Comparison of GHG emissions from circular and conventional building components

Andersen, Camilla Marlene Ernst; Kanafani, Kai; Zimmermann, Regitze Kjær; Rasmussen, Freja Nygaard; Birgisdóttir, Harpa

Published in:
Buildings and Cities

DOI (link to publication from Publisher):
10.5334/bc.55

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Andersen, C. E., *et al.* (2020). Comparison of GHG emissions from circular and conventional building components. *Buildings and Cities*, 1(1), pp. 379–392. DOI: https://doi.org/10.5334/bc.55

RESEARCH

Comparison of GHG emissions from circular and conventional building components

Camilla Ernst Andersen[1], Kai Kanafani[2], Regitze Kjær Zimmermann[3], Freja Nygaard Rasmussen[4] and Harpa Birgisdóttir[5]

Abstract

The concept of circular economy has been introduced as a strategy to reduce the greenhouse gas (GHG) emissions from buildings and mitigate climate change. Although many innovative circular solutions exist, the business model is challenged by a lack of environmental data on the circular solutions, and thus the potential benefits are not verifiable. The study assesses the embodied GHG emissions of five circular building elements/components. Circular solutions are compared with conventional solutions to ascertain whether the business model has the potential to reduce GHG emissions. The GHG emissions are quantified using life-cycle assessment (LCA) for five circular-economy and three conventional building elements/components. The environmental data show that circular building components have the potential to reduce GHG emissions. However, there is a risk of increasing the GHG emissions when compared with conventional solutions, emphasising the need for standardised environmental data. Lastly, the study identifies logistic, economic, technological and regulatory barriers that prevent complete implementation of circular economy.

Practice relevance

Standardised environmental data on building elements/components are needed to support decision-making at local and national levels. Uncertainties about waste from manufacture and transport in the production stage can affect the environmental potential to such an extent that the benefits from introducing circular economy are lost. One central barrier is identified that prevents complete implementation of the circular economy in buildings; the industry is not geared to support a steady supply of some circular building elements/components. In general, it is clear that the implementation of circular economy requires the identification of environmental, logistical, economic, technological and regulatory concerns.

Keywords: buildings; carbon metrics; circular economy; components; embodied carbon; life-cycle assessment; reuse

1. Introduction

Buildings play an essential role in climate change mitigation. Globally, buildings and constructions are responsible for 36% of the final energy consumption and 39% of energy and process-related CO_2 emissions (International Energy Agency & Global Alliance for Buildings and Construction 2019). Emissions from the extraction, production and disposal of building materials (embodied emissions) account for 11% of all energy-related CO_2 emissions (International Energy Agency & Global Alliance for Buildings and Construction 2018). The current approach to material consumption in the built environment is predominantly linear, *i.e.* extract, produce, use and dispose, vast amounts of waste materials are generated (Akanbi *et al.* 2018; Aye *et al.* 2012; Kylili & Fokaides 2017).

[1] Department of the Built Environment, Aalborg University, Copenhagen, DK. ORCID: 0000-0001-7750-8329

[2] Department of the Built Environment, Aalborg University, Copenhagen, DK. ORCID: 0000-0002-8169-1610

[3] Department of the Built Environment, Aalborg University, Copenhagen, DK. ORCID: 0000-0001-5852-3136

[4] Department of the Built Environment, Aalborg University, Copenhagen, DK. ORCID: 0000-0002-9168-2021

[5] Department of the Built Environment, Aalborg University, Copenhagen, DK. ORCID: 0000-0001-7642-4107

Corresponding author: Camilla Ernst Andersen (caa@sbi.aau.dk)

The concept of circular economy is increasingly being applied in the built environment as an approach to reduce the embodied emissions associated with buildings. Circular economy aims at preserving finite stocks of natural resources and ensuring a renewable flow of products and materials (Ellen MacArthur Foundation 2015, 2016; European Commission 2015). In the built environment, this is often manifested by the inclusion of recycled materials and components in the construction (Islam *et al.* 2016; Ramos Huarachi *et al.* 2020) or by the provision of recyclable and reusable materials and components at the end of life (Densley Tingley & Davison 2012; Eberhardt, Birgisdóttir, & Birkved 2018). Since the use of recycled materials addresses the immediate global concerns about reducing carbon emissions, this recycling strategy is a particular focus for the construction industry as well as for the waste industry (Di Maria, Eyckmans, & Van Acker 2018).

The literature provides rich discussions on different approaches to allocate impacts and benefits associated with recycling (Allacker *et al.* 2014; Frischknecht 2010; Gala, Raugei, & Fullana-i-Palmer 2015). However, for building practice, attention has centred on the methodological approach outlined by the EN 15804 and EN 15978 standards for life-cycle assessment (LCA) on building products and whole buildings (CEN 2012b, 2019), which harmonise the otherwise widely differing approaches in building LCA (Säynäjoki *et al.* 2017). These standards draw upon the data in environmental product declarations (EPDs), particularly in the European market (Passer *et al.* 2015). Standardised EPDs, or similar information sources, are used in a range of certification systems for evaluating the environmental performance of buildings, and several countries are also developing regulations and benchmarks based on these standards (Frischknecht *et al.* 2019; Lützkendorf 2017).

The business model for material reuse and recycling in buildings is challenged by institutional settings and market structures (Nußholz *et al.* 2019b). Hence, even though several pilot initiatives from practice seek to incorporate the recycling agenda in building design, environmental data based on the standards is missing, and potential benefits are thus not verifiable (Lendager Group 2013, 2018, 2019; Region Midtjylland n.d.). This lack of environmental data points to a need to bridge research and practice by evaluating pilot initiatives in the standardised LCA format of the European standards.

This study aims to contribute to filling the data gap for recycled products in building practice by presenting LCA-based greenhouse gas (GHG) profiles of conventional and circular building elements and components at a screening level. Circular scenarios are compared with corresponding conventional scenarios to assess the potential reductions in GHG emissions achieved through circular economy. Finally, the study assesses the reductions in GHG emissions achievable at Danish national level and the barriers that hinder the transformation towards circular economy.

2. Methods

2.1 Life-cycle assessment (LCA)

LCA is used to identify the GHG emissions of circular and conventional building elements/components. The LCAs follow the standardisation in EN 15804 and EN 15978 (CEN 2012a, 2012b).

2.1.1 Goal, scope and functional unit

The research aim is to compare conventional and corresponding circular building elements/components. The functional unit was defined as ‘1 m^2 of building element/component’. The functional unit assumes that the circular scenarios are equal to the conventional scenarios in terms of functionality, quality and service life. However, comparability regarding quality and longevity relies on the authors’ estimation, since data are not yet available due to the novelty of the circular scenarios.

According to EN 15978, a building LCA may include 17 life-cycle modules. The scope of the present research is limited to include six modules related to production (stages A1–A3), end of Life (stages C3 and C4) and benefits/loads beyond the system boundary (stage D) (**Figure 1**). Since the study is a screening, the service life is assumed to be identical for the conventional and circular scenarios and therefore module B4 is excluded.

