Cardinal Stefan Wyszynski University in Warsaw
Institute of Philosophy
Center for Ecology and Ecophilosophy

STUDIA ECOLOGIAE ET BIOETHICAE

24/1 (2026)

STUDIA ECOLOGIAE ET BIOETHICAE

2026, 24, 1: 93-113
p-ISSN 1733-1218; e-ISSN 2719-826X
https://doi.org/10.21697/seb.5862

Environmental Life-Cycle Assessment of Waste Management in the Building Sector. A Case Study of a Building Project in Karlstad in Central-Sweden

Ocena cyklu życia odpadów w sektorze budowlanym. Studium przypadku projektu budowlanego w Karlstad w środkowej Szwecji

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Received: 2 Mar, 2025; Revised: 30 Jul, 2025; Accepted: 8 Aug, 2025

Abstract: The overarching objective of study is to carry out a detailed environmental life-cycle analysis (E-LCA), to quantify and understand the adverse (and beneficial) impacts, waste handling has on the environment, for a building project in Karlstad in central Sweden, which generated close to 574000 kilograms of diverse types of wastes. The study identifies the relevant environmental aspects of building-wastes management (a combination of recycling, incineration and landfilling, in other words), and avails of contribution, scenario and variation analyses to obtain and communicate some insights relevant and useful in a transition to a circular economy in the future. The emphasis on recycling plastics (which account for about 6% of the total mass), and not continuing to combust them in waste-to-energy plants is particularly strong. Quite obviously, recycling all metals and plastics, and resorting to forestry/garden wastes as a fuel source in lieu of plastics, shows tremendous climate change mitigation potential, in addition to contributing to a truncation of the acidification and eutrophication footprints of the life-cycles of buildings. Life-cycle thinking entails not just end-of-pipe waste management, but also re-designing and re-thinking on the upstream (for reusability, durability, recyclability), and trans-materialising and dematerializing from the point of view of minimising the amounts of waste generated. The study implicitly points at the need for not just continued research in the field of waste management in general (SDG 9), but also sustained collaboration among several stakeholders in the fray (SDG 17), which was gathered from the interviews carried out by the first author to incorporate the social dimension of the sustainability of waste management.

Keywords: building sector, environmental life-cycle assessment, incineration, landfilling, recycling, SDG 12: Responsible Consumption and Production, SDG 11: Sustainable Cities and Communities, SDG 13: Climate Action, SDG 9: Industry, Innovation and Infrastructure

Streszczenie: Głównym celem tego opracowania jest przeprowadzenie szczegółowej analizy cyklu życia odpadów (E-LCA), aby określić ilościowo i zrozumieć negatywny (i korzystny) wpływ gospodarki odpadami na środowisko w przypadku projektu budowlanego w Karlstad w środkowej Szwecji, który wygenerował blisko 574 000 kilogramów różnych rodzajów odpadów. Badanie identyfikuje istotne aspekty środowiskowe gospodarki odpadami budowlanymi (innymi słowy, połączenie recyklingu, spalania i składowania) oraz wykorzystuje analizy wkładów, scenariuszy i wariantów, aby uzyskać i przekazać pewne spostrzeżenia istotne i przydatne w przyszłym przejściu na gospodarkę o obiegu zamkniętym. Szczególnie duży nacisk położono na recykling tworzyw sztucznych (które stanowią około 6% całkowitej masy) i zaprzestanie ich spalania w elektrowniach przetwarzających odpady na energię. Oczywistym jest, że recykling wszystkich metali i tworzyw sztucznych oraz wykorzystywanie odpadów leśnych/ogrodniczych jako paliwa zamiast tworzyw sztucznych ma ogromny potencjał w zakresie łagodzenia zmian klimatu, a także przyczynia się do skrócenia śladów zakwaszenia i eutrofizacji w cyklu życia budynków. Myślenie w kategoriach cyklu życia obejmuje nie tylko gospodarkę odpadami na końcu cyklu, ale także przeprojektowanie i przemyślenie procesu na początku (pod kątem możliwości ponownego wykorzystania, trwałości, możliwości recyklingu) oraz transformację i dematerializację z punktu widzenia minimalizacji ilości generowanych odpadów. Badanie pośrednio wskazuje na potrzebę nie tylko dalszych badań w dziedzinie gospodarki odpadami w ogólności (Cel Zrównoważonego Rozwoju 9), ale także stałej współpracy między różnymi interesariuszami (Cel Zrównoważonego Rozwoju 17). Informacje te zostały pozyskane w oparciu o wywiady przeprowadzone przez pierwszego autora w celu uwzględnienia społecznego wymiaru zrównoważonego gospodarowania odpadami.

Słowa kluczowe: sektor budowlany, ocena cyklu życia, spalanie, składowanie odpadów, recykling, SDG 12: Odpowiedzialna konsumpcja i produkcja, SDG 11: Zrównoważone miasta i społeczności, SDG 13: Działania w dziedzinie klimatu, SDG 9: Przemysł, innowacyjność i infrastruktura

Introduction: Transition of the Building Sector to a Circular Economy

The building and construction sector (often referred to as the ABC sector, with architecture added in) has, over the decades, followed the linear 'take-make-use-throw' economic model (Kightlinger n.d.). This, needless to add, has resulted in unsustainable resource consumption and waste generation; making this sector one of the largest waste-generators in Sweden (the country in which this particular case study is based). In 2020, this figure was 14.2 million tonnes (close to 40% of the total waste generated in the country), according to Boverket (2023). This sector, in general, experiences constant growth. If the linear economic model is not supplanted by a circular one, as soon as possible, resource depletion and environmental deterioration will continue (Byggföretagen 2021). A circular economy, in simple terms, reduces waste generation by focusing on redesigning and rethinking on the upstream of the life-cycles of buildings and constructions, reusing, repurposing and recycling materials and components as much as possible, and obviating the need for relegating wastes to landfills. As observed by Byggföretagen (2021), in order to entrench a circular economic model firmly in the country (or for that matter, anywhere in the world), technological innovations, attitudinal changes and increasingly-stringent (implementable) top-down regulations are indispensable.

The indisputable fact about a circular economic model is the win-win-win that it promises for the three pillars of sustainable development – environmental upkeep, social welfare and economic development. Additionally, promoting reuse and increasing the degree of recycled content in building materials, will improve the bottom-lines of the firms in the building sector, as rightly observed by Gálvez-Martos et al. (2018). However, Rome was not built in a day; and to get to this desired state, collaborations among all the stakeholders concerned are a *sine qua non.* These ought to put in place measures to make reuse and recycling obligatory, support research and development, create incentives (carrots), and fortify regulations (sticks) (Knoth et al. 2022). Changing the prevailing mindset which struggles to abandon the use of the word 'wastes' and replace it with 'resources', will enable a giant leap forward in this regard (Svenska FN-förbundet/Swedish UN-alliance 2015).

