OPPORTUNITIES FOR RECYCLING IN BUILDING CYCLE RENOVATIONS: A CASE STUDY OF PVC ROOFING MEMBRANES

Buddhika Hapuwatte - National Institute of Standards and Technology, Gaithersburg MD USA
and University of Maryland, College Park, MD, USA
Ashley Hartwell - National Institute of Standards and Technology, Gaithersburg MD, USA
Richard Krock - VyChlor Advisors, Westlake OH, USA
Brian Whelan - Roof Resources, Canton, MA, USA
Tribu Persaud - Norwich Plastics, Cambridge Ontario, CA

Abstract

Increasing global efforts towards a circular economy and emissions reductions emphasize alternative pathways for end-of-use recovery of products through value extension practices such as repair, refurbishment, and recycling to replace direct landfilling. Given the size of the built environment sector, including materials and construction, opportunities for emissions reductions are sought after. Embodied emission reduction efforts target not only new construction but also building renovations. This includes assessing the impacts associated with routinely replaced building materials. For comparison of options during renovations, the ability to measure the embodied emissions of the incoming material as well as those of the material being removed from the buildings is essential. Information on incoming materials is increasingly available from documentation such as environmental product declarations—EPDs and product carbon footprints-PCFs. The impact of the latter, the material removal, depends largely on the chosen end-of-use recovery pathway. Consequently, building owners and other stakeholders in the renovation process seek to compare the emissions of different end-of-use pathways to select the most advantageous alternative.

This paper presents the quantification of the emissions avoidance potential of alternative end-of-use pathways for routinely replaced materials by comparing them to the emissions of business-as-usual practices. Specifically, we examine the potential for avoidance through recycling polyvinyl chloride (PVC) single-ply roofing membranes of commercial buildings as a case study. First, we identify possible closed- and open-loop recycling pathways for this material and characterize the process steps involved. Then, we compile the relevant process data from representative EPDs, the U.S. Life Cycle Inventory (USLCI), and PVC recyclers. Using this data, we estimate the potential benefits of recycling these membranes when compared to the business-as-usual scenario of landfilling. Preliminary results show that closed-loop recycling and open-loop recycling of PVC roofing membranes can result in carbon avoidance. This process characterization and analysis can aid engineers, designers, and built environment practitioners as they perform Whole Building Life Cycle Assessments (wbLCAs) and support end-of-use management decision-making during cycle renovations (i.e., periodic renovations throughout a building's lifecycle). More broadly, this work highlights the utility of expanding recycling infrastructure for PVC membrane products and provides a case study for firms seeking to adopt carbon avoidance quantification.

1. Introduction and Motivation

As with many industrial sectors, the building sector is striving to reduce environmental emissions. The building sector contributes to between 37% - 40% of annual global carbon emissions, including operational and embodied contributions (Architecture2030, 2023; United Nations Environment Programme, 2024). Efforts to reduce these impacts are resulting in novel building design, low-carbon material selection, and more energy-efficient environmental controls. Future building technologies can enable building emissions reductions throughout the life cycle of a building (including embodied and operational sources) – not just at initial conception and construction. The result will be more efficient use of resources with fewer environmental impacts across the entire life cycle of the building.

Cycle renovations include maintenance and repair activities that happen at fixed intervals during a building's lifecycle to prolong the use of a structure. Despite their necessity, these renovations are often overlooked in research focused on environmental impact in the built environment. Roof replacement is a key renovation to consider for emissions reduction as it is estimated that of the 370+ million square meters of roofing installed annually, 75% of that is reroofing (Roof Resources LLC, 2024). Additionally, the average commercial low-sloped roof can last 15 – 30 years depending on use conditions, meaning replacement can be expected as many as 4 times during the lifespan of a building (assuming a life span of approximately 60 years) (Gonçalves et al., 2019).

Maintaining roof performance is critical as the roof protects the building and its occupants from weather and is a key heat transfer surface. Recently improved building codes, which impact both new roof construction and reroofing projects, have required increased R-values (thermal resistance) for the roof system in order to reduce a building's operational energy needs while maintaining occupant thermal comfort (Taylor et al., 2018). A tradeoff between up-front cost and performance exists as the price of insulation scales with R-value and generally dominates the roof assembly cost (Annibaldi et al., 2019). However, reroofing a structure may lead to a reduction in building life cycle costs as the roof (and its membrane), prevent water intrusion that can decrease insulation life and send the process- and cost-intensive material into landfills quicker.

