construction materials

Article

Recycling Potential of Construction Materials: A Comparative Approach

Matan Mayer

School of Architecture and Design, IE University, 28029 Madrid, Spain; matan.mayer@ie.edu

Abstract: Recovery and re-utilization of materials are regarded as key strategies for reducing greenhouse gas emissions in the built environment. Within those end-of-use scenarios, recycling is one of the widely used tactics, demonstrated by established infrastructure and developed supply chain networks in many geographic locations. While recycling is an increasingly common practice in the built environment, accurately defining recycling quality in order to compare technologies and material types remains methodologically contested. This is mainly due to the vast spectrum of scenarios that typically fall under the term 'recycling'. Remanufacturing, downcycling, upcycling, and even direct reuse are all referred to as types of recycling in non-scientific circles, depending on the sector they occur in. The main challenge in assessing the material recovery quality of those solutions is that they exist on a continuum without clear divisions. Within that context, this article presents and compares four methods for assessing recyclability. The featured methods measure recycling potential from different perspectives: economic dimensions of the recycling industry; patterns of resource depletion; the energy cost of recycling; and the carbon intensity of recovery processes. The scientific foundations of the four methods are presented and a range of widely used construction materials are tested. The performance of materials is then compared across the four assessment methods to note observations and gain insights. Some of the materials are found to consistently outperform others, whereas some materials perform well on one method while performing poorly on others. This comparative study is followed by a discussion that looks at the limitations of each approach and reasons, or lack thereof, for the adoption of one method over the others in industry and academia. Lastly, the article looks at future research trajectories and examines the path ahead for recycling in the construction industry.

Keywords: recycling; material recovery; construction materials; assessment metrics; life cycle engineering

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Citation: Mayer, M. Recycling Potential of Construction Materials: A Comparative Approach. *Constr. Mater.* **2024**, *4*, 238–250. https://doi.org/10.3390/constrmater4010013

Received: 18 October 2023
Revised: 9 January 2024
Accepted: 24 January 2024
Published: 8 February 2024

1. Introduction

Material recycling is well documented as an effective method for reducing environmental impacts that result from consumption and disposal across various industries [1–4]. In the built environment, recycling of construction materials is an increasingly common end-of-use practice [5], demonstrated by established infrastructure and developed supply chain networks in many geographic locations. Despite its growing presence, accurately quantifying the quality of recycling operations across various materials in a manner that would allow direct comparison between them remains challenging. The ability to conduct such comparisons is a crucial component in future regulation in this field. It would allow national and local governments to require and enforce minimal thresholds for recycling quality. A precise recyclability assessment is largely necessary as recyclability is not a binary quality where materials and products can be labeled as 'recyclable' versus 'non-recyclable'. Take, for example, aluminum and steel. Both materials are considered recyclable, however not to the same degree. Determining which material has a higher recycling potential would enable consumers and designers to make informed procurement and use decisions. In light of those challenges and the clear need for accurate measuring, over the last two decades, a number of studies focusing on recycling potential have been conducted.