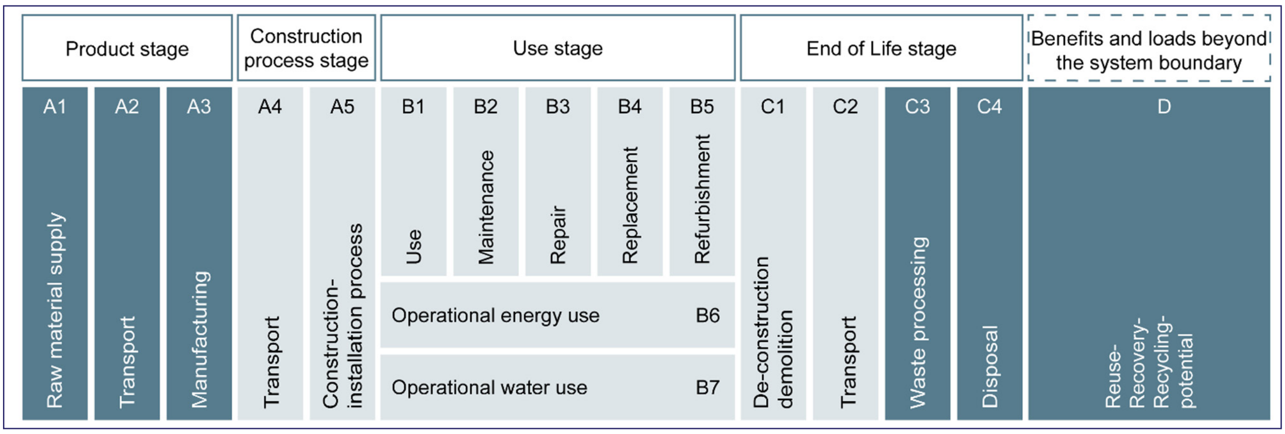

Figure 1: Life-cycle stages according EN 15978 (CEN 2012b). The included life-cycle modules are marked in dark blue.

The system boundary is defined by the cut-off allocation method according to EN 15804/15978 (CEN 2012a, 2012b), where the first and second lives of the element are considered as two independent life-cycles. In the first life-cycle, the building element/component is considered until the material reaches the end-of-waste state (CEN 2013). In the second life-cycle in the product stage (A1–A3), only the processing of the element/component to be transformed into a new product is included, hence the recycled and reused materials themselves are considered as 'free' and without impact. The allocation method follows the calculation practices from Product Category Rules (PCR) for Construction Products EPD (CEN 2013).

2.1.2 Data and assumptions

Data on both the conventional and circular scenarios were obtained from EPDs, the Ökobaudat (2019) database and reports examining the circular scenarios as a part of a pilot project (for specific data sources, see section 2.2 and the supplemental data online).

To model the inventory, it was necessary to make overall assumptions due to a lack of data. Thus, some assumptions are based on the authors' estimation. In life-cycle stages A1–A3, a generic wastage rate of 10% and a transportation distance of 50 km was assumed (Rosholm, Kalvig, & Fold 2016) for all virgin raw materials. The waste scenarios in life-cycle stages C3 and C4 are generally the same for the conventional and circular scenarios. In life-cycle stage D, a distance of 30 km was assumed as avoided transportation when materials are recycled at the end-of-life stage. This was based on the assumption that recyclable building elements/components are obtained from a nearby demolition site and thus the environmental loads from transporting virgin elements/components over longer distances are avoided.

The inventory was modelled using the database ecoinvent v3.4 (2020) and SimaPro 9.0 (PRÉ 2020) software. The geographical boundary of the data covers Denmark and Europe when available. Likewise, the data represent the current level of technology and current waste management systems.

2.1.3 Impact assessment

For the life-cycle impact assessment, the method ILCD 2011 midpoint+ (European Commission & Joint Research Centre 2012) was applied. Generally, when conducting LCA, all environmental indicators should be considered in order to avoid burden shifting. However, to limit the scope of this study, only GHG (kg CO_2e) was included, since it is highly relevant in terms of both environmental concerns and political discussions (Danish Government 2019; United Nations 2015). The life-cycle impact assessment was conducted by multiplying the quantity of a material or process by the impact provided when applying the ILCD 2011 midpoint+ characterisation factors from the ecoinvent data set in SimaPro. When adding all impacts in each life-cycle stage, the total GHG emissions of each scenario is found using equation (1):

$$\text{Impact potential} = \sum\nolimits_{i=0}^{n} q_{p,i} \cdot I_{p,i} + \sum\nolimits_{i=0}^{n} q_{t,i} \cdot I_{t,i} + \sum\nolimits_{i=0}^{n} q_{w,i} \cdot I_{w,i} + \sum\nolimits_{i=0}^{n} q_{EoL,i} \cdot I_{EoL,i} + \sum\nolimits_{i=0}^{n} q_{ap,i} \cdot I_{ap,i} + \sum\nolimits_{i=0}^{n} q_{at,i} \cdot I_{at,i} \quad (1)$$

where q is the quantity a given material or process; i is the impact potential per quantity unit based on the ecoinvent data set; $q_{p,i}$ and $I_{p,i}$ represent the materials and processes in the production stage; $q_{t,i}$ and $I_{t,i}$ are the transport of materials in the production stage; $q_{w,i}$ and $I_{w,i}$ are the waste materials in the production stage; $q_{EoL,i}$ and $I_{EoL,i}$ are the processes in the end-of-life stage; $q_{ap,i}$ and $I_{ap,i}$ are the avoided production in life-cycle stage D; and $q_{at,i}$ and $I_{at,i}$ are the avoided transportation in life-cycle stage D.

2.2 Case study

This above method was applied to three conventional and five circular building elements/components. The scenarios are based on building materials widely used in buildings in Denmark: concrete, bricks and glass. The scenarios are shown in **Table 1** and **Figure 2**.

2.2.1 Concrete

2.2.1.1 Scenario A: Conventional concrete

This scenario reflects the life-cycle of a conventional unreinforced concrete wall with a thickness of 300 mm and the structural capacity of 25 MPa (Aalborg Portland 2010) (**Figure 2**). The functional unit is 1 m^2 of 25 MPa concrete element.

In life-cycle stages A1–A3, the constituents and amount are based on the concrete manufacturer's formula (Aalborg Portland 2010). The mixing of the concrete is based on a standard data set from the ecoinvent database. Although structural concrete is typically reinforced, this assessment does not include the reinforcing steel. The assumption is that the compared scenarios—A: Conventional concrete, D: Recycled concrete and E: Reused concrete elementa—would contain the same amount of steel.

In life-cycle stages C3 and C4, the concrete is assumed to be crushed and 90% recycled as road filling (Danish Environmental Protection Agency 2015). Hence, the consumption of gravel for road filling and transportation thereof

Table 1: Conventional and circular scenarios assessed. Each scenario is based on 1 m² of the material.

