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Lowering Environmental Footprint by Using Recyclable Resources in Residential Architecture

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Abstract

As 40% of global CO_2 emissions and waste and 40% to 50% of natural resource usage come from the built environment, more urgently than ever, it is imperative that architectural design and construction practices be crafted with current environmental needs in mind. Commonly available sustainable building materials were assessed using a conceptual or decision-oriented assessment framework informed by life-cycle principles and illustrated through the Green Grow Home case study. In terms of embodied carbon, recyclability, resource efficiency, environmental impact, and durability, insulated concrete forms (ICFs), structural insulated panels (SIPs), engineered wood products (EWPs), recycled concrete aggregate (RCA), and cellulose insulation were compared. The data used in the literature-based assessment are drawn from different studies with potentially varying system boundaries. Therefore, the reported values are used as indicative evidence rather than as a normalized comparative life-cycle assessment (LCA). Within the respective literature sources, cellulose insulation and RCA are reported with embodied carbon values of 1.1 and 2.55 $kgCO_{2e}/m^2$. The key advantage of EWPs is that they provide a compromise between relatively low embodied carbon, durability and circular economy benefits, while SIPs and ICFs mainly help to improve operational energy performance. These principles applied to the Green Grow Home further illustrate how material substitution and selection based on life cycle can greatly minimize environmental impacts. The switch from plywood to strand board decreased the embodied energy by 59%, and total material changes were estimated to save around 39,010 MJ of energy. The paper concludes that a transition to sustainable construction materials in residential architecture is a necessary change that will lower carbon footprints and energy consumption of buildings.

Keywords: sustainable materials; circular economy; life-cycle assessment; renewable resources

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1. Introduction; A Need for Sustainable Building Materials

As the supply of non-renewable resources has become depleted, their costs have gone up. This makes the need to adapt architectural design and construction practices to be more environmentally minded vital [1]. This poses a complex challenge as there is an increased need for less costly renewable resources that can be used and reused for longer. This challenge has prompted the key actors in material production to use alternative products in a manner that is more innovative than traditional methods of sourcing materials. Some examples of this type of design already exist, such as the Green Grow Home, which saves over 39,010 MJ of energy compared to a typical home design [2]. With the construction industry being responsible for 40% of global carbon emissions, there is increasing research, design and development to mitigate the carbon footprint of the construction industry [3].

There are non-renewable materials such as steel, aluminum, zinc, and copper that are commonly used in construction, and it is the widespread use and the extraction of these materials in large quantities that is putting them at risk of permanent depletion. These metals cannot be replaced at a pace that is quick enough to be able to keep up with the rate at which they are currently being consumed and replenished. According to recent research, the continued growth in global demand may place increasing pressure on the availability of several commonly used metals [4]. For example, 47%, 88%, and 63% of construction projects involving iron, bauxite, and copper respectively face social, governance risks, and issues such as climate change that limit the long-term supply of these metals and would hamper construction projects if an alternative is not found [4].

Another area affected by the construction industry's need for materials is lumber. Forests, particularly tropical forests, are necessary not just for their resources but also for their indispensable ability to absorb and store excess carbon found in the atmosphere. The felling of forests releases stored carbon which contributes to climate change. Of the emissions that trap heat in the atmosphere, 10% of those emissions result from deforestation, with this amount being equal to the emissions released by 600 million cars every year [5]. The construction industry is one of the greatest perpetrators of deforestation due to its demand for timber. Illustrating this point is the fact that over 380,000 hectares (939,000 acres) are consumed annually for the purpose of lumber production [5]. Clearly, there is a strong need for a reconsideration of how materials are selected for construction.

The traditional method that architects and their clients would use for selecting materials would consider factors such as availability, cost, embodied carbon, circularity, toxicity, social sustainability, resilience, and aesthetics. However, nowadays, selecting materials based on these parameters alone is no longer a sustainable practice. Architects and builders need to begin to consider other factors when deciding which materials to use. Increasingly, there are concerns regarding security, ethics, safety, and carbon footprint. All these concerns and others are beginning to introduce new approaches to the preservation of construction materials. These new approaches are being shaped in such a way that architects and builders can preserve these materials and use them for as long as they possibly can rather than discarding them without making an effort to reuse them [6]. By reusing materials for as long as possible, there is less energy used to produce these materials, reducing the carbon footprint of the building overall. Therefore, preserving and reusing construction materials as opposed to discarding them after a single use is a proper choice for lowering the carbon footprint of residential architecture overall.

2. Methodology/Research Approach

The research question that the paper aims to answer is what kinds of available recycled materials can be used in residential construction in the North American context? Using available data, the paper investigates the use of renewable resources in reducing the environmental footprint of residential architecture. It examined these aspects through a literature review, comparative material analysis, life-cycle principles, case study evaluation, and implementation barriers. The literature review component is a narrative/non-systematic review. The sources were selected due to their relevancy to the materials' selection process and the selected materials themselves. The paper is made up of three integrated components: a narrative review in which the key issues related to the choice of "green" materials are introduced, a discussion of the process of selecting alternative construction products and as a descriptive case study where these issues have been implemented. In the process of material selection, the paper evaluates materials that are commonly available to mainstream North American builders. The idea is to select materials with a low carbon footprint without increasing the building cost. Scientific papers, technical reports, and

industrial research were used to develop the theoretical underpinning of sustainable construction, circular economy concepts, material passports, and life cycle thinking in the built environments. A comparison is made of chosen sustainable construction materials, such as insulated concrete forms (ICFs), structural insulated panels (SIPs), engineered wood products (EWPs), recycled concrete aggregate (RCA), and cellulose insulation. Materials are assessed using characteristics, such as embodied energy, recyclability, resource efficiency, environmental effect, durability, and contribution to circular economy goals.

Life cycle thinking supports material-selection decisions, while the Green Grow Home illustrates the practical application of these principles. The case study looks at material selection tactics, embodied energy reduction measures, and the incorporation of renewable and recycled materials into residential architecture. Life-cycle principles are used to analyze the environmental performance of specific materials, taking into account resource extraction, manufacture, usage, and end-of-life recovery possibilities. In addition, the study critically evaluates the limitations of incorporating sustainable materials into home building. Economic, legislative, technological, and societal aspects are examined to determine the viability of widespread adoption. By combining literature findings, comparative material assessments, and case study evidence, the study presents a comprehensive assessment of how recyclable and renewable materials might help to reduce the environmental footprint of residential architecture. The paper is therefore a sequential research-based thought process of learning about materials, selecting them and implementing them in an actual "real world" case. The contribution of the paper rests in offering a thought process for the selection of green materials and demonstrating the use of these materials in an actual residential building which is not commonly done.

3. Systems Thinking in Materials' Selection

A way to imagine the linear economy is by using a river analogy that is ever flowing towards something believed to be bigger, better, faster, more profitable than what already exists. While such a system is always moving forward efficiently, it squanders resources. The production of waste deteriorates the *natural capital* of the environment, by using unsustainable methods to extract resources [7]. Natural capital is a term that refers to the natural assets that the earth has, including aspects such as geology, soil, air, water, and living organisms.