In their study, Townsend et al. [6] focus on the potential of waste debris (namely fines) to replace natural soil as a fill material in construction projects. Vefago and Avellaneda [7] conducted a study where recyclability is characterized by the ability of materials to maintain their original properties over multiple use cycles. In their study, Bravo et al. [8] explore the impact of concrete aggregates that originate from end-of-use concrete on the mechanical properties and structural performance of the concrete slabs and beams in which they are embedded. They find that while fine aggregates degrade the structural performance of the concrete elements they are used in, coarse aggregates help to improve abrasion resistance and other properties in structural elements. Pytel [9] assesses the potential of sand that originated from disposed molds for use in the production of new ceramic elements for construction. The study finds that while this practice is feasible, cross-contamination is a major issue that should be addressed before this process can be further developed. In their study, Ulsen et al. [10] test the potential of construction and demolition waste that has been ground into small particles for reintroduction into the consumption stream as a substitute for sand in concrete and other mixtures. They find that this practice produces components with similar mechanical properties to specimens that have been produced using primary-use sand. Soutsos et al. [11] examine the potential of post-consumer concrete aggregates for use in precast concrete blocks for structural purposes. Their analysis finds that the recycled content does not reduce the structural performance of the blocks and therefore does not require additional costs to offset any strength deficiencies caused by the introduction of secondary-use components. The results pave the way for commercial applications of this approach at scale. Hoglmeier et al. [12] evaluate the potential of waste wood from construction and demolition activities for use in new building stock. They analyzed the current practices in this field and found that in their study context of Bavaria, about 26% of waste timber is already being utilized and another 27% could find secondary uses through relatively simple means. Saghafi and Teshnizi [13] propose to study recycling potential based on the energy savings it can generate. They find that the energy that was avoided in the extraction and processing of raw materials can render recycling an environmentally beneficial practice. Thormark [14] studied material selection in the context of recycling potential. The findings of the study indicate that in a passive house scenario in a cold climate, embodied energy can reach 40% of the total life cycle energy of the building (considering a 50-year lifespan). This share can be decreased to 17% by using recycled materials and an additional 6% can be reduced by implementing energy-oriented material selection strategies. Takano et al. [15] added to knowledge in this research domain by exploring the environmental impact reduction associated with material selection. Studying a hypothetical residential building in the climatic context of Finland, the authors found that with regards to reducing embodied energy, material selection for the structural frame is most consequential in terms of environmental impact reduction. Additionally, this study found that the material groups in which recycling was most beneficial in this specific scenario were timber and plastic. Duran et al. [16] explored the recycling potential of the building industry in Ireland. The authors found that the recycling of construction and demolition waste is environmentally beneficial and financially viable as long as landfilling carries with it a cost greater than that of recycling operations per kg of material. Additionally, the study found that the scale of recycling operations plays a significant role in increasing its feasibility. Pappu et al. [17] evaluated the potential of recycling construction and demolition waste materials in India. In their study, they identify opportunities and barriers to the full implementation of recycling schemes. The most significant opportunity lies in the fact that India already has a significant, albeit informal, market for secondary materials and consequently also technical know-how with regards to constructing with recycled content. In terms of barriers, the authors identify technological inefficiencies as one of the major inhibitors of the extensive utilization of recycled materials in the Indian building sector. Vrancken and Laethem [18] focus their study on the recycling potential of gypsum from construction and demolition waste. Their study finds that the extraction of sulfur content from discarded panels is the most crucial component in enabling this recycling stream as it drives the market demand for this product. Additionally, the authors find that impurities in secondary-use gypsum resulting from unselective demolition activities are a major barrier to increasing the recycling stream of this material. Zhao et al. [19] investigated the recycling potential of construction and demolition waste materials in Chongqing, China. The study finds that the recycling industry in this geographic context shows vast expansion potential due to the accelerated demolition of assets on one side, along with extensive construction activities on the other. Technological gaps and lack of proper regulation are found to be major barriers to realizing this expansion. Sukmak et al. [20] examined the potential of industrial waste for use as recycled content in construction. Specifically, the authors focus on electric and furnace slag as a possible waste stream for re-utilization. Findings indicate that a key concern in the employment of this waste stream in construction applications is the fact that this type of slag tends to expand when integrated into construction material mixtures. The authors devise a method for reducing the expansion, which is found to be successful in an experimental setting. Ahmad et al. [21] evaluated the potential of applying recycled materials as rooftop insulation in Peshawar, Pakistan. The authors compared the use of byproducts of the local agriculture industry such as straw bale and sheep wool to the utilization of recycled glass. Findings show that in this specific climatic and geographical context, recycled glass has the highest potential compared to other insulators. When the focus is expanded beyond the built environment, several studies provide additional methods of analysis for assessing the feasibility of recycling. Looking at the e-waste sector, Zeng et al. [22] propose a simplified evaluation method that comparatively measures recycling potential and sets a priority hierarchy based on four performance criteria, including existing condition, substance toxicity, economic conditions, and technical conditions. Studying the global aluminum industry, Hatayama et al. [23] propose a location-based method for assessing material recycling potential. Employing a dynamic material flow analysis of urban stocks, they find that Japan, the U.S., and Europe could substantially increase their recycled aluminum consumption and therefore drastically reduce their dependence on primary-use aluminum. Lee et al. [24] examined the recycling potential of medical plastic waste streams. They found that the origin and level of contamination risk play a major role in determining the recycling potential of medical waste. As a response, the authors propose to establish a classification method for waste-generating sources.

While previous work in this field offers a wide range of methodological approaches and valuable findings, it arguably falls short of providing industry-wide solutions for the precise assessment and characterization of the recycling potential of construction materials. This is due to two key deficiencies. First, in most cases, the studies focus on a specific industry subsector, a particular material group, or a limited geographical context; and secondly, the proposed assessment frameworks are mostly complex, requiring extensive input and generating findings that aim to be interpreted by experts, rather than a simple calculation and a single numerical output that can be compared across various materials and locations. In order to facilitate direct and simple comparison between different materials in the construction industry, there is a need for a universal calculation method for estimating recycling potential. Within this context, this article presents and compares four recycling potential calculation approaches that aim to provide a simple and easily comparable solution across materials and industries. Each of the four approaches emphasizes a facet of interest to recycling operations: economics, reserve depletion, energy, and carbon. The article describes the calculation method for each index, demonstrates an evaluation of common material groups, and concludes with a comparative assessment of all four methods and a discussion regarding their limitations and future research trajectories.

2. Methodology

Following the identified limitations of previous work in this field, this section is dedicated to presenting the scientific underpinnings of four indexes for evaluating recycling potential in construction materials that were developed by the author. Each of the calculation methods is explained and demonstrated on a collection of common construction material groups. In order to increase transparency and consistency, the article uses a single, publicly available database throughout the text [25]. This database originates from the United Kingdom and therefore the energy mix used to calculate energy consumption and resulting greenhouse gas emissions should be assumed to relate to western Europe, with the scope of the assessment for embodied impacts being cradle to gate. Data regarding material depletion and available reserves should be assumed to be global in nature.

