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Comparative Assessment of the Carbon Footprint of on-site and off-site Wall Element Constructions

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Abstract. Off-site construction is considered as environmentally preferable to on-site due to the controlled environment for planning and production before assembly in the construction site. However, evaluating the actual environmental benefits and drawbacks from a life cycle perspective is important to avoid problem shifting. The aim of the paper is to evaluate the environmental performance of conventional on-site construction of wall elements, in comparison with off-site wall element production in a factory and assembly on the construction site. This study has been a collaboration with a Norwegian contractor using wall constructions with elements produced either on- or off-site. The contractor seeks to reduce the negative environmental consequences from building activities by establishing a local factory for off-site element production, thus motivating this study to provide environmental inputs to a decision-making process. The wall elements which either fulfil the Norwegian building code (TEK17) or passive house (PH) standard are evaluated using three scenarios: 1) on-site construction with local materials obtained from Norwegian manufacturers/suppliers, 2) off-site wall element production and wall construction in Norway, and 3) off-site wall element production in Estonia and wall construction in Norway. The GHG emissions from the scenarios are calculated using screening LCA method for life cycle stages of production (A1-A3) and construction (A4-A5). The results show that lowest GHG emissions are attributed to local Norwegian off-site TEK-wall element production, whereas the Norwegian on-site PH-wall has the highest GHG emissions. The results also highlighted the contribution to GHG emissions of specific building materials, as well as the dependency of the results on the background data and the methodological choices used in the study.

1. Introduction

Buildings and construction are responsible for ca. 37% of global energy and process related GHG emissions in 2021 [1]. Of those total GHG emissions, ca. 27% are from building operational energy use (9% from fossil fuels and 19% due to electricity use) and ca. 9% from embodied emissions related to building materials and constructions. The average share of embodied GHG emissions from buildings are estimated to increase from 45-50% to up to 90% of the total GHG emission for highly efficient buildings [2]. Focusing only on reducing emissions from operational energy use through increasing energy efficiency, reducing operational energy use and conversion to renewable energy sources might result in higher embodied emissions. This shows the importance of consideration of embodied emission reduction measures, such as reusing materials, use of low or zero carbon materials, use of carbon sequestering materials, in addition to GHG emission reduction from operational energy use to avoid shifting of GHG emissions and achieve environmental goals.

Selection of construction method has been discussed as one means of GHG emission reduction from the construction industry. Off-site construction (OSC), including prefabrication and modules, is an alternative to conventional on-site construction where building components are prefabricated in an off-site manufacturing facility, with more controlled production line, and transported to the construction site for assembly. Previous research has highlighted several benefits of OSC compared to conventional construction, amongst these are safer and faster on-site assembly with potential of reducing material and energy consumption, waste generation and GHG emissions, reducing construction time and workloads providing reduced costs, and other potential impact reduction from construction site activities (e.g., noise and dust generation) [3–5]. Previous literature reviews indicated significant differences on the environmental performance of OSC, which also reflects differences in the GHG emission results due to the difference, among others, in the selected case studies, system boundary, assumptions and material choices [6,7]. Variations are found for both embodied carbon (93-864 $kgCO_2/m^2$) and operational carbon (11-76 $kgCO_2/m^2$/year) [6,7]. While the operational emissions during the building use phase are relatively similar between OSC and conventional construction [8–10], the embodied impacts are generally found to be lower for OSC [6,7,11]. To what degree prefabrication reduces GHG emissions is also subjected to the variations, where studies show that prefabricated buildings, on average, achieve 15.6 and 3.2 % reduction of embodied and operational GHG emissions, respectively [7]. Comparative life cycle assessments from cradle-to-gate show lower embodied GHG emissions for prefabrication compared to conventional construction methods ranging from 3.2 % to as much as 65 % reduced embodied impacts [6,10,12–15]. The contribution of embodied GHG impacts are estimated to be more than half of the total GHG emissions [6]. Some studies also find higher embodied emissions for OSC compared to conventional construction, mainly due to the choice of the structural material [8]. For example, prefabrication of steel buildings are found to have higher GHG emissions than conventional construction methods [8,9]. However, the basis for comparing OSC and conventional construction methods is not optimal when comparing building structures of different structural materials, e.g., prefabricated steel and timber buildings with conventional concrete construction [6,8]. Performing comparative assessments of on- and off-site construction methods with similar materials [10,12–14] would form better basis for investigating the potential benefits of off-site construction. In addition to reduced GHG emissions, several studies report significant waste reduction potential with prefabrication. For instance, waste generation through building life cycle is estimated to be reduced by 60 % by prefabrication [9]; while other studies estimated that prefabrication may lead to five times less waste generation [6] and conventional construction may generate 2.5 times more solid waste than OSC [16]. In other studies, OSC has been described as an enabler of 'design for disassembly' [3], and previous research show that reuse of materials from prefabricated steel and timber structures may save up to 69 and 81 % of initial embodied energy, respectively, and 36 and 51 % of initial materials by mass, respectively [8].