The focus of this study is mechanically attached, single-ply roofs made from polyvinyl chloride (PVC) membranes. These systems are widely used in the U.S. due to ease of installation, durability, and their white color that reflects solar radiation. Additionally, at the end of their service life, these membranes are suitable to recycle back into roofing products (i.e., closed-loop recycling), such as a new membrane, or other pathways such as flooring (i.e., open-loop recycling). Although recycling for PVC roofing membranes has been available for 30 years in the U.S., the practice has been relatively limited to a few membrane manufacturers. Roofing recycling has been a largely overlooked alternative due to a lack of data on which to quantify the benefits. Given the lack of data, decision makers have limited insight into the PVC recycling process and the potential environmental benefits it offers. In addition, roofing recycling features logistical challenges including the collection and distribution of used material. Combined these challenges default to less favorable end-of-use (EOU) outcomes such as landfilling. This work fills these data gaps by providing a characterization of the PVC roofing membrane recycling process, and an estimation of the carbon avoidance potential for both open- and closed-loop pathways for recycling of PVC roofing membrane.

2. Review of Related Work

To address the need to better characterize the recycling of used roofing materials we reviewed existing efforts on PVC recycling as well as a measure of carbon avoidance for adopting the recycled products. The existing life cycle assessments (LCA) used in this assessment area are also described below.

2.1. Efforts for sustainability in PVC roofing via recycling

For many decades, much of the pre-consumer generated material or internally generated PVC roofing scrap has been mechanically recycled. This includes processed materials that are outside of specification and edge trimmings (CFFA, 2024). In the United States, post-consumer recycling of PVC roof membranes began in 1999 with the production of a highway cold patching material made from old PVC roofing membranes and other recovered plastics (Oblock et al., 2023). As grinding equipment improved at separating polyester reinforcement and felt backing from the vinyl part of the membrane, EOU roofing membranes were able to be converted into feedstock for production of new products. Closed-loop applications include new single-ply roof membranes and open-loop applications target products such as commercial-grade flooring and concrete expansion joints (CFFA, 2024).

Manufacturers of PVC single-ply roofing membranes have been leaders in recycling PVC. As part of its industry-wide sustainability initiative, the Chemical Fabrics and Film Association (CFFA) Vinyl Roof Division (VRD)[1] has tracked PVC roof membrane recycling in the U.S. and Canada since 2014 (Figure 1). On an accumulated basis, 8.9×10^7 kg (196.2 million pounds) of pre-consumer and 6.0×10^6 kg (13.2 million pounds) of post-consumer PVC membranes were recycled from 2014 through 2024 (CFFA, 2025b). In 2023, CFFA-VRD members undertook their "Pathway to Zero" recycling initiative to further minimize any production waste being sent to landfills. This recycling initiative asks members to voluntarily submit information on the amount of production scrap reused and recycled (CFFA, 2025a). Establishing and tracking key performance indicators (KPIs) such as these are crucial for a transition to circular manufacturing (Aljamal et al., 2024). Since the initiation of the Pathway to Zero program, production waste material sent to landfill by all VRD members and two non-members has declined by 59% and this correspondingly raised the effective material utilization to 99.6%, as determined by pounds of production raw material procured minus raw material landfilled divided by production raw materials procured (CFFA, 2025c).

Oblock et al., (2023) has discussed the sustainability opportunities in recycled PVC roofing membranes and Contarini (2012) identified the importance of quantifying environmental and economic benefits of roofing renovation.

[1] The commercial terms and/or products identified in this paper do not imply recommendation or endorsement by NIST. Nor does it imply that they are necessarily the best available for the purpose.

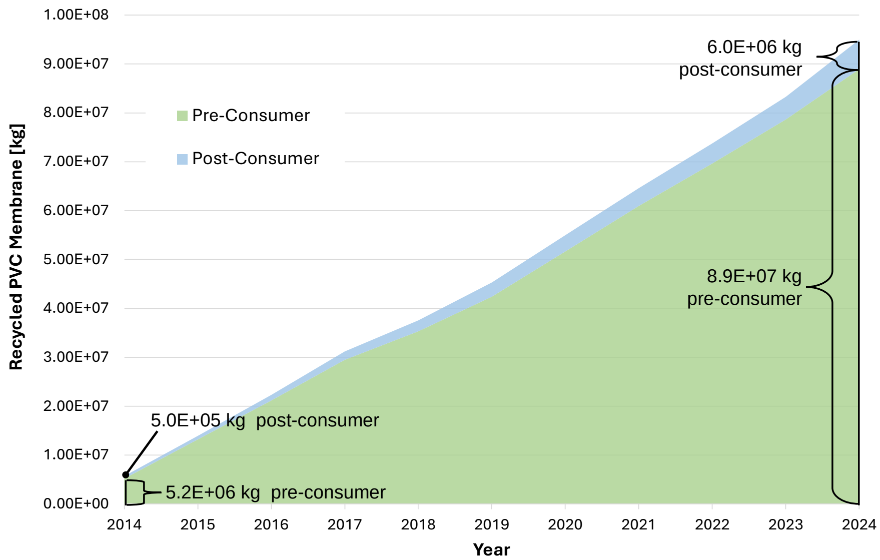

Figure 1. Recycling of Single Ply Roof Membrane by Year (on accumulative basis) of CFFA VRD Members and two non-members for 2024 (Courtesy CFFA)