2.1. Market Value Recyclability Index

This index is based on the notion that as construction materials progress throughout their life cycle, from extraction through processing, to manufacturing, construction, use, disposal, and recovery, their market value fluctuates (see Figure 1). The fluctuations in the material's market value, especially between its point-of-sale value and its end-of-use value, indicate the existence of demand for the material in its recycled form, as well as the readiness and availability of recycling technologies and return supply chains [26].

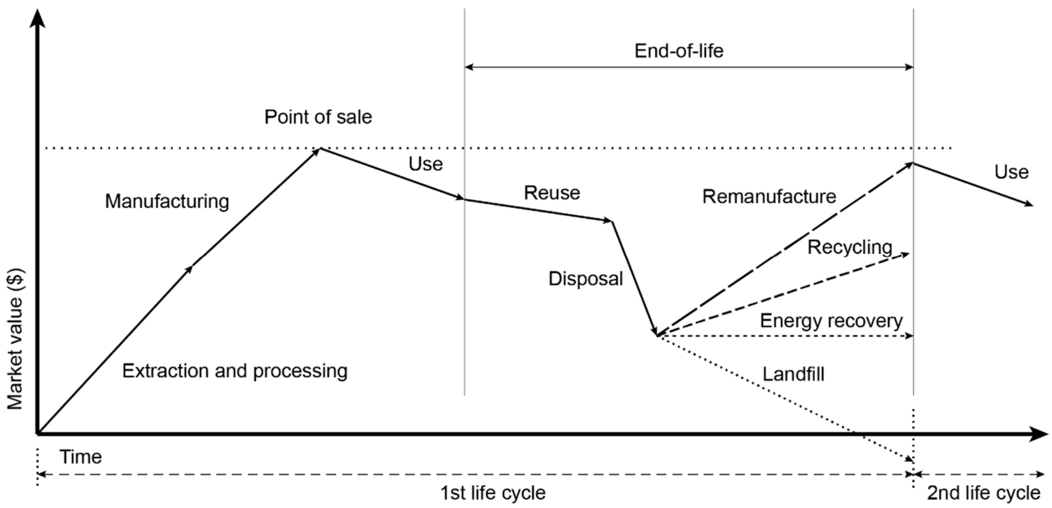

Figure 1. Market value fluctuations throughout a generic construction material life cycle. Adapted from [27].

Therefore, by computing the ratio between the value of a material at its point of sale and its end of use, it is possible to compare the recyclability of different materials on the same scale. A higher value for this index indicates higher recycling potential from a market value perspective. In other words, a high score in this index means that the studied material has been able to maintain much of its market value throughout the recovery process. For example, steel, which enjoys a highly developed recycling infrastructure and a consistent market demand in its recycled form, is expected to score highly. The value of the index (R_{MV}) is computed as follows:

$$R_{MV} = \frac{V_P}{V_V} \quad (1)$$

where V_V represents the market value of a primary-use material at its point of sale and V_P represents the market value of a material at its end of use.

Although market value gives an accurate indication of the readiness of a specific context to support the recycling of certain materials, it overlooks other important factors, primarily environmental considerations. The following three recycling potential indexes focus on various aspects of environmental impact related to recycling operations.

2.2. Resource Depletion Recyclability Index

This index looks at the issue of resource depletion, with an emphasis on the link between the availability of natural reserves of certain construction materials and their annual production rate. Construction materials with a high production rate and low natural reserves are at greater risk of depletion. Therefore, for these materials, we should ideally shift to relying on recycled content [28]. The index is computed in the following manner:

$$R_{RD} = \frac{AP}{Re} \quad (2)$$

where R_{RD} is the recyclability resource depletion index; AP is the annual production rate (ton per year); and Re represents natural reserves (ton). A low result indicates a better chance of sufficient reserves while a higher numerical outcome indicates that consumption patterns for the analyzed material should transition to recycled content in order to avoid depletion of natural reserves.

2.3. Energy Consumption Recyclability Index

Based on a similar logic, the following index focuses on the relationship between the energy invested in the recycling processes of construction materials and the energy needed for primary production. The consumption pattern of a material with an energy-intensive primary production process and a recycling process that demands less energy should ideally shift to recycling while a material with a relatively energy-intensive recycling process should ideally shift to direct reuse. High embodied energy in the recycling process might also indicate an inefficient recycling process. The index is therefore computed as follows:

$$R_{EC} = \frac{EE_R}{EE_{PP}} \quad (3)$$

where R_{EC} is the recyclability energy consumption index; EE_R is the embodied energy of the recycling process (MJ per kg); and EE_{PP} represents the embodied energy of the primary production process (MJ per kg).