Conventional scenarios	Circular scenarios
(A) Conventional concrete	(D) Recycled concrete (common practice)
	(E) Reused concrete elements
(B) Conventional brick wall	(F) Facade cladding with reused bricks (common practice)
	(G) Recycled brick facade element
(C) Conventional thermal window	(H) Thermal window with reused double-glazing

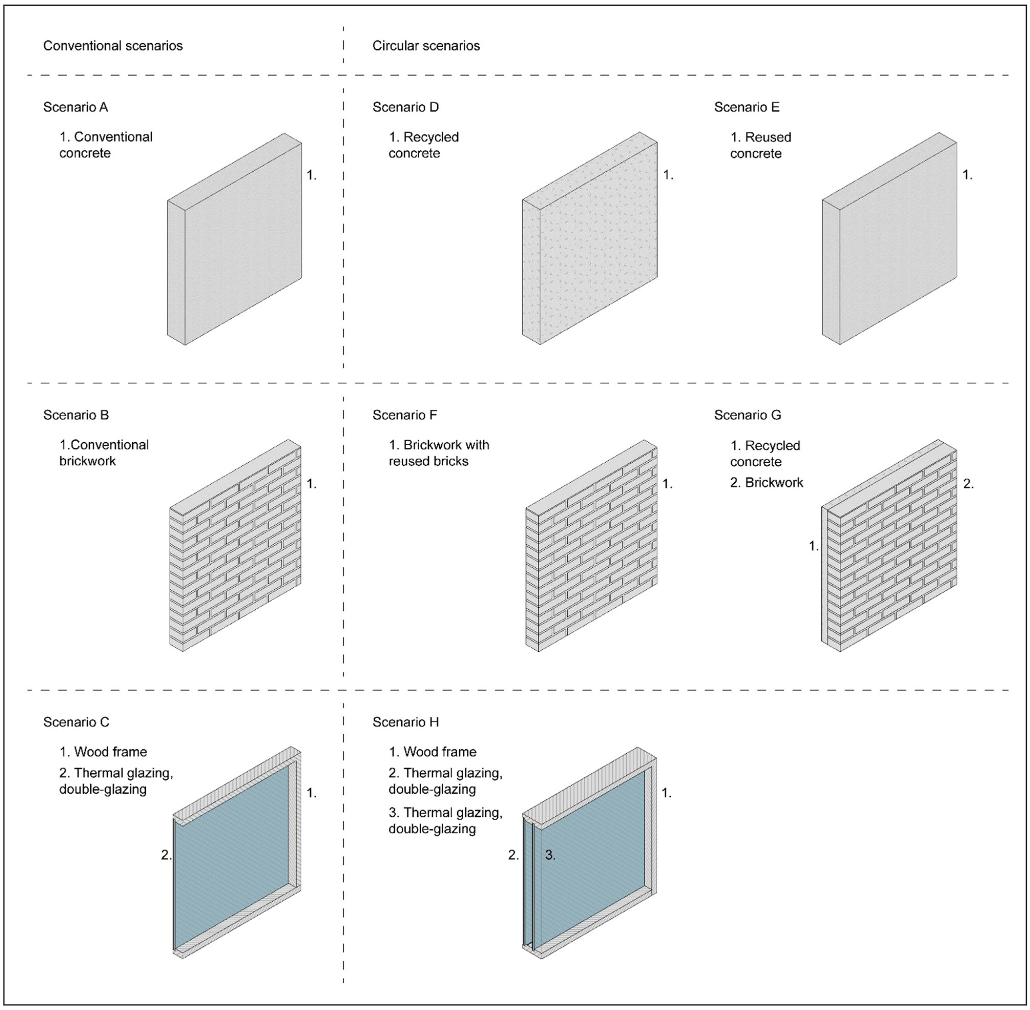

Figure 2: Composition of conventional and circular scenarios A–H.

(30 km) is avoided (life-cycle stage D) (for the inventory, see the supplemental data online). This scenario serves as a reference to the scenarios Recycled concrete and Recycled concrete elements.

2.2.1.2 Scenario D: Recycled concrete (circular scenario)

This circular scenario deals with recycling old concrete as aggregate in new concrete (**Figure 2**). The concrete is used for an unreinforced concrete wall with a thickness of 300 mm. The functional unit is 1 m² of 25 MPa concrete element.

In life-cycle stages A1–A3, concrete is reclaimed from an old building and crushed on the construction site. Next, the concrete manufacturer produces concrete (following the formula in Aalborg Portland 2010) on-site and replaces the coarse natural aggregate, in this case gravel, with the crushed concrete. In Denmark, according to DS 411, it is allowed to replace 20% of the coarse aggregate for concrete structures in the passive environmental class (Danish Standards 2006) due to structural requirements as well as requirements for the workability in the construction stage (Danish Environmental Protection Agency 2015). However, pilot projects testing the replacement of 100% of the coarse aggregate with crushed concrete show that this is feasible without compromising the structural capacity and workability (Danish Environmental Protection Agency 2018). Thus, in this scenario, crushed concrete is assumed to replace 100% of the coarse aggregate as a way of demonstrating the more far-reaching potentials of circular economy. It is assumed that approximately 50% of the crushed concrete is too fine in grain size to use as replacement for coarse aggregate and thus ends up as waste (DTU Department of Civil Engineering 2019).

In life-cycle stages C3 and C4, the concrete is crushed and 90% is recycled as road filling (Danish Environmental Protection Agency 2015), thereby avoiding the use and transportation of natural aggregate (30 km) (life-cycle stage D). In the replacement of natural aggregate with crushed concrete in life-cycle stage D, it is assumed that 1 tonne of crushed concrete can substitute 1.1 tonne of natural gravel aggregate due to differences in density (Wahlström *et al.* 2014) (for the inventory, see the supplemental data online).

2.2.1.3 Scenario F: Reused concrete elements (circular scenario)

This circular scenario focuses on the reuse of a 300 mm concrete element from an old building in a new building (**Figure 2**). The functional unit is 1 m^2 of 25 MPa concrete element.

In the demolition of an old building, an unreinforced concrete element is cut out of the existing building and reused on site as a structural element for a new building. It is assumed that 10% of the concrete element is waste because of modifications when fitting the element to its new purpose.

In life-cycle stages C3 and C4, it is assumed that this concrete element is crushed and used as road filling (for the inventory, see the supplemental data online). Since all input materials are reused, there are no benefits and loads beyond the system boundary (due to calculation practices according to PCR for Construction Products EPD; CEN 2013).

2.2.2 Bricks

2.2.2.1 Scenario B: Conventional brick wall

This scenario deals with the life-cycle of a standard solid brick wall used for an exterior facade (**Figure 2**). The functional unit of this scenario is 1 m^2 of brick facade element.

In life-cycle stages A1–A3, bricks and cement mortar are constructed into a brick wall. It is assumed that 63 bricks are used per m^2, and that the joints are 13 mm in thickness (Randers Tegl n.d.).

As for the concrete scenarios, bricks and mortar are crushed and recycled as road filling (life-cycle stages C3 and C4), hence avoiding the consumption of raw materials and transportation thereof (30 km) (life-cycle stage D) (for the inventory, see the supporting data online). This scenario serves as a reference to the scenarios Facade cladding using reused bricks and Recycled brick facade element.

2.2.2.2 Scenario E: Facade cladding with reused bricks (circular scenario)

This circular scenario provides an exterior facade cladding constructed of reused bricks (**Figure 2**). The functional unit is 1 m^2 of brick facade element.

In life-cycle stages A1–A3, bricks reclaimed from a demolished building are sorted, cleaned and used for a new building's facade. Due to the process, in which the bricks are cleaned of mortar, only 64.5% of the old bricks are considered suitable for reuse in a new building (EPD Danmark, The Danish Technological Institute & Gamle Mursten 2017; Danish Environmental Protection Agency 2013). This wall is constructed of 63 bricks/m^2, and the joints are 13 mm in thickness (Randers Tegl n.d.). Contrary to the conventional scenario, lime mortar is assumed in this scenario as it permits recycling in the future.

In life-cycle stages C3 and C4, the brick facade is crushed and used as road filling, hence avoiding the use and transportation of natural aggregate (30 km) (life-cycle stage D) (for the inventory, see the supporting data online).

2.2.2.3 Scenario G: Recycled brick facade element (circular scenario)

This circular scenario deals with an innovative approach to recycling bricks and was tested in a building focusing on recycled materials (Lendager Group 2019) (**Figure 2**). The functional unit is 1 m^2 of brick facade element.

