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Waste free construction site–A buzzword, nice to have or more

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ABSTRACT

The building and construction industry is responsible for up to 25% of the total waste generated globally. Most construction sites in Norway on average generate 40–60 kg waste per gross floor area built and the average material recovery rate is ca. 46%. Existing requirements focus on waste sorting as a measure to increase material recovery rates. There are on-going national activities with an ambition to achieve waste free construction sites. However, there is lack of a common definition, standard and transparent data collection, and reporting system. This study presents a method for the evaluation and follow-up of construction waste and the associated greenhouse gas (GHG) emissions. The methodology was tested using the actual construction waste data collected from 36 Norwegian building cases to evaluate the quantity of construction waste, waste-related GHG emissions per building typology, sorting grade and waste recycling rate. The buildings in total generated ca. 7800 tonnes of waste and ca.12900 tonnes CO_2eq and on average ca. 51 kg/m^2 waste and 88kgCO_2eq/m^2. The building projects had a high average sorting grade (89%) and a low average recycling rate (32%). Gypsum, mixed wood, clean wood, and mixed waste are the top waste fractions representing ca. 56% of the total waste volume. This highlights there is still a long way to go to achieve waste free construction sites ambitions. The results also suggest the need for using transparent data collection and communication methods, collaboration in the value chain, stricter regulations, and incentives for encouraging the development of new and existing waste prevention solutions and technologies.

1. Introduction

The building and construction industry in 2020 accounted for 36% of the global energy consumption and 37% of energy related greenhouse gas (GHG) emissions (UNEP, 2021). Of these emissions, the indirect GHG emissions (for generation of electricity and heat) from residential and non-residential buildings represented 18%, whilst the manufacturing of building construction materials represented 10%. Even if there is a 1% reduction in energy demand and GHG emissions in 2020 compared to 2019, GHG emissions from operational energy, embodied energy and material and construction processes will need to be reduced across the full life cycle to reach carbon neutrality by 2050. In contrast to the global average, including most of EU countries, the construction sector in Norway is responsible for around only 15% of the national GHG emissions, which come mostly from direct emissions from construction sites, production and transport of materials and products, due to high share of renewable energy, making indirect emissions low (FOG Innovation, 2021).

The building and construction industry is responsible for around 25% of the waste generated globally (Benachio et al., 2020). Despite the requirement set by the Waste Framework Directive (WFD) to recycle 70% of CDW, the recycling rate in most European countries is about 50% (European Commission, 2018a). Data from Statistics Norway (SSB) show that between 2013 and 2020, the Norwegian construction industry on average generated ca. 1.9 million tonnes of construction and demolition waste (CDW) annually. This is ca. 25% of the total annual waste. Of this, up to 39% comes from demolition, 33% from construction and 29% from rehabilitation activities (Statistics Norway, 2022a). Even if hazardous waste represented less than 2% of the total CDW volume, only less than half of the waste was recycled (ca. 46%) (Statistics Norway, 2022b). Moreover, on average ca. 24% of the total CDW was landfilled despite the potential environmental damage and depletion of landfill

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spaces. Norwegian construction sites on average generate 40–60 kg/m^2 waste (Nordby and Wærner, 2017), and ambitious projects set minimum waste generation goals to below 25 kg/m^2 (Fufa et al., 2021). The Norwegian SSB data shows Norway is behind the requirement for 70% material recovery set by the Waste Framework Directive (WFD) (European Commission, 2008). Moreover, there is a difference between the Norwegian and European statistical data on the material recovery rate of the Norwegian CDW. Lack of use of harmonised definition of terms for waste collection, means of waste handling methods (e.g., considering waste recovery through backfilling and downcycling instead of recycling) and lack of regulation in the waste reporting methods are some of the factors which leads to uncertainties in the national and European statistical waste data (NIRAS, 2022).

The EU waste legislations, such as the WFD and Landfill Directive (European Commission, 2018b), are one of the main drivers for waste prevention and management. The EU's circular economy action plan (European Commission, 2020), which is also one of the backbone for the European Green Deal, encourages circular economy processes to ensure waste prevention and increase resource efficiency measures. The Norwegian Building Regulation (TEK) sets a requirement mainly focusing on waste management such as a minimum of 70% waste sorting, waste reporting including the waste fraction that goes to landfill and recycling, and mapping of hazardous waste and materials suitable for reuse. Moreover, TEK incorporates the requirement for GHG emissions calculations from materials and construction waste following the national standard NS3720 for production (A1-A3), transport to building site (A4), construction waste (in A5), maintenance (B2) and replacement (B4) life cycle stages of residential and commercial buildings (Direktoratet for byggkvalitet, 2022). However, there is a gap in the requirement for concrete waste reduction measures (e.g., maximum requirement for the amount of construction waste generated per project) and recycling rate (e.g., 70% following the WFD target (European Commission, 2008)). There is also lack clear description of the GHG emission calculation method from construction waste (A5). On the other hand, the current BREEAM-NOR V6.0 (Norwegian Green Building Council, 2022), the Norwegian adaptation of BREEAM, includes more ambitious and measurable goals for the amount of waste from construction sites (ranging from 40 to 19 kg/m^2), sorting grade (ranging from 75%−90%) and percentage of reuse and recycling rate (50–70%) (Table 1). Still, there is lack of information in BREEAM-NOR manual regarding the scope of GHG emission calculation from the construction waste.

Life cycle assessment (LCA) is a widely used method to evaluate the environmental performance of CDW prevention (Bizcocho and Llatas, 2019; Llatas et al., 2021), reduction (e.g., through reuse) and selection of best CDW management measures (e.g., on-site/off-site recycling and landfill) (Devaki and Shanmugapriya, 2022; Liu et al., 2020a, 2020b; Mesa et al., 2021). Most of LCA studies focus on evaluation of CDW generated during end-of-life (demolition) phase of buildings (Liu et al., 2020a), while limited studies focus on CDW generated during the construction and use phase (mainly from renovation activities) (Bovea and Powell, 2016).

Table 1
Overview of credits for total amount of waste (Wst 01–01) and sorting, reuse and recycling rate (Wst 01–02) (Norwegian Green Building Council 2022).