A useful framework for considering how construction materials can be re-thought for preservation and reuse is the concept of a circular economy. According to Stahel [6], the best way to represent a circular economy is to use a lake analogy. Like a lake, any time something is added or taken away from the building, the entire building and its surrounding environment are affected. In a circular economy model, all parts of the process of selecting, using, and reusing construction materials are designed for the purpose of maximizing ecosystem function as well as human wellbeing [7]. This circular economy model aims to take materials that are no longer useful for construction and find other uses for them, closing loops in the ecosystem and reducing overall waste (Figure 1). Specific procedures of each stage vary according to the material type, condition, and available waste-management practices. Common materials, such as concrete, wood, steel, aluminum, zinc, glass, and insulation, follow this life-cycle model. There are two ways of categorizing circular economy models: those that promote the reuse and extension of the life of a building component through repair, remanufacturing, and retrofits [8]; and those that recycle materials that have been used [9,10].

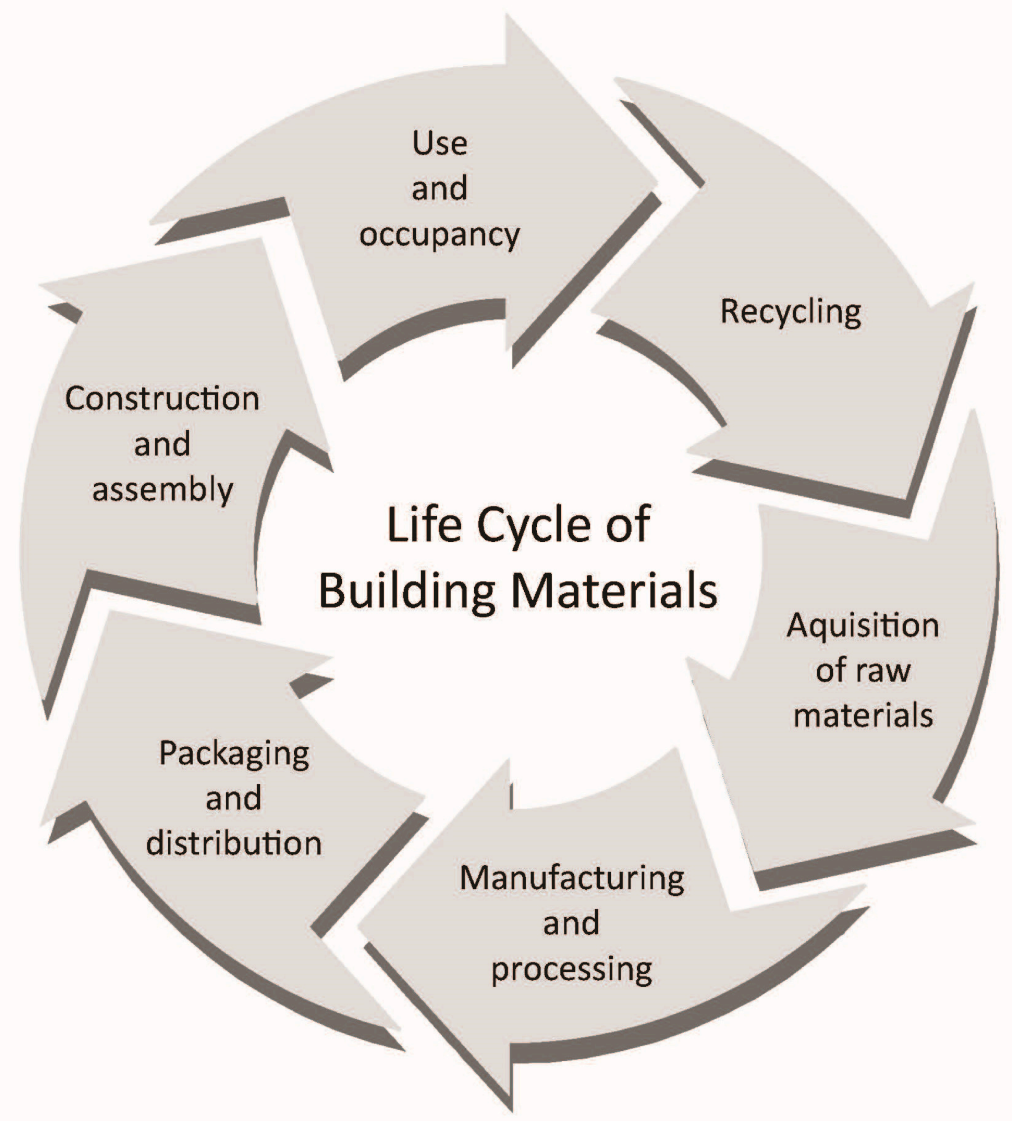


Figure 1. A circular economy strives to convert construction materials (concrete, wood, steel, aluminum, zinc, glass, and insulation) at the end of their life into resources for other purposes, creating cycles of material use in industrial ecosystems, and preventing waste (created by the author).

Throughout the design process that is informed by the circular economy model, there are several tools that a designer can consult. Among these tools there are *life-cycle assessments*, which consider a building or product's entire life, and *material passports*, which list the vital attributes of selected products. These tools help quantify both *embodied energy* (i.e., the energy consumed by harvesting and processing) and *operational energy* (i.e., the energy required for the function and maintenance of a building) (Figure 2) [11]. These tools will both be explained further below.

The life cycle approach and analysis used in the paper are key to achieving a circular economy. Each phase of a building life cycle must consider and achieve circularity principles for genuine sustainability to be met. The circular economy framework consists of principles to be employed at various stages of a building's life cycle. It comprises the following tenets: circular supply-chain, recovery and recycling, product life-extension, sharing platform, service model, regenerate, and virtualization. These tenets reflect numerous goals and indicators of the 17 United Nations Sustainable Development Goals, and discuss the role of data and technology, collaboration, climate action, economic growth, and health and

well-being. Virtualization is inherently relevant to each life cycle stage; the incorporation of technology allows other tenets to be achieved.

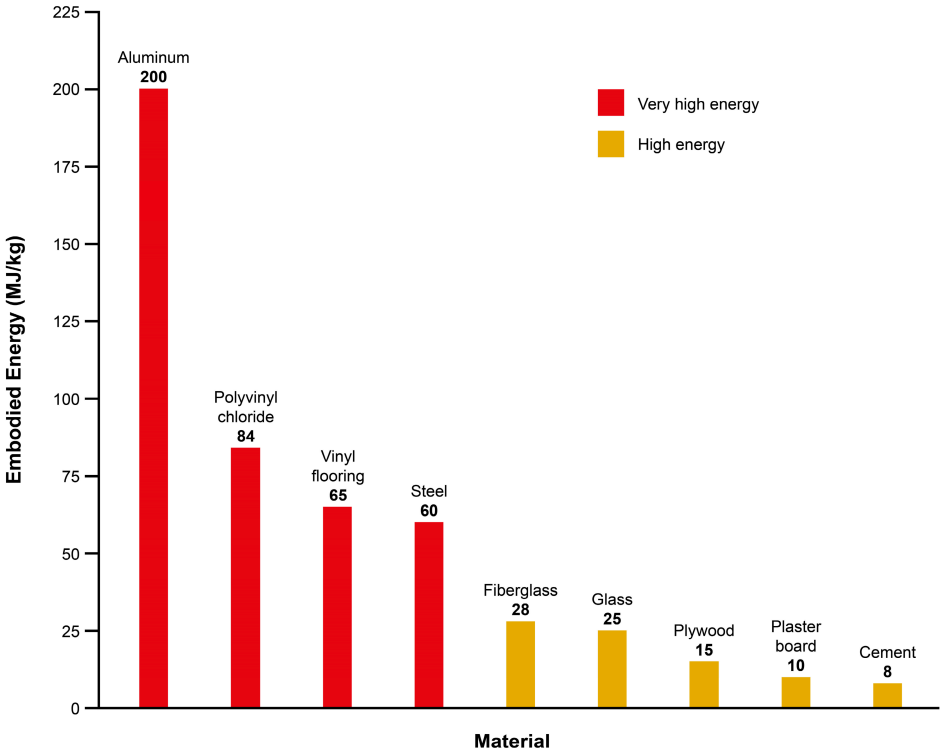


Figure 2. A bar graph displaying the amount of embodied energy in megajoules per kilogram used in the production of various materials [12].

