tipper trucks are already approaching competitiveness with HVO operation.

Finally, Figure 12 shows the effect of assuming a 5-year service life with normal residual value for internal combustion vehicles and some (but with some adjustment for uncertainty) residual value for battery-powered vehicles, compared with assuming a 7-year service life with full depreciation (zero residual value) for diesel-, HVO- and battery-powered vehicles. The figure reveals that costs per km are somewhat higher for all energy technologies when vehicles are used and fully written-down over 7 years, but that the difference is greatest for battery-powered vehicles. In other words, the size of the residual value resulting from the higher initial purchase cost has a greater effect on the competitiveness of battery-powered vehicles.

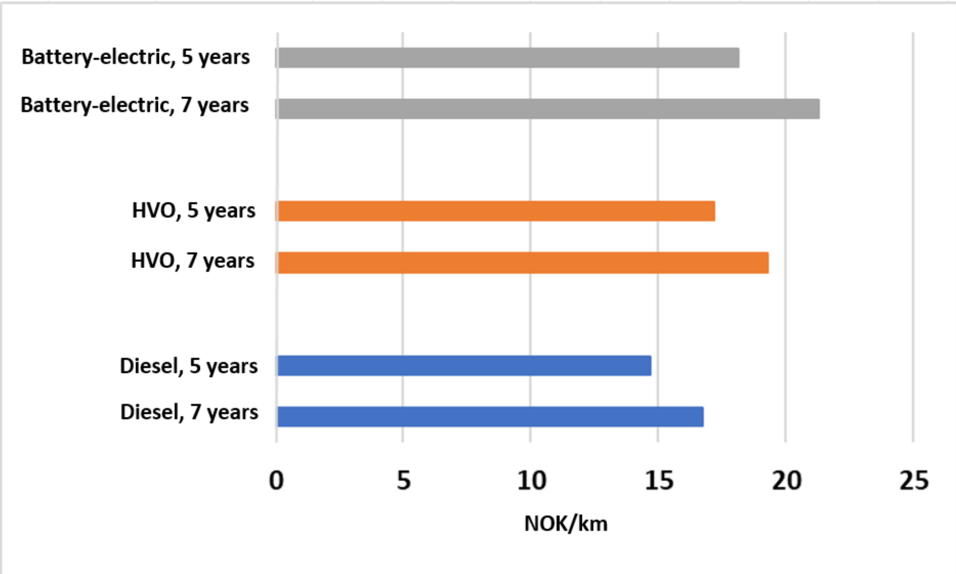


Figure 12.
Lifetime costs in NOK/km for tipper trucks in 2022 using different energy technologies and for 5-year analysis periods and normal residual value for vehicles with internal combustion engines and some (adjusted for uncertainty) residual value for battery-powered vehicles, and for 7-year analysis periods with full depreciation (zero residual value) for all energy technologies.

Cost analyses, construction machinery

Cost analyses have previously been carried out for excavators during the research project studying zero-emission excavators (the ZED project) (22). The following analyses are based on the results of the ZED project. Cost analyses were carried out for a small, medium, and large excavator, corresponding to 8.5, 17.5 and 38 tonnes. The analyses did not include construction machines under 8.5 tonnes. Electric excavators may have different propulsion configurations: battery, cable or a combination of battery and cable. For the purposes of this analysis, it was assumed that a small excavator is powered by battery, a medium-sized excavator has a combination of battery and cable, and a large excavator is powered by cable. Estimated power output and battery ratings is shown in Table 5.

Table 5.
Overview of main parameters for small, medium, and large excavators

Machine size	Small	Medium	Large
Energy system	Battery	Battery + cable	Cable
Weight class	8.5-16 tonnes	16-23 tonnes	>23 tonnes
Estimated battery rating or power output	>100 kW	70-260 kW	>260 kW

Investment costs

The investment costs for a small, medium, and large excavator in the current market are based on figures from the ZED project and have been updated based on interviews and workshops. The investment cost for diesel- and HVO-powered machines are estimated to be equal, but the cost for electric machines is about three times the equivalent cost for a diesel-powered machine (see Table 6). In creating the future scenarios, it is assumed the electric excavators are relatively cheap, compared with diesel-powered excavators. Based on interviews and a workshop with market representatives, it is difficult to make exact statements about this development, but the consensus is that prices will be reduced as time goes by. It is therefore assumed that prices for small and medium electric excavators will be about 2.5 times as expensive as diesel-powered in 2025 and 1.9 times as expensive in 2030. The investment cost for a large excavator is currently lower than for a small or medium machine, since the large machine runs only on cable supply and there are no costs connected with batteries. The investment cost today is approximately 2.4 times as great as for a diesel-powered machine and it is assumed that this will become twice as expensive in 2025 and 1.8 times as expensive by 2030. These figures are slightly higher than those that emerge in Endrava's report, commissioned by The City of Oslo's Agency for Improvement and Development in 2021, however, the trends are the same (17).

The investment costs include all costs connected with purchasing a machine, any modification, and any necessary extra equipment, such as a cable drum, rapid chargers and cables at the building and construction site. The cost of an electric excavator also considers an Enova subsidy of 40% of the additional costs.

Operational and maintenance costs

The operational costs equal the cost of consumption of diesel, HVO or electricity (see Table 3). It is assumed that all the machines have an operating time of 1,800 hours per year. Table 6 shows energy consumption for different sizes of excavator for each energy carrier.

Table 6.
Energy consumption for different sizes of excavator

		Small (8-16 tonnes)	Medium (16-23 tonnes)	Large (>23 tonnes)
Diesel	Litres/h	5.5	10	30
HVO	Litres/h	5.79	10.52	31.57
Electric	kWh/h	13	28	100

Originally, in the ZED research project, the maintenance costs for electric excavators were assumed to be somewhat lower than for diesel machines since they have fewer moving parts and hence less need for replacement of individual components. However, after a few more years of experience of the maintenance of electric machines it appears that the maintenance costs do not vary so much between different types of energy carrier. This is because the machines need regular inspection and maintenance regardless. Based on this, the maintenance costs are independent of the energy carrier (see Table 7). For a small excavator, a cost of 26 NOK per operational hour is assumed, while for medium and large machines a cost of 33 NOK per operational hour is assumed (22).

Other costs and residual value

It is assumed that other costs connected with, among other things, annual insurance are around 2.5% for all machine types and energy carriers. The residual value of electric excavators is still difficult to estimate since they have not been on the market long enough for figures to be available. It has therefore been assumed that the percentage residual value is the same as for diesel-powered machines. In the case of traditional diesel-powered machines, the assumed residual value is approximately 25% of the purchase cost after an analysis period of six years. Table 7 shows a summary of all costs for a small, medium, and large excavator at the present time (2022).

Table 7.
Summary of costs for a small (8-16 tonne), medium (16-23 tonne) and large (>23 tonne) excavator in 2022.

	Unit	Small Diesel/ HVO	Small Electric	Medium Diesel/ HVO	Medium Electric	Large Diesel/ HVO	Large Electric
Investment	mNOK/ machine	1.3	2.86	1.65	3.63	2.1	3.85
Maintenance	NOK/year	46 800	46 800	59 400	59 400	59 400	59 400
Other costs	NOK/year	32 500	32 500	41 250	41 250	52 500	52 500
Residual value	mNOK/ machine	0.32	0.72	0.41	0.9	0.52	0.96

Results of cost analysis, construction machinery

Cost analyses have been carried out for three different sizes of excavator – small, medium, and large – based on analyses of specific machines studied in the ZED research project. The analyses are based on the current (2022) cost situation and assumptions about the development of costs in 2025 and 2030. In addition, a sensitivity analysis has been carried out for reduction or increase in energy costs, to study the effect of increased electricity prices or reduced diesel and HVO prices.

Figure 9 shows the distribution of lifetime costs for the various cost categories: purchasing costs, operating costs, maintenance costs, other costs, and residual value after six years for the three types of excavators and three energy carriers in 2022. For excavators fuelled by diesel or HVO, the cost item connected with operation of the machines, consisting of fuel costs, maintenance, and other costs, varies. Operating costs for a small diesel-powered excavator amount to 41% of the total costs, while the operating costs for a large HVO-powered excavator amount to 68% of the total costs, disregarding the residual value. For electric excavators, it is clear that the purchase cost is the largest cost element, amounting to 75% of the total costs for a large excavator and 84% of the total costs for a small excavator, when the subsidy amounting to 40% of the additional costs is taken into account but the residual value is disregarded. This assumes standard energy prices as specified in Table 3. The development of total lifetime costs for a small, medium, and large excavator for each energy carrier is shown in Figure 14.

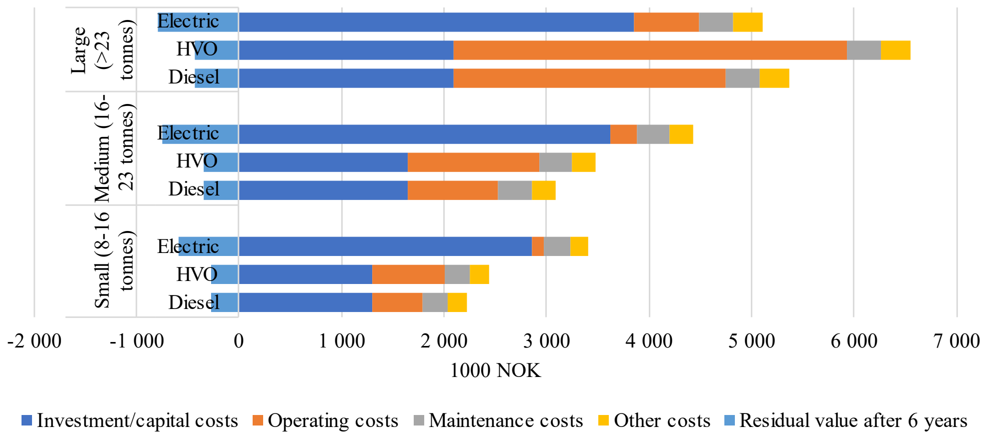


Figure 13.
Lifetime costs for a small, medium, and large excavator divided into cost categories in 2022.