BREEAM-NOR credits	Amount of waste generated in kg/m^2 (gross internal floor area)	
1	$\leq$ 40	
2	$\leq$ 25	
Exemplary level (1 point)	$\leq$ 19	
BREEAM-NOR credits	Waste sorting (%)	Percentage of ready for reuse or recycling (%)
Minimum requirement (no credit)	75%	–
1	85%	50%
2	90%	70%

The LCA based study conducted by Llatas et al. (2021) show the potential construction waste reduction of up to 57% from waste prevention measures (using alternative building elements) compared to non-prevention (such as reuse, recycling and/or incineration). The study also pointed out limited LCA studies on evaluation of waste prevention measures compared to waste management. The results from a Norwegian socio-economic analysis show that waste reduction measures such as early planning, increased use of prefabricated elements, sale of surplus materials and changes in the construction process are more profitable than reuse of construction products (Ibenholt et al., 2020). However, lack of legal requirements, lack of collaboration in the value chain and high costs related to waste reduction measures on the one hand, and relatively low cost of materials and waste treatment on the other, have been barriers to reducing waste and allowing materials to move up in the waste hierarchy (Fufa et al., 2021; Halogen, 2019; NIRAS, 2022). Even if there is a requirement for preparation of a waste plan in the early phase of new construction, rehabilitation or demolition, waste plans are primarily prepared to get approval to start the construction process, not to understand the material flow. There is also lack of a systematic method to data collection and reporting (NIRAS, 2022). The involvement of several actors with different levels of willingness, knowledge, and expertise towards proper waste management system, makes the information and resource flow challenging. Even if there are LCA studies evaluating the environmental performance of waste management measures, there are limited studies on evaluation of the environmental performance of construction waste. Moreover, there is lack of transparency in existing studies.

Despite lack of stricter regulations and several other challenges related to lack of technologies, infrastructure, data, and knowledge related to waste reduction, there are on-going international (Liyanage et al., 2019) and national initiatives with an ambition of achieving waste free/zero waste construction sites. For example,(Lu et al., 2021) developed a framework for zero waste construction site using case studies in China, using a definition of "zero waste" as on-site or off-site construction waste consumption through the 3Rs (reduce, reuse and recycle) with no waste sent to final disposal (incineration or landfill). The authors demonstrated that zero waste is challenging but achievable through amongst others balancing on-site and off-site operation strategies. As an input to UK's ambition to eliminate avoidable waste by 2050, GCB (2020) interpreted Zero avoidable waste (ZAW) as preventing waste generation from all stages of building and infrastructure. Construction waste is also considered avoidable waste, which can be either prevented, reused, or recycled but not sent to either landfill or energy recovery. Similarly, eleven major Norwegian actors initiated the waste free construction site activities aiming for eliminating different waste fractions through industrialisation, off-site construction and solutions for reusing and recovery of left over materials (FOG Innovation, 2021). This is evidence from the critics of the ambitions of the existing policies that it is the Norwegian public and private building owners and developers that are the main drivers for achieving ambitious goals. Norway is also following the upcoming WFD revision process, which aims to support overall or individual waste prevention and reduction measures, waste sorting, reuse, preparation for reuse and recycling and improve compliance with Extended producer Responsibility requirements (European Commission, 2022). This will require more collaboration across industries and research based innovative waste management plan, which is central to the Norwegian research project NADA (SINTEF, 2021). The NADA project aims to enable public building owners to set ambitious but achievable set of requirements for waste reduction from construction site activities through innovative public procurement procedures. The project works on developing a common framework for innovative waste reduction measures, standard and transparent data collection and reporting system to support the market and the procurement process.

The aim of this paper is to present a methodology for calculating and reporting construction waste and related GHG emissions. It demonstrates the implementation of the methodology using 36 building projects across three Norwegian municipalities and uses the results to discuss the status and way forward for achieving waste free construction sites in Norway. The scope of this study is limited to waste generated during the construction phase of Norwegian buildings. That means waste from infrastructure projects as well as waste from demolition and rehabilitation of building and infrastructure projects are not included in the analysis. After this introduction section, first, the waste and emission calculation methods are outlined. Then, the developed method is applied in the selected case studies and the results from the case studies are presented and discussed. Next, some important waste reduction measures that need to be considered and the limitations of the work are described. Finally, the conclusion drawn from the study is presented.

2. Materials and methods

Below is a description of the pilot projects and, waste and emission calculation methods developed in this study.

2.1. Pilot projects

The waste data from 36 construction site activities of new buildings are collected from pilot projects in Oslo, Asker and Bærum municipalities. The selected projects represent 14 school, 19 kindergarten and 3 nursing home building typologies. The selected buildings were completed between 2014 and 2021. The waste data per waste fraction is collected from the construction site final waste reports. Additional information such as the building area (gross floor area (GFA) were collected. It is important to note that the selected pilot projects did not set waste free construction site ambitions. Rather the projects were selected to test the methodology, get an overview of the status of building project construction waste, and discuss the way ahead to waste free construction sites.

2.2. Waste category and treatment

For the waste and GHG emission calculation, the waste categories and the percentage of waste treatment per each category is first developed. The list of waste categories follows the Norwegian standard for waste classification, NS 9431 (NS 9431, 2011). The list of the main waste categories used in a waste plan and report are selected using 4 digits. These waste categories are harmonised with the national statistical CDW categories (Statistics Norway, 2022a), which uses a different waste fraction reporting method (Table 2). Herein, the waste categories or classifications are referred as waste fractions.

The waste treatment percentages are based on the average SSB CDW data from 2013 to 2020 for percentage of recycling, incineration and landfill (Statistics Norway, 2022b). The percentage of construction waste treatment is calculated based on the CDW data due to lack of a separate waste data from construction, rehabilitation, and demolition activities of buildings and infrastructure. This data is considered as reasonable as the waste fractions from rehabilitation, demolition and construction of building and infrastructure projects end up at the same treatment facilities. However, it is also acknowledged that there is some uncertainty as demolition waste can contain more contaminated waste than construction waste.

Table 2
Waste fraction and percentage of treatment per fraction (Statistics Norway, 2022a).