The *life-cycle assessment (LCA)* method systematically evaluates the embodied and operational energy of materials [11]. According to ISO 14040 and ISO 14044, an LCA consists of four interconnected phases: (1) goal and scope definition, (2) life-cycle inventory (LCI), (3) life-cycle impact assessment (LCIA), and (4) interpretation [13]. The goal and scope phase defines the aim, functional unit, system boundaries, assumptions and data requirements of the assessment. The LCI phase quantifies relevant material and energy inputs, environmental outputs to the environment, and releases to the environment throughout the defined product system. These inventory data are then assessed by LCIA to identify their potential environmental impacts in selected impact categories. Finally, the interpretation phase assesses the results, identifies important environmental issues and develops conclusions that are consistent with the defined goal and scope. This standardized framework provides a structured basis for assessing and comparing the environmental performance of construction materials over the life cycle of the materials. This assessment explains how the overall environmental impact of a building is affected by different construction materials and processes. However, the paper does not follow all four phases of a conventional LCA. Instead, the framework is based on life-cycle principles to examine material impacts across extraction, production, use and end-of-life stages. In this study, a cradle-to-grave life-cycle perspective is primarily considered, covering raw material extraction, production, construction, use, and end-of-life stages. Potential reuse and recycling pathways are also considered at the end-of-life stage to reflect circular economy principles.

It is important to investigate the life cycle costs (LCC) of various construction materials to gain a fuller understanding of their environmental impact throughout the course of their life. These life cycle cost evaluations must involve the use of several terms to determine if a material is a good fit (Figure 3). A necessary aspect of this evaluation includes understand-

ing the different types of data at hand. *Baseline data* is the cost in the present day, before any required cost reductions in materials. It also serves as the point of comparison for costs later on. That is why it is crucial to collect baseline data so that the change in costs can be measured properly. It is also important to consider *sunk costs*, costs occurring before the baseline years or before the user of a building possesses it. They are "sunk" costs because they usually cannot be recovered. The reason why sunk costs are such a valuable part of life cycle cost analyses is because all costs, past, present, and future, of a building and its materials must be considered to make an informed decision regarding material choice. The last important part of the equation is the end point; the last year of analysis of a life cycle cost analysis is referred to as a *time horizon*. A time horizon might partially or completely be a function of the householder's objectives, such as an intention to stay in the unit for a pre-determined, limited number of years. Time horizons consider the actual intentions of the householder, whether they are trying to save money, promote a sustainable household, or another goal.

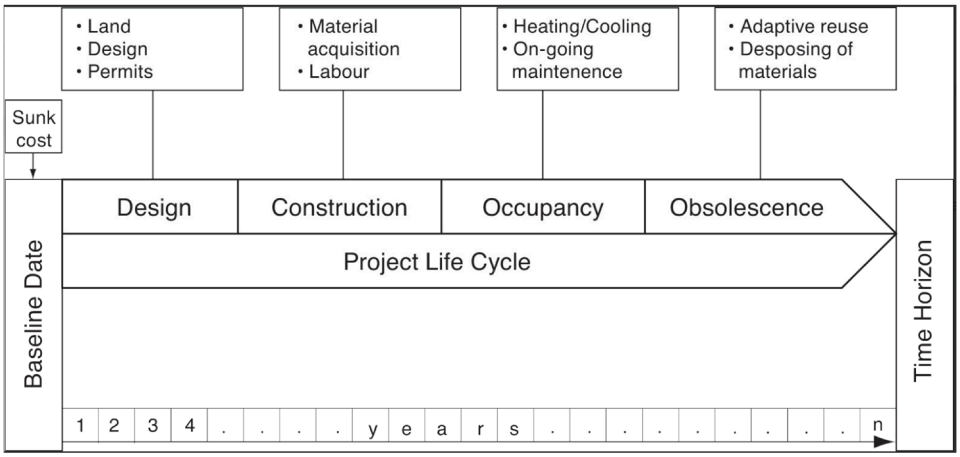


Figure 3. The embodied and operational energy of materials can both be evaluated using the life-cycle assessment (LCA) method (created by the author).

Regarding "Obsolescence" the author envisions employing the principles of Reduce, Reuse, Recycle, Redesign, Recover and Remanufacture that are essential for achieving sustainable goals. The author investigates ways in which the six R's can be regarded not only as environmental standards, but also as active design drivers that impact decisions that are made regarding planning, the selection of materials, and the construction processes.

The recycling of resources is a fundamental aspect of the circular economy. Waste recycling relies on industrial symbiosis when firms work together to reuse each other's waste. In this model, one could see "*waste-as-food*", where the unwanted outputs from one industrial process are used as raw materials for another [7]. Embodied energy of products can be minimized through streamlined manufacturing and high-quality maintenance that increase the overall longevity of a product.

The selection process has been improved by *material passports* that evaluate and list the recycling potential of various building materials (Figure 4). Using building information modeling (BIM)-based material passports allows for the assessment of both qualitative and quantitative properties of materials, such as their ability to be recycled and how much they could potentially reduce environmental impacts [14]. Architects can refer back to the material passport throughout their decision-making process, optimizing design.