2.2. Carbon avoidance quantification for recovery processes

Different EOU circular pathways such as reuse, remanufacture, and recycle have varying environmental impacts (IRP, 2018) and prior work has described frameworks to model their environmental impacts (Mathur et al., 2023). Voluntary commitments on reducing environmental impacts, global sustainability initiatives, certain regional adoption of International Green Construction Codes, and public scrutiny of carbon emissions have incentivized businesses to quantify and reduce their total emissions (Bendig et al., 2023). With proper evaluation, businesses can estimate the potential carbon avoidance of using circular pathways such as recycling and the resulting displacement of virgin production, as opposed to the historical practice of disposing at landfill (Hapuwatte et al., 2023). Although Hapuwatte et al. previously found that these recovery methods may not qualify for *carbon credits*, such estimates remain valuable for industry stakeholders (WBCSD & WRI, 2005). They help organizations recognize the benefits of recycling initiatives and encourage a shift from conventional practices of landfilling EOU roofing materials. Hapuwatte et al.'s work outlined a basic framework for carbon avoidance estimation. Section 3.2 of this paper discusses the approach taken to establish scenarios for comparison and estimate the carbon avoidance potential of each scenario.

3. Technology Approach

The analysis of potential environmental benefits of recycling roofing membranes is decomposed into two parts. First the PVC membrane recycling process is examined to determine the different pathways available, and the process steps involved. Next, this information is used to develop scenarios for circular materials flows, and ultimately applying the carbon avoidance calculations. This work focuses on the embodied emissions associated with the roofing membrane.

3.1. Characterization of PVC membrane recycling process

At the EOU, a PVC roofing membrane is blown free of debris, sliced and rolled as it's removed from the lower roof substrate. It is then either landfilled or packaged and transported to a recycling facility that can process the PVC sheet material. The PVC membrane recycling process (outlined in Table 1) shares process steps with general mechanical recycling, such as pulverization and pelletizing, although key differences arise due to the material properties, cleaning needs, and secondary material applications (closed- vs. open-loop recycling). For example, the reinforcing fibers in the roofing membrane must be removed to recycle the EOU PVC roofing membrane into a new one. Some open-loop PVC applications may be able to tolerate a degree of fiber contamination or lower purity material. Pulverization and separation post the blending step is also application-dependent, particularly if the new PVC product has cosmetic specifications. Finally, the need to pelletize recycled PVC material for its next application will depend on the demand of the next product's manufacturer. Some manufacturers have processes and equipment that can use the powdered/granular PVC remaining at the end of the blending and pulverization steps, whereas others may use machines that require pellet feedstock. It should also be noted that the refinement needs of the recyclate can be determined by the life expectancy of new secondary product being made. For example, a new PVC roof membrane would be expected to last another 15-30 years where other material applications may have shorter life spans.

Table 1: Recycling steps for closed- and open-loop recycling of PVC roofing membrane.
✓- required, ○ - optional (Ait-Touchente et al., 2024; VinylPlus, 2017)

Recycling Step	Description	Closed Loop	Open Loop
Shredding	Large pieces of membrane are sliced and reduced to smaller pieces on the order of 2 – 6 cm long	✓	✓
Fiber Removal	More than 90% of reinforcing polyester fibers (.8mm) are removed from the membrane through aspiration after high-speed mechanical processing.	✓	○
Blending	Previously used PVC may be combined with virgin materials to improve quality of new feedstock	✓	✓
Pulverizing	Material is milled into fine powders and sieved for uniformity and residual fiber removal. Resulting particle sizes can range from 400 to 1000 microns	✓	○
Pelletizing	PVC is remelted into pellets that are .25 inches (6.35mm) in diameter	○	○
Packaging	Recycled PVC is placed in containers for transport to manufacturers	✓	✓