As the willingness to transit from the linear model to the circular, manifests itself, the imperativeness of strong regulations, bolstered by the need to reach the targets set by the UN's sustainable development goals (SDGs) is being felt in this sector (see Figure 1). Worth mentioning at this juncture, are SDGs 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production); and 13 (Climate Action).

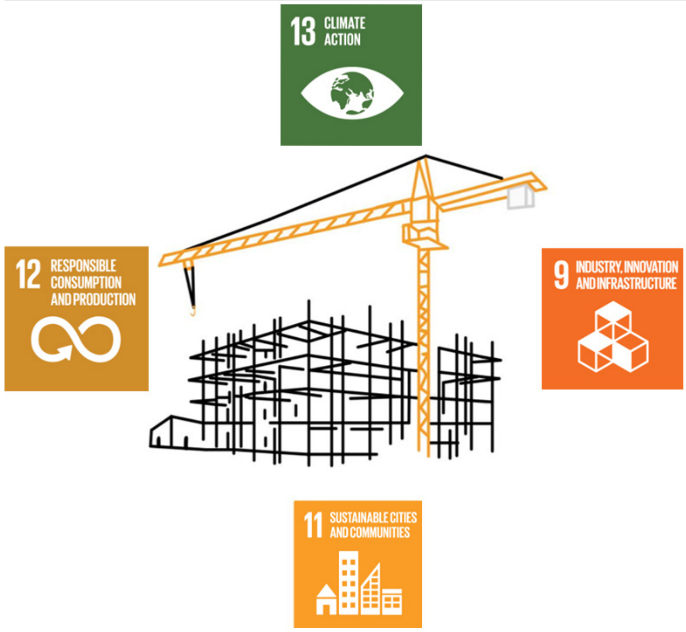

Figure 1. The SDGs in the fray

It follows that an analysis of the types and quantities of wastes generated at building and construction sites, will be the first and necessary step in the direction of improving the sustainability of the building sector in a circular economy.

The overarching objective of this study is to carry out a detailed environmental life-cycle assessment (E-LCA), to quantify and understand the adverse (and beneficial) impacts, waste handling has on the environment, and thereby look for ways and means to truncate the environmental footprint of this stage of the life-cycle.

1. Literature Review

The literature review has been presented in a tabulated format in the Appendix, unconventionally (to enhance reader-friendliness). The peer-reviewed articles studied in preparation for, and to support this particular case study originate from different countries around the world – Sweden, Spain, Germany, Israel, USA, Australia, Cyprus, South Africa and China and were published in the time-period 2014-2023. Some relevant websites and official documents (from Swedish government agencies) were also relied upon to source data and obtain information to base assumptions on. The highlights from each of these sources of data/information have been tabulated in the third column of the Appendix referred to, and represent the diverse building waste management options in vogue in Sweden and around the world

2. Methodology

2.1. Description of the case study

Invencon is a consultancy which has its head office in Karlstad (Sweden). It specialises in industrial development and innovations, and technology-startups. This study was commissioned by Invencon (for the master thesis of the first author of this paper), and supported by Skanska AB, a Stockholm-based 136-year-old building-sector giant with operations in the Nordic region, the rest of Europé and the USA. Skanska AB seeks to attain the much-coveted 'net-zero-emissions' status by the end of 2024 (Skanska 2024). That, by the way, is also a prime driver behind the commissioning of this master thesis assignment.

The focus here is only on the waste management stage (associated with the upstream building and construction process of a new project consisting of a total of 250 apartments, and not demolition), commencing from the generation and sorting of different types of wastes, to their respective final fates. The project itself lasted from January 2022 to February 2024 and served as the main source of primary data collected by the first author.

2.2. Data-gathering

2.2.1. Interviews and personal communication

A semi-structured interviewing format was adopted in this study, to obtain data, information about on-the-ground facts, and opinions about aspects related to waste management in the building and construction sector. This supplemented the literature review (section 2). A semi-structured interview begins with a pre-decided set of questions, and along the way, the conversation makes room for additional questions inspired by the responses given by the interviewee.

The interviewees were stakeholders in the building-and-construction value chain, and directly/indirectly associated with the generation and management of wastes. Among those the first author interacted with were:

- Skanska AB and Consto AB – to understand the processes and methods that are in place, as regards waste management, and the practical challenges and hurdles which exist and have to be overcome en route to greater environmental and economic sustainability.
- Avfall Sverige – to understand more about waste management in general in the country, and top-down initiatives and policies supporting the transition to circularity.
- PreZero Recycling AB – to get an idea about the logistics associated with the end-of-life management of building wastes.
- Karlstads Universitet (Carina Rehnström, from the department of Engineering and Chemical Sciences) – to get a perspective on innovative ways to reuse/recycle wood waste in the future.

The interviews were conducted either via e-mail, virtual meetings via Zoom and Teams, or in-person, as per the convenience of the interviewees. The interviews were semi-structured; and started off with initial predetermined sets of questions which spawned more during the course of the interactions.

2.2.2. Documents, peer-reviewed literature, and websites

The literatures which were reviewed for an understanding of the background, as well as for obtaining data/information, included those in Table 1, as well as some others from websites of building and construction companies, government agencies. The peer-reviewed journal articles provided the necessary grounding for the E-LCA carried out in this study. Taken together, they provided the first author with the necessary theoretical and practical knowledge on which the analysis could be based.

2.2.3. Site visit

A site visit to observe and record data and interact with the personnel on-the-field was considered necessary to understand reality, so to write. During the visit, informal conversations provided useful insights about the reason for the status quo, and the opportunities for improvement.

2.3. Material flow analysis (MFA) and environmental life-cycle assessment (E-LCA)

According to Brunner & Rechberg (2005), MFA is a tool in industrial ecology which is used to systematically map and characterise the flows and stocks of materials/substances/goods within a predefined system. It uses the principle of conservation of mass to track and quantify inflows to 'destinations' and outflows to 'sources.' Bauman & Tillman (2004) define E-LCA as a tool used to assess the environmental impacts of processes, and (life-cycles of) products and services of which processes are a part. These processes include raw material extraction (from mines, forests, fields), production and manufacturing, use and eventually waste management. These processes are linked together by transport stretches ('flows' between processes, in MFA parlance). As mentioned, E-LCA can also be used to train the lens on specific processes or stages in life-cycles of products (or services). That is what has been done in this particular study. E-LCA is practised in accordance with the ISO 14040 standards, and is composed of the following four steps (Bauman & Tillman 2004), which have been described in brief in the sub-sub-sections that follow:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation of the results

2.3.1. Goal and scope definition

The overarching goal of this E-LCA is to assess the environmental impacts of the management of wastes generated at the study-site in Karlstad (Sweden). The analysis branches out to the identification of the environmental impacts associated with the different end-of-life alternatives to which the wastes are subjected – recycling, incineration (with energy recovery), and landfilling. The functional unit is the end-of-life handling of the total amount of wastes generated at the case-study site (over the 25month construction period referred to above in sub-section 3.1) – the composition of which is very diverse. The environmental impact categories which are considered in this study, and the reasons for the selection of the same, are named and discussed in sub-sub-section 3.3.3.