In life-cycle stages A1–A3, the exterior part of an existing brick facade is cut into elements of 1 m^2 and reused on-site. In order for the elements to be manageable, the elements are supported with 50 mm of 20% recycled concrete (Andersen *et al.* 2019) and reinforcement (Lendager & Vind 2018). Since this circular scenario is quite innovative and new to the market, the construction of the element is based on the authors' best judgment.

In life-cycle stages C3 and C4, the brick facade element is crushed and recycled as road filling, thereby avoiding consumption and transportation of natural aggregate and (30 km) (life-cycle stage D) (for the inventory, see the supporting data online).

2.2.3 Thermal window

2.2.3.1 Scenario C: Conventional thermal window

This scenario reflects the production of a conventional thermal window with a wooden frame and double-glazing (**Figure 2**). The functional unit is 1 m^2 of thermal window with wooden frame.

In life-cycle stages A1–A3, 1 m^2 of double-glazing with a density of 20 kg/m^2 is assumed (Ökobaudat 2018). The window frame is a new, standard wooden frame with dimensions according to Vinduesgrossisten (n.d.). In this study, only the impacts from forestry and wood processing are included in the assessment of the wood. Biogenic carbon is therefore not included in the calculation of the GHG emissions in order to simplify the methodology, and as biogenic carbon is calculated as zero throughout the life-cycle according to EN 15804:2012+A2:2019 (CEN 2019), this assumption is not considered to be essential for total GHG emissions.

In life-cycle stages C3 and C4, the double-glazing is landfilled and the wooden frame incinerated. Since this happens in the far future and since the energy grid mix is increasingly based on renewable resources, this study assumes that there are no benefits in life-cycle stage D (for the inventory, see the supporting data online). This scenario serves as a reference to the circular scenario Thermal window with reused double-glazing.

2.2.3.2 Scenario H: Thermal window with reused double-glazing (circular scenario)

This circular scenario focuses on reusing double-glazing for new windows (**Figure 2**). This solution was tested in a building case focusing on using upcycled materials (Lendager Group 2018). The functional unit is 1 m^2 of thermal window with wooden frame.

In life-cycle stages A1–A3, two 1 m^2 double-glazed units reclaimed from existing buildings are combined into one thermal window with a wooden frame. According to the Lendager Group (2018), it is necessary to combine two double-glazed units to meet the legal insulation requirements for new windows. Each unit is assumed to have a density of 20 kg/m^2 (Ökobaudat 2018) and the new wooden frame is assumed to be twice the dimensions of the conventional windows in order to fit two double-glazed units (Vinduesgrossisten n.d.). Again, biogenic carbon is not considered in the calculation of the GHG emissions (see Conventional thermal window).

In life-cycle stages C3 and C4, the double-glazing is assumed to be landfilled and the wooden frame is incinerated. As for Conventional thermal window, no benefits are beyond the system boundary (for the inventory, see the supporting data online).

2.3. Basis for uncertainty and sensitivity analysis

The uncertainty analysis was conducted quantitatively considering relevant input parameters. **Table 2** presents the qualitative uncertainty analysis along with a justification of why the parameters are considered uncertain.

From **Table 2**, the parameters Waste (A1), Transport (A2) and Avoided transport are identified as uncertain, and thus these parameters are tested for sensitivity in the life-cycle inventory model. In the sensitivity analysis, the input parameters are variated according to the ranges provided in **Table 2** and the relative change calculated.

3. Results

Table 3 shows the results in GHG (kg CO_2e) for the considered life-cycle stages and all scenarios. All results are based on the inventory and the ecoinvent database presented in the supplemental data online.

Table 2: Qualitative uncertainty analysis of the relevant input parameters.

Input parameter		Chosen data	Variation	Uncertain?	
Production (A1–A3)	Waste (A1)	10%	Minimum 5%, maximum 15%	Yes	Waste in the production of raw materials is estimated to be 10%. Based on the authors' estimation, the parameter is considered uncertain
	Transport (A2)	50 km	Minimum 25 km, maximum 75 km	Yes	Transport of raw materials is assumed to be 50 km. Since the studied systems have very little empirical transport data, this figure has high variability and is thus considered highly uncertain (Danish Regions, Research Center for Environment and Resources 2017)
Functional unit	Material properties and dimensions	–	–	No	Raw materials and dimensions are not considered uncertain because the input data in the compared scenarios have the same level of detail
	Performance	–	–	No	Functionality of the circular building elements/components is equal to the functionality of the conventional ones
Beyond system boundary (D)	Avoided transport	30 km	0 km	Yes	Avoided transport in life-cycle stage D is considered uncertain. Transport is consistently assumed to be 30 km. However, a conservative future scenario may in fact be 0 km because future technology might allow local recycling to a higher degree than today

Table 3: Greenhouse gases (GHG) for three conventional and five circular scenarios.

Scenario	Stages A1–A3 (kg CO_2e/m^2)	Stages C3 and C4 (kg CO_2e/m^2)	Sum (kg CO_2e/m^2)	Stage D (kg CO_2e/m^2)
(A) Conventional concrete	99.1	3.7	102.8	–10.3
(D) Recycled concrete	95.4	3.7	99.1	–7.9
(F) Reused concrete elements	0.4	3.7	4.0	0.0
(B) Conventional brick wall	66.4	1.1	67.4	–3.3
(E) Facade cladding with reused bricks	14.4	1.1	15.5	–0.7
(G) Recycled brick facade element	24.1	1.5	25.6	–0.1
(C) Conventional thermal glazing	43.5	0.3	43.8	0.0
(H) Thermal window with reused double-glazing	1.4	0.6	2.0	0.0

The results show that life-cycle stages A1–A3 account for the largest share of the impacts with the exception of Reused concrete elements. Furthermore, the results suggest that scenarios concerning reuse and recycling have lower GHG emissions in life-cycle stages A1–A3 than conventional scenarios due to the allocation method where the majority of the impact has already taken place in the first life-cycle (see section 2.1).

The results show that life-cycle stage D has little effect on the total impact in five out of eight scenarios. In three scenarios—Conventional concrete, Conventional brick wall and Recycled concrete—life-cycle stage D contributes considerably to the impact. This is because the three scenarios contain relatively large shares of virgin raw materials, and when recycling the building elements for road filling at the end of life, the virgin raw materials result in large amounts of avoided products being credited. In the other five scenarios in life-cycle stages A1–A3, the share of reused and recycled materials is relatively high, resulting in less crediting when recycling (see section 2.1 for calculation practices).

3.1 GHG reductions

Figure 3 presents the GHG reductions when each of the five circular scenarios are compared with the corresponding conventional scenario. The GHG reductions include the range in which the results vary based on the relative change for each scenario from the sensitivity analysis. The relative changes for each scenario and for the uncertain input parameters are presented in Table S22 in the supplemental data online. The sensitivity results show that variations in the wastage rates cause the largest relative change in six out of eight scenarios.

The reductions in GHG emissions vary between 1% and 19% (**Figure 3**). The two scenarios Reused concrete element and Thermal window with reused double-glazing result in reductions of around 95–96% when compared with Conventional concrete and Conventional thermal window, respectively. The reductions from reusing the concrete element are due to the relatively few transformation processes needed for the concrete element to be fit for reuse. Likewise, few transformation processes are needed to fit the double-glazing for reuse, and since the double-glazing, which would have been the main contributor, has no impact in life-cycle stages A1–A3, high reductions occur.

