Estimated and actual construction inventory data in embodied greenhouse gas emission calculations for a Norwegian zero emission building (ZEB) construction site

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Abstract. The Norwegian construction industry is responsible for approximately 1.2% of national GHG emissions during the construction phase. Consequently, there is a growing interest in addressing construction emissions. Therefore, this article aims to comprehensively document and analyse construction phase emissions from a Norwegian ZEB construction site, and compare estimated and actual data in embodied construction emission calculations. Construction site activities considered include transportation and installation of building materials, construction machinery, temporary works, energy use, waste management and person transport. The environmental performance is calculated in terms of GHG emissions weighted as carbon dioxide equivalents (CO_{2eq}). The embodied construction emission results are 1.1 $kgCO_{2eq}/m^2/yr$ for estimated data, and 2 $kgCO_{2eq}/m^2/yr$ for actual data. The results show a 44% increase in emissions when using actual data instead of estimated data. The largest contributors to emissions are the operation of construction machinery (47%), energy use (17%), transport of building materials to site (15%) person transport (10%), installation of building materials (10%), followed by temporary works (0.8%) and construction waste (0.3%). This study highlights the importance of embodied construction emissions in Norwegian ZEBs, and recommends paying more attention to the construction phase in the future. These results may be used in future Norwegian construction projects, to help measure, evaluate and compare the environmental performance of construction activities.

Keywords: Embodied construction emission, Embodied GHG emission, Zero emission building

1 Introduction

The Paris climate conference in 2015 (COP21) saw the first ever legally binding global climate deal, with the ambitious renewal of targets every five years from 2020. In response, Norway initiated goals to reduce greenhouse gas (GHG) emissions by at least 40% compared to 1990 levels by 2030 [1]. In light of these ambitious targets, the Norwegian construction industry is responsible for approximately 1.2% of national GHG emissions during the construction phase, which corresponds to around 660,000 tCO_{2eq}

[2]. Most of these emissions arise from the combustion of fossil fuels. Of these construction phase emissions, about 5% arise from the heating and drying of buildings (ca. 30,600 tCO2eq) whilst the remainder originate from transportation and operation of machinery [2]. It is estimated that 7500t propane and 3000t diesel are used annually on Norwegian building sites to heat and dry constructions [2], whilst construction machinery is estimated to be responsible for 30% of total CO_{2eq} emissions from the transport sector [3]. A comprehensive Swiss study of non-road energy consumption and pollutant emissions found construction machinery as the largest contributor to CO_2 emissions and third largest contributor to CO emissions [4], whilst the McKinsey report estimates that 10-15% of building materials are wasted during construction [5].

Life cycle assessment (LCA) is a well-established methodology used for the environmental assessment of buildings [6]. Due to the long lifespan of buildings, operational energy use has traditionally been identified as the main contributor to high GHG emissions in buildings. However, because of increasingly stringent energy requirements and improved energy efficiency, the significance of emissions from operational energy has decreased [6]. In contrast, environmental impacts from the production, construction, maintenance, replacement and demolition phases are gaining significance [6]. This trend is even more pronounced in zero emission buildings (ZEBs), whereby the embodied emissions associated with materials and construction contribute to a large proportion of total GHG emissions [7]. The significance of construction phase emissions becomes clear when one considers that construction phase emissions occur for a brief period, during the early stages of a whole building's lifecycle. In comparison, use phase emissions occur over the lifetime of the building, typically over a 60-year period. Existing climate change mitigation targets include the decarbonisation of the electricity grid, and hence a depreciation in embodied operational energy use emissions [8]. Given the magnitude of the construction phase carbon spike, emissions may be high enough to question whether new construction can contribute to reaching GHG mitigation goals, no matter how energy efficient buildings are during operation [9]. Although many LCA studies document GHG emissions from buildings, few focus on the construction phase, and even fewer use detailed life cycle inventory data from the construction site in emission calculations. Reasons for this may include complexity of construction activities, time and cost issues in collecting specific life cycle inventory data directly from the construction site, as well as a lack of good data to make robust estimations of impacts arising from transport, construction workers, building materials, construction equipment and energy use in and around the construction site .

The aim of this study is to comprehensively document and analyse construction phase emissions from a Norwegian ZEB construction site, and compare estimated and actual data in embodied construction emission calculations. This includes analysing the system boundaries, construction inventories, emission factors and calculation methodologies used to explain the disparity in construction emission results between estimated and actual data. This analysis also highlights the main drivers of high CO_{2eq} emissions during the construction phase. The results from this study may be used in future construction projects, to help measure, evaluate and compare the environmental performance of various construction activities. This article outlines the methodology used for documenting and analysing construction phase emissions, presents results and discussion of the embodied construction emission, and finally lessons learnt from embodied construction emission calculations in using estimated and actual data in the conclusion.