The system boundary for the analysis is represented in Figure 2. The upstream processes are not part of the quantitative analysis per se, though it goes without saying that redesigning and rethinking the upstream will have an undeniable impact on the waste management stage, downstream. The wastes which enter the system, are considered to have zero environmental footprints, when they start their journeys via the transportation steps to the end-of-life handling processes. The assumptions made have been stated at relevant junctures in the sub-sub-sections 3.3.2 and 3.3.3, instead of being listed in Goal and Scope definition (which is the conventional approach, by the way).

2.3.2. Inventory analysis

The data-gathering methods outlined in sub-section 3.2 enabled the setting up of the inventory required for the subsequent

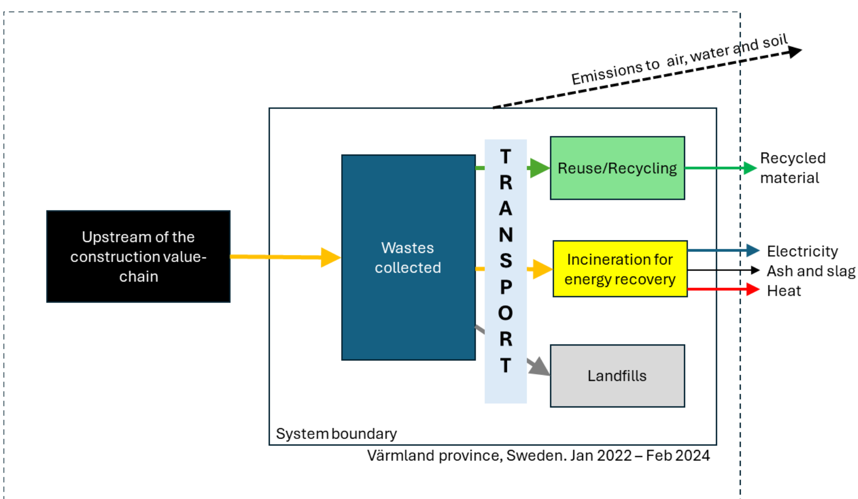

Figure 2. The downstream waste handling stage/s on which this E-LCA focusses on

Table 1. Transport distances to the different end-of-life handling destinations (Eriksson 2024)
The table lists the main waste handling facilities and other destinations used in the case study and shows the transport distance in kilometres from the construction site to each destination.

Destination	Distance (kilometres)
Electronic wastes recycling	481.5
Gypsum recycling	265.2
Hazardous waste incineration	123.0
Incineration for energy recovery (wood etc.)	214.1
Landfilling	168.2
Metal recycling	82.2
Plastics recycling	239.7

impact assessment. Practical knowledge obtained from experts, and studied assumptions and estimates, were necessary. Andreen (2024) informed the first author that most of the copper is usually sold directly to recyclers, and thereby does not end up in the containers for segregation, unlike iron/steel and aluminium. Detailed data for plastic waste generated in the European construction and demolition sector in 2018 (Plasticseurope 2021) was used as a proxy to analyse (and assume) the composition of the plastic wastes at the site studied. Takano et al. (2015) provided a base for an approximate determination of the fractions and end-fates of different types of wastes. Landfilling of organic wastes is legally forbidden in Sweden, since 2022 (Naturvårdsverket n.d.A). Fluorescent tubes and batteries which were completely recycled, accounted for a mere 0.006% of the total mass of wastes, and hence have not been included in this analysis.

Eriksson (2024), from PreZero Recycling AB provided data as regards the transport distances between the building-site and the end-of-life handling destinations (incineration plant, recycling units and landfills) (see Table 1). The fuel used by the trucks, as learnt from Eriksson (2024) is HVO100 (hydrogenated vegetable oil), which is classified as a Euro-6 fuel.

When plastics and wood are incinerated for energy (heat, electricity and steam) recovery in combined heat and power plants (CHPs), the energy input (chemical) and the output [heat and electricity; the efficiency of conversion is usually in the range of 80-90%, as gathered from Karlsson et al. (2018)] can be estimated. The specific energy content (higher heating value) of polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethylene (PE) and wood is 44, 40, 18, 43 and 19.2 MJ/kg respectively (Marczak, 2022; Kofman, 2010). Refer Table 2 in the Impact Assessment subsection which tabulates the stoichiometric equations of the combustion of the four types of plastics in the mix.

2.3.3. Impact assessment

The choice of the environmental impact categories – global warming potential (GWP100, kg-CO_2eq), acidification potential (AP, kg-SO_2-eq), and eutrophication potential (EP, kg PO_4^{3-} eq) was made on the basis of three different 'scales of concern' so to say – global (GWP), local (AP) and local/regional (EP). A report published earlier this decade (Swedish Environmental Research Institute, 2021) considers acidification and eutrophication as problems to be contended with, especially in the southern parts of Sweden, and recommends that GWP must not be allowed to overshadow these. EP also happens to be a regional concern shared by Norway, Denmark, Germany, Poland, Sweden, Finland, Lativia, Lithuania and Estonia (Murray Ciarin et al. 2019; Naturvårdsverket n.d.C). The impact assessment availed of the software Simapro 9.3.0.3 (PRé Consultants), the database Ecoinvent 3.10 (Swiss

Table 2. Combustion of plastics in the incinerator, energy content, specific CO_2- emissions and recyclability (Science History Institute n.d.; Marczak 2022; Picvisa n.d.)

The table summarises key properties of the main waste materials, including their chemical symbols, typical combustion reactions, associated CO_2 emissions per kilogram and a simple indication of how easy each material is to recycle.

Material	Chemical symbol	Chemical reaction	Energy content (MJ/kg)	CO_2 emitted (kg/kg combusted)	Easy of recyclability
PP	$(C_3H_6)_n$	$2C_3H6 + 9O_2 \rightarrow 6CO_2 + 6H_2O$	44	3.1	Feasible
PS	$(C_8H_8)_n$	$C_8H_8 + 10O_2 \rightarrow 8CO_2 + 4H_2O$	40	3.4	Difficult
PVC	$(C_2H_3Cl)_n$	$2C_2H_3Cl + 5O_2 \rightarrow 2H_2O + 4CO_2 + 2HCl$	18	1.6	Very difficult
PE	$(C_2H_4)_n$	$C2H_4 + 3O_2 \rightarrow 2CO_2+2H_2O$	43	3.1	Easy/feasible

Table 3. The scenarios and the embedded variation analysis

The table describes the waste management scenarios considered in the life-cycle assessment, giving each scenario a number and a short textual description of how waste is handled in that case.