The two scenarios Facade cladding with reused bricks and Recycled brick facade element both result in large reductions varying from 59% to 79%. Consistent for both scenarios is that few transformation processes are required in life-cycle stages A1–A3 and that the bricks, which would have been the main contributor, have no impact. Thus, great reductions in GHG emissions are achieved.

In contrast, the results show that it is questionable whether the circular scenario Recycled concrete results in reductions when including the variation from the sensitivity analysis. The results vary from a 10% reduction to a 9% additional load when comparing the conventional and circular scenario. The scenario considers crushed concrete as a substitute for coarse natural aggregate; however, as cement is the main contributor to the GHG emission, only small reductions are achieved.

3.2 Large-scale potentials (Denmark)

Even though four out of five circular scenarios show a clear potential to reduce GHG emissions, circular economy greatly depends on the availability of input waste resources. In 2017, in Denmark, 4,479,000 tonnes of construction waste were generated, of which 1,182,000 tonnes were concrete, 211,000 tonnes bricks and 21,000 tonnes glass (Danish Environmental Protection Agency 2019). In **Table 4**, the reductions in GHG emissions (from section 3.1) are scaled to a national level and represent the reductions that can be achieved from using all waste resources. The assessment is a screening and may serve as an indicator for potential national reductions.

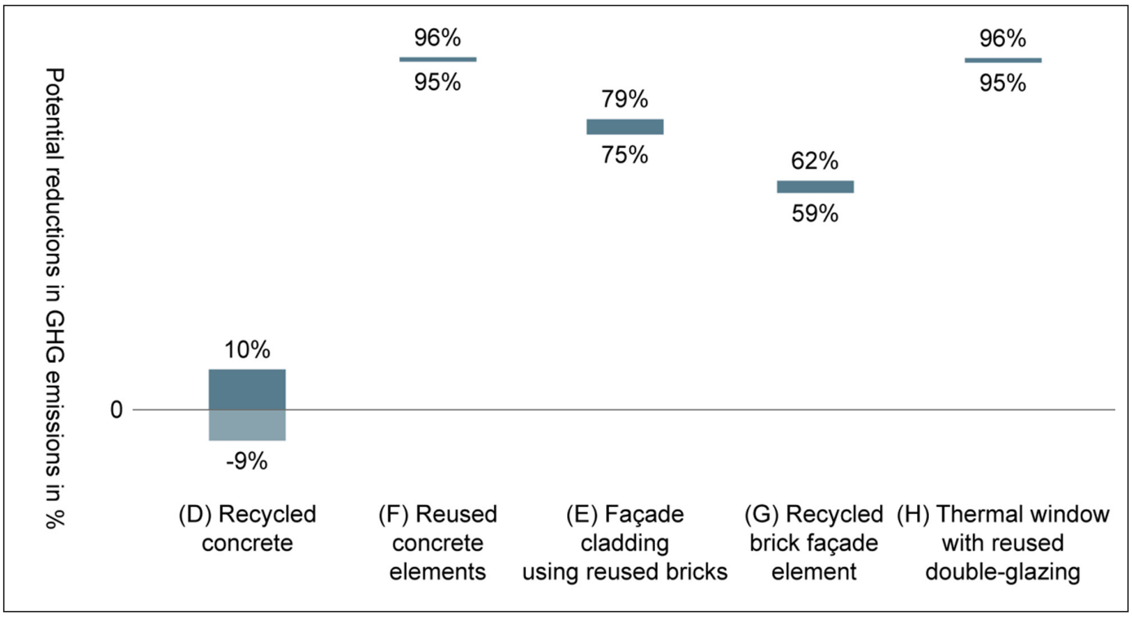

Figure 3: Potential reduction of greenhouse gas (GHG) emissions (%) when comparing five circular scenarios with three corresponding conventional scenarios, including the ranges found from the sensitivity analysis (see Table S22 in the supplemental data online). The reductions in GHG emissions are associated with providing and disposing of the elements/components.

Table 4: Screening of potential reductions in greenhouse gas (GHG) emissions for the circular scenarios.

	(D) Recycled concrete	**(F) Reused concrete elements**	**(E) Facade cladding using reused bricks**	**(G) Recycled brick facade element**	**(H) Thermal window with reused double-glazing**
Reduction in GHG emissions[a] (kg CO_2e/m^2)	–7.5 to 10.2	83.6–93.3	45.7–53.0	34.5–42.9	39.7–43.9
Waste available nationally (tonnes)[b]	1,182,000	1,182,000	211,000	211,000	n.a.
National potential reduction in GHG emissions (thousands of tons CO_2e/year)[c]	–18,800 to 25,500	67,100–78,800	22,600–26,200	13,700–17,100	–
Assumptions	All waste concrete available is used for recycled concrete	50% of the waste concrete available is reused as complete elements instead of being disposed of (Danish Environmental Protection Agency 2015)	Brickwork with cement mortar is too strong to separate brick by brick. Thus, only bricks laid with lime mortar can be reused, corresponding to 50% of the demolished brickwork in Denmark (Sandahl 2019)	Brickwork with cement mortar is particularly suitable in this scenario due to its strength. In this scenario, brickwork with cement mortar is recycled as a facade element corresponding to 50% of the waste bricks produced in Denmark (Sandahl 2019)	Since only limited data on the generation of waste thermal glazing exist, it is not possible to estimate the potential national reductions

Notes: [a] The reductions in kg CO_2e/m^2 are based on Figure 3, where the reductions are shown as percentages. The ranges in reductions are found from the sensitivity analysis (see the supplemental data online), where the derivation of the data results in a negative figure in scenario (D) Recycled concrete.

[b] Data were obtained from the Danish Environmental Protection Agency (2019).

[c] Reductions/m^2 (the first row) are scaled to a national level by coupling waste amounts and the consumption of waste in each circular scenario.

Table 4 shows that the circular scenarios entail great opportunities for reducing the GHG emissions at the Danish market level. However, it is clear that the circular scenarios pose a risk of increasing the GHG emissions instead of reducing them. Thus, it is essential to consider how the waste materials are used in the best possible way to reduce the GHG emissions as well as the natural resource consumption. As an example, recycled crushed concrete can only to some extent reduce the consumption of natural resources. In 2014, the Danish consumption of aggregate was 49,989,000 tonnes, thus waste concrete produced in Denmark can only constitute approximately 2% of demand. Recent studies suggest that up to 15–17% of the CO_2 emitted in the production of concrete can be absorbed by concrete later in the life-cycle because of a CO_2 uptake (Yang, Seo, & Tae 2014). This makes it relevant to consider whether recycling waste concrete in new concrete is the environmentally best way or if the waste concrete might be better used in other ways (Kallesøe *et al.* 2016). In addition, it is essential that nearby building activities are able to absorb the waste materials generated. If not, the waste materials might not be used or might be transported over long distances, resulting in additional environmental loads (Gala *et al.* 2015; Geyer *et al.* 2016; Nußholz *et al.* 2019a; Vadenbo, Hellweg, & Astrup 2017).

In order to exploit the environmental benefits of the circular economy, it is important to identify—and avoid—potential downsides. Failure to identify the environmental effect of circular economy might otherwise become a barrier for large-scale implementation.

4. Discussion

4.1 Barriers and potential for the implementation of circular scenarios

This section assesses the barriers to large-scale implementation of the circular scenarios. A necessity for large scale implementation of circular economy in the built environment is that the reused and recycled building elements/components/materials are guaranteed to meet the current building standard so that building owners, contractors, architects and engineers know that the elements/components/materials are sound and fit for purpose (Kibert 2016). Another essential for circular economy to be widely implemented is that the capacity of manufacturers are large enough to support a steady supply. If not, the architects, engineers and contractors will not be able to plan building projects, and the waste materials might not be used (Danish Environmental Protection Agency 2015).