Waste fraction			Percentage of waste treatment per fraction		
Waste fractions according to NS 9431		Wase fractions according to SSB	Sent to recycling	Energy recovery	Landfill
1100	Biowaste and sludge	Other waste	19.8%	1.7%	78.5%
1141	Clean wood waste	Wood waste	3.3%	96.5%	0.2%
1142	Impregnated wood waste	Wood waste	3.3%	96.5%	0.2%
1149	Mixed wood waste	Mixed waste	2.9%	91.7%	5.4%
1200	Paper, carton	Paper and board	96.9%	1.7%	1.4%
1300	Glass	Glass	70.6%	9.4%	20.0%
1400	Metal	Metals	100.0%	0.0%	0.0%
1500	EE-waste	EE-waste	85.2%	12.4%	2.4%
1600	Masses and inorganic materials	Bricks and concrete and other heavy building materials	67.4%	0.0%	32.6%
1611	Concrete without iron	Bricks and concrete and other heavy building materials	67.4%	0.0%	32.6%
1612	Concrete with iron	Bricks and concrete and other heavy building materials	67.4%	0.0%	32.6%
1613	Bricks and roof tiles	Bricks and concrete and other heavy building materials	67.4%	0.0%	32.6%
1614	Contaminated concrete and bricks	Polluted bricks and concrete	0.4%	0.0%	99.6%
1615	Gypsum	Gypsum	56.1%	0.4%	43.5%
1617	Rock and glass wool	Other waste	19.8%	1.7%	78.5%
1619	Asphalt	Asphalt	99.8%	0.0%	0.2%
1621	Roll roofing	Other waste	19.8%	1.7%	78.5%
1699	Inert mixed waste	Mixed waste	2.9%	91.7%	5.4%
1700	Plastics	Plastics	50.0%	29.6%	20.4%
7000	Hazardous waste	Hazardous waste	24.3%	28.1%	47.6%
9900	Mixed waste	Mixed waste	2.9%	91.7%	5.4%

2.3. GHG emission calculation

The GHG emission calculation in this analysis follows a life cycle assessment (LCA) methodology, which is a well-established method for evaluating the environmental performance of buildings. The system boundary for the GHG emission calculation follows the life cycle modular principles given under the Norwegian standard for GHG emission from buildings, NS 3720 (2018), and the latest draft European standard prEN 15978–1 (2021). The life cycle modules included in the analysis are presented in Table 3. The GHG emission methodology presented here focuses on the impact of construction waste only. As such, it includes the transport of waste fractions to different treatment facilities, waste processing and disposal activities, as represented by A5.1, as well as product stage (A1-A3) and transport (A4) of new equivalent materials used to replace the wasted materials.

The GHG emission calculation from construction waste (materials lost during the construction and installation process) considers the transport of the waste fractions to the different waste treatment facilities, waste processing (recycling or incineration) and waste disposal (landfill) processes and are reported under the life cycle stage A5.1. In addition, the potential impact from production and transport of materials used to replace the waste generated during the construction and installation process is reported under the production (A1-A3) and transport (A4) life cycle stages, respectively. The GHG emissions are reported in terms of kgCO_2eq. The background emission data is based on average generic data (from Ecoinvent v3.6 databases).

The total GHG emission calculation method is as follows:

Table 3
Life cycle modules included in the analysis.

Life cycle stages		Life cycle modules	Included (X)
Building life cycle stages	A1-A3 Product phase	A1: Raw material	X
		A2: Transport	X
		A3: Production	X
	A4-A5 Construction installation	A4: Transport	X
		A5.1: Construction and installation - Waste	X
		A5.2: Construction and installation - Other activities	
	B1-B7 Use phase	B1: Use	
		B2: Maintenance	
		B3: Repair	
		B4: Replacement	
		B5: Refurbishment	
		B6: Energy consumption in operation	
		B7: Water consumption in operation	
		B8: Transport in operation	
	C1-C4 End of life	C1: Demolition	
		C2: Transport	
		C3: Waste processing	
		C4: Disposal	
Supplementary	D Benefits and loads beyond the system boundary	D1: Recycling and energy recovery, reuse	
		D2: Export of own produced energy	

- GHG emission from A5.1 (kgCO2eq) = [quantity of construction waste per waste fraction (kg) x transport distance to different waste handling units (km) x emission factor per means of transport ($kgCO_2eq/kgkm$))] + [quantity of construction waste per fraction (kg) x emission factor per type of waste treatment ($kgCO_2eq/kg$)]

Amount of waste per waste fraction is collected from the projects' final waste reports. The waste fractions are assumed to be transported with 16–32t EURO5 transport mode to a close by recycling, energy recovery and/or landfill site located within 50 km. The GHG emission factor for the means of transport is taken from the Ecoinvent v3.6 process for "Transport, freight, lorry 16–32t, EURO5| Alloc rec". The GHG emission factors for the waste fractions per type of treatment is taken from corresponding Ecoinvent v3.6 processes.

- GHG emission from A1-A3 ($kgCO_2eq$) = [quantity of new materials needed to replace the waste fractions (kg) x emission factors from production of new materials ($kgCO_2eq/kg$)]

The quantity of new materials needed to replace the waste is assumed to be equivalent to the quantity of waste per fraction (e.g., 1 kg of new wood material for 1 kg of wood waste). This is a rough estimate due to lack of data on the actual purchased material and their quantities in the waste data gathered from the municipal building projects. The emission factors for the equivalent new materials are collected from Ecoinvent v3.6. An average emission factor per material fraction, except for mixed waste, has been considered to get a representative number. For mixed waste, an average emission factor from all new products used to replace the waste fractions is used, assuming the mixed waste is an equal mixture of all other waste fractions.

- GHG emission from A4 ($kgCO_2eq$) = [quantity of new materials needed to replace the waste fractions (kg) x transport distance to the construction site (km) x emission factor per means of transport ($kgCO_2eq/kgkm$)]

The quantity of new material needed is assumed to be the same as the amount given in the GHG emission from A1-A3 phase. The transport distance for different material groups is taken from the default transport distance given in product category rules (PCR) used in EPDs. The means of transport and emission factor is assumed to be the same as in A5.1.

In addition to the total GHG emissions shown above, the GHG emission per gross floor area (GFA) is calculated. The 100:0 allocation approach to recycling is considered to allocate the environmental impacts of the recycling to the product using a recycled material, with no burden from recycling operations at the end-of-life treatment of construction waste fractions (A5.1).

3. Results

The total amount of waste and GHG emission per waste fraction, waste and GHG emissions per GFA for the three-building typologies is presented below.

3.1. Total waste and GHG emissions

The results from the total amount of waste and the associated emissions generated per project is presented in Fig. 1. The projects generated between 26 and 845 tons of waste and 53–1037 tons of CO_2eq.

The waste and GHG emission results per GFA show that the projects generated 14–82 kg/m^2 waste and from 29 to 174$kgCO_2eq/m^2$ GHG emissions (Fig. 2).