Scenario #	Description	
1	Baseline scenario (refer Table 5)	
2	100% of the metal wastes are recycled	
3	100% of the plastics are recycled, with wood substituting for the plastics diverted from incineration, to ensure that the chemical energy input to the CHP/s remain the same	
Variation analysis		
4a (2+3)	100% of metals and 100% of plastics are recycled	Wood in the form of forestry and garden wastes, substitutes for the plastics diverted, to ensure that the chemical energy input to the CHP/s remain the same
4b	100% of metals and 100% of plastics are recycled	Natural gas substitutes for the plastics diverted, to ensure that chemical energy input to the CHPs remains the same. This may happen due to the nonavailability of garden/forestry wastes.

Centre for Life-cycle Inventories 2023) and the CML-IA baseline method (CML, University of Leiden 2016).

Sweden-specific datasets (from the database in the software referred to) are preferred over average European ones. In the absence of both these, global average datasets are used as proxies, while being aware of the uncertainties they introduce into the results of the analysis. As gathered from Avfall Sverige (2022), the exhaust cleaning systems in the combined heat and power plants in Sweden, are able to almost completely trap and treat NOx, SOx, dioxins, acid gases (like the HCl associated with PVC; Table 3), and other pollutants. This bit of information supports the omission of AP and EP from the analysis of the incineration process. As no organic wastes are landfilled in Sweden after 2022 (Naturvårdsverket n.d.A), there are no emissions of greenhouse gases from the landfills. Any GWP associated with landfilling is solely due to the transport of wastes. Landfills in Sweden are sanitary and the probability of leaching of chemicals, heavy metals etc. into the soil around it, or the groundwater, is relatively low, though it cannot be completely ruled out, as gathered from personal communication with Avfall Sverige (2024).

The combustion reactions of the plastics are tabulated in Table 2. The carbon dioxide (CO_2) emissions and thereby the GWP of the incineration of plastics can be determined from the same. The transport-related impacts for each of the three end-of-life handling alternatives are added on, and not indicated separately in Table 6.

2.3.4. Interpretation

The interpretation step in this study includes a scenario analysis, with an inbuilt variation analysis in one of the scenarios (Table 3), followed by an improvement analysis. The baseline case is labelled as Scenario 1.

Improvement analysis: The results of the scenario and variation analyses, in combination with the insights – about the challenges and opportunities, hurdles and incentives – obtained from the semi-structured interviews, form the basis of recommendations for changes in the status quo.

3. Results and Discussion

This section presents and discusses the results obtained by adopting the methods elaborated in section 3. It has been organised in different sub-sections, to maintain coherence and cogency.

3.1. Inventory analysis

3.1.1. Quantities of wastes and their destinations (baseline scenario)

As seen in Figure 5, concrete (30.4%) and non-impregnated wood (28.6%) together account for more than half of the mass of the total wastes generated at the case-study site over the 2-year construction period. Quite evidently, these are the most common materials in building structures, the concrete being used for elements in frames and foundations; and wood finding use in scaffoldings and interior frames. Park et al. (2020) have emphasized the importance of optimising the construction process (with respect to the utilisation of resources, in general), in order to minimise as much as possible, the quantities of wastes generated. Metals, taken together, account for about 13% of the total, with iron and steel far surpassing the non-ferrous metals. Plastics accounted for 5.8%, with PVC (which is relatively more difficult to recycle, vis-à-vis PP, PE and PS; and besides, also has the lowest energy content among the four – Table 2) topping the list.

Gypsum (plaster) is necessary to make sure that the walls and roofs have smooth surfaces. Owing to the high standards set on precision, a good deal of it (10.2% in this case study), ends up as waste. As Jalaei et al. (2021) recommend, true life-cycle thinking must entail re-thinking and re-designing, from a perspective of dematerialisation. Dunmar (2024) – from Skanska AB – opines that the Building Information Modelling (BIM) tool, in its current version, is limited to a 'decimeter-level' precision. This results in superfluous resource inflows, and subsequently, greater waste generation. A smooth transition to a millimeter-level precision, boosted by technological innovations, additional investments, and spurred by stricter regulations, will, by reducing the quantities of waste generated, justify the necessary capital infusion by guaranteeing attractive returns on the investments made (Wang et al. 2015).

3.1.2. Wastes to recycling

As seen in Table 4, close to 60% of the wastes ended up in recycling centres. This included all of the concrete and gypsum (plaster), 98% of bricks, 95% of cement, 94% of the iron and steel, 93% of the aluminium, 21% of PE, 15% of PVC, 11% of PP, and 4.6% of the PS. The lower degrees of recycling of the plastics are characteristic of Sweden, where plastic wastes have been looked upon for several years now, as a source of energy (non-renewable and fossil-based, nevertheless). Crushing concrete and using it extensively as filler-material in the construction sector, contributes immensely to the truncation of the environmental footprint of the building sector, by minimising resource consumption upstream (Strand Nyhlin & Åfreds 2022). These authors have also observed

Table 4. Quantities of the different categories of waste generated, and the partitioning among the three end-of-life handling alternatives (data gathered on-site from Skanska AB)
The table presents the amounts of different types of construction waste generated on the site and shows how many kilograms of each waste type are sent to the various end-of-life treatment options (such as recycling, energy recovery or landfill).

Type of waste	Generated quantity (kilograms)	End-of-life handling method to which the wastes are subjected (kilograms)		
		Recycling	Land filling	Incineration for energy recovery
Concrete	174316	174316	0	0
Wood (nonimpregnated)	164451	0	0	164451
Iron/steel	69189	65474	3715	0
Gypsum (plaster)	58828	58828	0	0
Incinerable waste	30272	0	0	30272
Bricks	20231	19826	0	0
Polyvinylchloride (PVC)	19847	3118	405	16729
Cement	17173	16829	344	0
Polyethylene (PE)	7533	1605	0	5928
Insulation materials	4080	0	4080	0
Polystyrene (PS)	3516	163	0	3353
Polypropylene (PP)	2772	306	0	2466
Impregnated wood	1180	0	0	1180
Hazardous waste	289	0	0	289
Aluminium	246	231	15	0
Batteries	32	32	0	0
Copper	23	23	0	0
Paints	18	0	18	0
Fluorescent tubes	1	1	0	0
Total	573 997	340752 (59.4%)	8577 (1.6%)	224668 (39%)

that there is a market for recycled plaster which is growing steadily, substantiated by developments in building-material production technologies. The degree of recycling of metals – ferrous and non-ferrous – is usually high in the developed world countries, and is favourable from both economic and environmental perspectives, as also gathered from Kucukvar et al. (2016).

About 15% of all the plastics, were recycled in this case study, with PP (11%) and PS (4.6%), both of which are relatively more recyclable than PVC, recording lower percentages. As reported by Lahl and Lahl (2024), 'the lion's share of PVC waste in Europe is still going to waste-to-energy plants, where it tends to be a nuisance.... and the announcements to expand chemical recycling in parallel have not been successful.' In addition to the preference for directing the plastics to CHP plants, inability to sort mixed plastics is also a deterrent to improving the degree of recycling (Eriksson 2024). One may suppose that recycling centres are operating well below their maximum capacity, and there is every reason to put in place, rigorous sorting procedures (in general, and not just for the building sector) to improve capacity utilisation.