4.1.1 Recycling concrete

For several years, recycled concrete has been an approach to reduce natural resource consumption (Danish Environmental Protection Agency 2015). However, several barriers exist, hindering complete implementation at the industry level. One aspect is to test and identify the formula of recycled concrete. It has been widely discussed whether recycled concrete requires extra cement compared with conventional concrete (Danish Environmental Protection Agency 2015). As cement has high GHG emissions, extra cement might increase the impact considerably. This requires further assessment.

Another barrier is profitability. Manufacturers state that it is more profitable to sell crushed concrete as road fill instead of selling the crushed concrete for recycled concrete (Danish Environmental Protection Agency 2015). Moreover, concrete manufacturers need to invest in silos and equipment to support a steady supply.

4.1.2 Reusing concrete elements

The reuse of concrete elements is a new approach to use the concrete available in Danish buildings. Consequently, logistical and technological barriers hinder the reuse of concrete elements.

Previous studies of reusing concrete elements show that the costs for transport and mounting, *i.e.* positioning and fixing, are responsible for 30–40% of the production cost (Danish Environmental Protection Agency 2015). As these costs are present for both new and reused concrete elements, the economic incentive is lost. This barrier could, however, be eliminated through careful planning (Danish Environmental Protection Agency 2015).

Additionally, a complete implementation of reused concrete elements would require a system for registering and managing the elements after demolition (Danish Environmental Protection Agency 2015). To ease reuse, the concrete elements could be designed for disassembly using standard dimensions and structural capacities. This, however, contradicts the current trend, where buildings are customised to the needs of the users (Danish Environmental Protection Agency 2015).

4.1.3 Recycling bricks as facade cladding

Reuse of waste bricks is a frequent solution for facade claddings in Denmark due to aesthetics. However, even though the reuse of bricks is already a widely implemented solution, barriers for a complete implementation are still present.

A logistical barrier includes tight conditions at the demolition site, which complicate the sorting and storing of the bricks on-site. Moreover, the reuse of bricks delays demolition and is more time-consuming than demolishing for recycling as road filling. This makes the solution less attractive and profitable. Studies find that reuse of bricks is most profitable for large-scale demolitions and at sites where the distance to the sorting and cleaning plant is relatively short (Danish Environmental Protection Agency 2016).

4.1.4 Recycling a brick facade element

This circular scenario is a new approach, which has only been applied in a single project in Denmark (Lendager Group 2019). Recycling a brick facade element requires that construction workers protect the existing facade, which makes the demolition more time-consuming. However, it is possible that the demolition and production of the brick facade elements could be less time-consuming in future due to process optimisation.

4.1.5 Reusing double-glazing for thermal windows

As for the scenario Recycled brick facade element, the reuse of double-glazing is a new approach that has only been tested to a limited extent (Lendager Group 2018). Again, the supply chain is a central barrier, and thus a system for registering and managing the waste double-glazing is necessary. Moreover, the reuse of double-glazing requires a degree of aesthetic liberty in the new building since the size of the windows will depend on waste materials available.

4.2 Limitations

This study shows that the reductions in GHG emissions of implementing circular economy in buildings can be substantial. However, there is a risk of increasing the GHG emissions and shifting the burdens if not thoroughly investigated. Especially for the circular scenario Recycled concrete, the uncertainties affect the results to such an extent that the conclusion might change. Thus, it is essential to generate thorough environmental assessments to eliminate uncertainties.

A limitation of this study is the service life. To limit the scope of the study, and since data on the service life of the circular solutions rarely exist, the service life was not included. Circular building elements/components entering a second life-cycle may have a shorter service life than conventional ones, when they are exposed to ageing factors such as climate. For example, Amorim Júnior *et al.* (2019) found that recycled concrete has a lower strength and a 40% shorter service life compared with conventional concrete. Thus, this might cause the GHG reductions to be less substantial and is a highly relevant aspect to consider in future research.

Another limitation is the choice of a single environmental indicator, GHG emissions. For some circular scenarios, *e.g.* Recycled concrete, the main environmental impact could be in other indicators such as resource depletion. Thus, the true environmental potential might only be revealed through a more comprehensive LCA considering all indicators, which would be highly relevant to consider in future research.

Other aspects, which could affect the reductions obtained through circular economy, include wastage rates, transportation distances, system boundaries, and choices of LCA database and software. The influence of wastage rates and transportation distances was briefly assessed in this study; however, future research might benefit from assessing the influence of the system boundaries and the choice of LCA database and software as these might prove to affect the results considerably (Emami *et al.* 2019).

It is important to consider the potentials of implementing circular solutions at a national level. This study provides a preliminary screening of the national reductions in GHG emissions, and these potential reductions should be assessed more thoroughly. Furthermore, it is essential to consider the consequences of introducing circular economy widely, as a complete implementation of circular economy can possibly alter the market dynamics and ultimately change the environmental benefits (Nußholz *et al.* 2019a; Zink & Geyer 2017). Thus, it is essential to consider market dynamics and the consequences of introducing circular economy at industry level (Nußholz *et al.* 2019a).

5. Conclusions

The greenhouse gas (GHG) profiles of five circular and three conventional building components/elements were quantified and compared in order to understand the GHG reductions that can be achieved if circular solutions are implemented. The study found that four of five circular scenarios give a considerable reduction in GHG emissions when compared with the conventional scenario. This conclusion is found to be robust towards the uncertainties of the model. The study finds that one circular scenario, Recycled concrete, may pose an additional environmental load compared with the conventional scenario. This highlights the need for standardised environmental data on conventional and circular building elements/components as decisions whether, for example, aggregates form crushed concrete should be used in building elements or as road filling are becoming increasingly important.

It is clear that considerable reductions in GHG emissions can be achieved through a circular business model, but logistical, economic, technological and regulatory barriers need to be overcome to support a complete transformation towards circular economy. Furthermore, the new use of recycled materials influences the market dynamics, the production processes and ultimately the GHG profiles, making these essential aspects to consider in future research to ensure a sustainable transformation.

Acknowledgements

The research in this paper is part of the Danish project Circularity City (Region Midtjylland n.d.). The project resulted in the publications *Dialogue Tool—Circular Value Creation in the Existing Building Stock* (Birgisdóttir *et al.* 2019) and *Life-Cycle Assessment of Circular Scenarios Focusing on GHG Emissions: Pre-Study* (Andersen *et al.* 2019) on which the research in this paper is based.

Competing Interests
The authors have no competing interests to declare.

Funding
The results of this study were a part of the Danish Building Research Institute/BUILD deliverable to the Circularity City project (www.circularitycity.dk).