2.4. Carbon Emissions Recyclability Index

Embodied carbon emissions are a direct outcome of the energy invested in extraction and manufacturing processes. This index looks at the ratio between carbon that is emitted during the production process of primary-use materials and carbon emissions that are generated during the recycling process of those materials. A high level of carbon emissions during the recycling process in relation to the primary production process indicates that it might be most environmentally beneficial to shift the consumption pattern of the material towards remanufacturing or direct reuse. The index is computed as follows:

$$R_{CE} = \frac{C_R}{C_{PP}} \quad (4)$$

where R_{CE} is the recyclability carbon emissions index; C_R is the carbon emissions of the recycling process (kg per kg); and C_{PP} represents the carbon emissions of the primary production process (kg per kg). A low result indicates that the analyzed material has a relatively efficient recycling process and therefore consumption of this material should transition to relying on recycled content.

2.5. System Boundaries

Given the broad range of material attributes that the four proposed indexes cover, data sources vary for each index. Consequently, the geographic coverage and scope for each data source vary as well. Table 1 lists the data providers, regions covered, and scope for each of the material attributes in the study.

Table 1. Data providers, regions covered, and scope for each of the material attributes in the study.

Material Attribute	Data Provider	Regions Covered	Scope
Point-of-sale market value	The World Bank [29]	Africa, Asia-Pacific, North America, South America, Western Asia, Europe	N/A
End-of-use market value	Scrap Index [30]	U.S. and Canada	N/A
Resource depletion	The U.S. Geological Survey (USGIS) [31]	U.S.	N/A
Embodied energy	Ansys Granta EduPack [32]	U.S.	Cradle to gate
Embodied carbon	Ansys Granta EduPack [32]	U.S.	Cradle to gate

2.6. Intended Users

Beyond researchers, the intended audience for the presented indexes comprises a range of industry and public sector stakeholders. Primarily, the indexes are aimed at supporting policymaking efforts by enabling public and private agencies to enforce precise material recovery levels for various material groups (for example, a regulation that limits the use of construction materials with low recovery potential). Additionally, the indexes are intended to be used by property developers, designers, engineers, and consultants who are involved in projects that aim to reach a certain material recovery level (for example, a zero-waste development). Lastly, the indexes are developed to be integrated into national and global environmental rating systems for buildings and cities. Currently, many widely used green building rating systems do not account for material recovery potential. When released for public use, the indexes are intended to be provided to users with access to a database and a web application, similar to certification and labeling programs in this field [33].

3. Results

In this section, the four presented indexes are demonstrated on a series of construction material groups to identify trends, opportunities, and limitations. The main objective of this demonstration is to examine how the indexes might be used in practice to assist stakeholders in making recovery-oriented material choices in design and construction processes.

3.1. Market Value Recyclability Index

This index was applied to 51 materials resulting in computed values that range from 0.84 for extruded aluminum to −0.42 for clay brick. The findings, shown in Figure 2, allow comparisons between similar materials that are generally considered fully recyclable. For example, in a comparison between extruded aluminum and extruded steel, aluminum is found to be 40% more recyclable than steel (0.84 versus 0.60). Data for this figure were obtained from worldbank.org for point-of-sale market values and scrapindex.com for end-of-use market values.

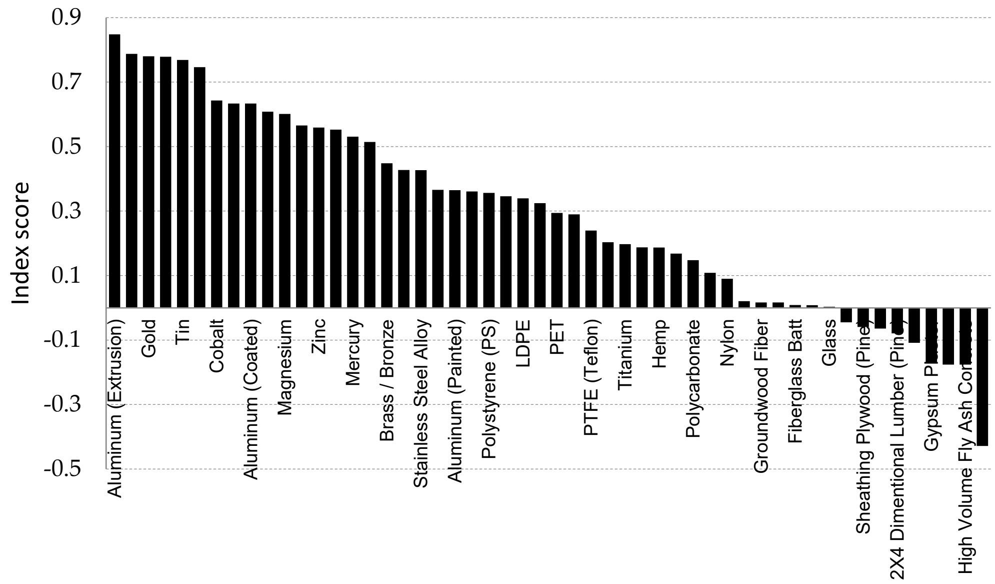

Figure 2. Market value recyclability index results.

