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The Circular Economy of Steel Roofing and Cladding and Its Environmental Impacts—A Case Study for New Zealand

Krishanu Roy [1,*], Aflah Alamsah Dani [1], Vince Say [2], Zhiyuan Fang [1,2] and James B. P. Lim [1,2]

[1] School of Engineering, The University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand
[2] Department of Civil & Environmental Engineering, The University of Auckland, Auckland 1010, New Zealand
* Correspondence: krishanu.roy@waikato.ac.nz

Abstract: This paper investigates the environmental impacts of two commonly used steel roofing and wall-cladding products in New Zealand over their life cycle, taking into consideration the recycling process. The recycling process of steel is in line with the Circular Economy (CE) approach, where the goal is to prolong the material's lifetime and possibly reduce its environmental impacts and material waste. Although the benefit of recycling steel is well recognised, the environmental impact values of different specific steel products cannot be generalised and need to be estimated. For this, life cycle assessment (LCA) methodology and Environmental Product Declaration (EPD) were implemented to quantify the environmental impacts of the investigated steel products and to analyse the significance of the recycling process in reducing the impacts on the environment. This study considered modules C1–C4 and D to estimate the impacts of steel products. It was found that the recycled steel materials have an effect on reducing the environmental impacts, particularly the global warming potential (GWP) and photochemical ozone creation potential (POCP), both of which were negative and of -2.36×10^6 kg CO_2eq and -8.10×10^2 kg C_2H_4eq, respectively. However, it is important to note that not all impacts were reduced by recycling steel, which creates trade-offs within each impact indicator. In addition, when compared with locally sourced material cladding, the imported material cladding had a 6% higher negative impact value for both GWP and POCP.

Keywords: circular economy; life cycle assessment; environmental impacts; global warming potential; steel roofing; wall-cladding; end-of-life; recycling; New Zealand

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1. Introduction

The ocean's acidity levels have increased by approximately 30% since the industrial revolution, with rising carbon emissions recognised as the primary driver of this [1]. This has been accompanied with a global rise in temperature of about 1.18 °C. Since 1970, carbon emissions have increased by about 90% [2].

The building sector alone contributes 30% of global carbon emissions [3] and in New Zealand the building and construction industries account for 20% of the total country's carbon emissions [4]. As a result, the New Zealand government targeted net-zero carbon by 2050 as its commitment under the Paris Agreement [5,6].

Steel consumption in construction is continuously growing, with virgin steel production increasing by 5% in 2018 to reach 1817 Mt [7]. Steel become one of the favourable materials for construction as it has a great performance, especially the cold-formed steel [8–10]. Current research is also continuously undertaken to optimise the material performance, including the structural and thermal performances [11,12]. However, it is well-known that the manufacture of virgin steel has high environmental impacts, with the processes of sorting, de-galvanizing, and smelting being energy intensive. On the other hand, steel has several advantages, as it can be infinitely recycled without degradation [13,14]. In New Zealand, 75% of steel products, including structural steel and sheets, will be recycled at the end-of-life (EOL) for buildings. 20% of steel reinforcement or mesh will be processed at EOL in a recycling facility [15]. Over 300,000 tons of steel sheets in the country are recycled annually [16]. This is likely to rise in the future; in 2019, steel had a 70% market share for roofing and wall-cladding products [17].

The advantages of steel for roofing and wall-cladding products include its low cost for lifetime maintenance, being more aesthetically pleasing than conventional New Zealand hardwood cladding, and its significant structural and labour cost savings compared to heavyweight roofing [18,19]. Given that New Zealand is seismically sensitive and with major cities near to the coast, the use of steel is also more appropriate for seismic and corrosion issues. It should be noted that steel roofing and wall-cladding products are coated or painted to help mitigate corrosion. Figure 1 illustrates the use of steel for roofing and wall-cladding in New Zealand.

(**a**) (**b**)

Figure 1. Steel products application in buildings in New Zealand: (**a**) steel roofing; (**b**) steel wall-cladding.

Given the dominance of steel for roofing and wall-cladding products, and its recyclability, this paper attempts to quantify the environmental impacts of these products, particularly in the context of a circular economy (CE) [20,21], where recycling reduces the need for virgin steel in the manufacturing stage. The primary purpose of CE in the construction sector is to retain the value of buildings and their elements while limiting construction and demolition waste as much as feasible [22]. This system is contrary to the traditional linear economy (LE) approach, where goods are manufactured and subsequently discarded as waste [23]. The present LE paradigm has led to the extraction of more than 30% of the global natural resources and the generation of 25% of solid waste [24]. Due to the fact that waste materials are moved to landfills rather than being repurposed, the LE method often leads to resource depletion and excessive carbon emissions. The construction sector accounts for around half of all material use and half of all solid waste production globally [25]. It is also a big problem in New Zealand, where construction waste accounts for up to 50% of all waste produced there [26]. The CE transition is likely a viable alternative for the industry, with production processes reintegrated as secondary resources, such as reusing and recycling construction materials to extend their life cycle [27].

The steel recycling process greatly contributes to the industry in achieving the CE model. Steel is endlessly recyclable, and its waste materials and byproducts are valuable resources [28]. For instance, the steelmaking by-product (e.g., slag) can be used for further civil work materials, such as cement and asphalt [29]. In New Zealand, an effort has been taken to promote the CE model throughout the sectors, including the building and construction industry [30]. The current practices in the industry in the country are through on-site waste separation, civil waste sharing platforms, and recycling of several materials, such as steel and co-mingled waste from the construction site [31]. However, it should be noted that the industry should continuously develop a strategy to fully create a CE model in its practice, as the current recycling process can still be improved, for instance, there is 25% of steel materials go to landfill as it is not fully recycled in the current recycling scenario [15]. Reverse logistics for environmental sustainability, sustainable green recycling practises, community involvement in waste management, and the use of emerging technologies are the four main strategies of the CE that might assist the sector in fully implementing this model [32]. There is a level of circularity, known as the 10R's, that outlines the order of priority of actions taken incorporating this CE concept, which are [33]: (i) refuse: refrain from using raw materials; (ii) reduce: lessen raw material consumption; (iii) renew: redesign the product to account for circularity; (iv) re-use: putting the product to use once again; (v) repair: maintain and repair the product; (vi) refurbish: revitalise the product; (vii) remanufacture: create a product from a used one; (viii) re-purpose: utilise an existing product for a new function; (ix) recycle: recover streams of material with the maximum potential value; (x) recover: incinerate waste with energy recovery.

As the industry is related to the huge production of materials, it should follow the standards that focus on the material efficiency for energy-related products, such as BS EN 45552 to EN 45559 [34–41]. The following factors of material efficiency are connected to the issues addressed in the standards; extending the usage period of products; enabling the reuse or recycling of materials at the end of their useful lives; and incorporating recycled or reused materials into products. Regarding the concept and practice of the CE approach, the circular economy standard, "BS 8001:2017 Framework for applying the principles of the circular economy in companies," was created and published by the British Standards Institution (BSI) [42]. In addition, in a well-structured CE model, the steel industry has significant competitive advantages over competing materials, and these can be demonstrated through a life cycle approach [43]. Therefore, the application of these standards and the use of a life cycle approach will benefit the steel industry in achieving the CE model through material efficiency and a sustainable end-of-life scenario.