There is a positive relationship between quantity of waste and GHG emissions generated, both at building level ($R^2 = 0.93$) and per m^2 GFA ($R^2 = 0.75$). However, the results also show that there are notable exceptions where high waste levels are paired with relatively low GHG emissions (e.g., School 10). Comparing Fig. 1 with Fig. 2 also highlights the importance of choosing appropriate units, as the relative ranking of the projects changes significantly when switching from total to per GFA results. For example, School 3 has low total waste and GHG emissions, but generated the largest quantity of waste per GFA. There is no clear difference between the three building typologies, especially at GFA level.

3.2. Waste and GHG emissions per fraction and treatment type

The average sorting grade across the projects is 89%, with one school (School 2A) and one kindergarten (KG 1) managing to sort 100% of their construction waste (Fig. 3). However, this does not translate in high recycling rates, which range from 19 to 45%. In contrast, energy recovery rates range from 34% up to 75%. The schools tend to have higher recycling rates with an average of 37% and a lower energy recovery rate (average 43%), compared to the kindergartens (which average respectively 28% and 59%). The landfill rate ranges from 5 to 27%, where kindergarten projects tend to be on the low end and school projects tend to be on the high end. The kindergarten with 100% sorting grade (KG 1) also has a relatively low recycling rate (23%), high energy recovery rate (58%) and high landfill rate (19%). This shows the importance of combining waste sorting with waste reduction, good waste management systems and infrastructure to get good results.

Across the 36 case studies, gypsum, mixed wood and clean wood are the top three waste fractions representing 45.5% of all waste. However, these three fractions only account for 10% of all GHG emissions. In contrast, metal and mixed waste make up only 18.2% of the waste generated but account for 53.4% of all GHG emissions. This is illustrated in Fig. 4, which plots total GHG emissions against total waste from all projects. Gypsum, mixed wood and clean wood are clear outliers in the bottom right of the plot (large waste quantities), while metal and mixed waste stand out in the top middle of the plot (high GHG emissions). EE waste produces the highest GHG emissions per unit of waste, but relatively little of this waste type is generated in the projects.

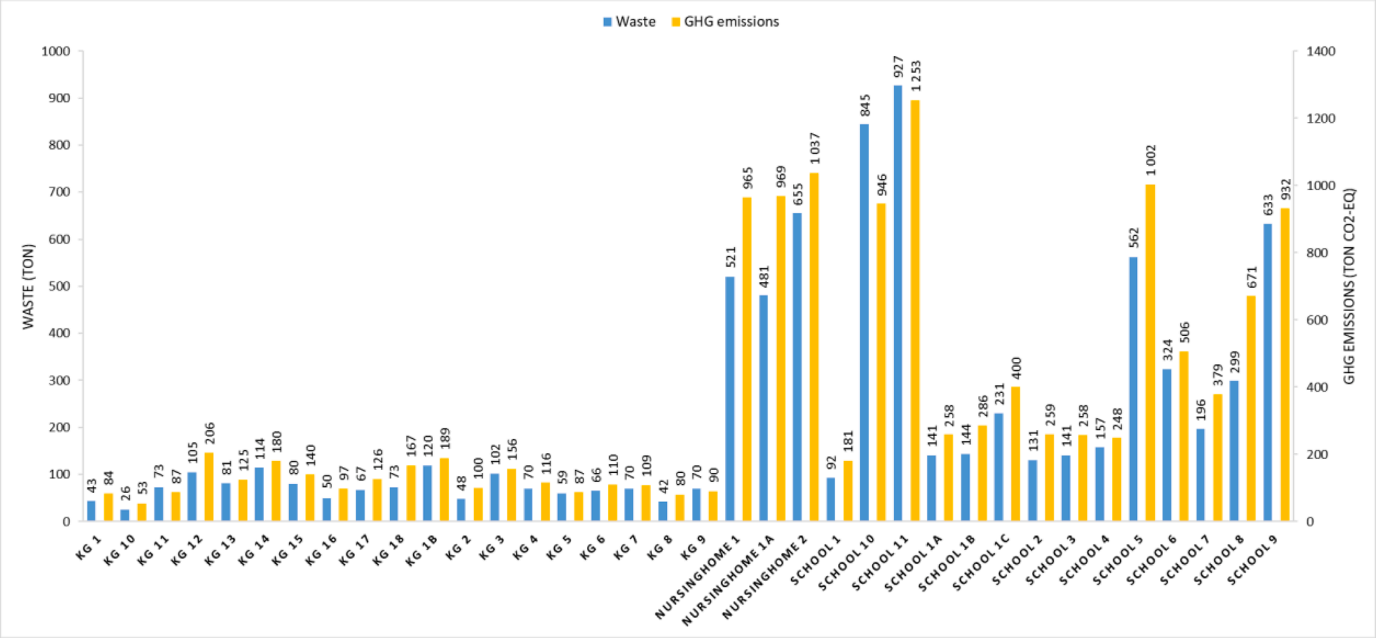

Fig. 1. Total amount of waste and GHG emissions per project.