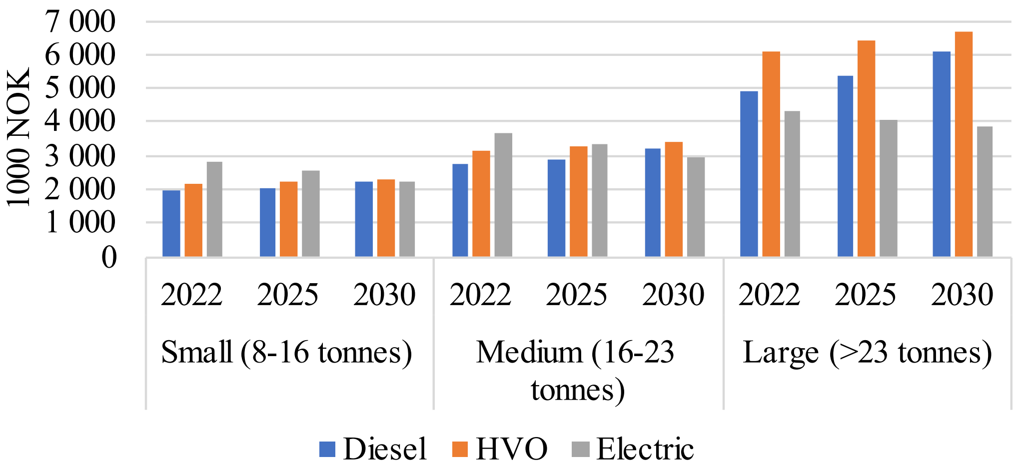


Figure 14.
Development of lifetime costs for 2022, 2025, 2030 for each excavator size and energy carrier.

The lifetime costs for a small and medium electric excavator are somewhat higher than for both a small diesel-powered and a small HVO-powered excavator in 2022 and 2025, even considering the subsidy of 40% of the additional costs at purchase. However, it is expected that this will even out as 2030 approaches since it is assumed that electric excavators will increasingly be mass-produced and that battery costs will fall with time. For the large excavator, the electric version is already a better alternative in 2022, seen in a lifetime perspective, compared with the HVO or diesel alternative. This is to a large extent because it is assumed that large electric excavators operate only on cable supply and therefore avoid the investment costs connected with batteries. This also means that large cable-operated excavators can be competitive pricewise in comparison with the current diesel-powered alternative, considering the subsidy of 40% of the additional costs at purchase.

The point of intersection at which the lifetime costs for an electric excavator become lower than those for one that runs on diesel or HVO is shown in Figure 15. The grey line shows the lifetime costs for an electric excavator, orange shows an HVO-powered excavator and blue shows a diesel-powered excavator. For the small excavator, the grey line does not cross the blue or orange lines either in 2022 or 2025, and barely crosses the orange line in 2030. This means that the investment costs are not recouped over the six-year analysis period. Investment costs for a medium electric excavator in 2030 will equal those for an HVO- or diesel-powered machine over the six-year analysis period. For the large excavator, the investment costs for the electric alternative will be recouped over the six-year analysis period, even for an investment carried out in 2022.

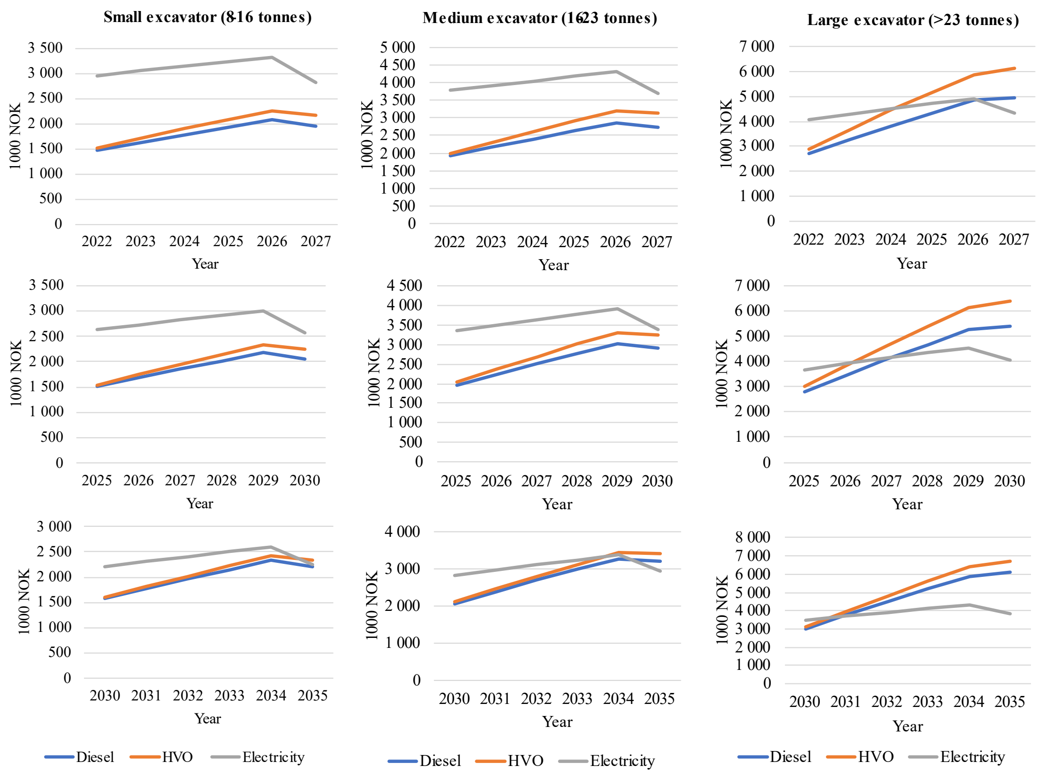


Figure 15.
Cost developments for a small, medium, and large excavator assuming investment in 2022, 2025 and 2030.

There are several sources of uncertainty connected with the cost estimates. The investment costs in 2025 and 2030 assume that the manufacture of zero emission alternatives will become cheaper, which implies an increasing degree of mass-production of machines and greater demand outside of the City of Oslo. This depends on market development. Another significant source of uncertainty is energy prices, and in particular carbon taxes and electricity prices. Sensitivity analyses have been carried out to assess the way in which energy prices may affect development.

Sensitivity analysis of energy prices

Sensitivity analysis has been carried out to assess the effect of changes in energy prices. Two alternative scenarios to the reference scenario have been considered, which are shown in the cost analyses for excavators and heavy vehicles.

1. **Pessimistic scenario.** Electricity prices are high and assumed to be three times as high as those specified in Table 3. It is assumed that carbon taxes are not as high as shown in Table 3, thereby reducing the total cost of diesel. It is also assumed that the cost of HVO falls by an amount corresponding to the reduction in carbon tax.
2. **Optimistic scenario.** Electricity prices are somewhat lower than assumed, being only 75% of those specified in Table 3. The carbon taxes are higher than assumed, being 1.5 times as high as those specified in Table 3. Hence the total cost of diesel power increases. It is also assumed that the cost of HVO rises by an amount corresponding to the rise in carbon tax.

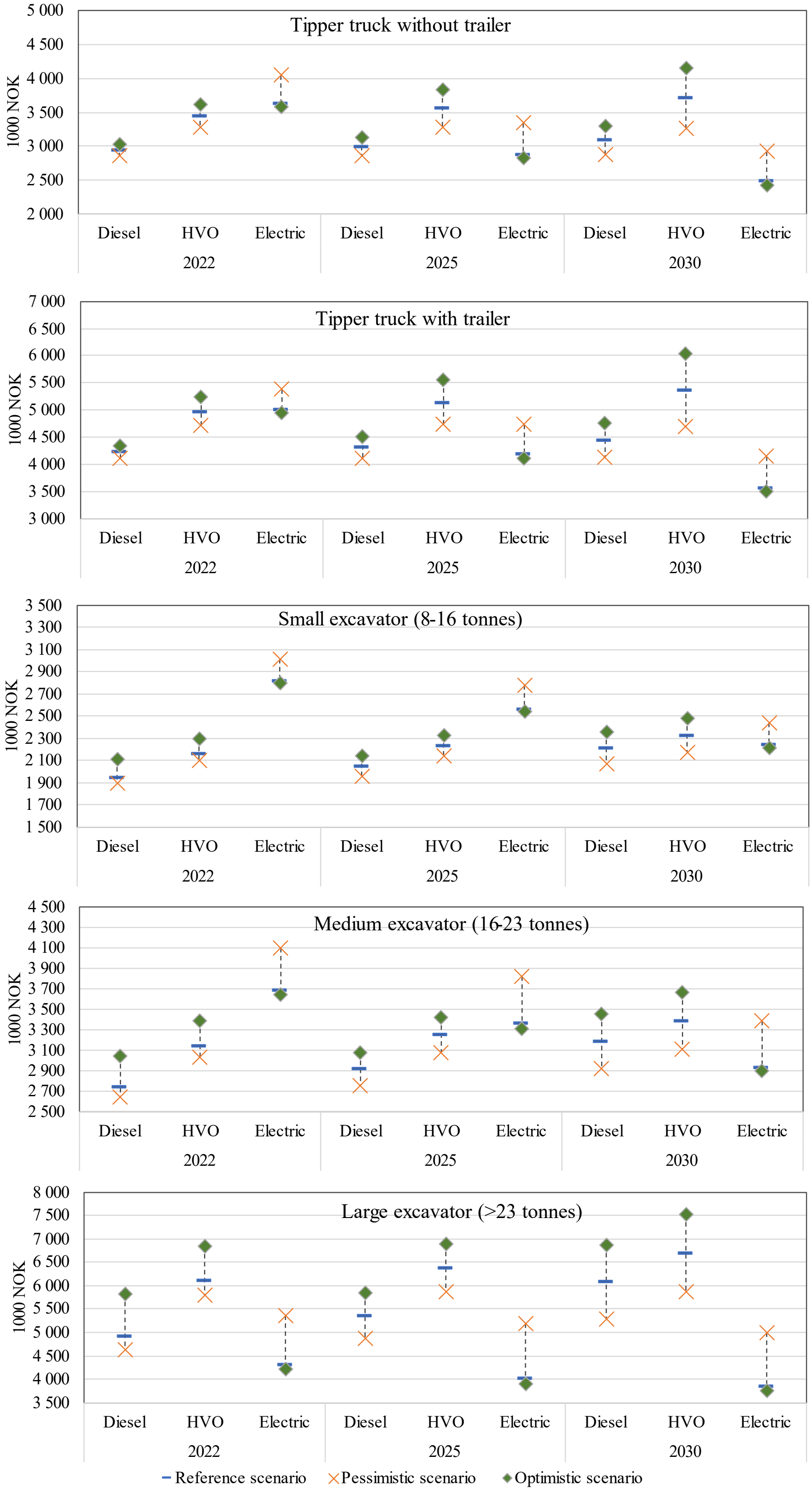


Figure 16.
Sensitivity analysis for changes in energy prices for tipper trucks with and without a trailer and small, medium and large excavators for 2022, 2025 and 2030.