3.1.3. Wastes to CHP-plants for energy recovery

About 40% of the wastes (Table 4) – 224668 kg – were combusted in waste-to-energy plants. This included 100% of the non-impregnated wood waste, all the incinerable and hazardous wastes (it goes without saying), and close to 85% of the plastics (Avfall Sverige 2022). Wood waste can be defended as a renewable source of energy, and the carbon-dioxide emanating from its complete combustion (assumed in this study) can be considered to be biogenic (Naturvårdsverket n.d.D). There are debates in environmental research circles about the writing-off of 'biogenic carbon dioxide' as innocuous from the point of global warming. However, it must be mentioned that in a country like Sweden with extremely advanced silvicultural practices, and extensive arboreal resources, 'biogenic' carbon dioxide may not have a long-enough residence time in the atmosphere to trap greenhouse gases. However, the GWP of CO_2 emitted by combusting wood waste is certainly not zero; and in real-life instances when the combustion is not 100%, other hydrocarbons with much higher GWP characterisation factors and higher residence times in the atmosphere, may be emitted.

Kucukvar et al. (2016) have also shown that combusting wood waste for energy is probably a better option vis-à-vis recycling, from the perspectives of water consumption and energy use. The authors however recommend recycling of plastics over incinerating them for energy recovery. As referred to earlier, the hindrances to sorting of plastics (owing to composites and blends) automatically makes energy recovery the easiest option to adopt, in general. However, some countries have taken giant strides in augmenting the degree of recycling of plastics, and this is likely to increase in the years to come.

3.1.4. Wastes to landfills

It is merely 1.6% of the wastes, that is directed to the landfills. Of the 8577 kilograms, there is insulation materials like glass wool and mineral wool (47.6%), iron and steel (43.3%), PVC (4.7%), cement (4%), paints (0.2%), aluminium (0.17%). In many cases – for the metals especially – these are losses which are difficult to avoid, owing to contamination and thereby non-conduciveness to recycling. Mineral wool, according to Strand Nyhlin & Åfreds (2022) can be recycled completely on-date, if one wishes to, but recycling infrastructure for glass wool does not exist in Sweden, at the time of writing.

3.2. Impact assessment and scenario analysis

The impact assessment for the baseline case (Scenario 1) and Scenarios 2 and 3 are presented in this sub-section, while results of the variation analysis (tested on Scenario 4, as 4a and 4b) are covered in sub-section 4.3.

As mentioned in the previous section, the transport-related impacts for each of the three end-of-life handling alternatives are added on, and not indicated separately in Table 6. Suffice to state that the transport-related GWP, AP and EP varied between 22817 and 24768 kg-CO_2-eq, 53 and 58 kg-SO_2eq, & 11.7 and 12.8 kg-PO_4^{3-}eq respectively.

Scenario 1: In the baseline scenario, with the currently extant degree of recycling, a reduction of 106515 kg-CO_2-eq (GWP), 314 kg-SO_2-eq (AP) and 158 kg-PO_4^{3-}eq (EP) (compared of course with a zero-recycling scenario), is achieved. However, incineration (90141 kg CO2-eq; largely due to the plastics), and landfilling to a small extent (305 kg CO_2-eq due only to the transport involved), contribute to the GWP. The result is a reduction in the benefits obtained by recycling, which puts the net values of GWP, AP and EP, in their respective units, at -16069, -289 and -147. Expressed in terms of per kilogram of the total wastes handled (573997 kg) in the case study, these translate to -28 gCO_2eq/kg, -0.5 gSO_2-eq/kg and -0.26 gPO_4^{3-}eq/kg. Figure 3 depicts the breakdown of the energy input to the CHP plant (based on numbers from Tables 2 and 4).

Scenario 2: Prima facie, the baseline case looks pretty impressive, and one may wish to conclude that the current profile of waste management (for this case, and by extension to other cases where a very similar approach is adopted) is extremely satisfactory.

Table 5. Summary of the results for the GWP, AP and EP for the first three scenarios
The table compares the environmental impacts of different end-of-life handling alternatives, using three indicators: global warming potential, acidification potential and eutrophication potential.

End-of-life handling alternatives	GWP ($kg\text{-}CO_2\text{-}eq$)	AP ($kg\text{-}SO_2\text{-}eq$)	EP ($kg\text{-}PO_4^{3-}eq$)
Baseline case (Scenario 1)			
Recycling	-106515	-314	-158
Landfilling	305	1.4	6.6
Incineration	90141	23.7	5.2
Net	-16069	-289	-147
Scenario 2			
Recycling	-112788	-334	-168
Landfilling	172	0.6	0.1
Incineration	90141	23.7	5.2
Net	-22474	-310	-163
Scenario 3			
Recycling	-154186	-393	-281
Landfilling	305	1.0	0.2
Incineration	30203	25.3	5.5
Net	-123678	-367	-276

However, it is worth exploring possibilities of further improvement, and that is where the other two scenarios depicted in Table 5 come in. By diverting the quantities of metals which are currently being landfilled (iron, steel and aluminium) to recycling, and accomplishing 100% recycling of the metal wastes generated (which account for 13% of the total), a further reduction in impacts can be achieved. It must be remarked here that the transport distance to the recycling centre (82.2 km, Table 1), is far less than that to the landfill (164 km). While this diversion decreased landfilling-related impacts by 133 $kg\text{-}CO_2\text{-}eq$, 0.3 $kg\text{-}SO_2\text{-}eq$, and 6.5 $kgPO_4^{3-}eq$, further benefits accrued by way of increasing the degree of metal recycling – corresponding additional decreases of 6273 $kg\text{-}CO_2\text{-}eq$, 20 $kg\text{-}SO_2\text{-}eq$, and 10 kg- $PO_4^{3-}eq$.

Scenario 3: Recycling of metals is an established practice, and one may well be able to get closer to a 100% recycling, in general. However, when it comes to plastics, there are numerous hurdles to be overcome. Scenario 3, as defined earlier, optimistically assumes a 100% recycling of all the plastics, and their simultaneous substitution with an equivalent amount of forestry/garden wastes being added to the fuel mix. The forestry/garden wastes referred to, are assumed to have the same energy content as the wood waste that continues to be incinerated at the CHP. This led to an estimated addition of 41500 kg, to substitute for the 30476 kg of PVC, PP, PE and PS diverted to recycling. Both these amounts correspond to 798.7 GJ of energy input (refer Figure 3, and add up the MJ values of the four plastics).

The net impacts decrease further, with respect to Scenario 2, as can be read from Table 6. While recycling plastics contributes to a decrease in upstream impacts associated with the production of plastics (global warming, acidification, eutrophication and more), not combusting them (and using forestry/garden wastes instead) provides additional benefits vis-a-vis Scenario 1.