3.2. Resource Depletion Recyclability Index

In an effort to focus solely on the most common material groups, the resource depletion recyclability index was tested on 13 material groups. As can be observed in Figures 3 and 4, aluminum is found to have the lowest depletion index score, meaning that it is currently used in quantities well below its existing natural reserves. On the other end, the annual consumption of titanium currently exceeds its known natural reserves. This finding indicates that using recycled or reused titanium is an essential condition for continued usage of that material. Soda-lime glass and stainless steel are found to be high-performing materials as well.

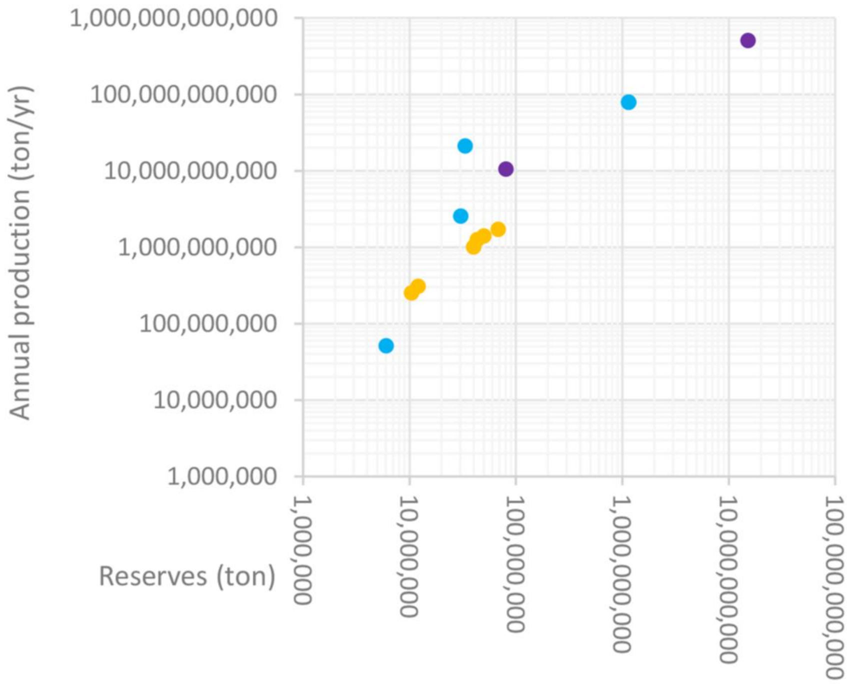

Figure 3. Annual production and natural reserves for the studied materials. Data source: [25]. The Dataset is available from the author upon request. • ceramics and glass, • metals, • polymers and elastomers.

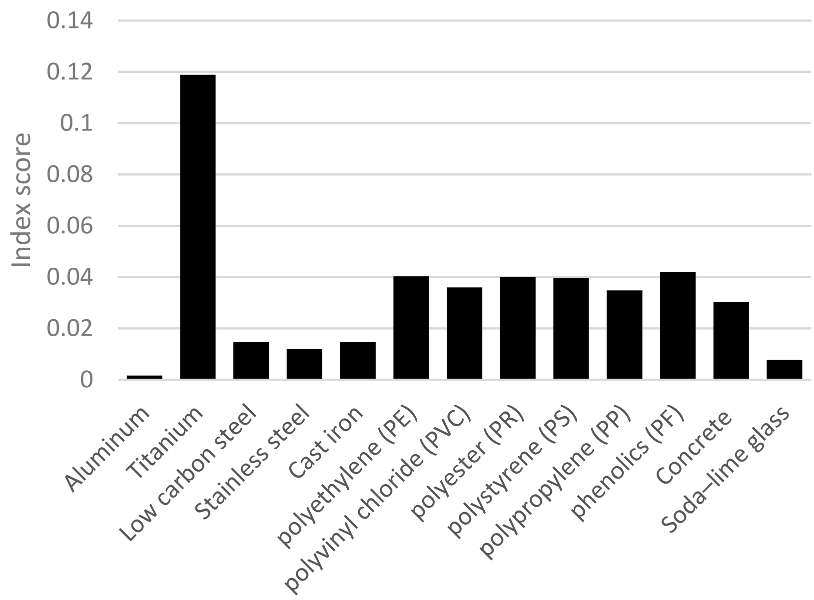

Figure 4. Resource depletion recyclability index findings for the studied materials. Data source: [25].