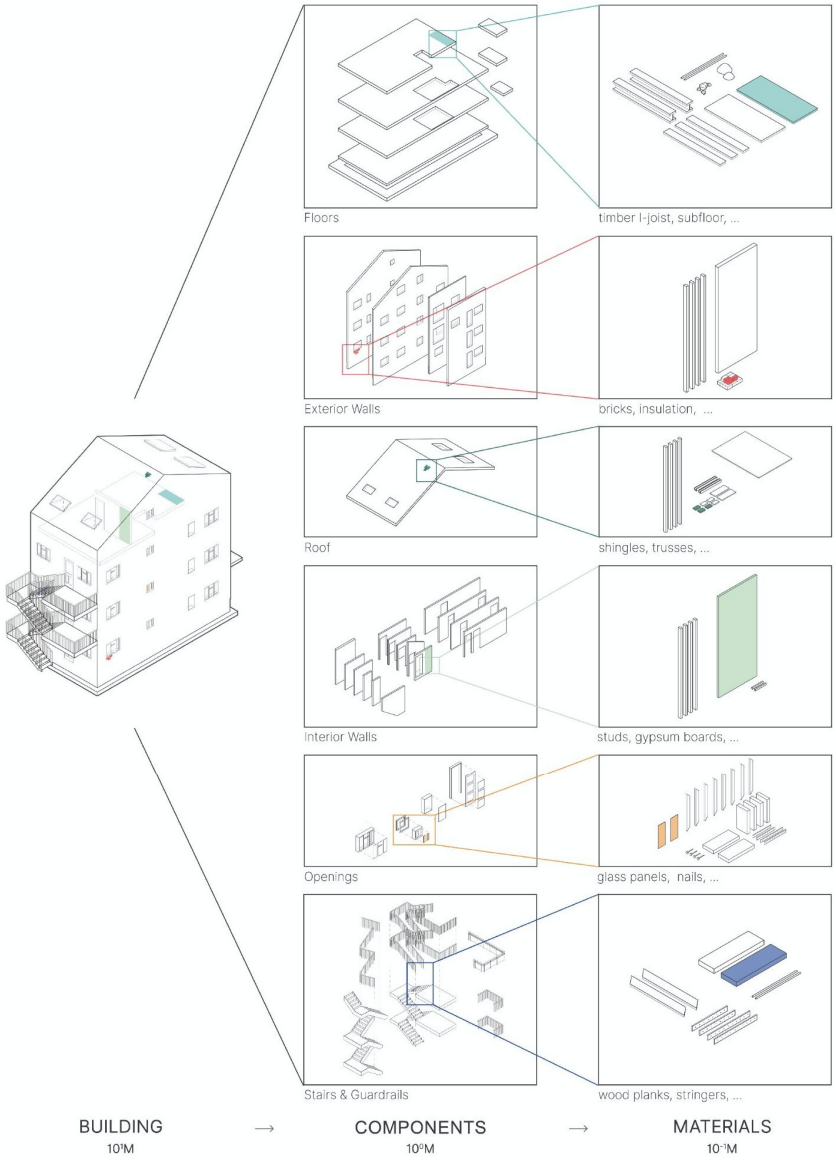


Figure 4. Housing Passport (HP) is a Multi Scalar documenting the building, component and material scales. (created by author).

Efficient recycling is also aided by the separation of *biological* (such as wood) and *technical* (such as laminate) cycles [15]. These products must be separated so that they can be deconstructed and reverted to their original state for recycling [15]. This process can include removing adhesives, coatings, lacquers, and other additions from biological materials such as wood or metal.

Stahel [6] argues that a circular economy relies on high-quality metallurgical and chemical analysis to be maintained. Despite that, knowledge on atomic-level disassembling of material blends is minimal. Increased knowledge on this subject would help in the movement towards a fully closed circular-economy loop. In the construction industry, safe methods of reusing and recycling materials are reliant on advanced technology that can depolymerize, de-alloy, de-laminate, and de-coat materials [6].

Beyond scientific advancement, evolving social attitudes can support a greater economic demand for a circular economy, while also demanding innovative investments in construction research. As the cost of alternative building products comes down, architects and home builders will be able to use more of them. In the following section, the carbon footprints of selected products will be discussed.

4. Alternative Green Building Components

There is not a definition of *green building* that is universally agreed upon, but most definitions commonly emphasize green building as a practice aimed at reducing environmental harm, promoting well-being of building occupants, yielding economic benefits for developers and communities, and considering the entire life cycle of a building in planning and development stages [16]. A significant aspect of green building is the sound selection of building sites and construction materials. Green building aims to use resources efficiently to potentially aid the economy, environment, and public health of communities in which it is being used [16].

The following section will outline some "green" products that have a lower impact on the environment and prevent exhaustion of natural resources, all while being more affordable as well. It must be noted, however, that most modified materials used in the construction of residential buildings rely on wood, metal, and concrete. However, as research grows, other materials and forms of energy are emerging to maximize the value of products, thus reinforcing the practice of reducing and recycling. These materials are special because they efficiently and creatively reduce energy consumption and are able to be reused and recycled or are made from recycled materials, reducing waste. It is for these reasons that these materials were used in the construction of the Green Grow Home, a sustainably designed home by the author and a case study that will be discussed later on in this article. The process of selecting materials for the home considered energy usage of individual materials and their ability to be recycled and reused, constraints that are not always considered in the materials selection process.

4.1. Insulated Concrete Forms (ICFs)

Insulated Concrete Forms (ICFs) are products that comprise expanded sheets of polystyrene, which is a rigid cellular plastic that has an expansion agent. ICFs are proven to be superior to traditional brick walls in terms of energy efficiency due to their better insulation capabilities [17]. One benefit of ICFs is their grid system, which holds up against natural disasters, making it suitable for areas prone to seismic activity. ICF walls also improve the energy efficiency of a building due to concrete's *thermal mass* which absorbs and releases heat slowly. The way that ICF walls contribute to higher energy efficiency is through their higher thermal mass and lower permeability which hold air tightly and create continuous insulation minimizing temperature fluctuation throughout the building. The higher thermal mass of ICF walls allows them to reduce energy demand by up to 52% compared to traditional walls [18]. ICFs save energy, can be constructed efficiently, are soundproof, and compared with other uses of concrete, require less maintenance (Figure 5). The properties of ICF support both environmental and social sustainability, as demonstrated by research; ICF is durable, resistant to natural disasters, and safe for both humans and the environment.

Despite these benefits, ICF construction also presents several environmental drawbacks. But ICF construction has a number of environmental disadvantages. One problem is the embodied carbon in its concrete core. Globally, cement and concrete production is a major source of greenhouse gas emissions, primarily because of the energy needed to produce clinker and CO_2 emissions from the calcination of limestone [19]. According to the research, more than 70% of greenhouse gases (GHG) emissions are directly related to concrete production [19]. The quantity and composition of concrete used in an ICF system can therefore greatly influence its embodied environmental footprint. Impacts can be mitigated by using lower carbon cementitious materials and supplementary cementitious materials [20]. When compared to conventional alternatives, an analysis of low-carbon

concrete materials revealed average embodied-carbon savings of 27.4% for supplementary cementitious materials (SCMs) and 52.6% for low-carbon cementitious binders [19].