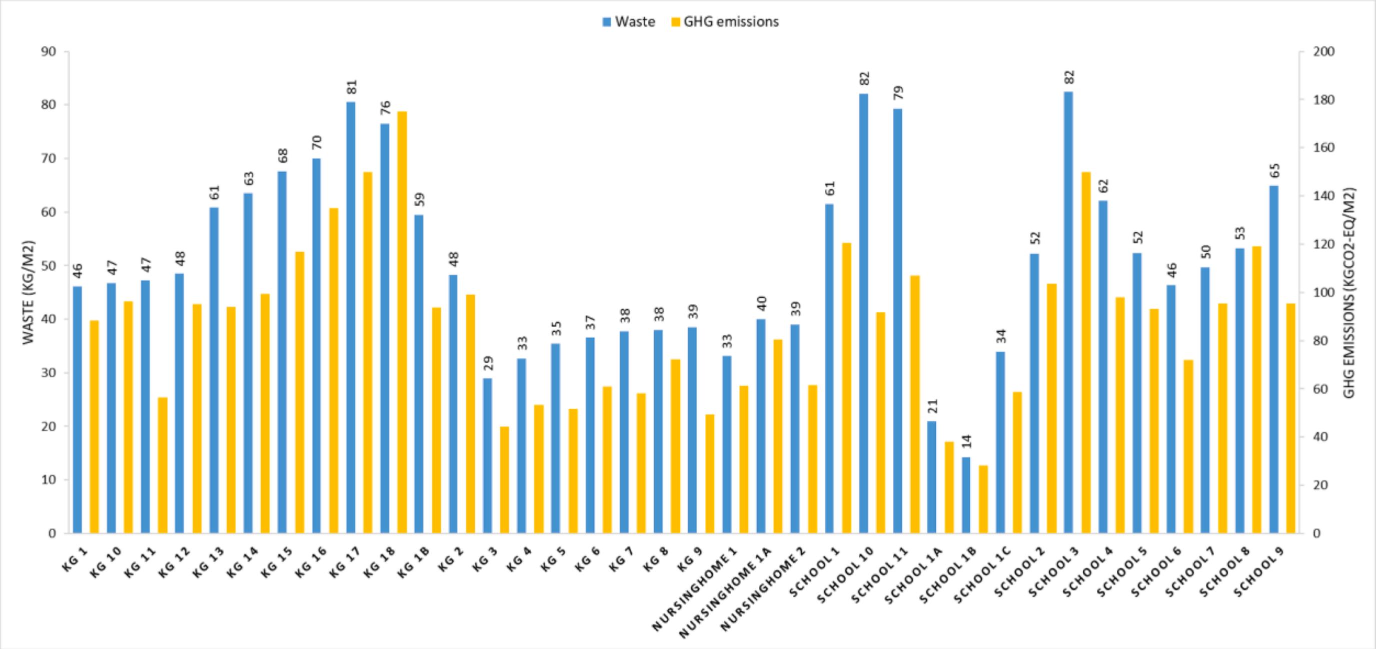

Fig. 2. Amount of waste and GHG emissions generated per GFA of the projects.

3.3. *Waste and GHG emissions per life cycle stage*

Fig. 5 shows the relative contribution of the different life cycle stages to the GHG emissions for each project. It is evident that the bulk of emissions can be ascribed to the production of new materials used to replace the waste (A1-A3). This highlights the importance of considering the upstream process in environmental impact assessment to avoid environmental impact shift from construction to the production process.

4. Discussion

The following section discusses the results and limitations highlighting some important issues, in light of previous studies, that can facilitate and support waste reduction and waste free construction site ambitions.

4.1. *Waste sorting and material recovery rate*

Even if waste prevention and reuse are the best options, the focus of the Norwegian construction industry lies on achieving higher sorting grades. The results from this study show that while most of the waste generated during the construction phase were sorted, with 89% average sorting grade, this did not result in higher recycling rates as the average recycling rate of the projects is ca. 32%. The low recycling rate could be attributed to lack of technologies for tracking of resource flows to reduce the volume of waste, lack of national recycling facilities (e.g., for wood,

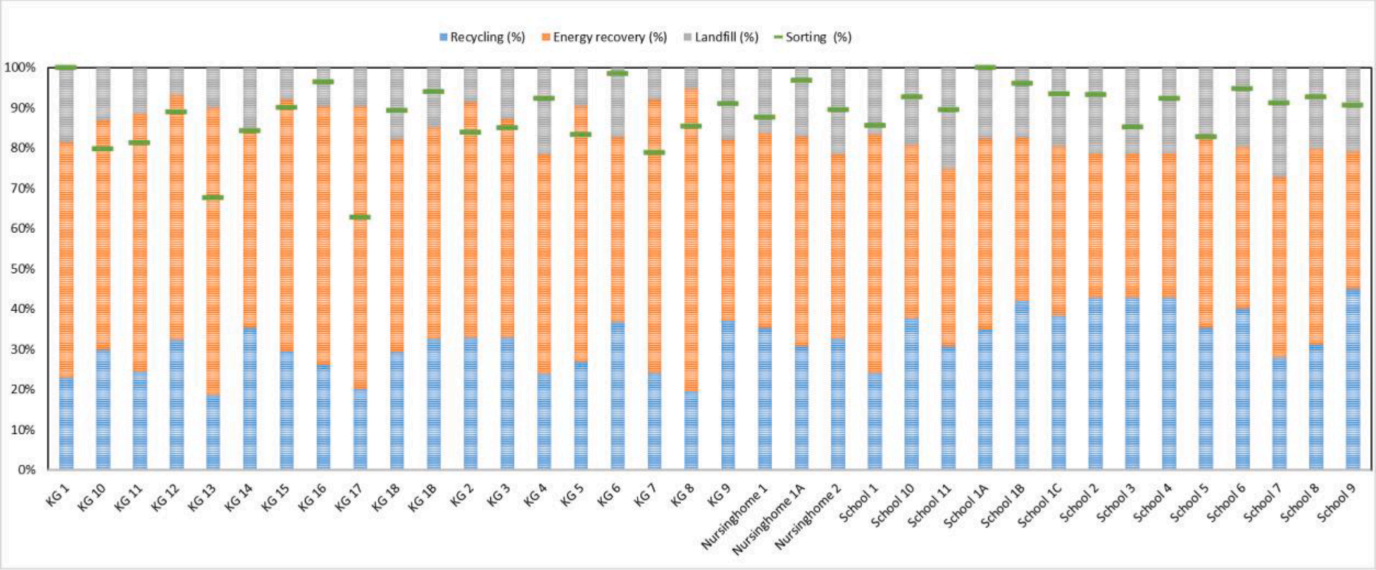

Fig. 3. Waste recycling, energy recovery, landfill, and sorting grade per project.