3.3. Energy Consumption Recyclability Index

Due to limited data regarding the phenolics (PF) material group, the findings for the energy consumption recyclability index include 12 material groups. As can be observed in Figures 5 and 6, concrete and aluminum exhibit the lowest index scores, meaning that the energy required for their recycling process is very low in relation to the energy that is required for their primary production. Recycling those materials for secondary use is highly beneficial from an environmental impact reduction standpoint. On the other end, both types of glass in the study perform poorly, indicating that reuse might be the best end-of-use solution for those materials.

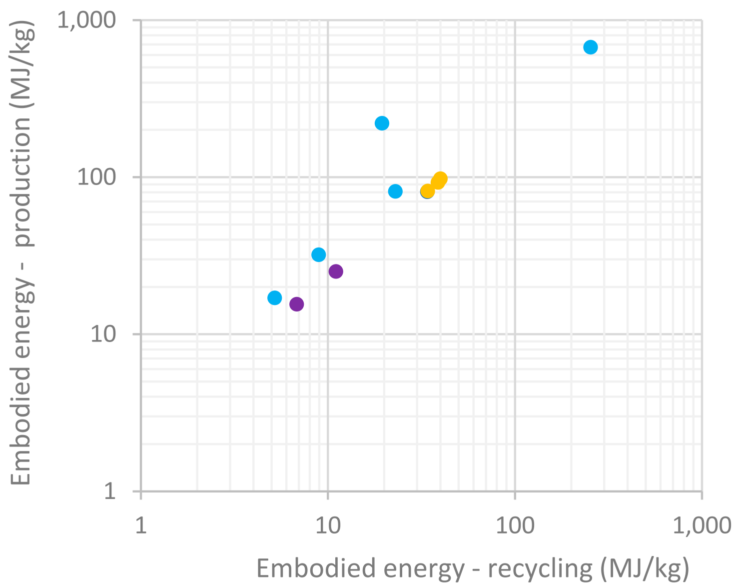

Figure 5. Embodied energy findings for primary production and recycling processes for the studied materials. Data source: [25]. The dataset is available from the author upon request. • ceramics and glass; • metals; • polymers and elastomers.

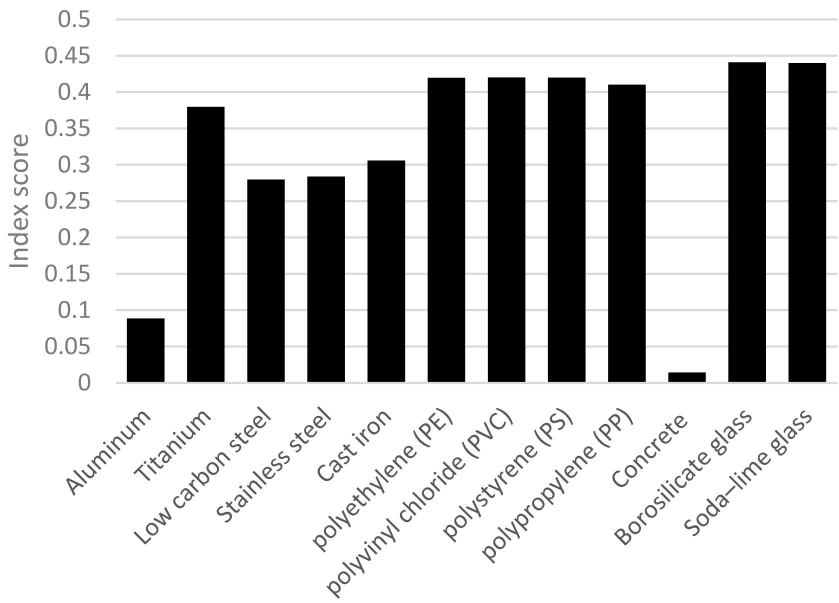

Figure 6. Energy consumption recyclability index values for the studied materials. Data source: [25].

3.4. Carbon Emissions Recyclability Index

In this index demonstration, the number of studied material groups is twelve. As shown in Figures 7 and 8, aluminum performs well in this category, indicating that relative to the carbon released into the atmosphere during its primary production, the carbon emissions associated with its recycling are very low. Glass and concrete receive the highest index scores in this category, meaning that their recycling carbon emissions are relatively high. These findings suggest that from a carbon emissions perspective, concrete and glass should ideally be re-manufactured or reused rather than recycled.