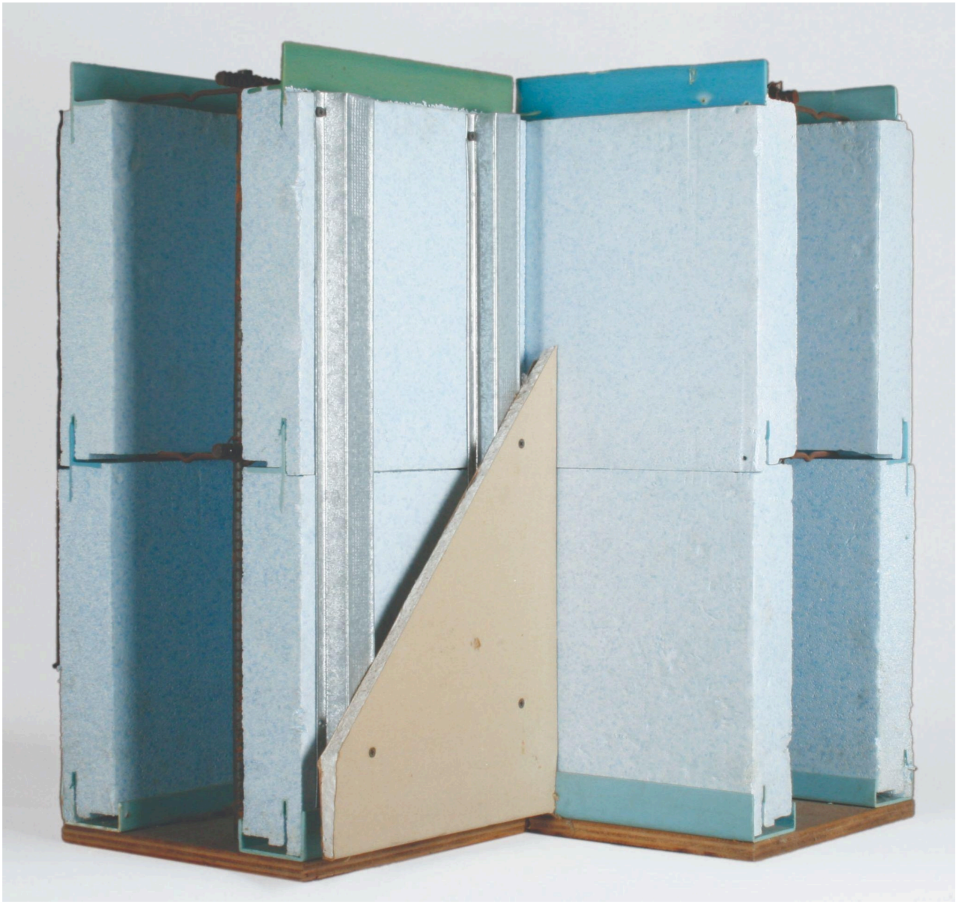


Figure 5. Using a combination of insulation and the thermal mass of concrete, insulated concrete form (ICF) walls improve the energy efficiency of buildings (photo by the author).

A further environmental issue is the expanded polystyrene (EPS) foam that is used as the insulating component of ICFs. While EPS has the potential to enhance the thermal performance of buildings and to lower the operational energy demand, the production and end-of-life treatment of EPS still lead to environmental impacts [21]. Recycling EPS from buildings can also be challenging, especially when the insulation is contaminated, bonded to other construction materials or contains additives that interfere with recovery and recycling processes [21]. Thus, the environmental performance of ICF systems should consider the trade-off between the operational energy benefits and the embodied and end-of-life impacts from concrete and EPS.

4.2. Structural Insulated Panel

Creating more sustainable practices in construction involves many steps, including transitioning from solid wood-reliant structures to modified structures. One modified structure is the incorporation of *structural insulated panels* (SIPs). SIPs consist of a core layer of wood particles from sustainably managed renewable timber and insulated foam, surrounded by plywood, cement particle board, and fiber-cement boards at the surface [21] (Figure 6). To create an SIP, all three commercial wood composite boards are adhered together using polyurethane and then clamped together until the adhesive is cured. SIPs are multifunctional, being able to be used for exterior walls, roofing, flooring, and even foundation systems [22]. Being a lightweight material, SIP is energy-efficient as it reduces

transport costs. SIPs are estimated to save between 15% and 20% of energy compared to traditional walls [23]. Compared to traditional timber framing, SIPs reduce costs by 22% over a 17-year lifespan of a building [24]. At the construction site, SIPs can be installed quite simply. What makes SIPs beneficial to the environment is their minimal use of wood compared to traditional wood frames, replacing the extra wood with other recyclable materials.

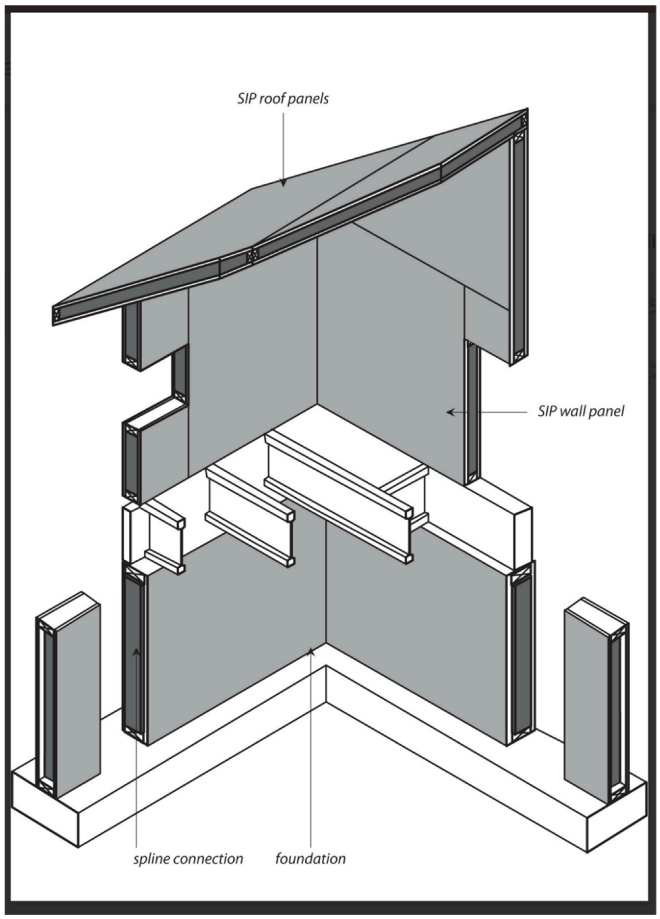


Figure 6. SIPs consist of a core layer of wood particles and insulated foam, surrounded by plywood, cement particle board, and fiber-cement boards at the surface (drawn by the author).

However, the recyclability of SIPs should be considered more critically. Common SIPs have an insulating foam core, such as expanded polystyrene (EPS), sandwiched between structural facings, which are often orientated strand board (OSB) [25]. The SIPs' polyisocyanurate foam core was the most important contributor to the LCA of a 434 m^2 building envelope, with traditional SIP construction requiring roughly 7053 kg of OSB, 1280 kg of EPS, and 1878 kg of adhesive, showing the large amount of bonded materials incorporated into the panel system [25]. Oliveira et al. found that although individual components are recyclable, the use of adhesives to permanently bond these materials can make separation and recovery more difficult at the end stage of building's life cycle [26]. The environmental benefits of SIPs therefore are more related to material efficiency, construction waste reduction and operational energy performance than recyclability alone.

4.3. Engineered Wood

By using less wood to do more than traditional wood-frame construction methods, *engineered wood products* (EWPs) maximize product performance and reduce CO2 emissions. EWPs, due to their lighter nature compared to traditional timber, reduce emissions from heavy transport vehicles by 20%. Further, buildings using EWPs as opposed to traditional

wood-frame construction methods or concrete and steel can reduce energy consumption and CO2 emissions by over 30% and 40%, respectively (Figure 7) [27]. This reduces the demand for wood and thus the effect of the timber industry on the forest ecosystem. A major benefit of using EWPs over traditional wood products is that EWPs redistribute natural defects of tree growth, such as knots, shakes, and spalting, thus reinforcing timber overall. Stronger wood lasts longer in a building, reducing the amount of wood used over time as fewer repairs and replacements are necessary. This process of redistributing natural defects creates efficient structural molds out of products that could not be achieved through traditional sawing [28]. This method can make use of wood that otherwise would be considered sub-par. Additionally, when the wood for EWPs is sourced from sustainably managed forests, they can be deconstructed and reused at the end of a building's life, making EWPs environmentally superior [29].



Figure 7. By using less wood to do more than traditional wood-frame construction methods, *engineered wood products* (EWPs) maximize product performance (photo by the author).

5. Products Made from Recycled Materials

5.1. Recycled Concrete Aggregate (RCA)

Another strategy for using demolition waste instead of immediately putting it in a landfill, is to use *recycled concrete aggregate* (RCA) as a substitute for *natural aggregates* (NA) in concrete products. RCAs are capable of reducing landfill use and energy consumption of a building by 85%, and they are capable of reducing a building's CO_2 emissions by 90%, a profound increase in sustainability [30]. Not only does using RCA reduce the need to exploit natural resources, it also lowers costs by reducing the need to mine for the components of concrete [31]. RCA consists typically of a mix of items taken from the resulting construction debris of demolition sites. This includes debris such as concrete, bricks, tiles, stone, timber, glass, and plastics.