The sensitivity analysis for tipper lorries shows that in the optimistic scenario (lower electricity prices and higher diesel and HVO costs), the lifetime costs for electric tipper trucks are relatively close to the costs for HVO-powered tipper trucks today, but still significantly higher than with diesel operation. With the cost development towards 2025, electric operation results in lower lifetime costs than HVO operation, except in the pessimistic scenario, in which the lifetime costs for the two technologies are approximately the same. Also compared with ordinary diesel operation, electric operation in 2025 can be competitive, except in the pessimistic scenario. With the cost development towards 2030, electric operation in that year will be significantly cheaper than HVO operation, even in the pessimistic scenario, and will be cheaper than ordinary diesel operation (or in the pessimistic scenario the lifetime costs will be approximately the same).

The sensitivity analysis for excavators shows that in the optimistic scenario (lower electricity prices and higher diesel and HVO costs), the lifetime costs for a small electric excavator are relatively close to those for an HVO-powered excavator over the six-year analysis period and can be competitive pricewise with both HVO- and diesel-powered excavators in 2030. With regards to the medium excavators, an electric machine is already competitive with an HVO-powered one by 2025 in the optimistic scenario. In the reference scenario and the optimistic scenario, a medium electric excavator is also competitive with the diesel-powered alternative by 2030. With regards to large excavators, the electric alternative was already competitive with both HVO and diesel in the reference scenario in 2022. Here it can be seen that in the pessimistic scenario (higher electricity prices and lower diesel and HVO prices), the large electric excavator will not be competitive with the diesel variant before 2030.

Additional costs, building and construction sites

Based on the cost analyses carried out for tipper trucks with and without a trailer and small, medium, and large excavators, an estimate has been made of additional costs connected with the transition to an electrified building and construction sites. Several cost elements are not included in the quantitative analysis, since figures based on past experiences are not available. This applies, among other things, to the transition to zero emission drying and heating of buildings, and to the expansion of the energy grid (both for electricity and district heating). The interviews and questionnaire revealed that the additional costs for the operation of a zero emission building and construction site, compared with a traditional site, are not fully known. Respondents suggested anything from 0-5% additional costs up to 40%. On the other hand, for drying and heating buildings it is estimated that there will not be large additional costs if there is adequate planning in the early project phase. Based on the calculations of the "*Norsk Prisbok*" database for building and construction, the shared costs, which include among other things rigging and operating a building site, are about 8% of the total cost of a building project (23). In the case of construction projects, it is assumed that this percentage will be somewhat larger, and dialogue with the market indicates that it may be up to 20% of the total costs.

The additional costs presented in this report will therefore represent a large percentage of the total additional costs, since both operation of construction machinery and operation of heavy vehicles are included. The largest source of uncertainty will relate to the customer contribution that may result from the need to expand the energy grid. However, it is assumed that this may be to a large extent avoided by good planning in the early project phase.

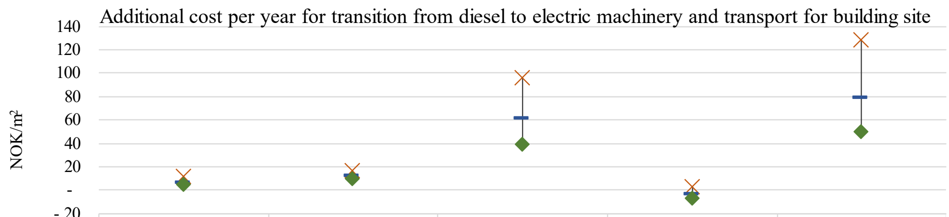
Table 8 shows the additional costs in kroner per kWh of consumption on transitioning from diesel to electric and from HVO to electric operation for all the types of machines for which cost analyses have been carried out. The values include the uncertainty analysis connected with changes in energy prices as shown in Figure 12. Values are shown for project start-up in 2022, 2025 and 2030. In connection with start-up in 2022, most of the values are positive, which means that transitioning from diesel or HVO operation to electric operation results in additional costs. This changes gradually, and in 2025 and 2030 the additional costs are reduced. In 2030 there may be some cases of reduced costs connected with electrification.

Table 8.
Additional costs per kWh on transitioning to electric operation, compared with diesel and HVO, for all types of machine and vehicles in 2022, 2025 and 2030.

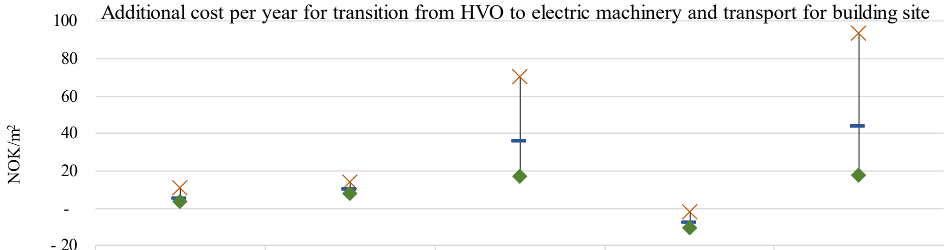
Additional cost in NOK per kWh		2022	2025	2030
Small excavator	Diesel to electric	[4.9] - [8.0]	[2.8] - [5.8]	[-1.0] - [2.6]
Small excavator	HVO to electric	[3.6] - [6.4]	[1.5] - [4.5]	[-1.9] - [1.9]
Medium excavator	Diesel to electric	[2.0] - [4.8]	[0.8] - [3.5]	[-1.8] - [1.5]
Medium excavator	HVO to electric	[0.9] - [3.5]	[-0.4] - [2.4]	[-2.5] - [0.9]
Large excavator	Diesel to electric	[-2.1] - [1.0]	[-2.5] - [0.4]	[-4.0] - [-0.4]
Large excavator	HVO to electric	[-3.4] - [-0.5]	[-3.9] - [-0.9]	[-4.9] - [-1.1]
Tipper truck	Diesel to electric	[1.94] - [4.19]	[-1.08] - [1.66]	[-3.08] - [0.15]
Tipper truck	HVO to electric	[1.20] - [3.67]	[-1.96] - [1.15]	[-4.15] - [-0.33]
Tipper truck with trailer	Diesel to electric	[1.44] - [3.02]	[-0.92] - [1.46]	[-3.00] - [0.06]
Tipper truck with trailer	HVO to electric	[0.7] - [2.51]	[-1.80] - [0.95]	[-4.07] - [-0.42]

Energy estimates have been carried out for the fully electric building and construction sites. Based on these estimates, an analysis has been carried out on the additional costs for a fully electric building project and a fully electric construction project. The additional costs for the building project are shown in NOK per square metre of building (NOK/m²) while the additional costs for the construction project are shown in NOK per million NOK of contract price (NOK/mNOK). The additional costs are based on additional costs per kWh for different types of machines and consider the sensitivity analysis connected with energy prices.

Calculated additional costs for a sample building site per machine type and in total for the operation of the building site assuming start-up in 2022, 2025 and 2030 are shown in Figures 17, 18 and 19 respectively. In comparison, the building cost for the building site is more than 25,000 NOK per m², but the total budget may be over 37,000 NOK per m² (23). This means that for the pessimistic scenario in 2022, in which the additional costs are estimated to be around 129 NOK per m², this represents less than 1% of the total budget of the project. Other additional costs will also accrue that are not considered in this analysis. For example, there may be a cost connected to the electricity supply, resulting in a customer contribution to the grid operator or a cost connected to mobile electricity supply systems such as battery banks.

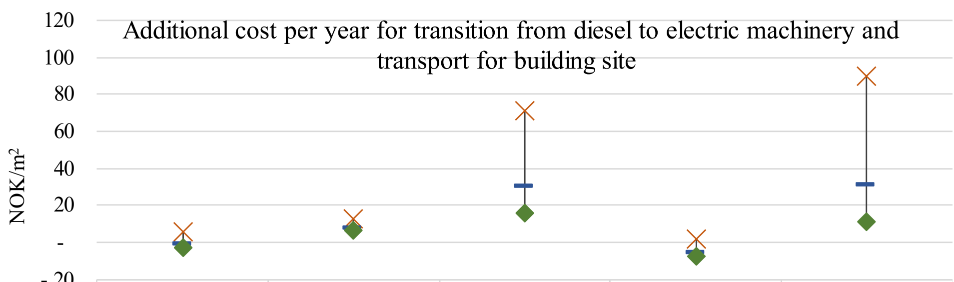


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	12	17	96	3	129
Reference scenario	7	13	62	- 3	80
Optimistic scenario	6	11	40	- 7	50

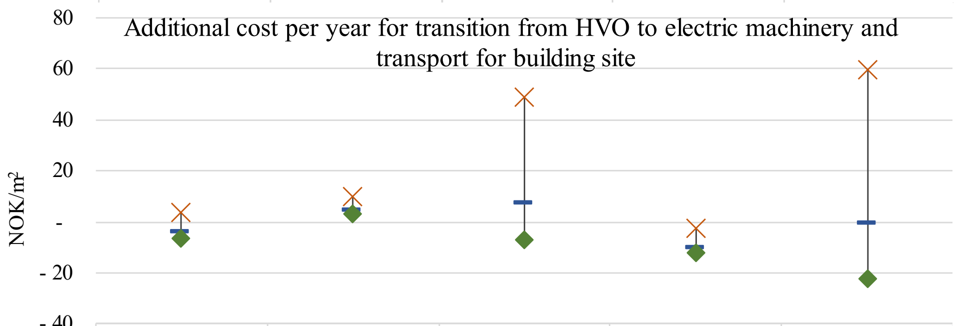


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	11	14	70	- 2	94
Reference scenario	5	10	36	- 7	44
Optimistic scenario	3	8	17	- 11	18