Several approaches can be used to quantify the carbon emissions of steel roofing and wall-cladding products, with life cycle assessment (LCA) being the most obvious [44–47]. LCA is an evaluation method used to measure the environmental impacts of a product throughout its life cycle, conducted in accordance with ISO 14040:2006 [48], the standard that governs the assessment framework. This approach can be useful during the material selection process of the building in the design and production stages as the process is crucial for having an environmentally friendly building construction [49]

It should be noted that when conducting an LCA, the manufacturing, production, and operating environmental impacts are normally only considered, with the implications of EOL being neglected. However, for the case of steel roofing and steel wall-cladding, the EOL stages can have a considerable influence on the carbon footprint [50]. These variables will also contribute to New Zealand's net-zero carbon objective [51], which is reflected by the potential carbon offset due to recycling.

In the literature, for demolition waste, Blengini [52] employed an LCA framework to compare the findings of recycling demolition waste to alternative end-of-life scenarios where no recycling occurred, to compare metrics and to assess the environmental impacts and the significance of including recycling potential. It was found for a typical building that the recycling potential was equal to 18% of greenhouse gas (GHG) emissions and 29% of the building's life cycle energy. As another example, Thormark [53] conducted an analysis on low-energy buildings and found that the recycling potential was between 35% and 40% of the embodied energy of the building. Broadbent [43] performed an LCA to analyse the benefits of recycling steel; it was found that every 1 kg of steel scrap recycled at the EOL stages saves 1.5 kg of carbon emissions, 13.4 MJ of primary energy, and 1.4 kg of iron ore.

In 2020, New Zealand's Ministry of Business, Innovation and Employment (MBIE) invested $10.9 million towards research and development. The aim was to "improve the country's long-term competitiveness, create value across the economy, and simultaneously provide regenerative environmental benefits and enable a sustainable, low-emission, climate-resilient future" [54].

In this paper, the end-of-life phase in the circular economy in New Zealand of steel roofing and steel wall-cladding products is investigated to assess the potential environmental impacts. The primary goal is to compare and quantify the environmental effects of steel roofing and wall-cladding commonly used in New Zealand, as well as to assess the importance of recycling for steel roofing and wall-cladding, which will be integrated within the CE approach for New Zealand's construction industry.

2. Materials and Methods

In this paper, LCA is used for interpreting the environmental implications associated with the end-of-life and recycling of steel roofing and cladding products. As noted by ISO 14040:2006 [48], an LCA comprises four major phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and result interpretation. Figure 2 shows the overall workflow of this study.

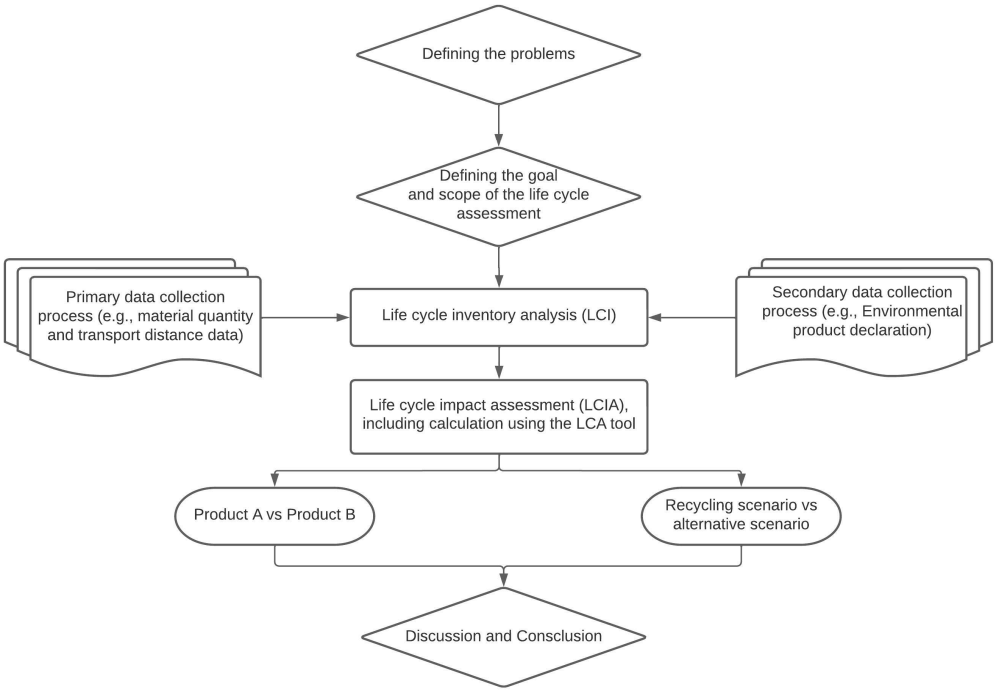


Figure 2. The overall workflow of the study.

Two typical New Zealand products are used: steel roofing and wall-cladding products that are manufactured using imported materials (Product A), and locally sourced materials (Product B). It is noted that Product A is made of hot-dipped zinc/aluminium/magnesium alloy coated steel coils with a nominal 200 gms/m^2 coating weight imported from South Korea. Flexible corrosion-resistant chromated primer is used with a nominal film thickness of 7 μ on the top side and 5 μ on the reverse. The finish coat is the flexible exterior acrylic, polyester, or modified polyester coating with a nominal film thickness of 18 μ [55]. While Product B, which is a competing product that uses materials sourced from New Zealand, is made of hot-dipped aluminium/zinc alloy coated steel coils with a nominal 150 gms/m^2 coating weight. Flexible corrosion-resistant chromated primer is used, with a nominal film thickness of 7 μ ± 1 μ on the top side and 5 μ ± 1 μ on the reverse. Flexible exterior acrylic, polyester, or modified polyester coatings are used as the finish coat with a nominal film thickness of 18 μ ± 2 μ [56]. These two products came up with two similar base metal thicknesses, which are 0.40 and 0.55 mm. In addition, steel waste from recycling roofing and cladding (re-roofing and re-cladding) and steel scraps from their industrial facilities were obtained from the local manufacturer as the source of the material quantity.

2.1. Goal and Scope Definition of the LCA Study

As mentioned previously, the objective is to compare and quantify the environmental impacts of typical steel roofing and wall cladding used in New Zealand, as well as to quantify the importance of effective recycling. The scope of the analysis is limited to modules C to D, as shown in Figure 3, of the LCA framework to BS EN 15978 [57].