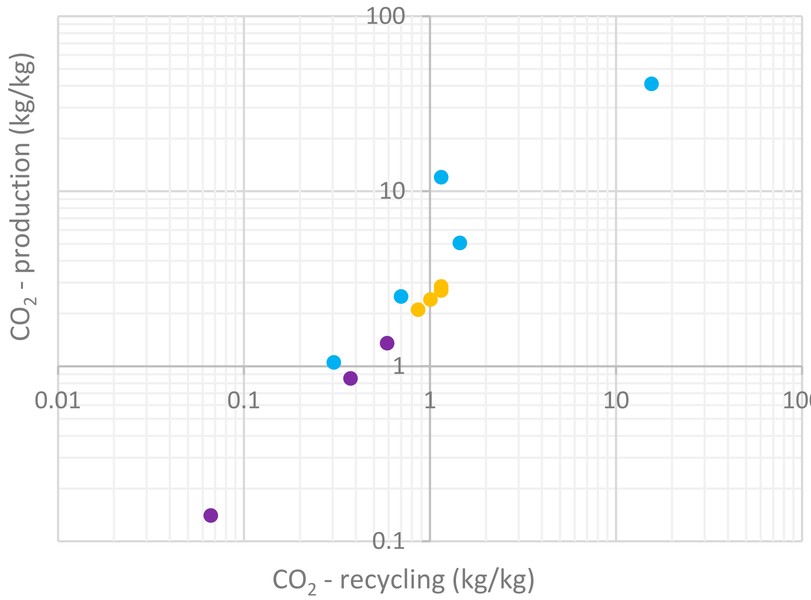

Figure 7. Carbon emissions findings for primary production and recycling processes for the studied materials. Data source: [25]. The dataset is available from the author upon request. • ceramics and glass, • metals, • polymers and elastomers.

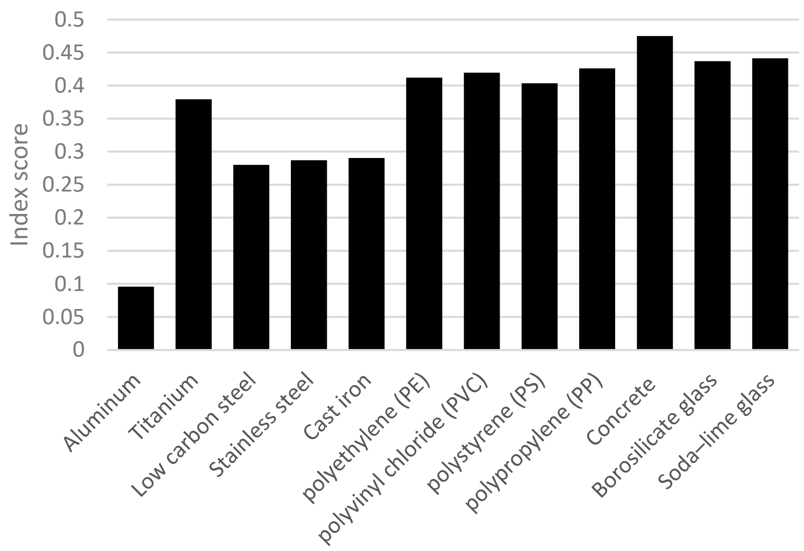

Figure 8. Carbon emissions recyclability index values for the studied materials. Data source: [25].

4. Discussion

4.1. Comparative Assessment

The four indexes presented in this study aim to provide a well-rounded assessment of various aspects of construction material recycling potential in a manner that enables simple calculation, interpretation, and comparison. In three out of the four index demonstrations in the previous section, aluminum exhibited the best performance among the evaluated material groups. The energy consumption recyclability index study was the only instance where aluminum was outperformed by another material (concrete). Titanium performed poorly from a resource depletion perspective and glass and concrete came last in embodied energy and carbon emissions scores, respectively. Given the mostly environmental focus of the indexes, the findings show that even though aluminum is often perceived as an environmentally harmful material due to its energy-intensive production process, it proves to be an ideal substance for material recovery in the built environment. This is in part due to the virtually unlimited number of recovery cycles that aluminum can endure without significantly compromising its mechanical and aesthetic properties. It may also be attributed to the relative maturity of technological solutions in this field [34], and the existence of a well-developed supply chain for aluminum recycling operations and trade.

4.2. Limitations and Future Research

Given the relative infancy of recycling potential estimation for construction materials, this practice still has a number of major limitations. One of the most evident shortcomings in this case is the absence of a weighing system that would allow a holistic assessment of recycling potential through all four lenses in one operation. Although devising a weighing system for this indicator suit is a relatively simple mathematical task, it requires general agreement in the industry regarding the respective importance of each of the indicators that are presented in this study. Reaching a full understanding of the various interests at play among practitioners with regards to recyclability requires conducting an extensive series of interviews and surveys. This is indeed the intention for one of the next steps of this project. Table 2 provides a preliminary and simplified glance at how a weighing study could look for 11 selected materials. Options A–D show weighing scenarios emphasizing one index over others by doubling its weight. Scenario A shows equal weighing of all indexes; scenario B emphasizes the resource depletion index; scenario C emphasizes the energy consumption index; and scenario D emphasizes the carbon emissions index.

Table 2. Composite index results using different weighing scenarios. Data source: [25].