Figure 17.
Additional costs for an electrified building project per year on transitioning from diesel and HVO to electric construction machinery and heavy transport. Based on 2022 figures

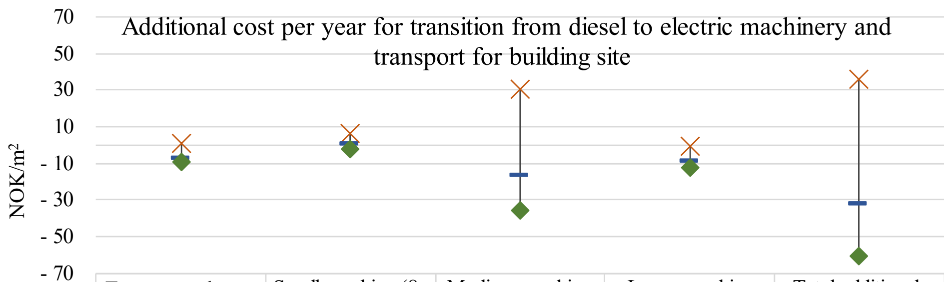


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	5	13	71	1	90
Reference scenario	- 1	8	30	- 5	31
Optimistic scenario	- 3	6	16	- 8	10

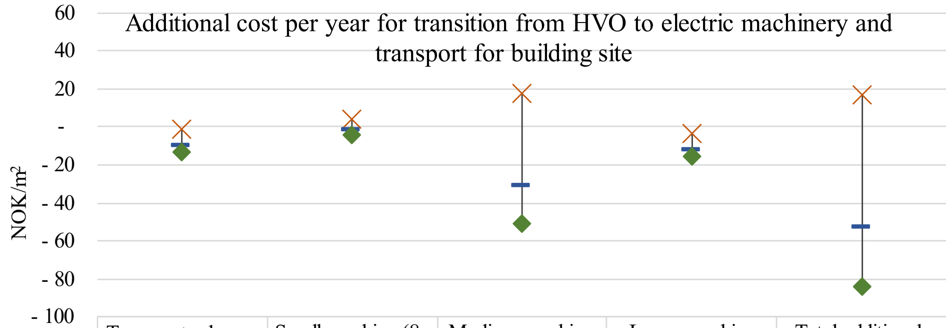


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	4	10	49	- 3	60
Reference scenario	- 4	5	8	- 10	- 0
Optimistic scenario	- 6	3	- 7	- 12	- 22

Figure 18.
Additional costs for an electrified building project per year on transitioning from diesel and HVO to electric construction machinery and heavy transport. Based on 2025 figures.



	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	0	6	31	- 1	35
Reference scenario	- 7	0	- 17	- 9	- 32
Optimistic scenario	- 10	- 2	- 36	- 13	- 61

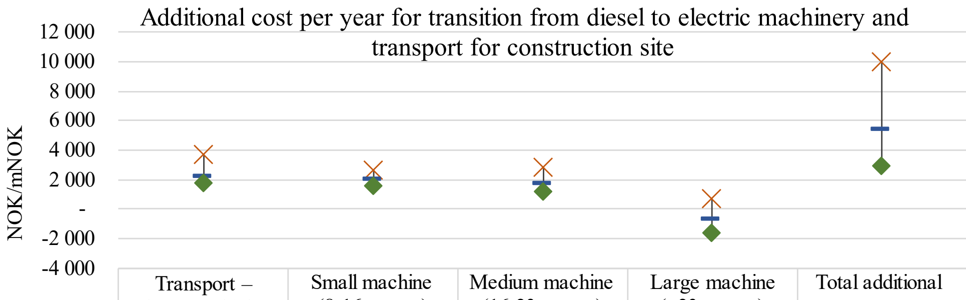


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	- 1	4	18	- 4	17
Reference scenario	- 9	- 1	- 30	- 12	- 53
Optimistic scenario	- 13	- 4	- 51	- 15	- 84

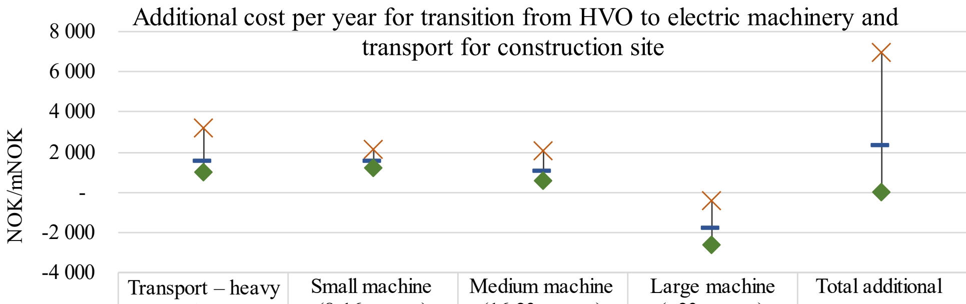
Figure 19.
Additional costs for an electrified building project per year on transitioning from diesel and HVO to electric construction machinery and heavy transport. Based on 2030 figures.

In 2022 and 2025 there will still be an additional cost on transitioning from diesel and HVO to a fully electrified building site. In 2030 there is significantly greater uncertainty connected with the figures, but assuming the right price conditions and market development, an electrified building site may be competitive with a site operated on either HVO or diesel.

Calculated additional costs for a sample construction site per machine type and in total for the operation of the construction site assuming start-up in 2022, 2025 and 2030 are shown in Figures 20, 21 and 22.



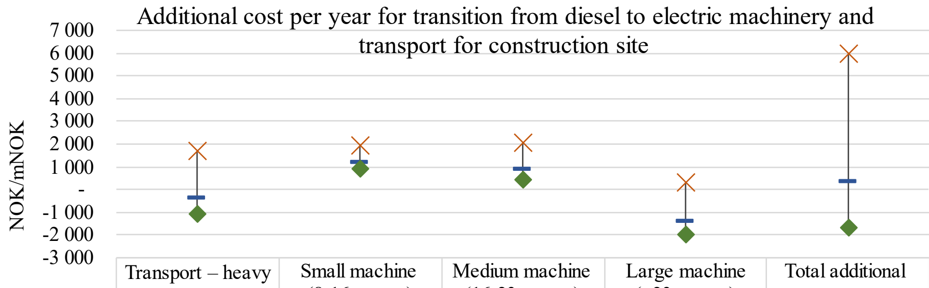
	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	3 753	2 633	2 819	758	9 962
Reference scenario	2 247	2 048	1 819	- 627	5 487
Optimistic scenario	1 772	1 626	1 176	-1 618	2 956



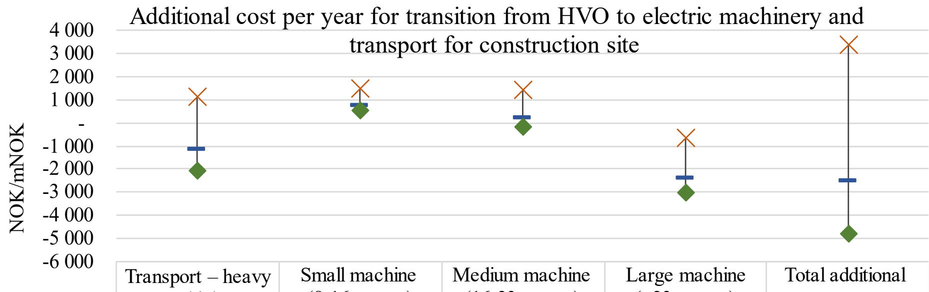
	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	3 170	2 129	2 065	- 422	6 941
Reference scenario	1 536	1 537	1 055	-1 823	2 305
Optimistic scenario	934	1 177	506	-2 667	- 50

Figure 20.
Additional costs for an electrified construction project per year on transitioning from diesel and HVO to electric construction machinery and heavy transport. Based on 2022 figures.

In 2022, a fully electrified construction site will involve additional costs compared with the use of both diesel and HVO. In 2025, according to the optimistic scenario, it will be possible to achieve an electrified construction site with approximately the same cost level as a construction site using diesel. In the 2030 scenario it is only in the pessimistic scenario with high electricity prices and low carbon taxes that there will be additional costs connected with an electrified construction site, as compared with one using diesel.

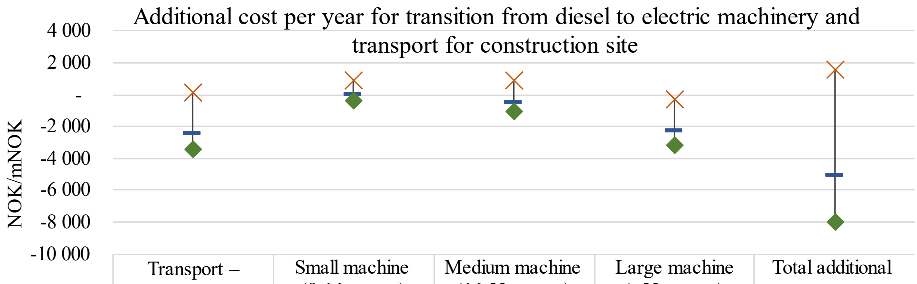


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	1 712	1 916	2 073	314	6 015
Reference scenario	- 369	1 212	884	-1 352	374
Optimistic scenario	-1 087	939	460	-1 993	-1 681

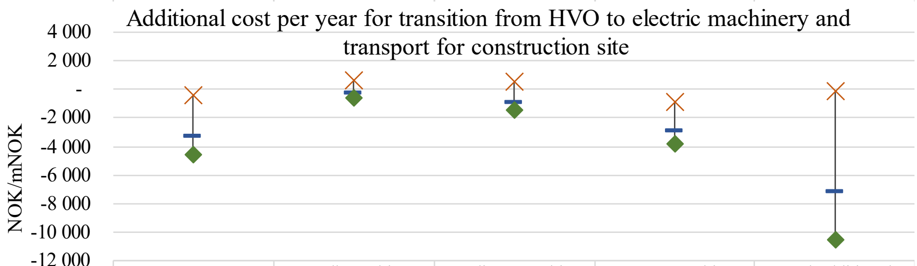


	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	1 128	1 489	1 436	- 684	3 368
Reference scenario	-1 158	774	230	-2 376	-2 529
Optimistic scenario	-2 079	491	- 211	-3 043	-4 842

Figure 21.
Additional costs for an electrified construction project per year on transitioning from diesel and HVO to electric construction machinery and heavy transport. Based on 2025 figures.