While previous research seems to broadly agree that OSC, on average, is expected to achieve better life cycle performance than conventional construction, certain research gaps are found in existing literature. For instance, there are significant inconsistencies in the reported embodied carbon emissions of OSC buildings [7] and only limited studies have been performed on the whole life cycle assessment of OSC [4]. In addition, few studies were conducted at the material and component level or for their use in a cold climate areas [7], even if external walls have been pointed as the greatest share of overall material volume in buildings, with the greatest potential for emission and waste reduction [8]. Thus, further studies on the environmental performance of OSC in general and wall elements in particular is warranted.

The objective of this paper is to evaluate the environmental performance of on-site and off-site wall element constructions. This work originates from a collaborative research project examining the carbon footprint of wall element constructions through screening LCA method. The project was conducted in close collaboration with a Norwegian contractor using wall constructions with elements produced either on- or off-site. The company is currently in the planning phase of establishing a local factory for off-site element production, and the project work was conducted to provide an input to the decision-making process. After this introduction section, the paper is structured as follows: Section 2 describes the data acquisition and methodology, section 3 presents results from the comparative assessment of the carbon footprint of on-site and off-site wall element constructions, section 4 includes the discussion, while section 5 concludes and gives recommendations for future activities.

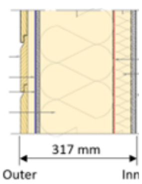
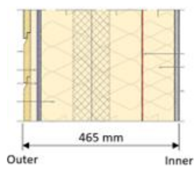
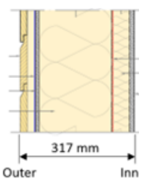
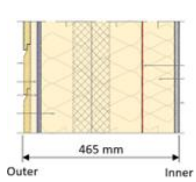
2. Methodology

The methodology used in this paper is a case study through comparative assessment of the environmental performance of on-site and off-site wall element constructions. The Norwegian contractor provided specific data on wall element production, construction method and construction installation activities, as well as playing a vital part in establishing realistic scenarios and viable assumptions for the study. In addition to the primary data sources, the study applies background emission data from Environmental product declarations (EPDs) and a generic database (Ecoinvent v3.1). The methodology section presents the wall elements considered in this study, the LCA methodology used to calculate the GHG emissions and scenarios considered for the comparative assessment.

2.1. Wall elements

Table 1 specifies the type of materials and dimensions of wall elements considered in this study, which either fulfil Norwegian building code (TEK17) or passive house (PH) standard, manufactured either on-site in Norway or off-site in Norway or Estonia. The composition of the Norwegian on-site and off-site wall elements are identical, while the Estonian wall elements are used for off-site production only. The wall element constructions have similar structures, consisting of ten material layers, including (from exterior to interior) cladding, wood battens, wind barrier, wood stud, fiberboard, insulation, vapor barrier, battens, insulation, and interior cladding. A distance of 60 cm is considered between individual studs and battens.