5.2. Cellulose Insulation

Another renewable product is *cellulose insulation*. *Cellulose insulation* is consists mainly of the fibers of recycled paper as well as some inorganic additives. The properties of cellulose insulation improve resistance to both mold and fire. What makes cellulose insulation resistant to fire is its mix of cellulose fibers and borates. Not all cellulose insulation contains borates as an additive, but most do. In cellulose insulation that does contain borates, they make up 20% of the cellulose fiber by weight, and they act as a natural flame retardant [32]. Cellulose fiber insulation on average has a thermal conductivity coefficient of 0.040 [33]. In addition to its resistance to fire, cellulose insulation is also a safe choice of building material because of its low levels of toxicity [32]. Toxicity is just one consideration in the safety of an insulator. Overall, cellulose insulation is understood to be safe for use in residential architecture. A common concern with traditional insulators, especially fiberglass, is the effect that these insulators have on respiratory health. However, the current occupational health literature suggests that modern fiberglass insulation presents relatively low health hazards when appropriately handled and protected [34].

Beyond safety, cellulose insulation is also a sustainable choice of material, something that is crucial as high energy use drives emissions of carbon dioxide [35]. Insulation is important for keeping residential buildings safe and comfortable, but many common insulators such as fiberglass or mineral wool present issues. Many of these insulators are not biodegradable and persist in the environment for a long time. Luckily, cellulose is promising as a sustainable choice for insulation as it is durable, biodegradable, low-density, and renewable, which makes it useful for reusing and reducing resources and closing resource loops. Cellulose is the most common polymer on the planet and is found in many agricultural by-products such as corn cobs and coconut husks [35]. These by-products that often would be thrown away by consumers can instead be recycled into cellulose insulation. This reduces waste of these natural resources and promotes a circular economy model. One aspect of cellulose insulation that makes it more sustainable than more traditional forms of insulation is its lower embodied energy, which makes it less resource intensive than traditional forms of insulation [36]. Cellulose fibers are a natural insulator, and as an added benefit, they regulate air humidity levels, keeping them stable and contributing to improved air quality overall.

Cellulose is not only sustainable and safe but also an effective insulator. One property of cellulose that contributes to its strength as an insulator is its low thermal diffusivity, meaning its ability to change temperature over time. Another contributor to this is cellulose insulation's low thermal conductivity value of 0.040 W/mK, allowing it to insulate better as it slows down heat transfer, regulating temperature. Cellulose insulation also has an embodied energy value of 0.94–3.3 MJ/kg, which is much lower compared to that of general insulation (45 MJ/kg) and fiberglass insulation (28 MJ/kg) (Table 1) [33]. Because cellulose fluctuates in temperature slowly, it is useful for insulating buildings experiencing rapid heat transfer and creates a more comfortable temperature inside the building while using less energy. This makes cellulose optimal for insulation (Figure 8). Air infiltration is a common culprit of temperature fluctuation within a building, but cellulose fiber is effective at mitigating this. A study found cellulose insulation was able to reduce the air change rate in a building from 87.5 to 29.4 ACH (air changes/hour). The ability of cellulose insulation to prevent air infiltration is 36% better than traditional fiberglass insulation [33]. Cellulose insulation can be a useful material to contribute to sustainable construction practices in residential architecture. It is abundantly available, effective as an insulator, sustainable, and safe.

Table 1. Embodied energy comparison of cellulose and conventional insulation materials.

Insulation Material	Embodied Energy (MJ/kg)
Cellulose insulation	0.94–3.3
Fiberglass insulation	28
General insulation materials	45



Figure 8. The primary components of cellulose insulation are recycled paper fibers and inorganic additives, which prevent the growth of mold and increase its resistance to fire (photo by the author).

6. Evaluation Framework and Comparative Assessment

The evaluation framework used in this section is based on major environmental and circular economy performance metrics found in the literature. The framework provides a uniform basis for the comparison of alternative construction materials and their suitability for residential architecture.

Five evaluative criteria were selected. The first criterion is embodied energy, which is the total energy used in the extraction, processing, manufacture, shipping and installation of materials. The second criterion is recyclability, or the ability to recover and reuse materials at the end of a building's service life. The third criterion is resource efficiency, which assesses the degree to which a material lowers the usage of virgin resources. The fourth criterion is the environmental impact, including carbon emissions, trash generation and ecological repercussions linked with the life cycle of the material. The fifth criterion is durability, which measures the predicted service life and maintenance needs. Rather than relying on a single performance indicator, the framework evaluates materials holistically, recognizing that sustainable material selection requires balancing environmental performance, resource conservation, and long-term durability.

The quantitative values shown in Table 2 are sourced from various literature sources. Therefore, the results represent indicative data provided in the literature and cannot be considered as a normalized comparative LCA or a general environmental ranking among the materials.

Table 2. Comparative assessment framework for selected sustainable building materials.

Material	Embodied Carbon	Recyclability	Resource Efficiency	Environmental Impact	Durability
Insulated Concrete Forms (ICFs)	64.8 $kgCO_{2e}/m^2$ (6.02 $kgCO_{2e}/ft^2$) [37]	Moderate	Moderate	Reduced operational energy demand	High
Structural Insulated Panels (SIPs)	23.1 $kgCO_{2e}/m^2$ (2.15 $kgCO_{2e}/ft^2$) [38]	Moderate	High	Reduced energy consumption	High
Engineered Wood Products (EWP)	19.3 $kgCO_{2e}/m^2$ (1.81$kgCO_{2e}/ft^2$) [39]	High	High	Reduced timber consumption	High
Recycled Concrete Aggregate (RCA)	2.55 $kgCO_{2e}/m^2$ (0.23 $kgCO_{2e}/ft^2$) [40]	Very High	Very High	Reduced waste and carbon emissions	High
Cellulose Insulation	1.1 $kgCO_{2e}/m^2$ (0.1 $kgCO_{2e}/ft^2$) [41]	High	High	Reduced energy and carbon emissions	Moderate

According to the table, we notice that the embodied carbon of the cellulose insulation is 1.1 $kgCO_{2e}/m^2$, and recycled concrete aggregate (RCA) only has 2.55 $kgCO_{2e}/m^2$ [40,41]. These results show great potential for reductions in greenhouse gases (GHG) emissions, while at the same time facilitating the reuse of recovered resources. RCA had a high score for recyclability and resource efficiency, as it can divert construction waste from landfills and reduce the need for new aggregates.

Engineered wood products (EWPs) also performed well in terms of sustainability, with a relatively low embodied carbon value of 19.3 $kgCO_{2e}/m^2$ [39]. EWPs are highly resource-efficient and can be largely recycled. They can also help reduce lumber consumption by optimizing the production process and using materials efficiently. The high durability is also in line with the circular economy's objectives of extending service life and reducing replacement frequency. Structural insulated panels (SIPs) and insulated concrete forms

(ICFs) have higher embodied carbon values than RCA, cellulose insulation and EWPs. Both materials, however, deliver significant operating energy savings with better thermal performance and building envelope efficiency. These materials can help reduce long-term operating energy usage, but they also have higher embodied carbon impacts which can offset some of the early environmental burden throughout the building's life cycle.