3.3. Variation analysis embedded in Scenario 4

Scenario 4 is bifurcated to 4a (combination of scenarios 2 and 3) and 4b (similar to 4a, except that instead of forestry/garden wastes substituting plastics, natural gas is availed of, to plug the deficit).

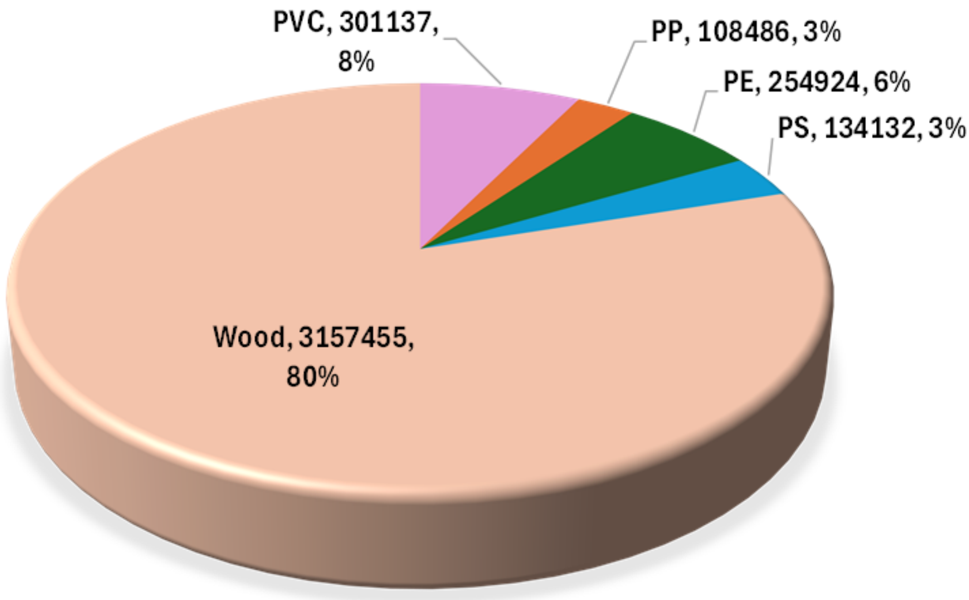

Figure 3. Energy input to the CHP in the baseline case [Waste type, energy content in MJ, % of the total]

Scenario 4a: In Scenario 4a (Table 6), the net GWP decreased by 114015 kg-CO_2-eq (over 700%), while AP and EP decreased by 33% and 83% respectively. This is primarily attributable to the obviation of far-upstream processes (in mines and oil rigs, metalworking and refineries), the recycling of metals and plastics makes possible. Additionally, replacing plastics with garden/forestry wastes as fuel, decreases the GHG-footprint of the CHP plant/s. Though landfills in Sweden can be looked upon as sanitary landfills, the possibility of leaching of metals to the soil and therefrom to the ground water cannot be totally overlooked (Naturvårdsverket n.d.C). Not landfilling metals, thus has a clear benefit as this uncertainty need not be dealt with at all. As with Scenario 3, transporting the garden/forestry wastes as substitute fuel (which were more massive than the plastics they replaced), added a little bit to the GWP, AP and EP. That, however, is a small price to pay for the bigger benefits that accrue as a result of the change.

Scenario 4b: While opting for natural gas will be an extreme case, prompted by the non-availability of renewable alternatives, comparing that possibility with the use of renewable, biological alternatives, helps to put things in perspective. A perceptible increase in the net GWP, vis-a-vis Scenario 4a, is seen in Table 6, alongwith marginal increases in the other two impact categories. Natural gas has a substantial 'well-to-CHP plant' GHG-footprint (environmental footprint in general), and emits carbon dioxide when it is combusted. In real cases (where 100% gas cleaning cannot be assumed), there are emissions of other gases too, causing a host of other environmental impacts. Transport and storage of natural gas (which is predominantly methane gas), may result in some leakage, enlarging the GHG-footprint in the process (Vattenfall n.d.). It can be mentioned here that the sulphur-content of natural gas is lower than that of solid and liquid fossil fuels, and hence the AP is slightly reduced, when compared to the latter (Konsumenternas energimarknadsbyrå n.d.).

Table 6. Summary of the results of GWP, AP and EP for the variation analysis embedded within Scenario 4

The table provides a similar impact comparison for alternative end-of-life scenarios (for example an improved or optimised scenario), showing how global warming, acidification and eutrophication potentials change across scenarios.

End-of-life handling alternatives	GWP (kg-CO_2-eq)	AP (kg-SO_2-eq)	EP (kg-PO_4^{3-}eq)
Scenario 4a			
Recycling	-160459	-412	-289
Landfilling	172	0.6	0.1
Incineration	30202	25	5.5
Net	-130084	-386	-283
Scenario 4b			
Recycling	-160459	-412	-289
Landfilling	172	0.9	0.1
Incineration	66128	41.6	10.3
Net	-94158	-370	-278

Figure 4 sums up the results of the scenario and variation analyses crisply, providing the reader with a recapitulation.

3.4. General discussion

3.4.1. Improvement analysis

Technological developments, process innovations, design improvements, and more simply, novel ways of operating, are all at the heart of much-desired change in the years to come. The building sector, by realising the fact that it is a key contributor to environmental impacts, can comprehend its potential to likewise become a trendsetter in the transition to a circular economy. By contributing to SDG 9, in this fashion, it can inspire other players in the socio-economic fabric of the country, to toe its line. SDG 9 will seamlessly feed into SDGs 13, 14 and 15, as resource-use optimisation and environmental-footprint-truncation will contribute to the upkeep of the biosphere, lithosphere, pedosphere and hydrosphere on earth, and the atmosphere enveloping it.

The anthroposphere in cities is fashioned by the building and construction sector, and thus, it can contribute to SDG 11 – Sustainable Cities and Communities. By investing in, and promoting recycling, and subsequently availing of building materials with greater recycled contents, the sector can set an example worthy of emulation, when it comes to reaching the targets of SDG 12 – Responsible Consumption and Production (see Figure 1).

SDG 7 also features briefly in this analysis. In Scenarios 3 and 4a, the possibility of recycling plastics for their material value was suggested. A substitution was necessary at the CHP-plant/s, and garden/forestry wastes or natural gas were considered as possible replacements. While opting for natural gas may be an extreme case, adding more organic wastes and biofuels to the fuel-mix, will be very much in tune with the circular bioeconomy paradigm being popularised in Sweden. Last but not the least, political support and strong and sustainable collaborative endeavours (SDG 17) will be sine qua non, if the change one wishes to bring about for the better, is to be for the long haul.