	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	89	876	895	- 302	1 558
Reference scenario	-2 372	66	- 485	-2 268	-5 060
Optimistic scenario	-3 423	- 335	-1 063	-3 158	-7 979



	Transport – heavy vehicle	Small machine (8-16 tonnes)	Medium machine (16-23 tonnes)	Large machine (>23 tonnes)	Total additional costs
Pessimistic scenario	- 454	628	523	- 884	- 187
Reference scenario	-3 247	- 201	- 884	-2 892	-7 222
Optimistic scenario	-4 628	- 619	-1 488	-3 824	-10 559

Figure 22.
Additional costs for an electrified construction project per year on transitioning from diesel and HVO to electric construction machinery and heavy transport. Based on 2030 figures.

Market analyses

A study has been carried out of market trends, using questionnaires and interviews of relevant operators, such as contractors, machinery suppliers, energy suppliers and trade organisations to assess the development of costs and availability of machinery and equipment for zero emission building and construction sites. The market analysis has been used to ascertain expectations for how investment development and availability will be in the years up to 2025 and 2030 for:

- Energy supply systems
- Drying and heating buildings
- Zero emission construction machinery
- Zero emission transport vehicles

Contributions from the market dialogue

The market dialogue was conducted by way of interviews with relevant operators, workshops, and a questionnaire with a wider distribution. The City of Oslo has set its sights on achieving zero emission municipal building and construction operations by 2025. All building and construction operations in the city shall be zero emission by 2030. Based on the interviews it appears that the most positive respondents believe that the City of Oslo will achieve its goals by 2025 and 2030, with a few exceptions. Few believe that it will be possible to achieve the 100% zero emission goal by 2030, since there are still many types of construction machines that have not yet begun the transition to zero emission operation. There appears to be a belief that infrastructure and excavators will be available to meet the demand in Oslo in 2025, but that availability of other machines, such as tractors, dumper trucks and wheel loaders, for which electric options are not available at present, will not be adequate. Neither will options for zero emission transport be in adequate supply by 2025, according to those responding. Many believe that hydrogen fuel cell concepts will not be on the market at all in 2025, and that they will only be available in limited numbers in 2030, while others are more optimistic about such systems. There appears to be little confidence that full electrification will have been achieved, but that there will need to be an energy mix in which district heating, hydrogen and biogas become increasingly used, especially where no electricity supply and infrastructure are available. Hybrid concepts as an interim solution do not appear to be a likely option. However, it is argued that it is easier to achieve fossil-free operation, which after all will be better than nothing.

The major manufacturers, such as Volvo, have begun to produce zero emission concepts for large excavators (over 8 tonnes), but these will not be mass produced by 2025. Some point out that Volvo is transitioning gradually to zero emission, via fossil-free concepts, and that this will continue after 2030. Several major manufacturers have commenced mass production of smaller construction machines (under 8 tonnes), but heavier machines are only being specially produced in smaller numbers. With a tripling of carbon taxation, some are of the opinion that Volvo and Scania may already reach parity by 2025. Nevertheless, the consensus appears to be that parity, both for vehicles and for construction machinery, will be more likely to be achieved in 2030. As a rule, it takes two to three years from the introduction of a machine until it is commercially available. Many models will therefore not be ready for sale in 2025. Some believe that is within the bounds of possibility that almost the entire market share (new investments) will be zero emission by 2030. Nevertheless, it is expected that there will continue to be a need for a good deal of HVO in many existing vehicles. The depreciation time is 5-6 years, but machines may have many years of service life on the after-market.

With regards to the significance for the market and value chain, there is a broad agreement that the transition requires expansion of the supply grid, both for district heating and for electricity, and that infrastructure for charging large vehicles must be in place. The availability of infrastructure for energy supply stands out as one of the most critical parameters. More machine suppliers are entering the market, which is very important, since if a zero emission situation is to be achieved, the market must transition from adaptation to mass production.

Zero emission building and construction sites also pave the way for new business models and business areas, such as systems for energy supply, data acquisition, data processing, analysis, and management. Another interesting market development is that contractors appear to be increasingly renting machines, rather than owning them.

Development scenarios

To elucidate the prospects for zero emission construction sites in Oslo in 2030, we have chosen to use a scenario process. This method is much used in the field of management (24) but can also be applied to a range of issues in various industry sectors. It is a suitable method when the future is expected to look radically different from the present situation. The method consists of bringing together a handful of operators with relevance to the issue. By means of mutual dialogue, they identify important driving forces, the main sources of uncertainty and potential future scenarios. The dialogue is open to new ideas and is intended to encourage creativity, but the scenarios should be realistic. The method forces us to avoid envisioning development paths merely based on historical trends. Uncertainty is the core of the method, and the main sources of uncertainty are the starting points for the scenarios. The main sources of uncertainty shall be scalable and as independent as possible of each other because they are intended to present four different scenarios in the form of a scenario matrix. The future scenarios are described by means of the driving forces that are identified. The scenarios are not a single figure, such as zero net CO_2 emissions or 2.5 °C temperature rise. The scenarios constitute future stories about what, for example, an industry sector may look like some time in the future. The scenario method also often includes discussion of potential development paths that may lead to these scenarios (24). This method has, for example, been used in previous SINTEF reports "*Framsikt 2050*" (Foresight 2050) (25) and "*Gull i grønne skoger*" (Gold in green forests) (26).

In this work, the scenario descriptions are based on interviews with relevant operators. The work was followed up with a questionnaire and then a workshop in which driving forces, the main sources of uncertainty and future scenarios were discussed. In this study, the future scenario is zero emission construction sites in Oslo in 2030. The main sources of uncertainty selected are requirements and technology development. "Requirements" means the requirements set by the City of Oslo, while technology development is seen as a global quantity. Figure 23 shows identified driving forces that affect the transition to zero emission building and construction sites. The main parameters are highlighted.

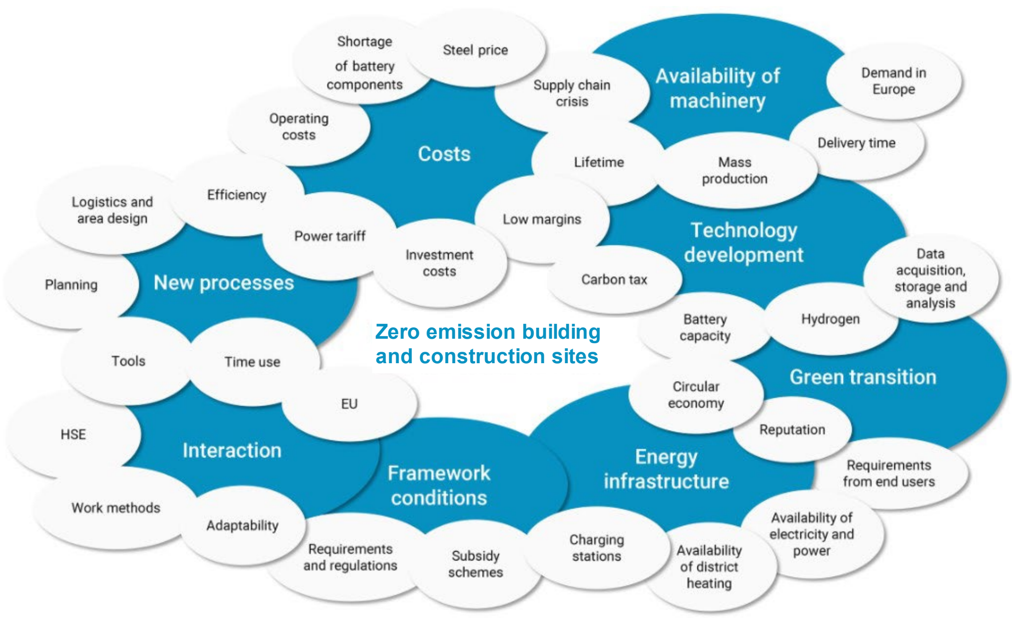


Figure 23.
Parameter list of driving forces affecting development.

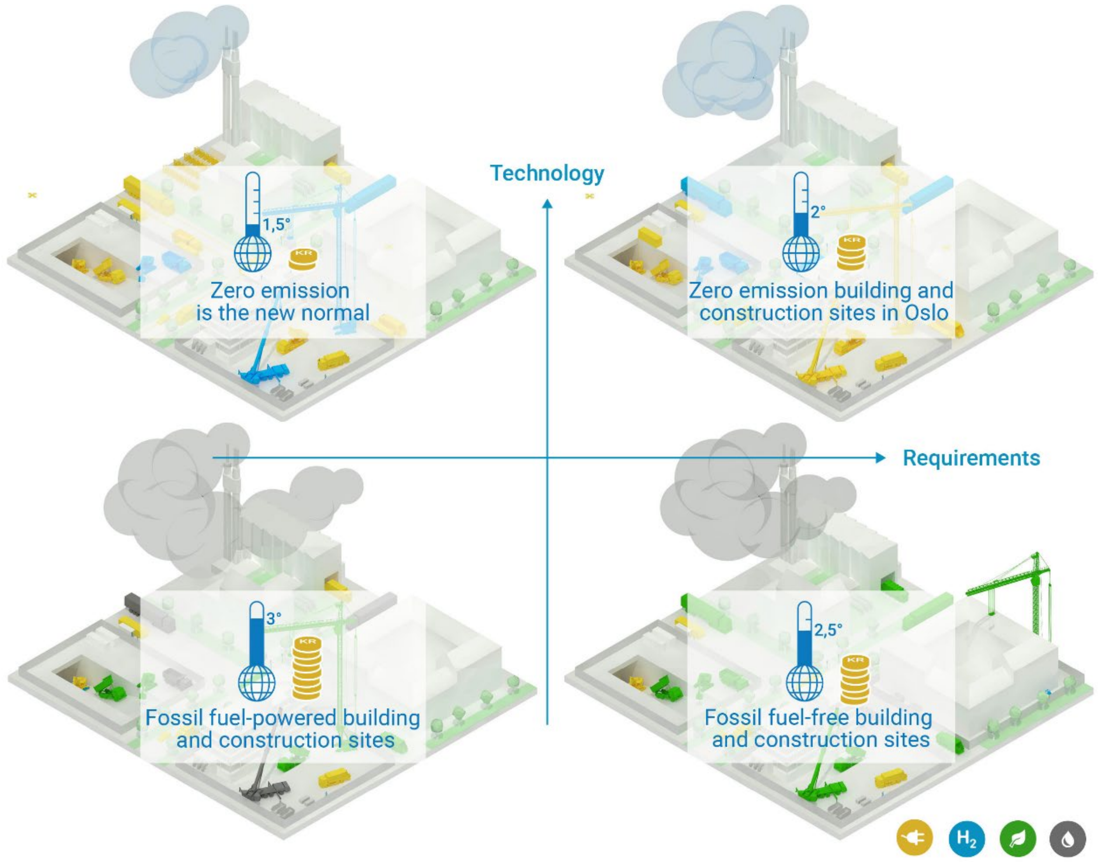


Figure 24.
Scenario matrix with four different scenarios that assesses the effect of requirements from the City of Oslo and accessibility of zero emission concepts up to 2025 and 2030.