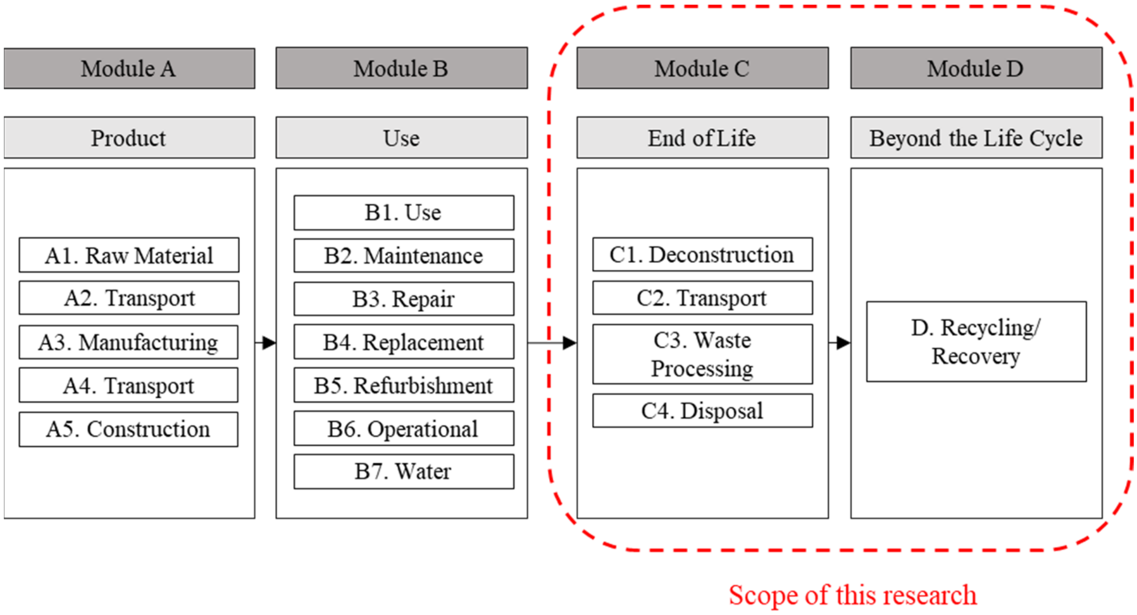


Figure 3. System boundaries of the study.

The modules tested encompassed the EOL stages (deconstruction, transport, waste processing, and disposal) and the steel recycling and recovery phases. The functional unit of this study was steel waste from re-roofing/re-cladding and steel-scraps from the manufacturing facilities in New Zealand recorded from 2019 to 2021, totalling 24 months.

2.2. Life Cycle Inventory (LCI) of the Study

The LCI was developed by collecting data on environmental inputs and outputs (e.g., material quantities and energy, transportation distance, and recycling processes). The data used was obtained from a steel roofing and cladding producer and its associated steel recycling company, situated throughout New Zealand.

2.2.1. Volume of Waste Steel Roofing and Wall-Cladding

The supporting manufacturing and recycling firm provided data on the quantities of steel roofing and cladding, which included the amount of steel scraps from the facilities and re-roofed/re-cladded steel that had been replaced at various project sites. As noted, steel scrap volumes produced at seven different manufacturing facilities were supplied. However, the data on re-roofing and re-cladding obtained from manufacturers initially consisted of a limited 163 jobs spread over seven months in 2019. As a result, the data were linearly extended to reflect 24 months, with the assumption of a consistent data trend (see Table 1). Figure 4 shows the volume of scrap steel roofing and cladding over the aforementioned period.

Furthermore, the amount of information that could be obtained for module C1 on the emissions and energy that contributed to the deconstruction of the material before it was transported to the recycling facilities for the re-roofing/re-cladding and steel scrap volumes was limited. As a result, the module C1 calculation was considered to be zero because the steel scraps would not require further deconstruction; the re-roofing and re-cladding data were also assumed to be zero.

Table 1. Volumes of steel scraps and re-roofing/re-cladding in New Zealand.

	Type of Data	Data Timeline	Duration (Months)	Volume (m^3)
Steel scraps from coils	Actual data	May 2019–June 2021	24	79.56
Re-roofing/re-cladding	Actual data	Jan 2019–July 2019	7	37.95
Re-roofing/re-cladding	Extrapolated data	Jan 2019–Jan 2021	24	151.80

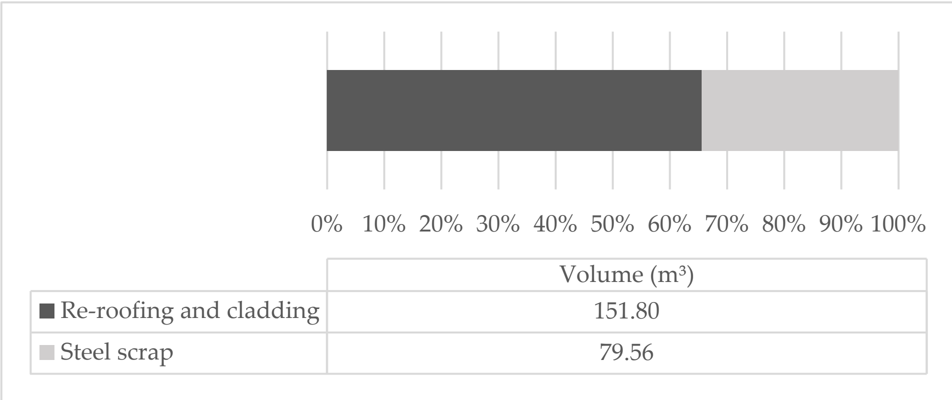


Figure 4. Volumes of steel waste over the 24 months.

2.2.2. Transport of Waste Steel Roofing and Wall-Cladding

The round-trip transportation of steel waste from the recycling facility to the site was included for module C2 under the EOL stages. The data obtained for the quantities of steel roofing and wall cladding included the location of the facility from where the waste originated; as mentioned before, this was across seven different sites in New Zealand. The distances between the origin of the waste and the recycling facility were estimated and are summarised in Table 2. The data on the waste from re-roofing and cladding (which was based in Auckland) varied from site to site and was based on the job location; thus, a distance of 30 km between the site and the recycling facility was assumed.

Table 2. Distances between steel waste origin to the recycling facility.

		Region	Distance (km)	Volume of Steel Waste (m^3)
Steel Scraps	Location 1	Auckland	10.9	23.46
	Location 2	Auckland	30.6	5.53
	Location 3	Christchurch	14	8.03
	Location 4	Wellington	2.2	9.18
	Location 5	Tauranga	10.3	8.16
	Location 6	Auckland	10.9	25.01
	Location 7	Auckland	10.9	0.19
Re-roofing and cladding	Location 8	Auckland	30 *	151.80

* Assumptions on the distance between the site and recycling facility.

2.3. *Life Cycle Impact Assessment of the Study*

The LCIA is divided into two categories: midpoints (e.g., global warming potential and acidification) and endpoints or damaged-oriented (e.g., human health and ecosystem) [58–61]. This study used the midpoints method in analysing the environmental impacts of the steel material, and five indicators of the environmental impacts are listed below, which follow the ReCiPe 2016 v1.1 report [62]:

- Global Warming Potential (GWP)—an indicator relevant to global warming impacts of different greenhouse gases (kg CO_2eq);
- Ozone Depletion Potential (ODP)—an indicator relevant to the degradation of the ozone layer (kg CFC_{11}eq);
- Acidification Potential (AP)—a measure of the potential of emissions causing acidifying effects in the environment (kg SO_2eq);
- Eutrophication Potential (EP)—an indicator relevant to the impacts on terrestrial and aquatic environments due to nitrogen and phosphorus (kg PO_4^{3-}eq);
- Photochemical Ozone Creation Potential (POCP)—an indicator relevant to the creation of smog and air pollution (kg C_2H_4eq).