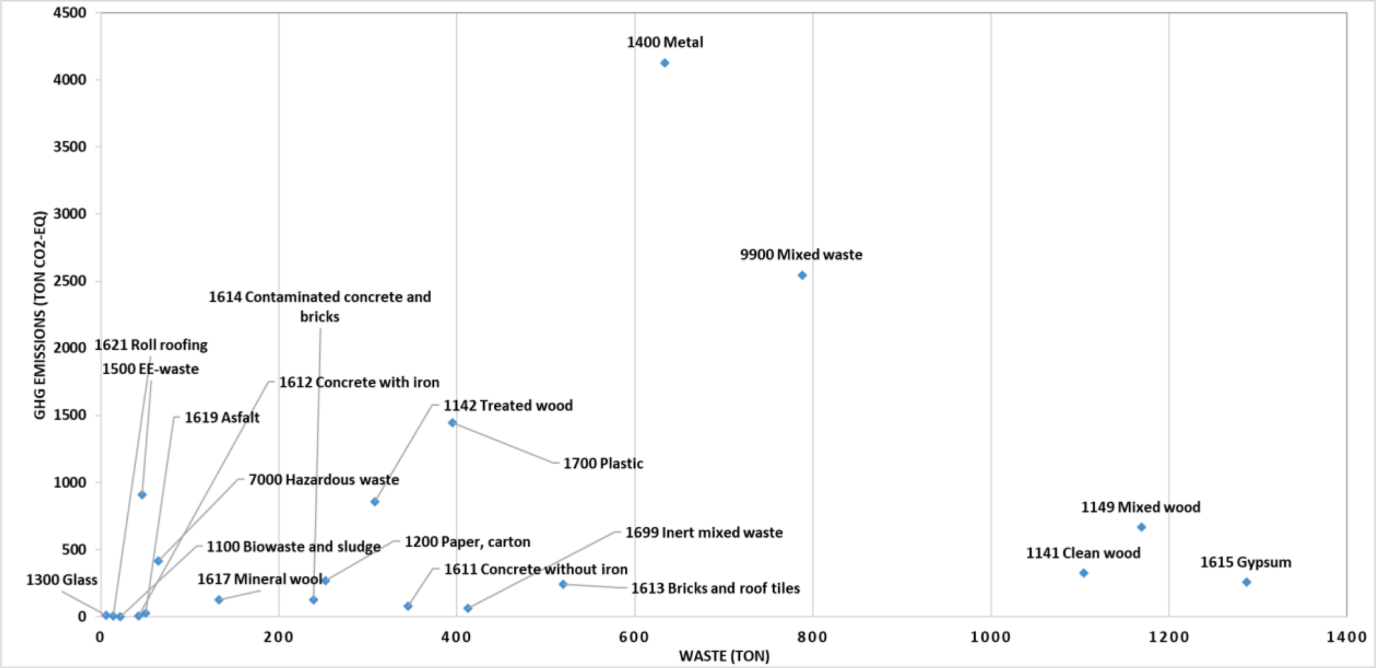

Fig. 4. Total amount of waste vs total GHG emissions per waste fraction across all 36 projects.

representing ca. 33% of the total waste volume), cost (e.g., cheaper incineration and landfill solutions than recycling), or lack of stricter regulations (e.g., lack of requirement or ambition to zero landfill) (NIRAS, 2022).

There is also lack of data on reuse rates, as the waste plan and report only focus on collecting data on the amount of waste generated. Moreover, several challenges such as technical, regulatory, infrastructure and different users' perceptions hinder reuse of construction products (Knoth et al., 2022).

Since higher sorting grade does not necessarily result in higher material recovery rate, the construction industry needs to shift focus and set ambitious goals and actions to reduce waste and plan properly for efficient resource management when waste is generated. Evaluation of the environmental performance of different solutions is important to avoid problem shifting (e.g., off-site waste recycling might not be a best option depending on the distance to the recycling facilities) (Mesa et al., 2021). Selection of recyclable, locally available, and low carbon materials can reduce the impact from the production of materials (used to replace waste (A1-A3)), waste disposal and technical performance during the operational process (Liu et al., 2020b).

The current shortage of construction materials and increase in material cost can force actors to consider new or better waste reduction measures, digital waste collection systems, and new technologies to get better knowledge on the resource flow. This will enable building owners to set ambitious waste prevention, reduction, and management goals. It is essential to develop and use advanced and sustainable methods to assess the performance of waste reduction measures (e.g., reuse of concrete formwork (Mei et al., 2022)), development of infrastructure (e.

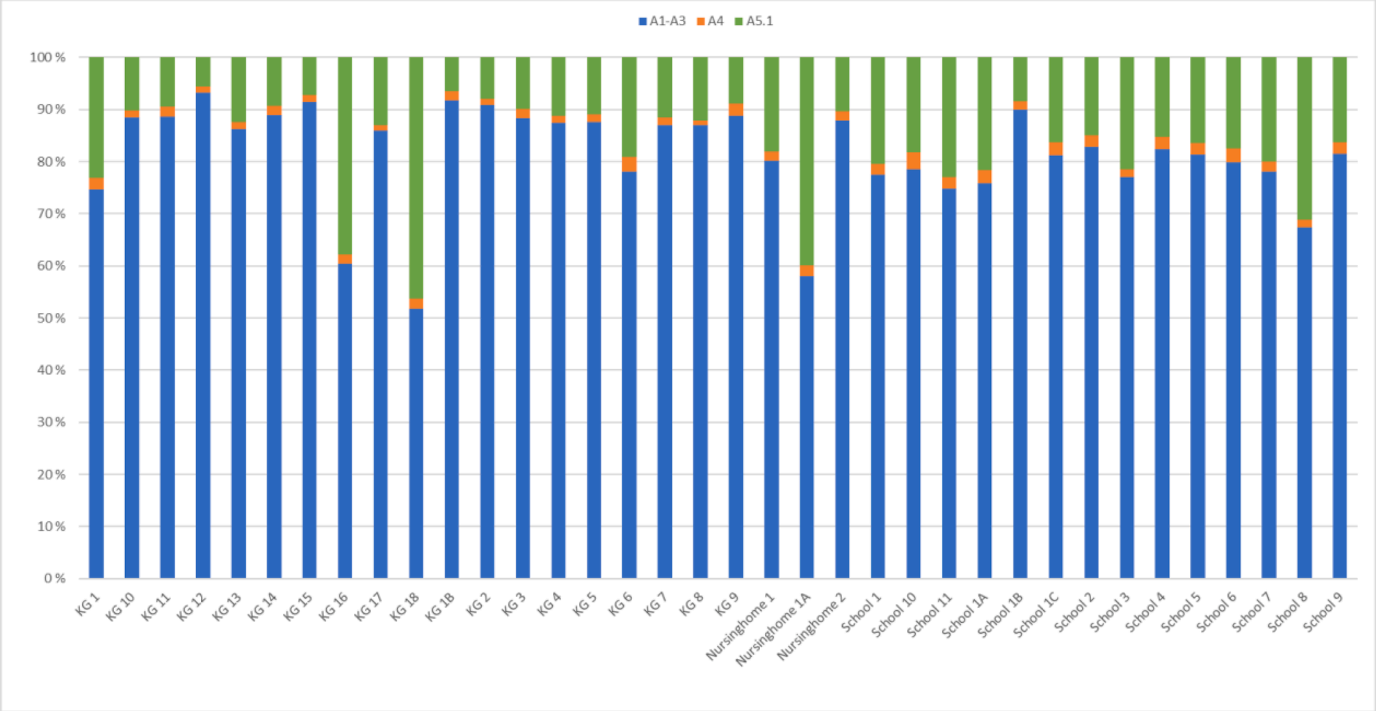

Fig. 5. GHG emissions per life cycle stage.

g., on-site recycling facilities (Bao et al., 2020)), communication and information technologies for mapping and tracking of resource flows (e.g. BIM (Wu et al., 2019)), real time monitoring systems (Rao et al., 2022)), and R&D activities, supported by regulations and incentives, for early planning of waste prevention and reduction.