Overall, the results indicate that there is no best material in all rating parameters. Sustainable material selection means weighing up embodied carbon, recyclability, resource efficiency, durability and operational performance instead. Materials, such as RCA and cellulose insulation, provide short-term embodied carbon reductions, but EWPs provide a compromise between low carbon impacts, durability and circular economy benefits. SIPs and ICFs contribute mainly through increases in operational energy efficiency. Thus, a combined strategy of material selection, involving a combination of multiple sustainable materials, may be the most effective technique to reduce the overall environmental footprint of residential architecture.

7. The Green Grow Home

The Green Grow Home is an expanded and updated version of an earlier project known as Grow Home that was built in 1990 on the campus of McGill University and soon after adopted by local builders. The Green Grow Home project was a follow-up and was designed as a prototype for the climatic conditions of Montreal. The construction method was a wood frame system. The key objectives of the Green Grow Home design were: 1. Minimize the environmental impact of building materials by selecting more economical and environmentally responsible materials without compromising environmental quality. 2. Improve the energy efficiency of the building's envelope by using energy-efficient mechanical systems and windows, air-tight construction and passive solar strategies. 3. Improve the efficiency of use of renewable resources by adopting strategies such as water-efficient fixtures and appropriate water-saving practices. 4. Minimize waste generated by adopting modular design strategies. Made up of timber from sustainably managed renewable wood, the form of the Grow Home is a two-story townhouse with a total area of 93 square meters (Figures 9 and 10). The lower floor contains a kitchen, bathroom, and living room, whereas the upper floor is unpartitioned but can be modified at the owner's discretion, allowing for multiple bedrooms and an extra bathroom. This functionality allows for the home to grow in accordance with the needs of the occupants [3]. The expansion of the Grow Home into the Green Grow Home focuses primarily on integrating the use of materials that promote environmental sustainability in both the interior and exterior of the unit. The process of selecting materials utilizes a life cycle thinking approach. During the design process, building materials were selected based on how sustainable they are throughout their entire life and all stages of their use. The goals of the Green Grow Home compared to the original Grow Home were to minimize the environmental impacts of building materials, improve the building envelope's energy efficiency, improve the efficiency of renewable resources, and minimize the waste generated by the home [2]. For example, strand boards, made from younger trees and wood scraps, were used instead of plywood, reducing embodied energy by 59% [3]. Further, the Green Grow Home also replaced carpet and vinyl flooring with parquetry and ceramic tile, which resulted in saving 12,342 MJ of embodied energy [3].

The architects used quantitative embodied-energy information and life-cycle considerations to examine selected material substitutions in the Green Grow Home (Table 3). This was done by examining how materials and waste products are used at several different points in their life cycle. To further gain this understanding, the architect of the Green Grow Home created tables that outlined sustainable alternatives for traditional building components (Table 3). These tables included the level of embodied energy for the quantity

of the material proposed for use. Additionally, the tables included specifications for the choice of each individual material [3]. For designers and builders to make informed choices to reduce energy consumption and environmental impact of the home, they needed to first understand in great detail how the components for constructing the home were acquired, processed, packaged, assembled, used, and disposed of properly. After all, an important aspect of the assessment of a building's sustainability is how it uses materials throughout its life cycle [3].



Figure 9. Elevation of the Grow Home demonstration unit. (Photo taken by author at the McGill University demonstration site).

There are several design choices that make the Green Grow Home sustainable, but the most sustainable element of the home is its use of structural wood. Structural wood is not only a renewable resource with low-embodied energy, but it is also easily reused and recycled, helping to close resource loops. As opposed to traditional plywood, strand boards were selected to use in floors, walls, and roof sheathing. This design choice was able to reduce the embodied energy of these components of the home by 59% compared to plywood [2]. While both plywood and strand boards have similar levels of strength and durability, strand boards can be created from younger trees and wood scraps, reducing waste and making better and more efficient use of resources.

To insulate the building, both fiberglass and cellulose insulation were used to improve the energy efficiency of the building and lower its environmental impact. By switching out some fiberglass insulation in the Green Grow Home with cellulose insulation, the embodied energy of the building was lowered. This is because the embodied energy of cellulose insulation is 0.94–3.3 MJ/kg, a lot lower than that of fiberglass insulation (28 MJ/kg) [32]. Fiberglass is not the most sustainable material, and this is due to the process of extracting its components, which are sand, limestone, and borax [3]. The process of mining these

resources contributes to air and water pollution which has a detrimental impact on air and water quality as well as biodiversity. That is why the fiberglass used for the Green Grow Home was supplemented with cellulose insulation. By replacing some fiberglass insulation with cellulose insulation, the environmental impact of traditional insulation used in the Green Grow Home is offset and the thermal performance of the home improves as well. As discussed in the previous section, cellulose fibers are an effective and efficient insulator.

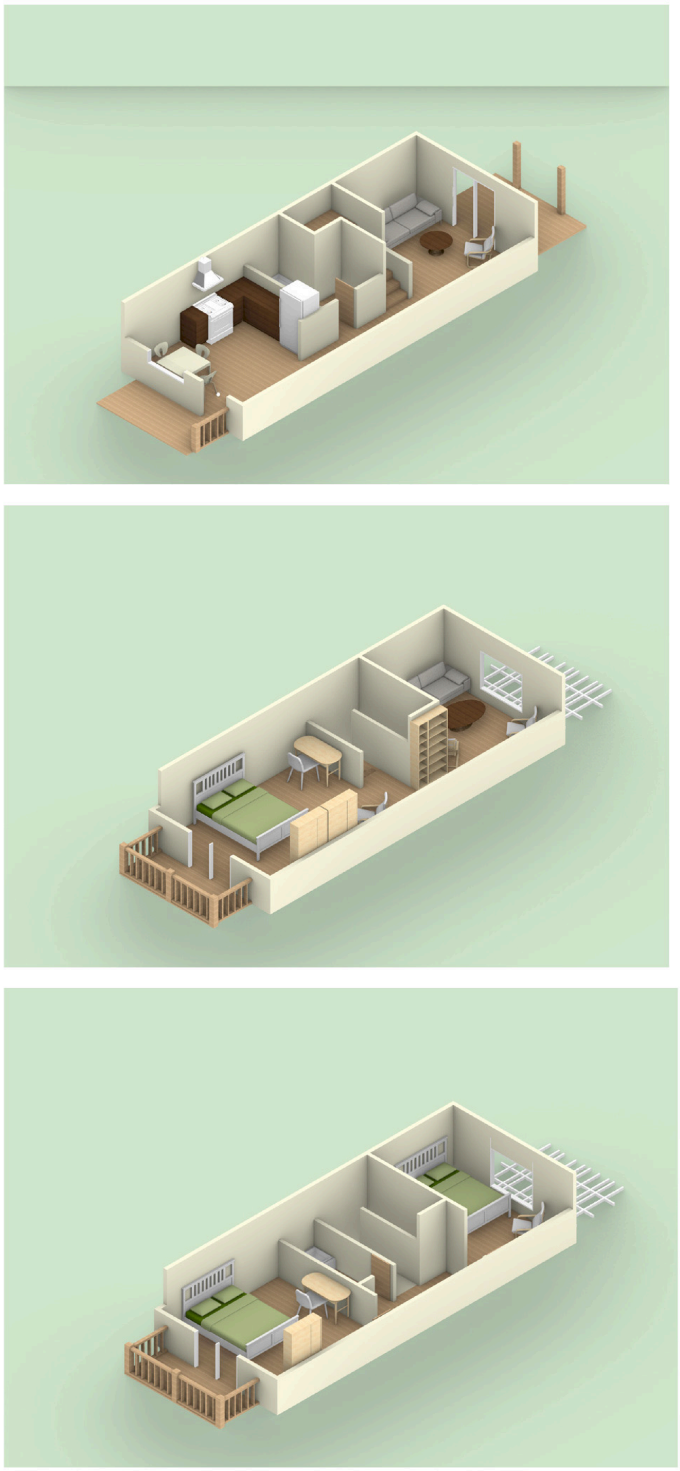


Figure 10. Renders showing the plans of the Green Grow Home that was modeled after the Grow Home. (Render made by author for this paper).