In order to achieve the first goal of comparing and quantifying the environmental effects of steel roofing and cladding commonly used in New Zealand, Environmental Product Declarations (EPDs) from Product A and Product B [63] were used to quantify environmental impacts from steel products and model modules C3, C4, and D to compare the environmental performance of these products. In the selected EPD, the LCA used primary data for all manufacturing processes up to the factory gate, and GaBi Databases 2018 [64] were referred to for all energy inputs, transportation methods, and raw materials. It is important to highlight that the environmental impacts for modules C1 and C2, which were the deconstruction and transport modules, were not included in the EPDs since these modules were highly dependent on the individual status of the material.

Furthermore, a comparison was made between the existing steel recycling situation in New Zealand and an alternative scenario (as proposed in ISO 14040:2006), in which there is no recycling process, and the waste is disposed of directly in a landfill. LCAQuick V3.4.4 [65], a New Zealand based LCA tool, was used to create alternative models, to be compared against the steel product with a recycling scenario. As a result, the study was able to analyse and identify hotspots of the environmental impacts associated with recycling steel roofing and wall cladding.

2.4. Assumptions in the LCA Study

In performing the LCA, some data could not be collected due to the lack of available information on the data within the country. Therefore, several assumptions were made to support the LCA process of the study.

- The amount of steel used for re-roofing and re-cladding was equal to the amount being replaced and sent to the recycling process. Therefore, the study was able to perform a linear extrapolation to represent 24 months of re-roofing and re-cladding volume.
- The transport distance of re-roofing and re-cladding was assumed to be 30 km based on most re-roofing and re-cladding jobs being located around the coasts of Auckland, where corrosion is more predominant and can be the leading cause of refurbishing roofs and cladding.
- A generic transport truck with a load capacity of 12,400 kg was assumed to represent the type of vehicle used to transport the steel waste into the recycling facility.
- The deconstruction phase or module C1 was assumed to be zero, whilst module C2 was represented by additional information on the common transportation scenario.

3. Results and Discussion

In the LCIA stage, data from LCI were analysed using the EPDs calculation model. Over 24 months, the current research used data from steel waste from re-roofing/re-cladding and steel scraps from local manufacturing facilities. As can be seen from Figure 3, the total volume of steel waste likely to be recycled was 231.4 m^3. Approximately 66% of the entire waste is garbage from re-roofing/re-cladding, with the other 34% being manufacturing waste.

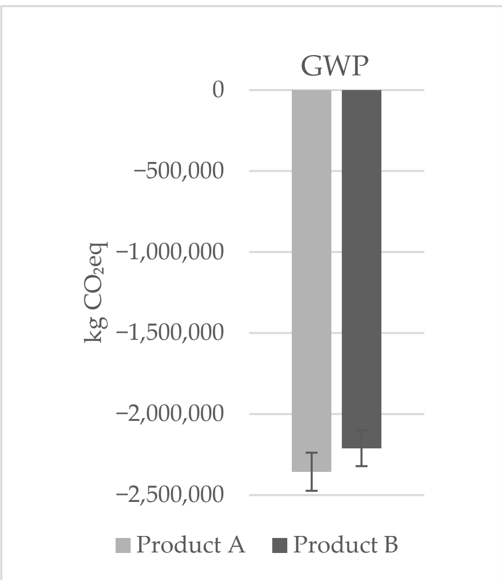
It was found that while re-roofing/re-cladding required a greater volume of steel, the quantity of steel scraps to be re-cycled was identified as a significant portion of total roofing and wall-cladding wastes. It should be noted, however, that the data collected in this study were gathered during a period when international events such as BREXIT, COVID-19, and a decrease in steel manufacturing in China occurred, all of which had an impact not only on the global steel market but also on conditions in New Zealand [66]. As a result, there was extreme volatility in the steel market, influencing the needs and volumes of steel utilised throughout New Zealand, as well as the amount of steel used and recycled in the construction industry.

3.1. Comparison of the Environmental Impacts of Steel Roofing and Cladding Commonly Used in New Zealand

Using the collected steel waste volume (re-roofing/re-cladding and steel scraps) from various building stocks that were sent for recycling over 24 months, the environmental effect values of Product A and Product B were evaluated during their respective life cycles. Table 3 and Figure 5 summarise the environmental impacts of each steel roofing type and illustrate the results in the respective modules. It was found that there were minor differences between the environmental impacts of the two roofing and wall-cladding products. Both materials had an overall net positive impact on the environment in terms of GWP and POCP. It was shown in Figure 3 that the overall recycling process of steel was beneficial in terms of these environmental impact indicators (GWP and POCP), as recycling created a circular economy where the recycled product replaced the demand for virgin materials.

Table 3. Environmental impacts of Product A and Product B during its life cycle stages.

Indicator	Unit	Module C: EOL Phase		Module D: Recycling		Module C + D	
		Product A	Product B	Product A	Product B	Product A	Product B
GWP	kg CO_2eq	5.48×10^4	5.25×10^4	-2.41×10^6	-2.26×10^6	-2.36×10^6	-2.21×10^6
ODP	kg CFC_{11}eq	2.94×10^9	2.70×10^9	1.54×10^2	1.45×10^2	1.54×10^2	1.45×10^2
AP	kg SO_2eq	2.15×10^2	2.09×10^2	3.44×10^3	3.04×10^3	3.65×10^3	3.25×10^3
EP	kg PO_4^{3-}eq	1.08×10^1	9.86	5.05×10^2	4.54×10^2	5.16×10^2	4.64×10^2
POCP	kg C_2H_4eq	6.03	6.58	-8.16×10^2	-7.74×10^2	-8.10×10^2	-7.68×10^2



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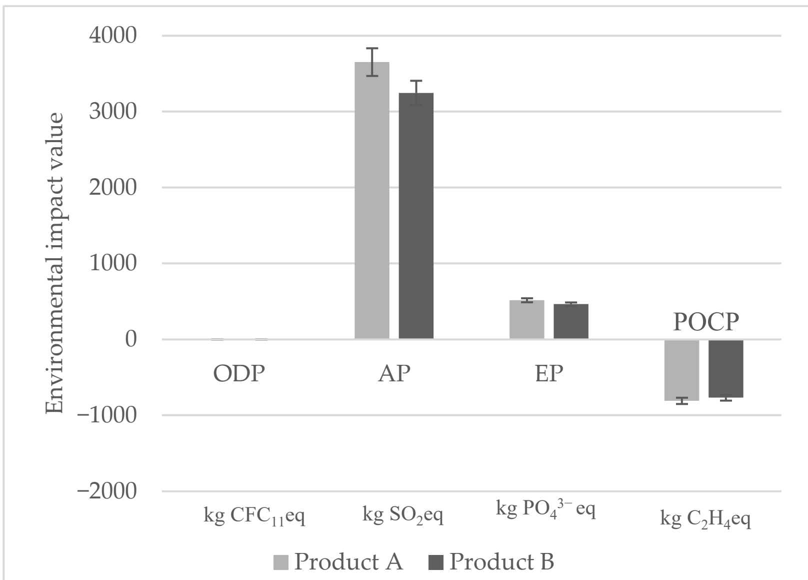