2 Methodology

2.1 Goal and scope

The goal of this study is to comprehensively document and analyse construction phase emission calculations from the selected case study and compare estimated and actual life cycle inventory data gathered during the design and construction process in embodied construction emission calculations. This includes analysing the system boundaries, construction inventories, emission factors and calculation methodologies used to explain the disparity in construction emission results from estimated and actual data. The case study originates from the Norwegian research centre for zero emission buildings (ZEB). A functional unit of 1 m^2 of heated floor area over an estimated building lifetime of 60 years is considered. The total heated floor area is 1141m^2. The environmental performance is calculated in terms of GHG emissions weighted as carbon dioxide equivalents (CO_{2eq}) according to the IPCC GWP 100-year method. The system boundary for estimated and actual data considered in this study is shown in Figure 1. The construction site activities considered harmonise EN 15804, EN 15978 and include person transport as outlined in prNS 3720 (a new Norwegian draft standard) [10-12].

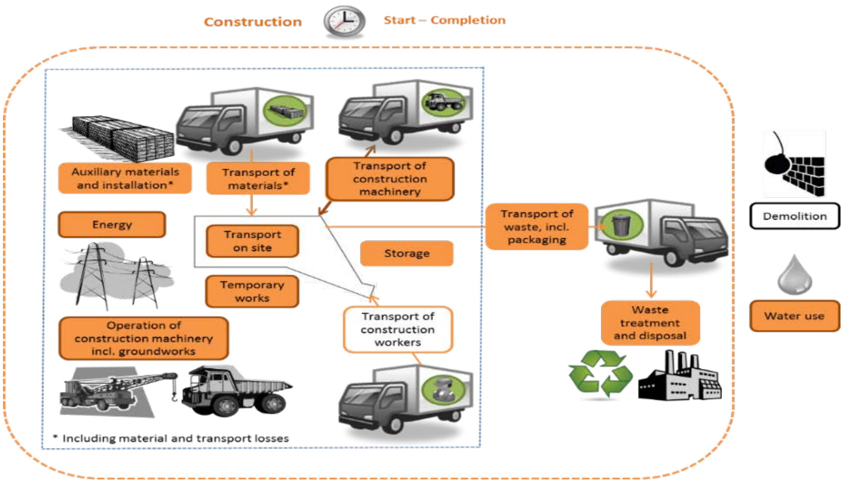

Fig. 1. System boundary for construction activities considered in the study, figure translated and adapted from Asplan Viak [13]. Blue dotted line: system boundary for estimated data. Orange dotted line: system boundary for actual data. Orange text boxes: system boundary described in EN 15978 and EN 15804. Orange text boxes with brown frames: construction activities described only in EN 15978. White text box with orange frame: construction activity included only in prNS 3720. White text box with black frame: demolition activity not included in EN 15978, EN 15804 or prNS 3720.

2.2 Case study

The building chosen for this study is a new zero emission administration and educational building at Campus Evenstad, located in Hedmark, Norway (latitude 61.43, longitude 11.07). The building is located in a rural area and is linked to an existing building on campus. It includes 24 offices for academic staff, seven offices for PhD students, a reception area, five meeting rooms, five classrooms and a conference venue with capacity for 250 people. The total heated floor area (BRA) of the pilot building is 1141 m^2, with an estimated office area of 580 m^2 and educational area of 225 m^2. The building consists of a solid wood construction, wood fibre insulation, and an untreated timber cladding. The energy system consists of a combined heat and power (CHP) unit, powered by the gasification of wood chips and generates both heat and electricity for the building. Further details, including a full overview of the life cycle inventory data and a detailed account of total embodied emissions from construction, operation and materials can be found in [14, 15].

2.3 Inventory and data source

Estimated data. In 2014, the estimated data calculations are performed based on experience-based estimates provided by the contractor through a series of partner workshops, due to limited previous emission calculation experiences and a lack of emission data [13]. Activities considered in the estimated data collection include transportation of building materials, construction machinery, temporary works, energy use, waste management and person transport (see Figure 1, blue dotted line). Estimates are based on diesel use in expected construction activities identified by the contractor. In addition, an estimate on construction energy use was provided. It was assumed that some of the heating and drying demand could be covered by the pre-existing onsite wood pellet boiler, and that the remaining energy demand could be met by electricity from the grid. The well-to-wheel emission factor for diesel is supplied from EN 16258: 2012 [16]. The emission factor for electricity and pellets are based on the ZEB research centre's emission factors [17]. To minimise the risk of underestimating emissions, an additional 10% was added to total calculated construction emissions. At this stage, the construction activities were not identified or harmonised with either of the system boundaries outlined in EN 15978, EN 15804 or prNS 3720.