Table 1 Specification of wall element constructions

Description	TEK 17		PH	
	Layout	Details (exterior to interior layers)	Layout	Details (exterior to interior layers)
Norwegian wall elements[a]		19 mm coated wooden cladding 23x48 mm wood battens 0.15 mm Isola wind barrier 48x198 mm wood stud 12 mm Hunton wind barrier 200 mm Glava insulation 0.15 mm Tommen Gram vapour barrier 48x48 mm wood battens 50 mm Glava insulation 13 mm Norgips gypsum board		19 mm coated wooden cladding 23x48 mm wood battens 0.15 mm Isola wind barrier 47x300 mm Iso3 wood stud 12 mm Hunton wind barrier 300 mm Glava insulation 0.15 mm Tommen Gram vapour barrier 48x98 mm wood battens 100 mm Glava insulation 13 mm Norgips gypsum board
Estonian wall elements[b]		19 mm coated wooden cladding 23x48 mm wood battens 0.15 mm Isola wind barrier 48x198 mm wood stud 12 mm OSB Kronolux wind barrier 200 mm Paroc Extra insulation 0.15 mm Rainmobar vapour barrier 48x48 mm wood battens 50 mm Glava insulation 13 mm Norgips gypsum board		19 mm coated wooden cladding 23x48 mm wood battens 0.15 mm Isola wind barrier 47x300 mm wood stud 12 mm OSB Kronolux wind barrier 300 mm Paroc Extra insulation 0.15 mm Rainmobar vapour barrier 48x98 mm wood battens 100 mm Glava insulation 13 mm Norgips gypsum board

[a] For off-site Norwegian TEK and PH wall constructions, layers 1-6 are assembled at the factory in Norway, and the rest of 7-10 layers are installed at the construction site in Norway. All materials used in 1-10 layers, except layer 3, are produced in Norway.
[b] For off-site Estonian TEK and PH wall constructions, layers 2-8 are assembled at the factory in Estonia, and the rest of 1, 9-10 layers are installed at the construction site in Norway using materials produced in Norway.

The selected wall elements represent actual wall constructions used by the contractor, satisfying requirements for either TEK17 or PH standard. Thus, this case study provides a comparison of realistic construction alternatives. See also specification of the comparative assessment scenarios in Section 2.3.

2.2. GHG emission calculation
The GHG emission calculation is performed following the standards for principles and framework for LCA (ISO 14040/44 [17,18]), environmental performance evaluation of building products (EN 15804 [19]) and buildings (NS 3720 [20]). A screening LCA method is used focusing on the embodied emissions from the production (A1-A3) and construction and installation (A4-A5) life cycle stages. A functional unit (FU) of 1 m^2 wall element is used in the study. The environmental performance of the wall constructions is calculated using Global warming potential (GWP) indicator measured in CO_2eq.

The background emission factors for A1-A3 life cycle stages are taken from product specific EPDs based on the information obtained about the wall constructions from the contractor. For wood-based products, EPDs without biogenic carbon are used as the end-of-life cycle stages are not included in the analysis. In lack of EPDs for products from Estonia, Norwegian EPDs have been used. Due to lack of data, energy use for both Norwegian and Estonian wall element at the element factory (A3) is excluded in the calculation. The transport distance from manufacturers to the element production site (A2, for off-site scenario) or to the construction site (A4, for on-site scenario) has been obtained from google map using the location of the manufacturers in EPDs. The element production site is considered to be in Norway or Estonia, and the construction site is assumed to be in Norway. The GHG emission calculations from the transport of materials and elements are calculated using the weight of the products given in the EPDs and generic emission factor from Ecoinvent database for "Lorry 16-32 metric ton, EURO6" used as a default means of transport.

The GHG emission calculations from construction site activities (A5) includes: 1) transport of waste generated from the construction and installation activities to the waste treatment facilities, waste handling activities per waste fraction, and production and transport of materials used to replace the waste generated, 2) production, transport, and operation of construction machineries, and 3) energy use for heating. The amount of waste and energy use for machineries and heating are calculated based on project specific background data (waste reports, type of fuel/energy source), technical data sheet (energy consumption, weight of machineries), and some assumptions (e.g., operation hours, transport distance to different waste treatment facilities per waste fraction). The background emission factor for waste treatment per waste fraction and treatment type, transport, energy, and fuel use are taken from Ecoinvent database.