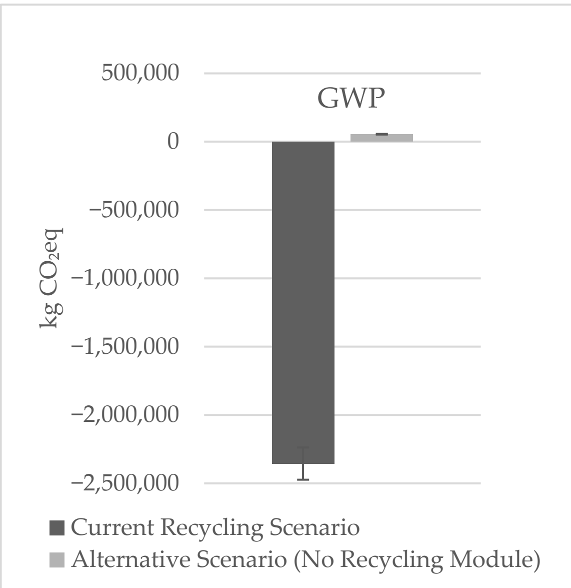
(**b**)

Figure 5. Environmental impacts of Product A and Product B: (**a**) GWP values; (**b**) ODP, AP, EP and POCP values.

A comparison between the environmental impacts of steel roofing and wall-cladding products (Product A and Product B) found that they had different environmental impact values, where the difference varied between environmental indicators. Product A had more favourable environmental consequences in terms of GWP and POCP, whereas Product B had more favourable impacts on ozone depletion, acidification, and eutrophication. Product A had 6% fewer impact values in GWP and POCP indicators compared to Product B. Despite the difference in GWP and POCP results, the two steel products had negative impact values, potentially benefiting the environment after being recycled. Product A, on the other hand, had higher AP (11%), EP (10%), and ODP (6%) compared to Product B. However, GWP is arguably one of the most important environmental impacts being assessed within the construction industry as it is associated with increased global temperatures. Therefore, it is driven by the numerous policies that are being implemented, such as the Climate Change Response (Zero-Carbon) Amendment Act 2019 [5], which aims to have all buildings operate at net zero carbon by 2050.

3.2. Comparison between Environmental Impacts of Current Steel Recycling and Alternative Scenarios

An alternative scenario was studied concerning the existing steel recycling situation in New Zealand to better comprehend the scale and relative relevance of effective material end-of-life management. The alternative scenario used in this study was no recycling process, and the steel waste was directly sent to a landfill, as per ISO 14040:2006 [30]. This scenario eliminated any environmental net gains, as the recycling potential of the material was lost. Figure 6 and Table 4 show the achieved result of comparing the two scenarios. Consequently, environmental impacts such as GWP and POCP were significantly increased in the scenario of no recycling. A difference of 2.41×10^6 kg CO_2eq and 8.16×10^2 kg C_2H_4eq was found between GWP and POCP of the two scenarios, where the current recycling scenario had a net positive impact on the environment, whereas the alternative scenario produced emissions harmful to the environment. Detrimental impacts such as ODP, AP and EP were enhanced with the recycling scenario, with differences of 1.54×10^{-2} kg CFC_{11}eq, 3.44×10^3 kg SO_2eq and 5.05×10^2 kg $PO_4{}^{3-}$eq in comparison to the alternative.



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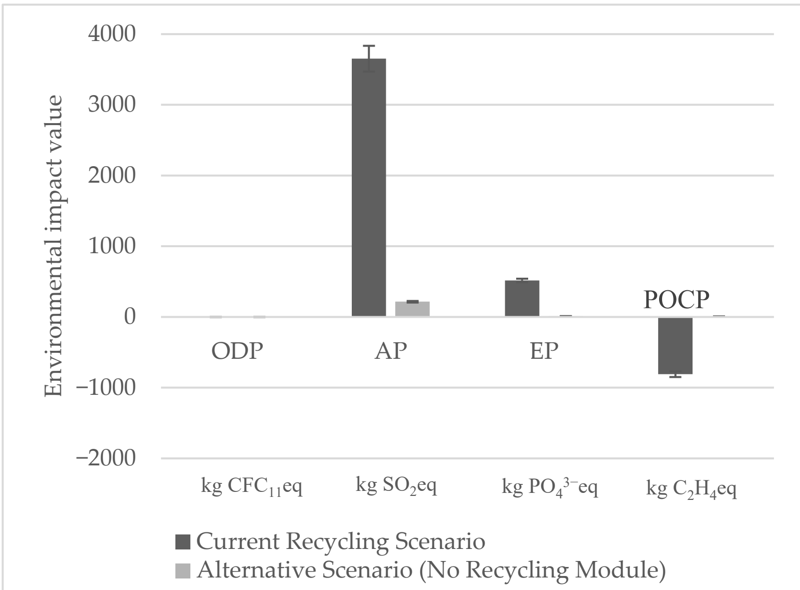

(**b**)

Figure 6. Environmental impacts of the current recycling and alternative scenarios: (**a**) GWP values; (**b**) ODP, AP, EP and POCP values.

Table 4. Comparison of the environmental impacts of the current recycling and alternative scenarios.

Indicator	Unit	Current Recycling Scenario	Alternative Scenario (No Recycling Module)	Difference
GWP	kg CO_2eq	-2.36×10^6	5.48×10^4	2.41×10^6
ODP	kg CFC_{11}eq	1.54×10^2	2.94×10^9	1.54×10^2
AP	kg SO_2eq	3.65×10^3	2.15×10^2	3.44×10^3
EP	kg $PO_4{}^{3-}$eq	5.16×10^2	1.08×10^1	5.05×10^2
POCP	kg C_2H_4eq	-8.10×10^2	6.58	8.16×10^2

The study compared the environmental impacts of present recycling methods in New Zealand with this alternative, where steel waste is immediately landfilled as part of the alternative recycling scenario. The research reveals that the recycling process reduces the environmental impacts of steel materials, resulting in the steel material's possible future advantages due to net negative impact values for the GWP and POCP indicators. The impacts were significantly reduced by having the recycling process after the EOL stages, with a difference of 2.41×10^6 kg CO_2eq and 8.16×10^2 kg C_2H_4eq between the current recycling scenario and an alternative where no recycling takes place. On the contrary, the alternative scenario, in which the waste was landfilled and no recycling occurred, had positive impact values on all indicators, negatively impacting the environment. In comparison with the previous study, Broadbent [43] examined the advantages of recycling steel using the LCA approach and discovered that for every kilogramme of steel scrap recycled at the EOL phases, 1.5 kg of carbon emissions, 13.4 MJ of primary energy, and 1.4 kg of iron ore are avoided. Liu et al. [67] quantified the carbon reduction potential of recycling construction waste in Jiangsu Province, China. According to their findings, recycling steel in the given scenario greatly reduces CO2 emissions, accounting for 39.48% of the possible reduction in carbon emissions. Blengini [52] used an LCA framework to compare the results of recycling demolition waste to alternative end-of-life scenarios without recycling in Italy. It was found that the recycling potential for a typical building was equivalent to 29% of life cycle energy and 18% of GHG emissions.