In the "Zero emission is the new normal" scenario, at the top left of the scenario matrix, few requirements are imposed by the City of Oslo, and global technology development is rapid. In the "Zero emission building and construction sites in Oslo" scenario, the City of Oslo imposes strict and effective requirements and technology development is rapid. In the "Fossil fuel-free building and construction sites" scenario, the City of Oslo imposes strict requirements and technology development is slow. In the fourth and last scenario "Fossil fuel-powered building and construction sites", the City of Oslo imposes few requirements and technology development is slow. Below we will describe the future scenarios in detail.

Zero emission is the new normal

Figure 25.
Scenario 1 – Zero emission is the new normal.

Zero emission has become the new normal and we are moving towards the 1.5ºC goal. National coordination with strict requirements and subsidy schemes in those markets that have made less progress has led to rapid technology growth in this scenario. Because Norwegian building codes (TEK30) requires zero emission building and construction sites at a national level, the City of Oslo no longer needs to impose strict requirements for such sites locally. It happens by itself. The technology development has contributed both to lower costs and to increased demand for zero emission concepts. The City of Oslo has received international assistance, among other things through high carbon pricing and the establishment of the EU taxonomy. Global development has led to mass production of machinery and equipment needed to operate a zero emission building or construction site. Zero emission construction machinery and small vehicles are now cost effective. Heavy transport is partially electrified and battery- or hydrogen-powered heavy transport is becoming increasingly common on the roads, although the costs are still high in comparison with biofuel. Biogas and hydrogen generation are being brought into use at building and construction sites, and to a large extent outside urban areas.

Infrastructure for energy supply at building and construction sites and charging of mass, waste and goods transport is established in Oslo and the surrounding areas. Some main routes in and out of Oslo are being developed as electric roads. The district heating grid has undergone major development, both in Oslo and in most urban areas in Norway. The use of fossil fuel for district heating peak load has been replaced by biogas. The remaining biofuel consumption is minimal, and the use of waste incineration in district heating has increased. Focus on a circular economy has also increased the use of surplus heat from industry, which among other things is used for fourth-generation district heating. As a result of a major energy efficiency effort and an energy mix of district heating, biogas and hydrogen, the energy price is relatively low.

New machinery suppliers, equipment suppliers and services linked to zero emission building and construction sites have entered the market, also in Norway and in the capital and its surrounds. Many effective methods exist for acquiring and analysing data and for efficient management of energy consumption. Moreover, the entire building process, from the early planning phase to operation has been standardised and runs smoothly. All in all, the building and construction industry is well organised and associated industries in Oslo can be transformed into zero emission building and construction sites in this scenario.

Zero emission building and construction sites in Oslo

Figure 26.
Scenario 2 – Zero emission building and construction sites in Oslo.

The Oslo region, as well as the largest Norwegian cities and some major international urban areas, has attained the goal of zero emission building and construction sites. Thanks to energy-efficient concepts and better logistics, the entire value chain has become zero emission. The rest of the country and the EU are on the way to achieving zero emission building and construction sites but have not quite reached the finishing line. Both the EU and urban municipalities in Norway are aiming for fossil-free conditions as an interim solution before becoming zero emission. This entails high demand for biofuels and leads to an emission level corresponding to an average temperature rise of 2ºC.

Because of slow global market development, and to maintain its reputation as a forerunner, the City of Oslo maintains its strict requirements in 2030. The requirements are formed in close communication with the market and stakeholders, but strict requirements are placed on both public procurement and the planning system, and requirements are imposed on private developers. The requirements have also been intensified to apply to the service life of machinery. Moreover, the requirements are coordinated with those in the largest towns and municipalities in the region around the capital, but the rest of Norway and Europe lag behind. Nevertheless, work proceeds in Norway on a national plan for energy supplies, aimed at making the entire building and construction industry in Norway zero emission. The shaping of these plans includes flexible, adapted concepts for energy supply and collaborative models for developing district heating, electricity grids and fibre networks.

The rather slow global market development results in relatively high costs, compared with that of the "Zero emission is the new normal" scenario. At the same time carbon taxation is high. Zero emission machinery and vehicles are available, and most purchases are zero emission, but the price of such construction machinery remains relatively high. Some electric heavy transport exists and even the heaviest construction machinery runs on batteries. Hydrogen and hybrid alternatives are also available. These are slightly more cost-effective than the battery-powered alternatives for the largest machines and vehicles. There is large-scale production of biogas from agriculture, which caters for urban road vehicle needs. For construction projects, only tunnel projects are successful in being zero emission outside of urban areas, and this is thanks to cable-powered concepts. Infrastructure is available for both charging and energy supply in the capital region and the largest towns such as Trondheim and Bergen. This applies to both electricity supply and district heating. Wireless charging has been introduced, but this is still a niche concept in a pilot stage and involves high costs.

Despite rather slow global development and relatively high costs, there appears to be a global trend towards zero emission building and construction sites, with the largest towns in the US and Europe demanding zero emission building site concepts, and the concept of zero emission building and construction sites has been introduced in China and India. Hence, we see market optimism and willingness to invest, accompanied by a belief that investment costs will fall further. In addition, Oslo has proved to be successful with standardised concepts, planning and procurement processes, and it is expected that the rest of Norway and the EU will catch up. Power grid operators have become very attractive workplaces and increasing numbers of climate and environmental consultants are being recruited who are contributing with emissions accounting, analysis, and optimisation. More and more new concepts are being offered for energy efficiency and data acquisition and analysis. The circular economy is given high priority and there is a growing secondary market for zero emission machinery and vehicles. All in all, we see that the building and construction industry and associated industries are finding it increasingly easy to transition to zero emission building and construction sites, after several demanding transitional years in this scenario.

Fossil fuel-free building and construction sites

Figure 27.
Scenario 3 – Fossil fuel-free building and construction sites

National emissions remain relatively high because technology does not exist to meet zero emission requirements. The projects that are successful in becoming zero emission are still regarded as pilot projects. The smallest building and construction projects can, as a rule, be implemented as zero emission in Oslo, but at a high cost. Because of the low availability of machines, many operators must apply for exemption from the requirements, and for larger construction projects it is normal that exemptions are granted. In practice, therefore, Oslo has achieved fossil-free, but not zero emission, building and construction sites in this scenario.

Only machines under 20 tonnes and vans have been electrified and demand for these is low, globally, and nationally. This results in very limited access to machinery. Conversion of diesel-powered machinery is still the norm and there is no mass production of zero emission construction machinery on the global market. The conversion capacity in Norway has increased, but the costs are high. Smaller machines are supplied by manufacturers without motors, but at a high price. The larger machines are supplied with diesel engines that are difficult to resell on the market.

Biogas and hydrogen concepts are available for mass and waste transport, but at very high cost, and major safety and logistics challenges remain in connection with hydrogen-powered electric concepts. Supply grid connection is available for building and construction sites in Oslo, but there is little development of charging stations for mass and waste transport. District heating has only been developed in the largest Norwegian towns.

High costs mean that there are few contractors who can submit tenders for contracts. Rental machinery is available, but because the global situation involves minimal use of large electric machines, the second-hand market involves major uncertainty. The other towns in Norway have not succeeded in keeping up. The example from Oslo appears to be slowing development and other towns are reluctant to follow. Increased fragmentation of the market is also apparent, and tense situations often arise between contractors and building project managers, because lack of technology leaves room for interpretation, creative solutions, and circumvention of the requirements. The City of Oslo plays a limited role as a unifying operator, having lost credibility by granting exemption from the requirements. Hence Oslo as a driving force is weakened.

The high costs and lack of machinery has triggered considerable need to offer subsidy schemes in parallel with the requirements. At the same time, because of high costs, combined with strict requirements, the focus is on rehabilitation and reuse of buildings, rather than building new. Moreover, thanks to initiatives in Oslo, operators connected with building and construction projects in the city have an advantage. However, with the slow market development, operators in the building and construction and associated industries do not experience any immediate benefit from this. The transition to zero emission building and construction sites is facing strong resistance in this scenario.

Fossil fuel-powered building and construction sites

Figure 28.
Scenario 4 – Fossil fuel-powered building and construction sites.

Norway has failed to reduce GHG emissions adequately and is heading towards an average temperature rise of 3°C. The European building and construction industry is at a standstill because costs are too high. The Green Deal in Europe now seems a distant dream. Enthusiasm for the green transition has now faded and the City of Oslo's new goal is fossil-free building and construction sites by 2050. The dialogue the City of Oslo has traditionally maintained with the market and stakeholders has become almost disconnected. Neither the authorities nor the end users dare to impose requirements for zero emission building and construction sites. Some pilot projects exist, mainly with public sector operators, who use converted construction machinery and electric vans in fossil-free building and construction projects in Oslo, but they attract little attention.