Actual data. The calculations using actual data are performed based on a detailed analysis of actual data collected onsite during the construction period, from 15th December 2015 until 22nd December 2016 (374 days). Actual inventory data were collected through building information modelling (BIM), the bill of quantities, invoices, building site reports, construction drawings, product data sheets and through transport logs and a waste plan filled out by the contractor and sub-contractors. Before construction began, the construction inventory was structured according to the construction activity posts identified in EN 15978, EN 15804 and prNS 3720. The main construction activities considered may be summarised into the following seven categories:

Transport of building materials. The building material inventory summarised in [14, 15] has been used to ascertain how much of each building material is transported to the construction site. The location of factories, any intermediary storage warehouses, and construction site is taken into consideration to ascertain the actual transport distances travelled by the building material. The emission factor for the transportation mode has been obtained from Ecoinvent v3.1. It has been assumed that any auxiliary materials required for the installation of the product are transported together with the building material.

Installation of building material. The installation of building materials, at the product level, includes auxiliary materials (e.g. sealing tapes and screws) and energy use from hand tools (e.g. drills) used during installation. The heavy equipment such as loaders, diggers and excavators' necessary to install the various building assemblies is reported at the building level under construction machinery. GHG emission data associated with the installation of building materials is collected from EPD scenario descriptions.

Construction machinery. The construction machinery includes both mobile and stationary machinery used during construction. The GHG emissions associated with construction machinery include the production of machinery, transport of machinery to the construction site, and combustion of fossil fuels during operation. The weight of the construction machinery has been collected from technical specifications. The onsite duration, service hours and fuel consumption of construction machinery is collected from transport logs filled out by the contactor and sub-contractors. The GHG emission factor from the production and transport of machinery has been obtained from Ecoinvent v3.1. The location of a construction park taken into consideration to ascertain the actual transport distances of construction machinery. The amount of fuel consumed was also collected from the contractor and sub-contractors weekly transport logs. The well-to-wheel emission factors for diesel and petrol are used [23].

Energy use. Energy use consists of onsite energy use for heating, cooling, ventilation, drying and lighting during the construction period. The operations manager has provided an estimate for onsite electricity use during the construction period. From the start of construction on the 15th December 2015 until the 6th September 2016, electricity has been supplied directly from the electricity grid. From the 6th September 2016 until the end of construction on the 22nd December 2016, electricity has been supplied from the combined heat and power (CHP) unit. GHG emission factors from the ZEB research centre [17] have been used for electricity from the grid and for the CHP unit.

Temporary works. Temporary works provide access, protection, support and services to construction workers, and aid the construction process. At Campus Evenstad, the temporary works include, amongst other things; construction offices, canteen, temporary roof cover, tarpaulins, insulating mats, road grit, lighting, security fences, diesel tank, hand tools, safety clothing, health and safety information boards, pallets, waste containers, provisional makeshift timber stairs and scaffolding. The emission calculations are carried out for just some of the temporary works due to lack of data. The material inventory for temporary works has been collected via observations from the construction diary, which includes weekly reports on construction site activities. The weight and service life time data of temporary works are collected from product specifications. The location of a construction park taken into consideration to ascertain the actual transport distances of construction machinery. The emission factor for the transportation mode has been obtained from Ecoinvent v3.1.

Construction waste. The construction waste includes material losses during the construction process, including packaging and the additional production and transportation processes to compensate for the loss of wasted products, and the processing of all waste up to an end-of-waste state or disposal of final residues. The GHG emission calculations associated with the construction waste consider the transport of waste to the treatment plant, waste processing (recycling or incineration) and waste disposal. Data on the total amount and type of onsite construction waste generated have been collected from the waste plan filled out by the contractor. The amount of materials going to the various treatment processes (recycling or incineration) and final disposal are based on waste treatment data from Statistics Norway. The transport distance of waste for treatment is based on an assumption and the GHG emission factor for transportation mode has been obtained from Ecoinvent v3.

Person transport. Person transport includes the one-way transport of construction professionals to the construction site. This includes transport of construction site workers, including construction equipment operators, electricians, plumbers, carpenters, floorers, roofers, painters, ventilation and CHP installers. Data on the number of trips, people per trip, and distance travelled are collected in the weekly transport logs from the contractor and sub-contractors. There is an assumption that all person transport is based on diesel fuel. When data was lacking, an assumption of two people per trip is considered. The emission factors are based on a well-to-wheel analysis that has been adapted by Civitas from the European JRC (2014) to represent the Norwegian transport park [14].