Recycling materials such as steel encourages a circular economy (CE) approach in which the recycled product is part of a closed-loop system. Recycling reduces the effects of GWP and POCP, which emphasises the need for a CE. According to the findings of this study, the end-of-life (EOL) and recycling phases are crucial from an environmental perspective and can be considered environmentally beneficial. It refers to the CE concept, in which the recycling of resources such as steel will return the substance to a new life cycle, reducing the demand for virgin materials to be extracted and easing the environmental strain. However, it is crucial to note that the recycling process has negative impacts, such as an increase in the potential for ozone depletion, acidification, and eutrophication, as demonstrated by this study. It is crucial to highlight that recycling does not decrease all consequences, producing trade-offs for each environmental effect. Consequently, there is opportunity for improvement in evaluating the recycling process, as these impacts could be decreased and managed through the use of alternative techniques.

4. Conclusions

The study evaluated the environmental effects of the end-of-life (EOL) and recycling phases of steel roofing and cladding in New Zealand. The primary goals of the study were to assess and quantify the environmental consequences, such as GWP, ODP, AP, EP, and POCP, of commonly used steel roofing and wall-cladding in New Zealand, and to evaluate the significance of the recycling process. Using an LCA technique and Environmental Product Declarations (EPDs), the environmental consequences of steel roof and wall cladding products were evaluated.

According to the conclusions of the LCA, the end-of-life and recycling phases play an important role from an environmental standpoint, as they may be judged helpful to the ecosystem. This relates to the concept of a "circular economy," in which the recycling of commodities such as steel will reintroduce the material into a new life cycle, reducing the demand for virgin materials to be mined and the environmental impact. The following is a summary of the primary findings of this study:

- A total of 231.4 m^3 of steel waste was recycled over a 2-year span from 2019–2021, which consisted of 66% originating from re-roofing/re-cladding, whilst the remaining 34% was from manufacturing scraps.
- When comparing Product A and Product B, which are two common roofing and cladding materials found in New Zealand, Product A is seen to have both 6% greater GWP and POCP impacts compared to Product B, which results in a net positive impact on the environment. However, Product A also displays higher AP (11%), EP (10%) and ODP (6%) values, which are net negative environmental impacts in comparison to Product B.
- When outlining the significance of proper material recycling associated with steel roofing and cladding, the results have shown that the recycling process has a substantial effect on the environmental impacts of the material. Environmental impact indicators such as GWP and POCP are greatly reduced, having a difference of 2.41×10^6 kg CO_{2-}eq and 8.16×10^2 kg C_2H_{4-}eq. between the current recycling scenario and an alternative where no recycling takes place. This change results in a net positive impact on the environment, whereas the alternative scenario increases emissions harmful to the environment in terms of ozone depletion, acidification, and eutrophication, with differences of 1.54×10^{-2} kg CFC_{11-}eq, 3.44×10^3 SO_2eq and 5.05×10^2 kg $PO_4{}^{3-}$eq in comparison to the alternative.

In conclusion, this study supports the concept of a circular economy, especially recycling steel roofing and cladding in New Zealand to reduce harmful environmental impacts. Meanwhile, it is important to note that not all environmental impacts are reduced as a result of recycling, thus creating trade-offs against each environmental effect. In addition, future research should take into account the assumptions used in this study, which will vary depending on the circumstances. It is advised that more data be gathered in order to fully simulate steel recycling processes.

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Abbreviations

	Meaning
AP	Acidification potential
CE	Circular economy
EOL	End-of-life stage
EP	Eutrophication potential
EPD	Environmental product declaration

GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LE	Linear economy
ODP	Ozone depletion potential
POCP	Photochemical ozone creation potential

References

1. NASA. Climate Change Evidence: How Do We Know? In *Climate Change: Vital Signs of the Planet*; NASA: Washington, DC, USA, 2020. Available online: https://climate.nasa.gov/evidence/ (accessed on 22 March 2022).
2. EPA. *Global Greenhouse Gas Emissions Data*; US EPA: Washington, DC, USA, 2021. Available online: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Trends (accessed on 23 March 2022).
3. UNEP. *Buildings and Climate Change: Summary for Decision Makers*; United Nations Environment Programme: Paris, France, 2009.
4. Ministry of Business, Innovation & Employment. *Whole-of-Life Embodied Carbon Emissions Reduction Framework*; MBIE: Wellington, New Zealand, 2020; p. 24. Available online: https://www.mbie.govt.nz/dmsdocument/11794-whole-of-life-embodied-carbon-emissions-reduction-framework (accessed on 17 April 2022).
5. Parliamentary Counsel Office. *Climate Change Response (Zero Carbon) Amendment Act 2019 No 61, Public Act Contents—New Zealand Legislation*; New Zealand Legislation: Wellington, New Zealand, 13 November 2019. Available online: https://www.legislation.govt.nz/act/public/2019/0061/latest/LMS183736.html (accessed on 12 April 2022).
6. BRANZ. *A Carbon Budget for New Zealand Houses. BRANZ Research Now: Zero-Carbon Built Environment*; BRANZ: Porirua, New Zealand, 2020; p. 4.
7. IEA. Global CO_2 Emissions by Sector, 2018—Charts—Data & Statistics. 2018. Available online: https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2018 (accessed on 20 April 2022).
8. Fang, Z.; Roy, K.; Mares, J.; Sham, C.W.; Chen, B.; Lim, J.B. Deep learning-based axial capacity prediction for cold-formed steel channel sections using Deep Belief Network. *Structures* **2021**, *33*, 2792–2802. [CrossRef]
9. Chen, B.; Roy, K.; Fang, Z.; Uzzaman, A.; Raftery, G.; Lim, J.B. Moment capacity of back-to-back cold-formed steel channels with edge-stiffened holes, un-stiffened holes, and plain webs. *Eng. Struct.* **2021**, *235*, 112042. [CrossRef]
10. Roy, K.; Ho Lau, H.; Fang, Z.; Masood, R.; Chui Huon Ting, T.; Lim, J.B.; Chieng Chen Lee, V. Effects of corrosion on the strength of self-drilling screw connections in cold-formed steel structures-experiments and finite element modeling. *Structures* **2022**, *36*, 1080–1096. [CrossRef]
11. Fang, Z.; Roy, K.; Liang, H.; Poologanathan, K.; Ghosh, K.; Mohamed, A.; Lim, J. Numerical Simulation and Design Recommendations for Web Crippling Strength of Cold-Formed Steel Channels with Web Holes under Interior-One-Flange Loading at Elevated Temperatures. *Buildings* **2021**, *11*, 666. [CrossRef]
12. Liang, H.; Roy, K.; Fang, Z.; Lim, J.B.P. A Critical Review on Optimization of Cold-Formed Steel Members for Better Structural and Thermal Performances. *Buildings* **2022**, *12*, 34. [CrossRef]
13. NZ Steel. *Steel Product Recycling*. Leading Manufacturer of Quality Steel in New Zealand | New Zealand Steel. 2020. Available online: https://www.nzsteel.co.nz/sustainability/our-environment/recycling/ (accessed on 11 May 2022).
14. He Pou a Rangi. *Chapter 4a: Reducing Emissions—Opportunities and Challenges across Sectors Heat, Industry and Power*; He Pou a Rangi; Climate Change Commission. 1 February 2021. Available online: https://www.climatecommission.govt.nz/get-involved/our-advice-and-evidence/ (accessed on 27 April 2022).
15. BRANZ. Data. Available online: https://www.branz.co.nz/environment-zero-carbon-research/framework/data/ (accessed on 20 April 2022).
16. HERA. Steel Recycling. Available online: https://www.hera.org.nz/sustainability/steel-recycling/ (accessed on 20 April 2022).
17. BRANZ. *Research Now Physical Characteristics of New Buildings #1*; BRANZ: Porirua, New Zealand, 2020; p. 6.
18. Flooks, M. *Structural Cost Savings. Lightweight vs Heavyweight Roofing*; NZ Metal Roofing Manufacturers. 2010. Available online: https://www.metalroofing.org.nz/technical/structural-cost-savings-lightweightvs-heavyweight-roofing (accessed on 10 July 2022).
19. MCA. *The ABCs of LCAs and EPDs*. Metal Construction Association—Metal Building Materials—Inspiring Building Design, Durability and Sustainability; June 2018. Available online: https://metalconstruction.org/view/download.php/online-education/education-materials/architect-resources/the-abcs-of-lcas-and-epds (accessed on 16 May 2022).
20. PwC. *Closing the Loop—The Circular Economy, What It Means and What It Can Do for You*; PricewaterhouseCoopers: London, UK, 2018; p. 48. Available online: https://www.pwc.com/hu/en/kiadvanyok/assets/pdf/Closing-the-loop-the-circular-economy.pdf (accessed on 20 April 2022).
21. Grdic, Z.S.; Nizic, M.K.; Rudan, E. Circular Economy Concept in the Context of Economic Development in EU Countries. *Sustainability* **2020**, *12*, 3060. [CrossRef]
22. Torgautov, B.; Zhanabayev, A.; Tleuken, A.; Turkyilmaz, A.; Mustafa, M.; Karaca, F. Circular Economy: Challenges and Opportunities in the Construction Sector of Kazakhstan. *Buildings* **2021**, *11*, 501. [CrossRef]