2.3. Scenario description
Three scenarios are considered to evaluate the environmental performance of the wall elements, see Table 2. These scenarios were selected by the construction company reflecting realistic processes in actual building projects. The scenarios are also motivated by the construction company' ongoing processes of establishing a local off-site element production facility in Norway.

Table 2 Scenario description

#	Scenario description
1	On-site TEK and PH wall construction in Norway with local materials obtained from Norwegian manufacturers/suppliers
2	Off-site TEK and PH wall element production and wall construction in Norway
3	Off-site TEK and PH wall element production in Estonia and wall construction in Norway

3. Results
The GHG emission results for scenario 1 and 2 (Norwegian elements produced either on- or off-site) are shown in Figure 1. The results show that off-site Norwegian TEK wall elements have the lowest

GHG emissions, while the on-site Norwegian PH wall elements resulted in the highest GHG emissions. Amongst the Norwegian wall elements, the off-site TEK and PH wall elements have the lowest total GHG emissions, showing ca. 17 and 20 % reductions compared to on-site TEK and PH wall elements, respectively. The GHG emissions per life cycles stages differ between the on-site and off-site TEK and PH wall elements, where the GHG emissions from the off-site wall elements are skewed towards A1-A3, while the GHG emissions from on-site wall elements are more equally distributed between A1-A3 and A4 life cycle stages. GHG emissions from A5 life cycle stages are similar for on-site and off-site wall constructions, ranging from 1-5 % of the total GHG emissions. It is noted that the comparison of TEK and PH walls in A1-A5 life cycle stages do not account for the potential energy savings and associated lower GHG emissions of PH walls during building's use phase (B6).

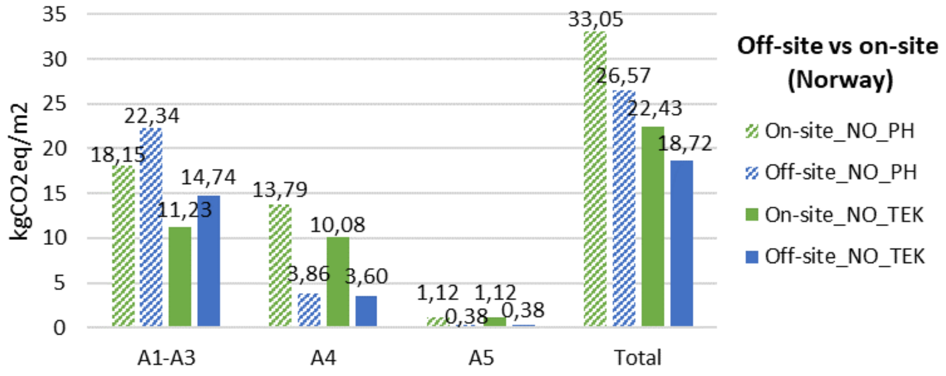


Figure 1 GHG emission results per life cycle stages of on-site and off-site TEK and PH wall construction in Norway (Scenario 1&2).

Figure 2 presents the GHG emission results from off-site TEK and PH wall elements of either Norwegian or Estonian origin, i.e., a combination of results for Scenario 2 and 3.