3.4.2. Gleanings from the semi-structured interviews

Corporate viewpoints: Dunmar (2024) emphasized the importance of material selection in the building sector. Designing for recyclability, non-toxicity, durability, and modularity are practices that can be incorporated into the industry. Even though systems like *CCbuild* can help the designer in this respect, practical and economic hurdles are to be overcome, before

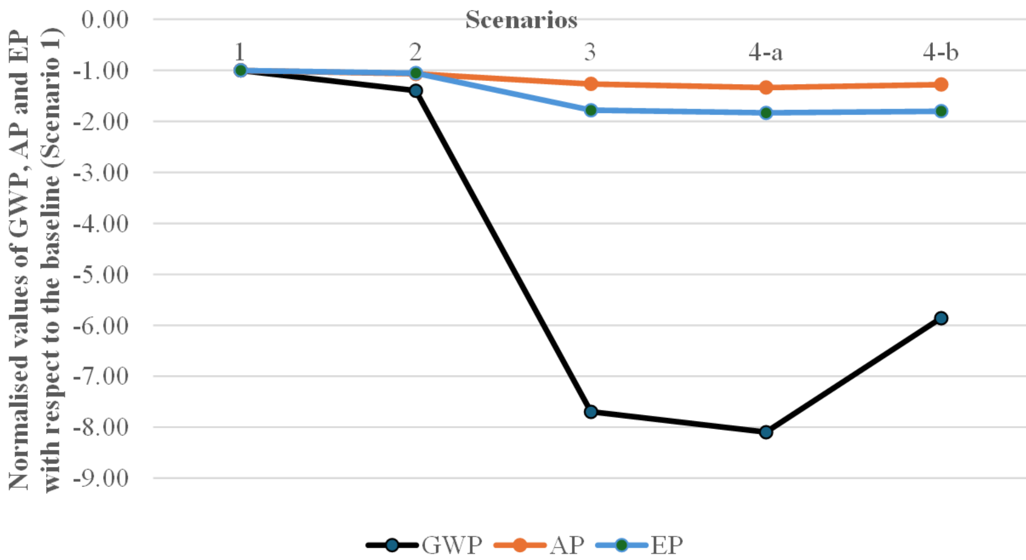

Figure 4. A comparison among the different scenarios, for the three different impact categories (Scenario 1, which is the baseline case, has been assigned the value of one for each of the three)

sustainability-thinking can be integrated into, and entrenched in the work culture prevalent in the building and construction sector. It is not that the sector does not wish to make efforts to become more sustainable and resource-efficient, and truncate its environmental footprint, but rather that lock-ins have to be toppled, and habits which are deeply ingrained have to be overhauled.

Digitalisation and artificial intelligence can be useful tools in the future, for the building sector in Sweden which is keen on reducing wastage by increasing the degree of precision and effectiveness in its operations. The BIM model, which was referred to earlier, reiterated Dunmar (2024), can eliminate unnecessary losses, be that of time, money or resources. However, economic hurdles do exist and need to be overcome. Such advanced control-technologies are expensive, even though a life-cycle costing (LCC) may well reveal that the net present value is positive! How the environment and resources are valued in resource economics, and factored into the LCC referred to, will be the deciding factor. Dunmar (2024), while agreeing that prefabricated structural components may play a role in minimising waste generation, pointed out that lack of precision is a disadvantage. Proper coordination between the component-suppliers and the construction firm, is called for. Any unplanned changes made in the construction process, renders such components unusable. At best, they may need to be re-machined on-site, and that is likely to lead to exactly what one intends to avoid by investing in such prefabricated components – wastes!

Skanska AB has committed itself to on-site sorting of wastes, but Dunmar (2024) observed that a lot more can be done by the other players at different levels in the building sector, so that the rewards thereof can be far-reaching and better-entrenched.

Academic research – Wood waste to pellets: An interview with Rehnström (2024) provided insights into the challenges and opportunities associated with the pelletization of wood waste from building sites. On date, wastes from the forestry sector are the preferred raw materials for pellet-production, while researchers have also been looking into the use of agricultural residues (Svensson et al. 2024). Rehnström pointed out to the presence of adhesives in wood waste as being a deterrent to pelletization. Wood waste related to particleboards and masonite generate a lot of ash when combusted, lowering the energy output in the process, and incurring additional maintenance-related expenditure.

However, as things stand in the third decade of the 21st century, the demand for sustainable and renewable alternatives to the in-vogue non-renewable and non-sustainable materials, is on the rise. This posits wood waste from building sites as a potential candidate for further research (technoeconomic, challenges likely during transport and storage, among other aspects) when it comes to the possibility of valorising it to pellets. The value-addition in this case can be much greater than when wood waste is simply ground and incinerated for energy recovery; and a possible export market may also be uncovered.

Conclusion

This article is the output of a case study conducted in Karlstad (Sweden) by the first author, in her master thesis work, by availing of literature review, site visit, semi-structured interviews, MFA and E-LCA. The overarching objective was to carry out a detailed E-LCA, to quantify and understand the adverse (and beneficial) impacts, waste handling has on the environment, and thereby look for ways and means to truncate the environmental footprint of this stage of the life-cycle.

The study identified the relevant environmental aspects of building-wastes management (a combination of recycling, incineration and landfilling, in other words). Availing of contribution, scenario and variation analyses (interpretative analytical aspects of an E-LCA), the authors could obtain and communicate some insights relevant and useful in a transition to a circular economy in the future. The emphasis on recycling plastics and not continuing to combust them in waste-to-energy plants is particularly strong. This, while conserving material resources and minimizing dependence on abiotic stock resources, will pave the way for greener and renewable alternatives. Quite obviously, recycling all metals and plastics, and resorting to forestry/garden wastes as a fuel source in lieu of plastics, shows tremendous climate change mitigation potential, in addition to contributing to a truncation of the acidification and eutrophication footprints of the life-cycles of buildings. Life-cycle thinking entails not just end-of-pipe waste management, but also re-designing and re-thinking on the upstream (for reusability, durability, recyclability), and trans-materialising and dematerialising from the point of view of minimising the amounts of waste generated (Venkatesh 2023A).

More importantly, the study implicitly points at the need for not just continued research in the field of waste management in general (SDG 9), but also sustained collaboration among several stakeholders in the fray (SDG 17) (Venkatesh 2023B).

Recommendations for further research

- *Detailed E-*LCA: This study narrowed down its focus to just three environmental impact categories. Others may be added on, in a more detailed E-LCA. Many assumptions and simplifications have been made in this analysis. Primary data and information can be obtained to improve the certainty of the results.
- *Disruptive innovations in a circular economy:* Once 'wastes' are looked upon as 'resources', there is a tremendous potential for innovative technological solutions to strike root, and gradually advance to higher technology-readiness levels (TRLs). The focus can be narrowed down to specific types of wastes (akin to Rehnstrom's research in pelletising wood waste, discussed earlier). A range of different uses for wood waste, other than being combusted for energy, can be explored.