Supplemental data
Supplemental data for this article can be accessed at https://doi.org/10.5334/bc.55.s1

References
Aalborg Portland. (2010). *Cement og Beton: Håndbog om cement, beton og mørtel* [Cement and concrete: Handbook of cement, concrete and mortar]. Aalborg: Aalborg Portland. Retrieved from www.aalborgportland.dk

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & **Bello, S. A.** (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling*, 129, 175–186. DOI: https://doi.org/10.1016/j.resconrec.2017.10.026

Allacker, K., Mathieux, F., Manfredi, S., Pelletier, N., De Camillis, C., Ardente, F., & **Pant, R.** (2014). Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. *Resources, Conservation and Recycling*, 88, 1–12. DOI: https://doi.org/10.1016/j.resconrec.2014.03.016

Amorim Júnior, N. S., Silva, G. A. O., Dias, C. M. R., & **Ribeiro, D. V.** (2019). Concrete containing recycled aggregates: Estimated lifetime using chloride migration test. *Construction and Building Materials*, 222, 108–118. DOI: https://doi.org/10.1016/j.conbuildmat.2019.06.136

Andersen, C. M. E., Zimmermann, R. K., Kanafani, K., Rasmussen, F. N., & **Birgisdottir, H.** (2019). *Livscyklusvurdering for cirkulære løsninger med fokus på klimapåvirkning: 620 Forundersøgelse* [Life cycle assessment of circular solutions focusing on GHG emissions: Pre-study]. Copenhagen: Statens Byggeforskningsinstitut, Aalborg Universitet.

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & **Mendis, P.** (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, 47, 159–168. DOI: https://doi.org/10.1016/j.enbuild.2011.11.049

Birgisdóttir, H., Kanafani, K., Kjaer, R., Andersen, C. M. E., Hatic, D., Elmbæk, M., Kamper, M., Falbe-Hansen, M., & **Sack-Nielsen, T.** (2019). *Dialogværktøj—Cirkulær værdigskabelse i den eksisterende bygningsmasse* [*Dialogue tool—Circular value creation in the existing building stock*]. Retrieved from www.circularitycity.dk

CEN. (2012a). *EN 15804:2013+A1: Sustainability of constructions works—Environmental product declarations—Core rules for the product category of construction products*. Brussels: European Committee for Standardization (CEN).

CEN. (2012b). *EN 15978: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method*. Brussels: European Committee for Standardization (CEN).

CEN. (2013). *Product category rule for type III environmental product declaration of construction products (to EN 15804:2012)*. Brussels: European Committee for Standardization (CEN).

CEN. (2019). *EN 15804:2012+A2:2019: Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products*. Brussels: European Committee for Standardization (CEN).

Danish Environmental Protection Agency. (2013). *LCA af genbrug af mursten* [LCA of recycling of bricks]. Copenhagen: Danish Environmental Protection Agency. Retrieved from www.mst.dk

Danish Environmental Protection Agency. (2015). *Udredning af teknologiske muligheder for at genbruge og genanvende beton—Miljøprojekt nr. 1667* [*Report of technological opportunities for concrete reuse and recycling of* [Report of technological opportunities for concrete reuse and recycling of] (Issue 2015). Copenhagen: Danish Environmental Protection Agency. Retrieved from www.mst.dk

Danish Environmental Protection Agency. (2016). *Samfundsøkonomisk analyse af genbrug af mursten—Miljøprojekt nr. 1904* [Cost–benefit analysis of recycling of bricks—Environmental projekt no. 1904]. Copenhagen: Danish Environmental Protection Agency. Retrieved from www.mst.dk

Danish Environmental Protection Agency. (2018). *Genanvendelse af knust beton i nye betonkonstruktioner* [Recycling of crushed concrete in new concrete structures]. Copenhagen: Danish Environmental Protection Agency. Retrieved from www.mst.dk

Danish Environmental Protection Agency. (2019). *Affaldsstatistik 2017—Miljøprojekt nr. 2012* [Waste statistics 2017—Environmental project no. 2012] (Issue 2102). Copenhagen: Danish Environmental Protection Agency. Retrieved from www.mst.dk

Danish Government. (2019). *Aftale om Klimalov* [Agreement of Climate policies]. Copenhagen: Danish Government.

Danish Regions, Research Center for Environment and Resources. (2017). *Råstoffer: Er der behov for en national strategi?* [Raw materials: Is there a need for a national strategy?]. Copenhagen: Danish Regions, Research Center for Environment and Resources.

Danish Standards. (2006). *DS 411 Norm for betonkonstruktioner* [DS 411 Standard for concrete structures]. Copenhagen: Danish Standards. https://nota.dk/bibliotek/bog/ds-411-norm-betonkonstruktioner#ebook

Densley Tingley, D., & **Davison, B.** (2012). Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment*, 57, 387–395. DOI: https://doi.org/10.1016/j.buildenv.2012.06.005

Di Maria, A., Eyckmans, J., & **Van Acker, K.** (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Management*, 75, 3–21. DOI: https://doi.org/10.1016/j.wasman.2018.01.028

DTU Department of Civil Engineering. (2019). *Skrøner om genbrug af gammel beton skal fakta-tjekkes* [Facts about recycling old concrete must be fact checked]. Kongens Lyngby: DTU Department of Civil Engineering. Retrieved from https://www.dtu.dk/nyheder/nyhed?id=986ABAA8-CFD2-4BC5-AA0B-C978D4C160FA

Eberhardt, L. C. M., Birgisdóttir, H., & **Birkved, M.** (2018). Life cycle assessment of a Danish office building designed for disassembly. *Building Research & Information*, 47(6), 1–15. DOI: https://doi.org/10.1080/09613218.2018.1517458

ecoinvent. (2020). *ecoinvent*. Retrieved from https://www.ecoinvent.org/

Ellen MacArthur Foundation. (2015). *Growth within: A circular economy vision for a competitive Europe*. Cowes: Ellen MacArthur Foundation.

Ellen MacArthur Foundation. (2016). *Circularity in the built environment: Case studies*. Cowes: Ellen MacArthur Foundation.

Emami, N., Heinonen, J., Marteinsson, B., Säynäjoki, A., Junnonen, J. M., Laine, J., & **Junnila, S.** (2019). A life cycle assessment of two residential buildings using two different LCA database–software combinations: Recognizing uniformities and inconsistencies. *Buildings*, 9(1), 1–20. DOI: https://doi.org/10.3390/buildings9010020

EPD Danmark, The Danish Technological Institute & **Gamle Mursten.** (2017). *EPD for Gamle Mursten* [EPD on recycled bricks] (MD-16077-DA). Retrieved from www.teknologisk.dk

European Commission. (2015). *Closing the loop—An EU action plan for the circular economy*. Brussels: European Commission. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1453384154337&uri=CELEX:52015DC0614

European Commission & **Joint Research Centre.** (2012). *The International Reference Life Cycle Data system (ILCD) handbook*. DOI: https://doi.org/10.2788/85727

Frischknecht, R. (2010). LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. *International Journal of Life Cycle Assessment*, 15(7), 666–671. DOI: https://doi.org/10.1007/s11367-010-0201-6

Frischknecht, R., Balouktsi, M., Lützkendorf, T., Aumann, A., Birgisdottir, H., Grosse Ruse, E., Hollberg, A., Kuittinen, M., Lavagna, M., Lupišek, A., Passer, A., Peuportier, B., Ramseier, L., Röck, M., Trigaux, D., & **Vancso, D.** (2019). Environmental benchmarks for buildings: needs, challenges and solutions—71st LCA forum, Swiss Federal Institute of Technology, Zürich, 18 June 2019. *International Journal of Life Cycle Assessment*, 24, 2272–2280. DOI: https://doi.org/10.1007/s11367-019-01690-y

Gala, A. B., Raugei, M., & **Fullana-i-Palmer, P.** (2015). Introducing a new method for calculating the environmental credits of end-of-life material recovery in attributional LCA. *International Journal of Life Cycle Assessment*, 20(5), 645–654. DOI: https://doi.org/10.1007/s11367-015-0861-3