In a national political context, market segments with the highest emission potential, such as CCS and marine transportation, have highest priority. However, development in the entire transport sector is still at the pilot stage. Hydrogen and biogas are still niche technologies and there are no prospects of mass production of zero emission heavy lorries before 2040. The secondary market for zero emission machinery and vehicles is a niche market and there is considerable demand for biofuel, which has driven the price up. There is little development of energy supply infrastructure apart from charging stations for electric construction worker vehicles. This applies both to development of charging facilities for heavy transport and to district heating. It is noticeable that battery components have become scarce and that as a result the costs are not sinking as rapidly as they were. The large batteries suitable for building and construction and for heavy transport on land and at sea have not had the same lifetime gains as electric car batteries have displayed. As a result of a changed market situation in Europe, market uncertainty is high, energy prices are high, and a prolonged supply chain crisis has caused high steel and lumber prices. To reduce costs in the long term, effort is put into energy efficiency, rehabilitation, and reuse, but government taxation of subsidy schemes is sky-high. Operators in the construction industry which still have research and development capacity have now begun to look at structures adapted for life on the Moon. In this scenario, we are approaching an admission of failure, not only for the building and construction industry but for the entire global society.

Conclusion

This impact assessment has studied the transition to a zero emission building process in Oslo in 2022 and in the years up to 2025 and 2030. Energy and power estimates have been carried out for two projects: one fully electric building project and one fully electric construction project. In addition, cost analyses have been carried out for three different sizes of excavator and two different types of heavy vehicle. Additional costs for electrification have been analysed. Based on the energy estimates and additional cost analyses, an estimate has been made of the additional costs connected with electrification of said building and construction project.

Energy and power estimates

The analysis based on energy consumption data from some of the earliest zero emission building and construction sites in Oslo confirm the main elements of earlier analyses by DNV GL, among other things regarding energy consumption and power requirements connected with the implementation of fully electric projects. Electricity consumption depends strongly on the construction machinery and vehicles in use, what they are used for and how much they are operated. Data have therefore been acquired from six different building and construction sites in the Oslo area that have either been completed recently or are in progress. SINTEF also has data from two building projects that can be incorporated in the overall collection of acquired data. All this information has been used to define a hypothetical 100% electrified building site and a hypothetical 100% electrified construction site.

Charging of external transport does not at present take place at building and construction sites, and few facilities exist for charging heavy transport vehicles. In the reference scenario, all rapid charging takes place at the construction site. An average scenario is constructed based on the reference scenario, but some optimisation is performed for the most demanding building operations and project phases. Some examples are the use of construction machinery with different technology solutions (cable and battery powered) and staggered lunch breaks to avoid charging all machinery at the same time. Some optimisation of transport logistics is also included. The optimal scenario is developed from the average scenario, with a high degree of optimisation of operation at the construction site.

The results demonstrate that the most energy-demanding construction phase is groundwork, followed by superstructure and demolition. The energy consumption of construction machinery is within the available power rating, and by making some adjustments to charging breaks and technology type (battery, cable, or cable/battery), the power issues presented by the construction machinery are resolved according to our calculations. This becomes a greater challenge if there is also to be enough power available for vehicle charging.

Our analyses show that effective planning and active facilitation for the use of zero emission machinery has considerable effect on power requirements at a building site. With the highest possible exploitation, control and management of the available electricity supply, a typical building and construction project will successfully reduce its weekly peak load.

Cost analyses

The cost analyses show that electrification of building and construction sites may result in additional costs for a project both in 2022 and in 2025. Depending on the market development and energy prices, electrified building and construction sites could be competitive pricewise in 2030. Assuming a market development as described in the “Zero emission is the new normal” scenario with relatively low or normal electricity prices and high carbon taxation on diesel operation, electrified building and construction sites can be fully competitive pricewise in 2030, compared with diesel-operated sites. Some cost elements have not been quantitatively analysed and may influence this situation. This applies particularly to costs connected with supply grid expansion (both electric and district heating) and any need for local energy supply such as batteries or hydrogen.

The investment costs can be recouped through the operation of the machinery since electricity costs are lower than the cost of diesel and HVO. This results both from lower electricity costs and from the higher energy efficiency of electric operation. On the other hand, given the current situation with high electricity prices and high investment costs (and, particularly for transport vehicles, limited range), it may be difficult to recoup the higher investment costs over the service life of the machinery. A functioning after-market will also be an important influence on willingness to invest. It is the owners of the machinery and vehicles who must absorb the initial increased investment costs, while the projects benefit from lower operating costs. This is achieved by way of different operating models, for example by way of rental rates. It is assumed that investment costs will fall in the period up to 2025 and 2030, based on a reduction in component costs (e.g., batteries, electric motors, and other components) and that electric vehicles and machinery will increasingly be mass produced. It is assumed that it will take somewhat longer before machines using larger batteries become profitable, since their investment costs are relatively high. Machinery supplied by cable requires lower investment costs and will therefore be competitive pricewise sooner. On the other hand, such machines may present other logistical challenges at a building site.

Investments connected with the transition to zero emission drying and heating of buildings are assumed to be lower if the projects plan for this at an early stage and involve the best operators. Investment connected with supply grid expansion (electricity and district heating) may lead to additional costs for a project. On the other hand, it is assumed that here too, early planning and optimisation of a building and construction site will reduce the need for investment in such development. If there is a need to expand the grid, it is the building and construction project that initially must bear the additional costs connected with the customer contribution. Alternatives to grid expansion are local energy systems such as battery banks, hydrogen fuel cell banks, etc. Additional costs connected with these have not been considered in this report.

Market development and scenario analysis

Based on a questionnaire, interviews, and a workshop involving the municipality and relevant operators in the market, a scenario matrix has been developed with three scenarios for the development towards a zero emission building process in the City of Oslo. These four scenarios are entitled “Zero emission is the new normal”, “Zero emission building and construction sites in Oslo”, “Fossil fuel-free building and construction sites” and “Fossil fuel-powered building and construction sites”. The four scenarios are not predictions, but illustrations of how the situation may be in 2030, depending on the development of several important parameters. The City of Oslo and other operators may be able to influence some of this development, for example by imposing requirements, while some of the development depends on major global trends and operators, such as technology development. Each scenario illustrates a potential outcome which one may either work towards or against and which one may prepare oneself to handle.

The main sources of uncertainty that form the basis of these scenarios are global technological development and requirements from the City of Oslo. In the "Zero emission is the new normal" scenario, the intensifying of the EU's climate change policy and more active national use of policy instruments, for example through result-oriented subsidies, taxes and regulations, together with rapid technology development have resulted in the mass production of zero emission concepts that are available to the building and construction industry, so that building and construction sites in the City of Oslo, as well as many other sites in Norway and in the EU are zero emission. In the "Zero emission building and construction sites in Oslo" scenario, the City of Oslo achieves its goal of zero emission building and construction sites by 2030. This is achieved thanks to rapid technology development and through continuing to impose strict requirements. In this scenario, emissions and costs are slightly higher because the rest of the country and the EU lag slightly behind, even though they are also moving towards zero emission building and construction sites. In the "Fossil fuel-free building and construction sites" scenario, technology development has not been rapid enough for the City of Oslo to achieve its goal of zero emission building and construction sites, and the sites are in practice fossil-free but not zero emission. Exemptions to requirements are granted and the rest of Norway and the EU are lagging. This scenario involves higher costs, higher emissions, and higher demand for biofuels. In the "Fossil fuel-powered building and construction sites" scenario, the City of Oslo has abandoned strict requirements. The technology is not in place and, nationally, other sectors are prioritised with greater potential for emission cuts than is possible within building sites. This scenario involves high costs, the highest emissions and high demand for biofuels.

Table 9 shows a summary of the consequences regarding energy and power requirements, additional costs, CO_2 emissions, biofuel consumption and prospects for wealth creation and employment in a building and construction sector with associated industries in the Oslo region that is to convert to zero emission building and construction sites according to the different scenarios. Using a scale from one to four (shown as + signs in the table), the consequences that the different scenarios will have on several listed topics are estimated. The energy and power requirements of the "Zero emission is the new normal" and "Zero emission building and construction sites in Oslo" scenarios will be higher. The highest additional costs will be in the scenario "Zero emission building and construction sites in Oslo", but GHG emissions will be lowest for "Zero emission is the new normal" and highest for "Fossil fuel-powered building and construction sites". Biofuel consumption will naturally be highest for the "Fossil-free building and construction sites" scenario. Wealth creation and employment in companies that are to be reorganised are assumed to correlate with the cost level for zero emission concepts.

In the case of the optimal scenario "Zero emission is the new normal", the energy and power requirements will naturally be higher than for fossil-free and fossil fuel-powered construction sites because there is higher demand on the electricity grid. Nevertheless, the energy and power requirements will be somewhat lower than in the "Zero emission building and construction sites in Oslo" scenario, because of broader involvement of the industry and several technological concepts that both improve the efficiency of building and construction site operation and more effectively reduce demand on the electricity grid. It is also assumed that the additional costs will be lower than in the other scenarios because a market has been established for zero emission concepts that are competitive pricewise with both fossil fuel and fossil-free alternatives. Moreover, there is a high level of mass production, and the pilot project phase is partly completed. For the City of Oslo, the level of GHG emissions will probably be equally low in the scenarios "Zero emission is the new normal" and "Zero emission building and construction sites in Oslo” scenarios, but because the rest of Norway and Europe also introduce zero emission concepts the effect of emission reductions outside the City of Oslo will be significantly larger.

Table 9.
Summary of consequences in each development scenario

	Zero emission is the new normal	Zero emission building and construction sites in Oslo	Fossil fuel-free building and construction sites	Fossil fuel-powered building and construction sites
Energy and power requirements	+++	++++	++	++
Additional costs	+	++	+++	++++
Greenhouse gas emissions	+	++	+++	++++
Biofuel consumption	+	++	++++	+++
Value creation and employment	++++	+++	++	+

Energy and power requirements: Few crosses indicates lower energy and power use- Additional costs: Few crosses indicates loweradditional costs for zero emission solutions– Greenhouse gas emissions: Few crosses indicates lower greenhouse gas emissions -Biofuel consumption: Few crosses indicates lower consumption of biofuel– Value creation and employment: Few crosses indicates lower value creation and employment within the pat of the industry that use zero emission solutions.

The City of Oslo has shown itself to be an important prime mover in the process of developing zero emission building and construction sites. This demonstrates the importance of local purchasing power. However, it is important that the rest of the country and Europe do not lag too far behind. Imposing requirements for concepts that are expensive and not easily available can have considerable negative effect on the building and construction industry and associated industries that are to be reorganised in the Oslo region. Having a system perspective, for example coordinating electricity and district heating grid expansion, and ensuring that this is in place before building and construction projects commence, can help to reduce costs.