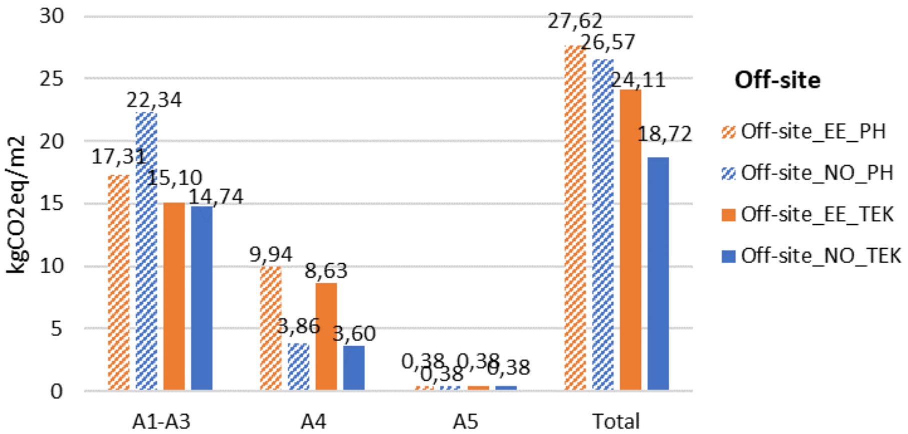


Figure 2 GHG emission results of wall elements per life cycle stages for off-site production (Scenario 2&3).

The results show that off-site Norwegian TEK wall elements have the lowest GHG emissions of all off-site elements, with an estimated reduction of 22 % compared to the Estonian TEK wall elements. Further, the Norwegian off-site PH wall elements have an estimated GHG emission reduction of 4 %, compared to the Estonian PH wall elements. The off-site Norwegian and Estonian TEK wall elements have 30 % and 13 % lower GHG emissions than the off-site PH wall constructions, respectively.

Except for the Norwegian PH wall elements, the GHG emissions from A1-A3 are relatively similar for Norwegian and Estonian off-site wall elements. The GHG emissions from A4 are, however, clearly higher for Estonian elements, which is not very surprising given that the construction site is in Norway.

Table 3 presents the percentage GHG emission contribution from A1-A3 life cycle stages of the materials used in TEK and PH wall constructions. The results show that gypsum board, insulation and exterior cladding are amongst the top three contributors to the total A1-A3 GHG emissions in the Norwegian on-site TEK wall elements. Wood stud, insulation and gypsum board are the top three contributors in the Norwegian on-site PH wall constructions, where a significant difference in GHG emission is observed for wood stud used in the PH (33%) compared to TEK17 (11%) wall elements. In the Norwegian off-site TEK wall elements, exterior cladding, insulation, and gypsum board are the top three materials. Whereas, wind barrier, gypsum board and exterior cladding are the top three materials in the Estonian off-site TEK wall elements, representing ca. 70% of the total A1-A3 GHG emissions. In the Norwegian off-site PH wall elements, wood stud, insulation and exterior cladding are the top three materials representing ca. 69% of the total A1-A3 GHG emissions. In the Estonian off-site PH wall elements, fiberboard, gypsum board and exterior cladding are the top three materials representing ca. 62% of the total A1-A3 GHG emissions.

Table 3 A1-A3 GHG emission results per materials used in the Norwegian and Estonian on-site and off-site wall elements.

Materials	On-site_NO_TEK	On-site_NO_PH	Off-site_NO_TEK	Off-site_EE_TEK	Off-site_NO_PH	Off-site_EE_PH
19 mm wooden cladding	20,5%	12,7%	23,0%	15,2%	15,2%	13,3%
23x48 mm wood battens	1,3%	0,8%	1,8%	1,0%	1,2%	0,9%
0.15 mm wind barrier	3,0%	1,8%	2,4%	2,3%	1,6%	2,0%
48 x 198/300 mm wood stud	10,8%	33,2%	15,2%	8,8%	34,6%	11,3%
12 mm wind barrier	5,3%	3,3%	8,1%	36,0%	5,4%	31,4%
200/300 mm insulation	21,4%	19,9%	20,7%	8,4%	19,1%	11,0%
0.15 mm vapour barrier	2,8%	1,7%	2,1%	2,2%	1,4%	1,9%
48 x 48/98 mm wood battens	2,6%	3,3%	2,0%	2,1%	2,7%	3,8%
50/100 mm insulation	5,4%	6,6%	4,1%	4,0%	5,4%	7,0%
13 mm gypsum board	26,9%	16,7%	20,5%	20,0%	13,5%	17,5%