Table 3. Embodied energy comparison of selected material substitutions in the Green Grow Home. (Table created by author).

Building Material	Environmental Benefits	Energy Savings (MJ)
Walls		
OSB	59% less embodied energy, efficient use of resources (better use of wood fiber)	17,493
RCA	Reduces waste by 85%, reduces CO_2 emissions by 90%	750
EWP	Reduces energy consumption by 30%and CO_2 emissions by 40%	59
SIP	Saves between 15%and 20% of energy compared to traditional walls	5262
Insulation		
Cellulose Insulation	56% less embodied energy, less resource depletion (recycled product), biodegradable	3104
Flooring		
Parquetry	75% less embodied energy, less resource depletion, less toxic waste	8347
Ceramic Tile	85% less embodied energy, less toxic waste	3995

Moreover, this project uses aluminum for window and door frames, flashing, and gutters because it is lightweight, corrosion-resistant and recyclable. Zinc serves as a protective coating for steel components such as fasteners, connectors and brackets. Both materials ensure building durability and can be recycled at end of life.

All material modifications between the original Grow Home and the updated Green Grow Home would result in saving 39,010 MJ of energy, which would be the amount of energy needed to heat the home for four years. The Green Grow Home as a case study in design illustrates how designers and builders can make informed choices regarding building components that will reduce embodied energy and promote sustainability in homes.

8. Discussion

Thus far, this article has emphasized the necessity of a transition to using construction materials comprising renewable resources, as well as a shift in both the construction industry as well as architecture to design and build with such materials in mind. Further, this article has argued on behalf of a shift to a circular economy model and the positive effects that it would have on both the environment and the economy. The article has also included an overview of several construction materials made from renewable resources, delving into some, particularly cellulose insulation, on a deeper level. The research suggests that shifting construction and architecture of residential architecture around renewable resources and a circular economy is a necessity and presents only benefits without any drawbacks. However, there must be a discussion of how realistic it actually is to shift to new materials. Even if these materials would greatly improve the sustainability of residential architecture, an industry change in favor of these materials may be challenging due to factors such as cost, complex production processes, and market acceptance challenges. This section aims to explore the challenges faced by the residential construction sector in an effort to increase use of renewable resource-based construction materials.

One common issue with attempting to implement the use of sustainable construction materials in place of traditional materials is the increased cost. Sustainable alternatives often cost more than their traditional counterparts. For example, a smog-eating cement facade on a five-story building, despite decreasing air pollution by 20%, would increase construction costs by 15%. As another example of this phenomenon, a study by the US Department of Housing and Urban Development found in a 2001 study that modular building costs 3% to 5% more than traditional construction [42]. One example of sustainable construction material is insulated concrete forms (ICFs), which were discussed earlier in this article. ICFs are highly energy-efficient and highly durable, allowing for them to be used in a building for a long period of time, reducing waste and closing resource loops [42]. This is not a huge discrepancy in price, but it is still more expensive and thus ICFs may not be an option in projects with a tight budget. Further, every architect must decide if the price is worth it. In addition to sustainable materials costing more, many building owners are losing money by using these materials because they are not using energy-efficient technology [43]. It is not enough to simply build using sustainable materials; the operation of the building must also have sustainability in mind. That being said, using sustainable materials can dramatically decrease the cost of the building's operation and maintenance over a long period of time. This is due to increased energy efficiency, with the average energy efficiency gain being 25% to 30% and resulting energy savings being up to 35%. The potential for energy savings in new and existing buildings, respectively, in the US is 9.9% and 19.2%, which is significant [42]. Overall, sustainable construction materials present a greater upfront cost, but greater savings over time compared to traditional materials. Of course, to reap these long-term savings, the building must be operated and maintained in a way that continues to make use of sustainable materials.

While many emerging materials have demonstrated promising environmental benefits, limited long-term field data are available to verify their durability, maintenance requirements, and performance under varying climatic conditions. In some cases, the lifespan of these materials remains uncertain compared to conventional construction products that have been tested and used for decades. Many of these new products are still in experimental phases and early development and must be evaluated further for factors such as toxicity and maintenance costs [44]. Furthermore, maintenance procedures, replacement cycles, and repair costs are not always well documented, creating additional risks for designers, builders, and homeowners. Scalability also presents a challenge, as some sustainable materials are currently produced on a limited scale, resulting in supply chain constraints, inconsistent availability, and higher costs. Consequently, further research, monitoring, and industry testing are required to better understand the long-term viability of these materials and support their wider adoption in residential construction.

Social cost is the total cost to society of producing or consuming a good or service [45]. When we consider sustainable construction materials, social costs encompass the wider effects on society as well as indirect costs and barriers to their uptake such as professional training, public education, policy implementation, regulatory adaptation and changes to established construction practices. These factors are important for evaluating how realistic the proliferation of sustainable construction materials is. To be supported and used widely, these materials need the help of government policies and subsidies to reduce costs, legal support, and a general consensus and acceptance [44]. Research suggesting improved energy efficiency or use of resources is not always enough to convince professionals in the architecture and construction industries as well as consumers that sustainable materials are the right choice for a project. Sustainable materials must also become ingrained in the culture of these industries and perceptions of architecture more broadly to be regularly opted for. Consumers are likely the most difficult to convince as they often lack knowledge

of sustainability and care more about costs and aesthetics. That being said, there is a widespread understanding of the importance of sustainability which is prompting a shift towards sustainable construction materials which will likely continue over time based on current patterns.

9. Conclusions

This paper contributes by developing a material selection framework based on circular economy principles and demonstrating its application through the Green Grow Home case study. While there are renewable construction materials for residential architecture, they are rarely used in projects as information on them is minimal in building codes, leading to a lack of knowledge regarding them. In addition, there would also be cultural influences that vary based on geographic context which could have the potential to slow down the process of integrating "green materials" into mainstream construction and architecture practices. The overall theme that was discussed in this article that should be considered is the need to diversify the materials used in construction and to consider the entire lifespan of a building in its design. Buildings should be designed with their end in mind, specifically how the materials used to construct the building initially can be recycled and reused to reduce waste and promote a circular economy. However, the main actors should not solely rely on "green" materials and products, and when they are used, they should be sourced locally and built in appropriate climates, so as to maximize the amount of time for which they will be useful. It is imperative on a moral level to make "green" materials and products better integrated into construction practices as soon as possible to live more sustainably and harmoniously with the environment. The study's conclusions suggest that the materials' modifications between the original Grow Home and the updated Green Grow Home resulted in saving 39,010 MJ of energy. It is a significant amount equivalent to the amount of energy needed to heat the home for four years. The Green Grow Home as a case study in design illustrates how designers and builders can make informed choices regarding building components that will reduce embodied energy and promote sustainability in homes.

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