This impact assessment shows that there will be significant additional costs connected with zero emission building operations, probably for some time approaching 2030, and perhaps also later. It underlines the need for national regulations and financial incentives in a transition period until zero emission concepts are competitive. There is also a need for national co-ordination of requirements, while pressure from the EU is decisive. It will probably also be necessary to reinforce existing subsidy schemes. For example, subsidies for establishing charging stations shall be based on the estimated number of users, rather than each charging station being considered as a single user. There is a need to develop charging stations for heavy transport and further financial incentives may help break down the “chicken-and-egg” barrier that appears to be delaying this development.

The energy estimates show an increased energy and power requirement which may be reduced significantly by means of smart energy consumption and other smart concepts. We recommend that the City of Oslo continues to press for mandatory registration of construction machinery. Achieving the best possible database will contribute to optimising operations. This should take place in combination with a significant increase in national investment in energy efficiency.

Development towards zero emission building and construction sites depends on technological development. While the development of concepts for excavators has come a long way, there are still few concepts for heavy transport, dumper trucks and wheel loaders. Further development of battery technology is needed. At the same time, a mix of energy carriers can make the market less vulnerable to fluctuations in energy prices. Broader investment in the research fields of hydrogen, ammonia, biogas, and synthetic fuels may lead to more rapid implementation of zero emission building and construction sites outside of urban areas and in countries with greater fossil fuel use and high energy prices.

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Appendix A: Interview Guide

Interview Guide – Impact assessment of zero emission building and construction sites in Oslo.

As we wrote in our enquiry: This is a project that SINTEF and TØI are conducting on behalf of the City of Oslo's Climate Agency. The intention is to investigate the consequences of a gradual transition to zero emission implementation of building processes in Oslo in the years up to 2025 and 2030. Among other things, we will assess energy consumption, energy supply, access to and operation of construction machinery, drying and heating of buildings, and zero emission transport. We will also consider operators, budgetary conditions, markets, economics, and practical conditions. Based on all this we will develop several scenarios.

We will make notes based on this interview which we will return to you for review and feedback. No direct quotations will be used in the report without your consent. We will also verify any information received from you before preparing the report. You may at any time request that your input be withdrawn from the study. Do you approve of the use of the information as we have described it?

Introductory questions: Can you tell us a little about your company and your role in it?
In what ways are you involved in zero emission building sites?

1 Energy supply

a) What alternative concepts exist for energy supply in the building phase?
b) What significant advantages or disadvantages or possible additional costs relate to zero emission energy supply to building sites?
c) How can these advantages, disadvantages and possible additional costs be expected to develop in the years up to 2025 and 2030?

2 Zero emission construction machinery

a) What additional costs relate to the use of zero emission alternatives, rather than biofuel and fossil fuel?
b) How can this be expected to develop in the years up to 2025 and 2030?
c) How much of the total development costs do these additional costs represent?
d) How can the market share and/or availability in the Oslo region regarding zero emission construction machinery be expected to develop up to 2030?
e) How does this affect industry operators, nationally and internationally?
f) How many machines should be in circulation and when can we expect that number to be reached?
g) What conditions will affect cost developments?
h) How will these conditions develop in the years up to 2025 and 2030?

3 Equipment for drying and heating buildings

a) What alternative concepts exist for drying and heating buildings in the building phase?
b) What additional costs relate to the use of zero emission equipment for drying and heating in the building phase?
c) How can this be expected to develop in the years up to 2025 and 2030?

4 Zero emission transport

a) What conditions will affect cost developments?
b) How will these conditions develop in the years up to 2025 and 2030?
c) How much of the total development costs constitute the additional costs connected with the use of zero emission transport in, and to and from, the building and construction site?
d) How can this be expected to develop in the years up to 2025 and 2030?

e) How can the market share of zero emission transport to and from the building and construction site be expected to develop up to 2030?
f) How many zero emission lorries should be in circulation to achieve zero emission transport to and from building and construction sites in Oslo?
g) When can we expect to have reached this number?

More general questions:

- How are you and your organisation working in connection with zero emission building and construction sites?
- What factors in addition to costs affect or will affect the selection of zero emission alternatives rather than biofuel or fossil fuel alternatives? (For your business? For projects? In general?)
- How do you see the market for zero emission concepts at building and construction sites?
    - Key words:
        - Accessibility
        - Technological development
        - Maturity
        - Potential
        - Demand
        - Existing concepts
        - Facilitators
        - Drivers
        - Barriers
        - Opportunities
        - Strengths
        - Weaknesses
        - Main sources of uncertainty
- Are there any countries you would point to as pioneering countries?
- Can you mention examples of operators (national and international) which promote zero emission building and construction sites?
- What types of operators are lacking?
- What expectations do you have of future business models and operators, and how is your business adapting to this?
- What are the simplest measures for achieving profitability?
- What framework conditions do you believe stand in the way of developing and making use of concepts for zero emission building and construction sites?
        - Regulatory
        - Financial
        - Organisational
        - Societal
- Do you have any proposals for alternative formulation of framework conditions?
- What types of incentives are used today for transitioning to electric operation? What other types of incentives should be used to speed up implementation?
- What is needed to achieve the goal of zero emission building and construction operations in the City of Oslo by 2030?

Appendix B: Questionnaire: Zero emission building and construction sites in Oslo

This questionnaire is part of a project that SINTEF and TØI are conducting on behalf of Oslo Municipality's Climate Agency. The intention is to investigate the consequences of a gradual transition to zero emission implementation of building processes in Oslo in the years up to 2025 and 2030. Among other things, we will assess energy consumption, energy supply, access to and operation of construction machinery, drying and heating of buildings, and emission-free transport.

Please provide your points of view by responding to the following questions. You may refrain from responding to any questions that are not relevant to you or to your company.

Participation in this survey is voluntary. If you decide to take part, you can withdraw your consent at any time without giving a reason. All your personal data will then be deleted. You will incur no negative consequences if you do not wish to take part, or if you decide to withdraw your consent later. We will use information about you only for the purposes described in this document. We process the data in confidence and in compliance with prevailing personal privacy regulations.

It will take about 10 minutes to complete the survey.

Introduction

1. We process information based on your consent. I consent to my responses being processed until the completion of the project.
    - Yes
    - No

2. What is the name of the company in which you are employed?
    - Your response

3. Which industry sector does your company belong to (you may select more than one alternative)?
    - Building contractor
    - Machine supplier
    - Transport
    - Machine hire
    - Principal contractor
    - Energy distribution
    - Energy production
    - Energy storage
    - Real estate
    - Waste and recycling
    - Consultancy
    - Other

4. What is your role in the company?
    - Your response

5. How likely is it that enough **emission-free construction machinery** will be available to achieve emission-free **municipal** building and construction projects in Oslo in **2025**?
    - Scale: from 0 "Not at all likely" to 10 "Very likely"

6. How likely is it that enough **emission-free construction machinery** will be available to enable **both public and private** building and construction projects in Oslo to be emission-free in **2030**?

- Scale: from 0 "Not at all likely" to 10 "Very likely"

7. How likely is it that enough **emission-free heavy vehicles** will be available to achieve emission-free **two-way transport** to **municipal** building and construction projects in Oslo in **2025**?

- Scale: from 0 "Not at all likely" to 10 "Very likely"

8. How likely is it that enough **emission-free heavy vehicles** will be available to enable **two-way transport** to **both public and private** building and construction projects in Oslo to be emission-free in **2030**?

- Scale: from 0 "Not at all likely" to 10 "Very likely"

9. How likely is it that enough **electricity** will be available to enable all **municipal** building and construction sites in Oslo to be emission-free in **2025**?

- Scale: from 0 "Not at all likely" to 10 "Very likely"

10. How likely is it that enough **electricity** will be available to enable **all** building and construction sites in Oslo to be emission-free in **2030**?

- Scale: from 0 "Not at all likely" to 10 "Very likely"

11. Do you have any other comments or additional information regarding the achievement of Oslo Municipality's goals in the years up to 2025 and 2030? (For example, what types of vehicles and machinery will not be available, what areas are most at risk of not being emission-free, etc.)

- Your response

12. Based on your assessment, in which year will all construction machinery at building and construction sites in Oslo Municipality be emission-free?

- Your response

13. Based on your assessment, in which year will all heavy vehicles driving to and from building and construction sites in Oslo Municipality be emission-free?

- Your response

14. How large a part of the costs connected with **the operation of a building and construction site** is represented by **the additional costs** for an emission-free building and construction site, as compared with costs for a traditional building and construction site?

- when using emission-free construction machinery?
- when using emission-free transport at, and to and from, the building and construction site?
- when using emission-free drying and heating of buildings?

15. Rank the most important **drivers** for achieving emission-free building and construction sites in Oslo Municipality in 2030 ("1" for the most important)

- Technology development
- Subsidy schemes
- Requirements and regulations
- Availability of machinery and other emission-free concepts
- Training and skills
- Mass production
- Reputation
- Green transition

16. Rank the most important **barriers** that may prevent us from achieving emission-free building and construction sites in Oslo Municipality in 2030

- Energy infrastructure
- Technology development
- Costs
- Subsidy schemes
- Requirements and regulations
- Availability of machinery and other emission-free concepts
- Experience and skills
- Mass production
- Available area
- HSE issues connected with new technology

17. In your opinion, are there other drivers and/or barriers that are important?
    - Your response
18. Thank you for taking the time to complete this questionnaire. You may write any further comments here.
    - Your response

Impact assessment of zero emission building processes in Oslo

The goal of the City of Oslo is that building and construction activities in Oslo shall be zero emission by 2030. This impact assessment has been initiated to study the consequences of a gradual transition to zero emission implementation of building processes in Oslo. This report considers energy consumption and energy supply at, as well as to/from a building site, cost analyses and market analyses, while assessing various development scenarios. To what extent zero emission construction machinery and vehicles are available in the local market in and around Oslo is studied, while assessing whether the use of such equipment entails significant disadvantages or additional costs, and how this is expected to develop in the years approaching 2030. Future scenarios have been established for the development of zero emission concepts for building and construction sites in the years up to 2025 and 2030 to identify how the City of Oslo may effectively facilitate the desired development.

The report is prepared by SINTEF and TØI on behalf of the City of Oslo's Climate Agency.

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