4.2. *Construction practices*

There is no clear difference between the building typologies examined in this study, as shown in Fig. 2. Due to a lack of more detailed data on construction choices such as construction methods (e.g. on-site, prefabrication, modular), construction types (e.g. concrete, steel, wood), and facade materials (e.g. tiles, wood), as well as implemented waste reduction measures, it is not possible to identify any other underlying causes for the observed differences between the projects.

Off-site construction - the design, planning and prefabrication of elements, modularization, and standardization of construction process outside the construction site (e.g., in a factory) - has been considered the best option for waste and environmental impact reduction on the construction site. Higher productivity and quality, quicker construction time, less workload and manpower needed, safer working environment, and less disruption to neighbours are some of the advantages (Halogen, 2019; Kong et al., 2018). However, off-site construction methods require, amongst others, detailed project planning, coordination and collaboration between actors in the supply chain, skills and expertise and on-site and off-site logistic solutions (Dixit et al., 2022; Durdyev and Ismail, 2019; Studer and De Brito Mello, 2021). Lack of flexibility for changes in design or project scope after the construction begins and renovation and additions to existing structures adds to these challenges. Despite these challenges, countries like Sweden (with 85% of new housing), Netherlands (with 20%) and Japan (with 12–16% of all new built housing) have been able to partly shift from on-site to off-site construction (Steinhardt and Manley, 2016). Evaluation of the lessons learned from the success of other countries is an area for further research.

Current activities focus on waste reduction mainly from the construction sites, without considering the waste from off-site activities, which might result in shifting waste from construction site to the production (e.g., prefabrication or module production) and transport phases (e.g., longer transport distance and waste from extra packaging need). The methodology presented in this paper also focuses only on evaluation of construction site waste. Waste prevention and reduction should begin in the design phase, through optimized designs, considering minimizing material usage, design for disassembly/deconstruction and design for reuse allowing flexibility and adaptability for future technological developments. Use of digital platforms such as BIM can increase productivity, reduce cost, time and waste generation related to design problems and changes as well as simplify the data availability of building materials for a life cycle assessment of waste reduction and management measures including material choices, construction method, material handling and maximizing reuse and recycling rate (Wu et al., 2016; Won and Cheng, 2017). Further analysis on collection and evaluation of waste from different construction methods can illustrate the actual performance of off-site construction methods.

4.3. *Collaboration in the value chain*

The 36 case studies from the three municipalities generated ca. 7900 tons of construction waste, of which less than 2700 tons was recycled. The average quantity of waste generated per project is 51 kg/m^2, which corresponds well with the previously reported average waste from Norwegian construction sites of 40–60 kg/m^2 (Nordby and Wærner, 2017). Only two projects (School 1A and School 1B) generated less waste than the current ‘ambitious’ target of 25 kg/m^2. This shows there is still a long way to go to achieve waste free construction site ambitions. Lack of knowledge, awareness, and willingness of involved actors to incorporate measures to increase resource efficiency are some of the main challenges for waste reduction from construction site activities. Moreover, lack of involvement of relevant actors during the preparation of a waste plan, such as logistic suppliers and waste handlers, lack of proper use of the waste plan, and lack of follow-up on waste reduction measures results in a poor overview of the resource flows in the construction process and the effectiveness of implemented waste reduction measures.

Proper and detailed waste management plans, considering both on-site and off-site waste reduction and consumption measures, are crucial for waste reduction and achieving waste free construction site ambitions (Lu et al., 2021). The methodology presented in this paper can be used to prepare a waste plan together with relevant actors, implement and follow up ambitious waste reduction measures, increase understanding of the resource flow, increase availability of waste data, and enhance collaboration between different actors to fulfil or go beyond waste goals. Involving manufacturers and suppliers in the waste reduction activities can enable waste reduction not only from the construction site activities but also from the production processes. A good collaboration between different waste handlers can accelerate the move towards waste free construction sites, through waste reduction, increased reuse and recycling rates, and supporting them in the transition from being a waste handler to a material supplier. The construction waste reduction activities should also be supported by digital technologies, such as RFID-enabled supply chain collaboration and information sharing (Benachio et al., 2020; Zhang and Atkins, 2015) to track, understand and improve resource flows.

4.4. Public procurement

The results from the case studies illustrate the variation in the waste data due to lack of requirements for reporting and follow up construction waste. Policy initiatives, regulations, awards and punishments for involved stakeholders are identified as the main driver as well as barriers for waste prevention, reuse and recycling (NIRAS, 2022). Public building owners in the Norwegian building and construction industry are frontrunners in setting ambitious goals and incorporate measures to reduce GHG emissions and increase resource utilization (Venås et al., 2020; Wiik et al., 2020). Activities related to emission free construction sites are good examples where Oslo and six other municipalities are working towards reaching zero emission construction sites by setting stricter requirements in all their public procurements. Public procurement has been the main driver to place Norway at the top leader position in emission and fossil free construction site activities (Bellona Europa, 2021). Regarding waste, measures like stricter governmental regulations could lift the bottom-performing projects. The methodology presented in this study can be used to create benchmark values that can guide the public sector in setting ambitious but realistic waste reduction requirements. It can also help to solve the current lack of harmonized evaluation, reporting and follow up method.

To induce new and efficient practices in the industry, there is a need for clients that challenge the contractors and suppliers and demand sustainable practices. Through the size of public procurements, and the role of public building owners in the Norwegian industry, innovation-orientated construction projects have the potential to overcome barriers and go from pilot projects on waste reduction to low-waste as a new, best practice in the industry. This methodology can be used as a data-driven framework to work with the waste challenges, that enables collaboration in the value chain and consistently and iteratively implements better solutions in the planning and execution of construction projects.