4. Discussions

This study has investigated the embodied GHG emissions from TEK and PH wall elements produced either on- or off-site by Norwegian or Estonian manufacturers and constructed on-site in Norway by a Norwegian contractor. The results show up to 17 and 20 % GHG emission reduction for off-site TEK and PH wall elements, which is comparable with previous research showing, on average, a 15.6 % reduction of embodied carbon for prefabricated buildings[7]. Previous research also refers to great variations in reported GHG emission savings from off-site construction [6,7]. The distribution of GHG emissions per life cycle stages can help to identify areas with greatest potential for emission reduction. While the production phase (A1-A3) represents most of the total GHG emissions (50-84%) for all wall elements, this study indicates that the transport of materials and elements to the construction site (A4) also represent a significant share of the total GHG emissions. The A4 GHG emissions are significant for both on-site TEK and PH wall elements (45 and 42%, respectively), and for off-site TEK and PH wall elements from Norway (ca. 19 and 15%, respectively) and Estonia (ca. 36%). The results also illustrate the importance of using locally available materials to reduce the GHG emissions from A4 as shown in the lower GHG emission results from off-site Norwegian wall elements compared to the one from Estonia. This is supported by a previous study arguing that impacts from transportations are potentially critical, even to the extent that they may balance out the potential benefits of off-site construction [11].

The GHG emissions from construction and installation phase (A5) represent 1-2% and 3-5% of total GHG emissions for off-site and on-site PH and TEK wall elements, respectively. The GHG emissions from off-site wall elements A5 life cycle stage is ca. 66% lower than the on-site wall elements. This is mainly due to the use of diesel driven machinery for installation activities, showing the importance of the on-going national initiatives towards electrification of construction machineries to achieve emission free construction site ambitions [21]. Here it should be noted that the GHG emission results from A5 for on-site TEK and PH Norwegian wall elements are the same due to the same assumptions considered in the background calculation. Similarly, the GHG emission results from A5 for the Norwegian and Estonian off-site wall elements are the same.

The GHG emissions per material results illustrate the importance of making reasonable material choices, where for instance the wood stud used in the Norwegian off-site PH wall element represents 35 % of the total A1-A3 GHG emissions and 29 % of the total A1-A5 GHG emissions. Further, the GHG emission from A1-A3 from wood stud used in the Norwegian off-site PH wall element has four times higher GHG emissions than the wood stud used in Estonian PH wall element. In general, few materials tend to represent a relatively high share of GHG emissions, thus sets prioritization on which materials to work with to improve environmental performance. This study further indicates that Norwegian on-site and off-site as well as the Estonian off-site PH wall elements generate 47%, 42% and 15 % more GHG emissions than TEK wall elements, respectively. However, as the scope of this study is limited to the A1-A5 life cycle stages, the potential energy savings and the associated lower GHG emissions from PH wall elements during the building's use phase (B6) is not accounted for. In this regard, consideration of the B6 life cycle stages in the GHG emission calculation might result in lower total GHG emissions from PH wall elements in comparison with TEK wall elements.

Finally, the authors acknowledge that this study is subjected to limitations and uncertainties that might affect the GHG emissions results. The results highlighted the dependency of the GHG emission results on the scope of the study (focusing on embodied emissions from production and construction life cycle stages), methodological choices, and background data used.

5. Conclusion

This study presented the results from a comparative assessment of embodied GHG emissions from production of on-site and off-site wall constructions using elements produced locally in Norway versus abroad in Estonia. Compared to the on-site TEK and PH Norwegian wall constructions, the results show 17 and 20 % lower GHG emissions for off-site TEK and PH Norwegian wall constructions, respectively. The Norwegian TEK and PH off-site elements are found to have 22 and 4 % lower GHG emissions compared to off-site TEK and PH wall elements produced in Estonia, respectively. The contribution of individual materials to the total GHG emissions is potentially significant, showing the importance of material choices and construction methods. This study can be used as an input to the on-going activities of establishing a local factory for off-site element production highlighting the importance of considering product selection, waste reduction during production and construction activities, and electrification of construction site activities. Future research could conduct detailed LCA analysis by widening the scope of the work and refining background data by using more project specific data.

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