3 Results and discussion

The embodied construction emission results are 1.1 kgCO_{2eq}/m^2/yr for estimated data, and 2 kgCO_{2eq}/m^2/yr for actual data (Figure 2). The largest contributor to CO_{2eq} emissions when using estimated data is the transport of building materials (39%), followed by person transport (23%), construction machinery (19%) and energy use (11%). Uncertainty contributes 8% to embodied construction emissions. The largest contributor to CO_{2eq} emissions when using actual data collected from the construction site is construction machinery (47%). This is followed by energy use (17%), transport of building materials (15%), person transport (10%) and installation of building materials (10%). The construction processes that contribute the least to CO_{2eq} emissions are temporary works (0.8%) and construction waste (0.3%).

When comparing estimated emissions to actual emissions, there is an 80% increase in emissions from construction machinery, 67% increase from energy use, 33% decrease from person transport and a 25% decrease from transport of building materials. When estimating emissions, no results are available for the installation of building materials, temporary works or construction waste, therefore these posts experience a 100%

increase in emissions. Uncertainty is not included in the actual emission calculations, as a detailed construction inventory based on actual data has been collected.

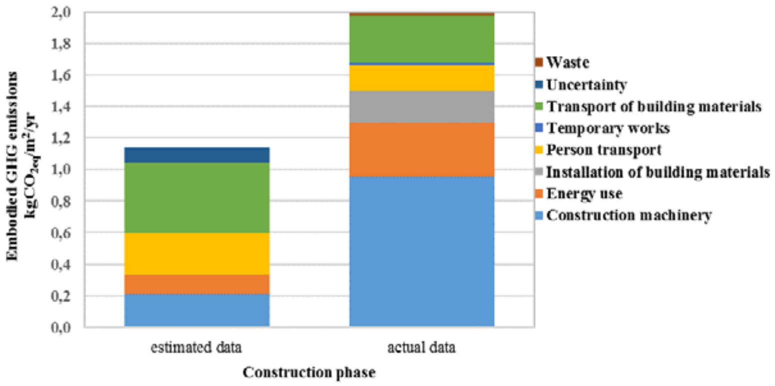

Fig. 2. Embodied construction emission results using estimated and actual data.

The results showed an 80% increase in emissions from construction machinery between estimated and actual data. Of the emissions from construction machinery, the largest contributor to CO_{2eq} emissions is the combustion of fossil fuels in the use of construction machinery (85%) (Figure 3).

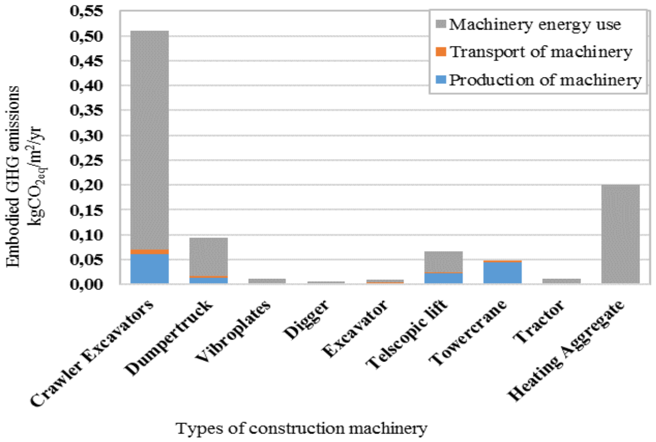

Fig. 3. Embodied emissions from construction machinery using actual data.

Out of the various types of construction machinery used onsite, the largest contributors to CO_{2eq} emissions are the crawler excavators used for groundwork and foundations (52%), the heating aggregate used for defrosting, heating and drying (21%), the dumper truck used for onsite transport of excavated material (10%) followed by the telescopic lift (7%) and tower crane (5%) used for the installation of building parts. The tractor, excavator, digger and vibroplates contribute 1% each to total construction machinery CO_{2eq} emissions. Before construction began, the contractor considered using biodiesel instead of ordinary diesel to further reduce emissions. However, at the start of 2016 there was a lot of uncertainty in Norway concerning the origin of biodiesel [18]. Suppliers could not guarantee that biodiesel did not contain palm oil from first generation production, or that the biodiesel was of second generation origin. Thus, an informed choice was made to not use biodiesel. Instead, a proper transport logistics plan was implemented to minimise operating machinery with empty loads, and to reduce how often excavated material was moved around onsite. The results show that the operation of construction machinery onsite was largely underestimated. Current Norwegian initiatives see a move from traditional diesel fueled construction machinery towards biodiesel, electric and even hydrogen-fueled construction machinery. Technological developments of construction machinery can thus be phased in as and when construction machinery parks are upgraded every five to ten years [2].