4.5. Data availability and presentation

The process of data collection from the 36 case studies presented several challenges. First, there is a lack of a harmonized waste reporting system, with each waste handler presenting the waste report in their own way (for example the Grønt Ansvar system developed by Norsk Gjenvinning(Norsk Gjenvinning, n.d.). However, those systems are not open and are mainly used by the contractors. This hinders automation of the data collection and limits the comparability of different waste reports. Moreover, the waste reports do not specify the actual treatment methods of the various waste fractions, nor any information on the transport to treatment facilities. Finally, there is a lack of additional information, such as construction method and type of construction materials, which would help to understand the reason behind higher or lower waste quantities. The projects in this study were not selected because of their ambitious waste reduction goals. More detailed analysis through quantitative interviews, and selecting ambitious case studies with best practices on waste reduction, could provide insight into the effectiveness of different waste reduction strategies and the influence of construction choices on waste generation.

Developing or using existing labelling systems can support a transparent communication of the resource flow from the construction process. Environmental Product Declarations (EPDs) are a good example in Norway which have been widely used by different actors as means of communication of the environmental performance of products (DTI, 2021; Schlanbusch et al., 2016). The requirements from Statsbygg, the Norwegian Directorate of public construction and property, and the rewards in BREEAM-NOR for products with EPDs promoted the development and use of EPDs. Along with the environmental impact and resource use indicators, EPDs provide end of life waste (hazardous waste, non-hazardous waste and radioactive waste disposed) and output flows (components for reuse, materials for recycling, materials for energy recovery, exported electric energy, exported thermal energy) per life cycle stage. However, EPDs do not provide detailed information per waste fraction. Asking for the waste report behind the end-of-life waste and output flows reported in EPD, from both production and construction activities, can be a useful approach to increase accessibility and transparency of waste data. Moreover, as EPDs are now being digitalized, they can be a good source of better and more specific data in waste and GHG emission assessments. The waste report can make the production waste data, which is currently missing, available, and make it possible to get the waste data from the whole life cycle of the construction process. Since EPDs already contain detailed information for other environmental indicators, the waste report can be added as an attachment to EPDs.

4.6. Background data, methodological choices and limitations

LCA is a widely used method for evaluation of the environmental performance of buildings. However, the quality of LCA result depends on the methodological choices and the background data. The methodology developed in this study is limited to the GHG emission from construction waste (A5.1) and the potential impacts from the production (A1-A3) and transport (A4) of materials used to replace the construction waste. Several assumptions are also made in the background data including replacement of 1 kg of waste with 1 kg of new materials, using average national statistical data for the type of waste treatment per fractions, and assumptions related to means of transport and transport distances. Quantitative uncertainty analysis related to the data quality and methodological choices is not covered due to lack of detailed information from the cases used to demonstrate the methodology. The authors also acknowledge the limitation in the generic data from Ecoinvent database. For instance, the emission factor for the landfill of different waste fractions process in Ecoinvent databases is very low, even if landfill can cause serious environmental problems due to the production of GHG gases, methane and release of leachates (Danthurebandara et al., 2013; Kumar et al., 2020). Since most EPDs use the background emission factors from Ecoinvent or other generic databases, the GHG emission results from EPDs might nevertheless be similar. Based on a systematic literature review of LCA studies, Wu et al. (2019) also point out lack of LCA database development, lack of sensitivity and uncertainty analysis in most of LCA studies.

Different waste fractions need different waste reduction and treatment measures. The type and amount of waste generated per building typology also varies. The methodology developed in this study can support a quantitative analysis of the environmental performance of waste reduction and treatment measures per waste fraction to avoid trade-offs in the potential environmental impacts. The results from the cases highlighted how the methodological choices, getting good background data per waste fraction and building typology can support the selection and development of potential waste prevention and reduction measures. The 100.0 allocation method considered in this study encourages recycling of waste. The methodology developed in this study is flexible for further modification using project specific data such as bill of materials, EPDs and waste treatment data from actual waste handlers. This will improve the validity of the results. In further work, the bill of material quantities from the projects should be collected and evaluated to get an overview of the actual quantities of materials purchased, used, and sent to waste. Scenario analysis on different allocation methods, evaluation of the impact of difference between using Ecoinvent and EPD data and possibilities for improvement of the background databases could be further explored in future studies.

The scope of the presented methodology excludes the use phase of the construction materials, as its focus lies on the impact of generating waste on the construction site. While this approach is effective for informing waste reduction activities, it cannot evaluate the effect of material choice on for example, energy efficiency of the building. Changing the insulation material to something that is more likely to be recycled, but is less effective as insulation, may increase the total life cycle impact due to increased heating needs. This methodology should therefore be combined with other methodologies that address aspects such as use phase and end-of-life emissions.

Further research should cover the whole life cycle impact assessment in terms of including all life cycle stages, other environmental impact indicators (such as resource use (e.g., fossil fuels), ecosystem services (e.g., ecotoxicity) and human health (e.g., human toxicity) categories), and economic and social impacts. The findings from the systematic review of LCA on construction and demolition waste conducted by Mesa et al. (2021) also pointed out the need for more research on design of methodologies for evaluating the whole life cycle of buildings and building materials including different project phases and circular waste handling measures. The presented methodology is limited to waste from new buildings, and future studies are encouraged to evaluate waste from demolition and rehabilitation activities. There is on-going activity through the research project NADA to develop a simplified tool for data collection, evaluation, reporting and follow up of construction waste reduction and management measures. Modification of the methodology presented in this work by incorporating most of the above-mentioned limitations will be part of the tool development work.

5. Conclusions

This study presented a methodology for evaluation and follow up of construction waste and related GHG emissions and illustrated its use through data collected from three municipalities in Norway. The quantitative analysis addresses the growing interest in waste free construction sites, confirming some existing findings and providing some new insights. The methodology addresses the current lack of construction waste assessment methods in the current LCA tools and national requirements. The results from the case studies confirms great potential as well as challenges for achieving the waste free construction site ambitions. Two projects generated less waste than the most used ambitious target of 25 kg/m^2, but most of the projects produced more than the reported average waste values. Moreover, the analysis showed a wide range in construction waste-related GHG emissions. The high sorting grade (with an average value of 89%), did not translate into a high recycling rate (with an average value of 32%), confirming the importance of considering a combination of waste prevention, waste reduction and proper waste management measures with stronger emphasis on reuse and material recycling. Construction methods, collaboration in the value chain and incentives and fines in regulations and public procurement are some of the potential drivers and barriers identified for waste prevention, increased reuse and recycling rate. There is no significant difference between the waste and GHG emission results between building typologies which needs to be explored further. This work provides a foundation and motivation for further research and setting policy framework on waste reduction measures aiming to achieve waste free construction sites. Future work needs to be conducted to generate more data including presentation of uncertainties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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