23. Garcés-Ayerbe, C.; Rivera-Torres, P.; Suárez-Perales, I.; Leyva-De La Hiz, D.I. Is It Possible to Change from a Linear to a Circular Economy? An Overview of Opportunities and Barriers for European Small and Medium-Sized Enterprise Companies. *Int. J. Environ. Res. Public Health* **2019**, *16*, 851. [CrossRef]
24. Benachio, G.L.F.; Freitas, M.D.C.D.; Tavares, S.F. Circular economy in the construction industry: A systematic literature review. *J. Clean. Prod.* **2020**, *260*, 121046. [CrossRef]
25. Australian Government. *CONSTRUCTION AND DEMOLITION WASTE GUIDE—RECYCLING AND REUSE ACROSS THE SUPPLY CHAIN*; Department of Sustainability, Environment, Water, Population and Communities: Canberra, Australia, 2012; p. 58. Available online: https://www.awe.gov.au/sites/default/files/documents/case-studies.pdf (accessed on 17 May 2022).
26. BRANZ. Reducing Building Material Waste. Available online: https://www.branz.co.nz/sustainable-building/reducing-building-waste/ (accessed on 30 January 2022).
27. Stephan, A.; Athanassiadis, A. Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. *Resour. Conserv. Recycl.* **2018**, *129*, 248–262. [CrossRef]
28. HERA. *Steel's Contribution to a Circular Economy and Low Carbon Future*; Heavy Engineering Research Association (HERA): Auckland, New Zealand, 2019. Available online: https://www.sustainablesteel.org.nz/wp-content/uploads/2019/09/Steels-contribution-to-a-circular-economy-low-carbon-future.pdf (accessed on 8 December 2022).
29. Worldsteel. *Circular Economy*. Steel-The Permanent Material in the Circular Economy. Available online: https://worldsteel.org/circulareconomy/ (accessed on 3 December 2022).
30. Ministry for the Environment. *Te Hau Mārohi Ki Anamata—Towards a Productive, Sustainable and Inclusive Economy*; Ministry for the Environment: Wellington, New Zealand, 2022; p. 348. Available online: https://environment.govt.nz/assets/publications/Aotearoa-New-Zealands-first-emissions-reduction-plan.pdf (accessed on 8 December 2022).
31. Low, J.K.; Wallis, S.L.; Hernandez, G.; Cerqueira, I.S.; Steinhorn, G.; Berry, T.-A. Encouraging Circular Waste Economies for the New Zealand Construction Industry: Opportunities and Barriers. *Front. Sustain. Cities* **2020**, *2*, 35. [CrossRef]
32. Kumar, R. *What Are the Four Main Concepts of the Circular Economy?* The Times of India: Mumbai, India, 2022. Available online: https://timesofindia.indiatimes.com/blogs/voices/what-are-the-four-main-concepts-of-the-circular-economy/ (accessed on 3 December 2022).
33. Cramer, J. The Raw Materials Transition in the Amsterdam Metropolitan Area: Added Value for the Economy, Well-Being, and the Environment. *Environ. Sci. Policy Sustain. Dev.* **2017**, *59*, 14–21. [CrossRef]
34. *BS EN 45552:2020*; General Method for the Assessment of the Durability of Energy-Related Products. European Standards: Pilsen, Czech Republic, 2020. Available online: https://www.en-standard.eu/bs-en-45552-2020-general-method-for-the-assessment-of-the-durability-of-energy-related-products/ (accessed on 7 December 2022).
35. *BS EN 45553:2020*; General Method for the Assessment of the Ability to Remanufacture Energy-Related Products. European Standards: Pilsen, Czech Republic, 2020. Available online: https://www.en-standard.eu/bs-en-45553-2020-general-method-for-the-assessment-of-the-ability-to-remanufacture-energy-related-products/ (accessed on 7 December 2022).
36. *BS EN 45554:2020*; General Methods for the Assessment of the Ability to Repair, Reuse and Upgrade Energy-Related Products. European Standards: Pilsen, Czech Republic, 2020. Available online: https://www.en-standard.eu/bs-en-45554-2020-general-methods-for-the-assessment-of-the-ability-to-repair-reuse-and-upgrade-energy-related-products/ (accessed on 7 December 2022).
37. *BS EN 45555:2019*; General Methods for Assessing the Recyclability and Recoverability of Energy-Related Products. European Standards: Pilsen, Czech Republic, 2019. Available online: https://www.en-standard.eu/bs-en-45555-2019-general-methods-for-assessing-the-recyclability-and-recoverability-of-energy-related-products/ (accessed on 7 December 2022).
38. *BS EN 45556:2019*; General Method for Assessing the Proportion of Reused Components in Energy-Related Products. European Standards: Pilsen, Czech Republic, 2019. Available online: https://www.en-standard.eu/bs-en-45556-2019-general-method-for-assessing-the-proportion-of-reused-components-in-energy-related-products/ (accessed on 7 December 2022).
39. *BS EN 45557:2020*; General Method for Assessing the Proportion of Recycled Material Content in Energy-Related Products. European Standards: Pilsen, Czech Republic, 2020. Available online: https://www.en-standard.eu/bs-en-45557-2020-general-method-for-assessing-the-proportion-of-recycled-material-content-in-energy-related-products/ (accessed on 7 December 2022).
40. *BS EN 45558:2019*; General Method to Declare the Use of Critical Raw Materials in Energy-Related Products. European Standards: Pilsen, Czech Republic, 2019. Available online: https://www.en-standard.eu/bs-en-45558-2019-general-method-to-declare-the-use-of-critical-raw-materials-in-energy-related-products/ (accessed on 7 December 2022).
41. *BS EN 45559:2019*; Methods for Providing Information Relating to Material Efficiency Aspects of Energy-Related Products. European Standards: Pilsen, Czech Republic, 2019. Available online: https://www.en-standard.eu/bs-en-45559-2019-methods-for-providing-information-relating-to-material-efficiency-aspects-of-energy-related-products/ (accessed on 7 December 2022).
42. *BS 8001:2017*; Framework for Implementing the Principles of the Circular Economy in Organizations. Guide. British Standard Institution: London, UK, 2017. Available online: https://www.en-standard.eu/bs-8001-2017-framework-for-implementing-the-principles-of-the-circular-economy-in-organizations-guide/ (accessed on 7 December 2022).
43. Broadbent, C. Steel's recyclability: Demonstrating the benefits of recycling steel to achieve a circular economy. *Int. J. Life Cycle Assess.* **2016**, *21*, 1658–1665. [CrossRef]