Material	Scenario A	Scenario B	Scenario C	Scenario D
Aluminum	0.061998333	0.0468975	0.06864875	0.0704488
Titanium	0.2926	0.24915	0.3144	0.31425
Low Carbon Steel	0.1914	0.1472	0.21345	0.21355
Stainless steel	0.1943	0.1487	0.2167	0.2175
Cast iron	0.2036	0.15635	0.22915	0.2253
Polyethylene (PE)	0.2906	0.228	0.322875	0.320925
Polyvinyl chloride (PVC)	0.291866667	0.227875	0.32395	0.323775
Polystyrene (PS)	0.2877	0.225675	0.320775	0.31665
Polypropylene (PP)	0.2903	0.226425	0.320275	0.3242
Concrete	0.173133333	0.137375	0.133425	0.2486
Soda-lime glass	0.296266667	0.224125	0.3322	0.332475

Additionally, future research in this domain should develop additional indexes to the ones presented in this article (for example, a toxicity-based index), and expand the range of indicators and the variety of the materials studied. To that end, Figure 9 depicts an exploration of materials of interest for further investigation regarding recycling potential. The chart shows the carbon footprint of primary production for 22 construction materials alongside the current recycle fraction of those materials in current supply. Materials with a relatively high carbon footprint and a relatively low recycle fraction in current supply should be focused on for research and development of dedicated recycling strategies. Considering the presented data, titanium, GFRP, CFRP, and structural foam could all benefit from additional research focus for increased recycling in the near future.

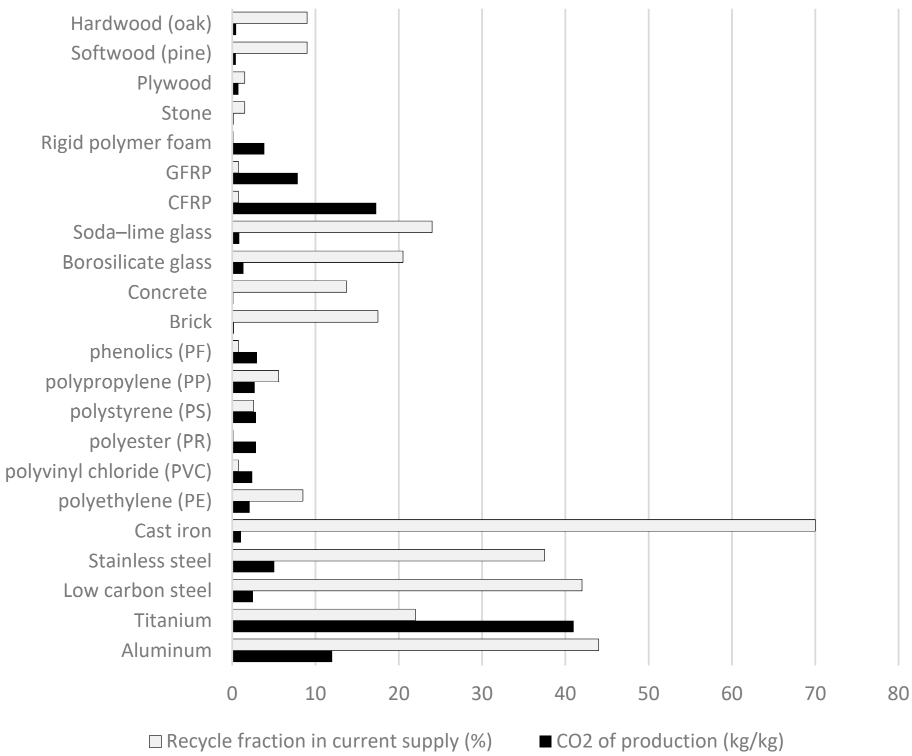

Figure 9. Carbon emissions from primary production and recycle fraction in current supply. Data source: [25].

5. Conclusions

Developing precise estimation of material recovery in the built environment is essential for ensuring that future policymaking and regulation in this field could rely on appropriate performance metrics. This article proposes four indexes to quantify the recovery potential of construction materials from four different perspectives: market value, resource depletion, energy consumption, and carbon emissions. The indexes are computed through simple calculations and are meant to provide researchers and stakeholders with a comparable indication of recovery potential, assisting them in making environmentally sound material choices. In order to examine their applicability in research and practice, the indexes are demonstrated on 12–51 widely used construction material groups. Results show that the indexes enable users to identify the most recoverable material choice even when the range of materials evaluated is highly diverse. Aluminum is found to present the best recovery potential in three out of the four indexes, while concrete is found to consistently perform poorly from a material recovery standpoint. Two major limitations of the indexes should be taken into consideration. First, in light of the competing and, at times, conflicting focal points of each proposed index, there is a need to develop a weighting strategy for a composite index that would reflect the relative significance of each assessment input in an overall material recovery potential score. Second, the four presented indexes focus solely on the environmental and economic dimensions of material recovery. Additional indexes that look at health-related, societal, and other aspects of material recovery should be developed.

Funding: This research received no external funding.

Data Availability Statement: The data used to calculate the various values in this article can be found in the following sources: Figure 2: worldbank.org for point-of-sale market values, and scrapindex.com for end-of-use market values; Figures 3–9: [25].

Conflicts of Interest: The author declares no conflicts of interest.

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