Geyer, R., Kuczenski, B., Zink, T., & **Henderson, A.** (2016). Common misconceptions about recycling. *Journal of Industrial Ecology*, 20(5), 1010–1017. DOI: https://doi.org/10.1111/jiec.12355

International Energy Agency & **Global Alliance for Buildings and Construction.** (2018). *2018 Global status report: Towards a zero-emission, efficient and resilient buildings and construction sector*. Retrieved from www.globalabc.org

International Energy Agency & **Global Alliance for Buildings and Construction.** (2019). *2019 Global status report for buildings and construction: Towards a zero-emissions, efficient and resilient buildings and construction sector*. Retrieved from www.iea.org

Islam, H., Zhang, G., Setunge, S., & **Bhuiyan, M. A.** (2016). Life cycle assessment of shipping container home: A sustainable construction. *Energy and Buildings*, 128, 673–685. DOI: https://doi.org/10.1016/j.enbuild.2016.07.002

Kallesøe, A. J., Clausen, R. J., Skar, S., Von Platen-Hallermund, F., Ditlefsen, C. B., Kalvig, P., & **Ma, M.** (2016). *Indvinding af danske mineralske råstoffer—en geografisk sammenstilling* [Extraction of Danish mineral raw materials] (Vol. Mima rappo 2016/1). Copenhagen: Videncenter for Mineralske Råstoffer og Materialer (MiMa) under De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS).

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*, 4th edn. Hoboken: Wiley.

Kylili, A., & **Fokaides, P. A.** (2017). Policy trends for the sustainability assessment of construction materials: A review. *Sustainable Cities and Society*, 35, 280–288. DOI: https://doi.org/10.1016/j.scs.2017.08.013

Lendager, A., & **Vind, D. L.** (2018). *A changemaker' guide to the future*. Retrieved from https://www.achangemakersguidetothefuture.com/

Lendager Group. (2013). *Upcycle house*. Copenhagen: Lendager Group. Retrieved from https://lendager.com/arkitektur/upcycle-house/

Lendager Group. (2018). *Upcycle studios*. Copenhagen: Lendager Group. Retrieved from https://lendager.com/arkitektur/upcycle-studios/

Lendager Group. (2019). *Ressourcerækkerne* [Resource rows]. Copenhagen: Lendager Group. Retrieved from https://lendager.com/arkitektur/ressourceraekkerne/

Lützkendorf, T. (2017). Assessing the environmental performance of buildings: Trends, lessons and tensions. *Building Research & Information*, 46(5), 594–614. DOI: https://doi.org/10.1080/09613218.2017.1356126

Nußholz, J. L. K., Rasmussen, F. N., & **Milios, L.** (2019a). Circular building materials: Carbon saving potential and the role of business model innovation and public policy. *Resources, Conservation and Recycling*, 141(February), 308–316. DOI: https://doi.org/10.1016/j.resconrec.2018.10.036

Nußholz, J. L. K., Rasmussen, F. N., Whalen, K., & **Plepys, A.** (2019b). A circular business model for material reuse in buildings: Implications on value creation. *Journal of Cleaner Production*, 245, 118546. DOI: https://doi.org/10.1016/j.jclepro.2019.118546

Ökobaudat. (2018). *Process data set: Isolierglas 2-Scheiben (en)*. Ökobaudat. Retrieved from https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d941f45e-1244-419c-a083-e4a49fb5498e&version=01.00.073

Ökobaudat. (2019). Ökobaudat. Retrieved from https://www.oekobaudat.de/

Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., Kellenberger, D., Gschösser, F., Wall, J., & **Wallbaum, H.** (2015). Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years' experience in different European countries. *International Journal of Life Cycle Assessment*, 20(9), 1199–1212. DOI: https://doi.org/10.1007/s11367-015-0926-3

PRÉ. (2020). *SimaPro*. Amersfoort: PRÉ. Retrieved from https://simapro.com/

Ramos Huarachi, D. A., Gonçalves, G., de Francisco, A. C., Canteri, M. H. G., & **Piekarski, C. M.** (2020). Life cycle assessment of traditional and alternative bricks: A review. *Environmental Impact Assessment Review*, 80, 106335. DOI: https://doi.org/10.1016/j.eiar.2019.106335

Randers Tegl. (n.d.). *Beregning af forbrug af mursten* [Calculating consumption of bricks]. Aalborg: Randers Tegl. Retrieved May 14, 2020, from https://www.randerstegl.dk/dk/mursten/fuldmuret-byggeri/beregning-af-murstensforbrug

Region Midtjylland. (n.d.). *Circularity city*. Aarhus: Region Midtjylland. Retrieved February 13, 2020, from http://www.circularitycity.dk/

Rosholm, L. S., Kalvig, P., & **Fold, N.** (2016). *Råstofforsyning. Fra sand og sten til betonbyggeri. MiMa rapport 2016/2* [Raw material supply. From sand and stone to concrete buildings. MiMa report 2016/2]. Copenhagen: Videncenter for Mineralske Råstoffer og Materialer (MiMa) under De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS).

Sandahl, M. W. (2019). *Teknologisk Institut: Mursten med cement-mørtel skal genanvendes* [Danish Technological Institute: Bricks with cement mortar must be reused]. Copenhagen: Bygge- & Anlægsavisen. Retrieved from https://bygge-anlaegsavisen.dk/Teknologisk-Institut-Mursten-med-cement-moertel-skal-genanvendes

Säynäjoki, A., Heinonen, J., Junnila, S., & **Horvath, A.** (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environmental Research Letters*, 12, 013001. DOI: https://doi.org/10.1088/1748-9326/aa54ee

United Nations. (2015). *The Paris Agreement | UNFCCC*. New York: United Nations. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Vadenbo, C., Hellweg, S., & **Astrup, T. F.** (2017). Let's be clear(er) about substitution: A reporting framework to account for product displacement in life cycle assessment. *Journal of Industrial Ecology*, 21(5), 1078–1089. DOI: https://doi.org/10.1111/jiec.12519

Vinduesgrossisten. (n.d.). *Snittegninger, 2 lags trævinduer* [Detail drawings, 2 layered wooden windows]. Svenstrup: Vinduesgrossisten.

Wahlström, M., Laine-Yliijoki, J., Järnström, H., Kaartinen, T., Erlandsson, M., Palm Cousins, A., Wik, O., Suer, P., Oberender, A., Hjelmar, O., Birgisdóttir, H., Butera, S., Astrup, T. F., & **Jørgensen, A.** (2014). *Environmentally sustainable construction products and materials—Assessment of release and emissions* (Vol. 28, 2014:3). Oslo: Nordic Innovation.

Yang, K. H., Seo, E. A., & **Tae, S. H.** (2014). Carbonation and CO_2 uptake of concrete. *Environmental Impact Assessment Review*, 46, 43–52. DOI: https://doi.org/10.1016/j.eiar.2014.01.004

Zink, T., & **Geyer, R.** (2017). Circular economy rebound. *Journal of Industrial Ecology*, 21(3), 593–602. DOI: https://doi.org/10.1111/jiec.12545

How to cite this article: Andersen, C. E., Kanafani, K., Zimmermann, R. K., Rasmussen, F. N., & Birgisdóttir, H. (2020). Comparison of GHG emissions from circular and conventional building components. *Buildings and Cities*, 1(1), pp. 379–392. DOI: https://doi.org/10.5334/bc.55

Submitted: 13 February 2020 **Accepted:** 12 June 2020 **Published:** 13 July 2020