44. Ortiz-Rodríguez, O.; Castells, F.; Sonnemann, G. Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. *Sci. Total Environ.* **2010**, *408*, 2435–2443. [CrossRef]
45. Dani, A.A.; Roy, K.; Masood, R.; Fang, Z.; Lim, J.B.P. A Comparative Study on the Life Cycle Assessment of New Zealand Residential Buildings. *Buildings* **2022**, *12*, 50. [CrossRef]
46. Roy, K.; Dani, A.A.; Ichhpuni, H.; Fang, Z.; Lim, J.B.P. Improving Sustainability of Steel Roofs: Life Cycle Assessment of a Case Study Roof. *Appl. Sci.* **2022**, *12*, 5943. [CrossRef]
47. Vilches, A.; Martinez, A.; Montanes, B. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy Build.* **2017**, *135*, 286–301. [CrossRef]
48. *ISO Standard No. 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 20 April 2022).
49. Luhar, S.; Suntharalingam, T.; Navaratnam, S.; Luhar, I.; Thamboo, J.; Poologanathan, K.; Gatheeshgar, P. Sustainable and renewable bio-based natural fibres and its application for 3D printed concrete: A review. *Sustainability* **2020**, *12*, 10485. [CrossRef]
50. Ministry of Business, Innovation & Employment. *Building for Climate Change: Transforming the Building and Construction Sector to Reduce Emissions and Improve Climate Resilience*; MBIE: Wellington, New Zealand, 2020. Available online: https://www.mbie.govt.nz/dmsdocument/11522 (accessed on 20 April 2022).
51. NZGBC. *A Zero Carbon Road Map for Aotearoa's Buildings*. New Zealand Green Building Council, 24 September 2019. Available online: https://www.nzgbc.org.nz/zerocarbon/roadmap (accessed on 17 July 2022).
52. Blengini, G.A. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Build. Environ.* **2009**, *44*, 319–330. [CrossRef]
53. Thormark, C. A low energy building in a life cycle—Its embodied energy, energy need for operation and recycling potential. *Build. Environ.* **2002**, *37*, 429–435. [CrossRef]
54. UoW. *Major Funding Boost for Circular Economy Research Programme*; University of Waikato: Hamilton, New Zealand, 2020; Available online: https://www.waikato.ac.nz/news-opinion/media/2020/major-funding-boost-for-circular-economy-research-programme (accessed on 16 June 2022).
55. Colorcote. Magna Flow—Technical Information. 2020, p. 10. Available online: https://www.colorcote.co.nz/wp-content/uploads/2020/06/3418-COLO-Tech-Brochure-MagnaFlow-web.pdf (accessed on 7 December 2022).
56. Colorcote. Zina Core—Technical Information. 2015, p. 10. Available online: https://www.colorcote.co.nz/wp-content/uploads/2015/08/ColorCote-Tech-Brochure-ZinaCore.pdf (accessed on 7 December 2022).
57. *BS EN 15978:2011*; Sustainability of Construction Works. Assessment of Performance of Buildings. Calculation Method. European Standards: Pilsen, Czech Republic, 2011. Available online: https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/ (accessed on 20 March 2022).
58. Wang, Z.; Liu, F. Chapter 7—Environmental assessment tools. In *Industrial Ventilation Design Guidebook*, 2nd ed.; Goodfellow, H.D., Wang, Y., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 435–448. [CrossRef]
59. Jolliet, O.; Müller-Wenk, R.; Bare, J.; Brent, A.; Goedkoop, M.; Heijungs, R.; Itsubo, N.; Peña, C.; Pennington, D.; Potting, J.; et al. The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *Int. J. Life Cycle Assess.* **2004**, *9*, 394. [CrossRef]
60. Bare, J.C.; Hofstetter, P.; Pennington, D.W.; De Haes, H.A.U. Midpoints versus endpoints: The sacrifices and benefits. *Int. J. Life Cycle Assess.* **2000**, *5*, 319. [CrossRef]
61. Saber, M.; Eğilmez, G.; Gedik, R.; Park, Y. A Comparative Time-Series Investigation of China and U.S. Manufacturing Industries' Global Supply-Chain-Linked Economic, Mid and End-Point Environmental Impacts. *Sustainability* **2021**, *13*, 5819. [CrossRef]
62. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Zijp, M.; Vanzelm, R. *ReCiPe 2016 v1.1—A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level—Report I: Characterization*; National Institute for Public Health and the Environment: Bilthoven, The Netherlands, 2017; Available online: https://pre-sustainability.com/legacy/download/Report_ReCiPe_2017.pdf (accessed on 13 June 2022).
63. ColorCote. In *Environmental Product Declaration for AlumiGard™, MagnaFlow™ and ZinaCore™ Pre-Painted Roofing and Cladding*; Australia EPD: Melton, Australia, 2019; Available online: https://www.colorcote.co.nz/wpcontent/uploads/2019/04/Colorcote-EPD-Document.pdf (accessed on 13 June 2022).
64. Thinkstep. *GaBi Database 2017 Life Cycle Inventory Data Documentation*; Thinkstep AG.: Leinfelden-Echterdingen, Germany, 2017; Available online: http://www.gabi-software.com/support/gabi/gabi-database-2017-lci-documentation/ (accessed on 13 June 2022).
65. BRANZ. *LCAQuick*; Version 3.4.4; BRANZ: New Zealand, UK, 1970; Available online: https://www.branz.co.nz/environment-zero-carbon-research/framework/lcaquick/ (accessed on 14 June 2022).
66. MTA. Metal Recycling. Available online: https://www.mta.org.nz/radiatorgo/metal-recycling/ (accessed on 17 April 2022).
67. Liu, H.; Guo, R.; Tian, J.; Sun, H.; Wang, Y.; Li, H.; Yao, L. Quantifying the Carbon Reduction Potential of Recycling Construction Waste Based on Life Cycle Assessment: A Case of Jiangsu Province. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12628. [CrossRef] [PubMed]