The results also showed a 67% increase in energy use between estimated and actual data. When using actual data, electricity imported from the grid was replaced with onsite electricity generated from the CHP unit during the last four months of construction, and reduced emissions by 0.13 kgCO2eq/m2/yr. If the CHP system had been implemented before the construction phase started, then the grid-based electricity could have been replaced by electricity and heat generated by the CHP system, leading to even lower embodied construction emissions. However, the CO_{2eq} emission factor of the CHP unit is dependent on the proportion of renewable resources used in energy production. Other ways of reducing emissions from energy use include reducing energy consumption at the construction site. This can be achieved by reducing the need for heating and drying, by keeping the building dry. For example, a temporary roof cover or tent may be installed to stop rain penetration, and building materials can be properly stored in dry places. Similarly, the seasons can be exploited to reduce onsite energy demands. For example, installing concrete foundations during the summer months reduces the need for thawing the ground and can improve curing times. NHO also suggest that heating demands can be reduced by 30% by simply mounting heating units inside of the building, instead of outside [2]. Energy consumption from lighting may be reduced by using energy-saving lightbulbs and motion sensors for security against break ins or theft outside of working hours, which means lighting is only required for 8 instead of 24 hours a day, leading to a 66% saving [2]. Another energy saving measure could include improving the construction of onsite construction cabins to include; thicker wall and roof insulation, heat recovery, thermostats, and air-to-air or water-to-air heat pumps.

Nevertheless, the estimated results were used to evaluate, plan and reduce emissions during the construction phase. For example, there is a 33% decrease in emissions from person transport and a 25% decrease in emissions from the transport of building materials. Campus Evenstad is located in a rural area. Therefore, the contractor enabled onsite living for construction workers to reduce emissions from person transport. Similarly, the contractor selected locally produced building materials to reduce distances travelled. Measures for the reduction of GHG emissions from transport include increasing the technological level of vehicle transport (i.e. EURO class 6). Current Norwegian initiatives see a move from traditional diesel fueled lorries towards biodiesel, electric and even hydrogen-fueled lorries. Furthermore, transport logistics can be planned to avoid driving empty or partial loads.

The quality of embodied construction emission calculations is dependent on multiple factors, such as the definition of system boundary, the quality of inventory data supplied by various stakeholders at different stages during the construction process, and the representativeness of emission factors used. When considering system boundaries, the results show that it is important to distinguish the boundary between EPD emission data (product level construction activities) and site-specific data (construction site level activities). Furthermore, the source of data used in the analysis should be clearly described to increase transparency. It is acknowledged that this is an under-researched area and requires further attention in the future. The laborious process of data collection in this study, has highlighted the importance of designing a standardized, detailed data collection sheet to simplify the construction site data collection process, and improve data quality and transparency. Although construction phase activities are typically project specific, the data collection procedure and calculation methodology presented in this work can be used as a reference for performing embodied emission calculations in future construction projects. In this study, GWP has been used to assess the environmental impacts arising from one construction site. Focusing on GWP as an environmental indicator has the benefit of reducing complexity for decision makers, and often correlates with other environmental impacts. However, it also risks ignoring important environmental impacts that do not correlate with GWP, such as; toxicity [19] and can potentially lead to problem shifting to other impact categories. The results of this study also highlight the importance of carrying out multiple iterations of embodied construction emission calculations, as and when detailed inventory data becomes available, to improve inventory and emission data quality, and to better plan and optimise the reduction of embodied construction emissions.

4 Conclusions

This work contributes to a better understanding of embodied GHG emissions arising from a Norwegian ZEB construction site, and pinpoints drivers of high emissions from the construction of buildings. The study also documents and explains the disparity in emission results between using estimated and actual data, and focuses on the importance of collecting actual data from construction sites, and including a complete construction phase system boundary. This work highlights considerable scope for further work including the development of a standardised, detailed data collection sheet to simplify the construction site data collection process, the inclusion of clear descriptions of construction system boundaries in future LCAs, as well as an improvement in construction scenario descriptions in EPDs. These measures will help lead to the better documentation of embodied GHG emissions arising from Norwegian construction sites, and support the initiative for fossil and emission-free construction sites in the future. In conclusion, this study recommends giving more attention to the construction phase in future embodied emission calculations of Norwegian ZEBs.

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