- *Economic analysis:* An E-LCA like the one carried out in this study can be supplemented with a cost-benefit analysis to ascertain that what is environmentally favourable is not economically infeasible.
- *Stakeholder survey:* This study could not widen the scope of the semi-structured interviews conducted, but there is a good possibility to interact with more stakeholders – in government agencies for instance – in order to glean more viewpoints and opinions.

Acknowledgements: The authors would like to thank Skanska AB and Invencon for the opportunity to conduct this analysis, and all the others (who have been identified in the article) who supported with data and information. Thanks to Karlstad University for 'housing' this master thesis work.

Author Contributions: Conceptualisation, W.H., G.V.; Methodology, W.H., G.V.; Formal Analysis, W.H.; Investigation W.H.; Writing, W.H, G.V.; Original Draft Preparation, G.V.; Visualisation, W.H., G.V. Both the authors have read and agreed to the published version of the manuscript. The paper is based on Wilma Harge's master thesis (written in Swedish) submitted at the Department of Engineering and Chemical Sciences in May-June 2024.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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Appendix 1

Supporting Data for Environmental Life-Cycle Assessment of Waste Management in the Building Sector. A Case Study of a Building Project in Karlstad in Central-Sweden

Table A1. Overview of selected literature on construction and waste management
The table summarises selected reports and scientific articles on construction and waste management, indicating where each study comes from and highlighting its main findings relevant to the case study.

Article/document	Place of origin (first author's affiliation)	Highlights
Avfall Sverige (2022)	Sweden	In 2020 1.5 million tons of building wastes (10% of the total) were directed to energy-recovering incineration plants. Slag and ash generated in the incineration plants are either landfilled or used for neutralising/rehabilitating soils (at and around mine-sites, for instance). Wood waste is primarily used as an energy source in incineration plants in Sweden, though there are possibilities for putting it to other material-uses.
Avfall Sverige (2024) (Personal communication)	Sweden	Landfills in Sweden are sanitary and the probability of leaching of chemicals, heavy metals etc. into the soil around it, or the groundwater, is relatively low.
Bizcocho & Llatas (2018)	Spain	Reuse and recycling, eventually will improve the bottomline of building and construction companies.
Byggföretagen (2021)	Sweden	Ceramics, bricks and stones, among the wastes, can be reused as additives in the production of fresh concrete. The predominant end-of-life handling method in Sweden for glass wastes at building sites, is recycling.
Hossain et al. (2017)	USA	Reuse and recycling, eventually will improve the bottomline of building and construction companies. On-site sorting of wastes has the potential of decreasing environmental impacts of waste management by 50% (vis-à-vis off-site sorting).
Johansson et al. (2017)	Sweden	Gypsum can very well be recycled, but owing to the fact that it is blended with other materials (which are inseparable from it), it is often landfilled or incinerated in Sweden
Kabirifar et al. (2020)	Australia	Environmental impacts associated with landfilling can be reduced substantially by circularising the waste management model. Sorting and systematically organising the different types of wastes is necessary, as well as upstream re-thinking and redesigning to both trans-materialise and dematerialise.
Kucukvar et al. (2014)	USA	Reuse and recycling eventually will improve the bottomline of building and construction companies. Energy and water use, and environmental impacts decrease substantially when plastics, ferrous and non-ferrous metals are recycled. Wood wastes perform better when subjected to incineration with energy recovery.
Lahl & Lahl (2024)	Germany	PVC waste in Europe largely goes to waste-to energy plants. Announcements to expand chemical recycling in parallel have not been successful.
Llatas et al. (2021)	Spain	Reuse and recycling, eventually will improve the bottom line of building and construction companies.
Maraqa et al. (2023)	Israel	Taking onboard the Building Information System and having stronger collaborations with suppliers and stakeholders on the downstream as well, are imperatives, going forward.

Article/document	Place of origin (first author's affiliation)	Highlights
Naturvårdsverket (2022)	Sweden	Annually, 150000 tons of plastic wastes are generated in the Swedish building sector. On date, extended polystyrene insulations, plastic pipes, floorings and wall-panels, as well as plastics used in the packaging of building materials transported to the site, are recycled.
Naturvårdsverket (2023A)	Sweden	Sustainable logistics (storage and transport) plays a key role in improving resource management efficiency. In greenfield construction projects, a maximum of 15% of building materials end up as wastes.
Naturvårdsverket (2023B)	Sweden	If there are bricks among the generated wastes, they can always be reused or repurposed within the building sector. The different types of wastes that can easily be sorted on-site are wood, concrete, ceramics, bricks, stone, metals, glass, gypsum, hazardous wastes, incinerable wastes, and wastes which are covered under 'extended producer responsibility'.
Naturvårdsverket (2024B)	Sweden	Recycling of building wastes can either within a facility owned by the generator (building firm, in this case), or may be outsourced to an external entity. Hazardous wastes are carefully segregated and despatched to landfills or incineration plants, so as to make sure that the recyclable materials are not contaminated with the toxic substances.
Naturvårdsverket (n.d.A)	Sweden	From 2022, the landfilling of incinerable and organic wastes is banned in Sweden.
Naturvårdsverket (n.d.B)	Sweden	The waste hierarchy needs to be respected, while ensuring economic feasibility.
Ortiz-Rodriguez et al. (2010)	Spain	Reuse and recycling, eventually will improve the bottom line of building and construction companies. Environmental impacts associated with the transport to the end-of-life destinations cannot always be overlooked.
Papamichael et al. (2023)	Cyprus	Reuse and recycling have a strong potential as far as truncating the environmental footprint of the building sector is concerned.
Park et al. (2020)	South Korea	Concrete blocks and insulation materials contribute the most to environmental impacts when they end up as wastes in the construction phase.
Plasticeurope (2021)	Pan-European website	1.7 million tons of plastic wastes were generated in the European building sector in 2018, of which 26% were recycled mechanically, 46.5% were incinerated for energy recovery and the rest were landfilled.
Ragnsells (n.d.A) & Ragnsells (n.d.B)	Sweden	Metallics wastes are most easily collected and recycled. Metals can be recycled again and again, as their properties do not get affected adversely in the process. Wood waste is ground down to chips before being fed into incinerators.
Strand Nyhlin & Åfreds (2022)	Sweden	Bricks can be separated from the cement and reused in new constructions, resulting in a 96% reduction in environmental impacts (associated only with the use of bricks in buildings). Wood waste which is largely incinerated in Sweden can be reused in furniture, wall-panels, window frames, doors, packaging, etc.
UNEP (2023)	Global	Though the lion's share of the environmental impacts in the life-cycle of a building happens in the upstream (material) production and the use phases, the waste management stage must not be swept under the carpet.
Wang et al. (2015)	China	Concrete production contributes to ozone depletion and photochemical oxidant formation, while the insulations used are responsible for abiotic depletion. Recycling/reusing/repurposing them as much as possible will thus contribute to a truncation of the life-cycle environmental footprint.