3.2. Carbon avoidance scenarios

This case study is designed to assess the potential benefits of recycling PVC roofing membranes when compared to the business-as-usual (BAU) scenario of landfilling the material at the EOU. We consider 3 scenarios for carbon avoidance calculation in addition to the BAU case (Table 2). In Scenario 1, a fully closed-loop recycling system is assumed, meaning all the roofing membrane collected from the site is allocated to produce recycled material for new roofing membrane material. Scenario 2 assesses the carbon avoidance from a fully open-loop recycling system where the collected roofing membrane is recycled into flooring. The open-loop processes are viable EOU pathways for applications such as flooring that can tolerate lower quality feedstock. The need to switch to more open-loop pathways could happen due to membranes in extreme use conditions (e.g., near food service cooking vents), contamination, or in the future, hitting the capacity limit for closed-loop PVC membrane recycling. Scenario 3 shares the available recycling material between both recycling pathways equally.

Table 2: Carbon Avoidance scenarios with various recycled PVC allocation

Scenario	Allocation to open-loop (Flooring)	Allocation to closed-loop (New Roof Membranes)
1 – Closed-Loop Recycling	0%	100%
2 – Open-Loop Recycling	100%	0%
3 – Material Split	50%	50%

With these allocations, as well as LCA data from industry EPDs, we calculate the carbon avoided from the primary production of the resin for new roofing membrane or flooring, by using the recyclate.

3.2.1. System Parameters and Assumptions:

The following assumptions were made after consulting with plastic film manufacturing and PVC membrane recycling experts. All carbon avoidance values were estimated for the commonly used bare-backed PVC membranes of thickness 60 mils (1.54 mm) and a typical commercial building roof area of 25,000 square feet—referred to in the industry as “250 squares” (2323 m^2). Therefore, the functional unit of these calculations is a single commercial building roof of 2323 m^2. This case study focuses on the production of recycled PVC resin which is used for roofing and/or flooring applications. Therefore, to estimate the net carbon avoidance of each scenario, the system focused on in this study consists of only the collection of EOU roofing, transportation to recycler, processes to create recycled PVC, transportation and landfilling of any disposed material, and any avoided primary productions. The avoided primary productions are calculated based on comparable BAU scenarios, which estimate carbon emissions due to the primary production of roofing or flooring material displaced from the respective closed- or open-loop recycling.

Site Collection: We assumed recovery of 95% of EOU membrane at the building site to account for any scrap during removal. Additionally, the amount of membrane installed is slightly larger than the flat area of the roof due to overlap. Therefore, the 95% recovery rate (out of 2323 m^2) can be considered a conservative number.

Transportation: The transportation distances between the building site where the EOU material is recovered, and recycler can vary depending on the capacity and technology of recycling facilities. The distance of 1500 miles (2415 km) was chosen as a conservative average for locations within the U.S., given the limited number of facilities able to process this material compared to municipal waste collection. Similarly, as conservative numbers, we assumed the average distances traveled from building site to landfill (in the BAU scenario or in the case of any excess material not recovered during collection in the other scenarios) and recycling facility to landfill (for any non-recoverable material) to be 100 miles (161 km). All transportation was taken to be medium- or heavy-duty trucks and emissions factor for those were taken as 0.171 $kgCO_2e$ per short-ton-miles (1.17e-4 $kgCO_2e$/kg-km) based on US EPA emissions factors (US EPA, 2023).

Recycling: Due to possible contamination, age and weathering of the roof material, some PVC material may not be suitable for the recycling process. Suitability also depends on the recycling type (i.e., closed-loop vs open-loop). For the closed-loop pathway, it was estimated that 85-90% of the material collected is recyclable. For the open-loop pathway, 85-100% of collected material was considered recyclable given the higher tolerance to fiber in some open-loop applications. Regardless of the recycling pathway, both were assumed to have an efficiency of 90%. The total recyclate output was assumed to be equal to the amount of primary material production avoided for roofing membrane (in closed-loop) and PVC flooring (in open-loop). An exact carbon intensity of EOU roofing membrane recycling process in the North American context is not available due to confidentiality reasons. As an approximation for this value, the recycling related GHG impact value 1.95e-1 $kgCO_2e$/kg based on a roofing membrane product EPD (Sika Corporation, 2023) was used. However, this value includes other activities (e.g., dismantling and transport) in addition to the recycling process related emissions. Therefore, it is a conservative value for the process impacts.

Disposal: Any scrap material from these recycling processes was assumed to be landfilled. Since the emissions factor for landfilling PVC membrane was unavailable, general PVC landfilling emissions factor, 0.438 $kgCO_2e$/kg (ecoinvent, 2021) was used as an estimate. It includes short-term emissions to air and long-term emissions to groundwater, along with burdens to treat wastewater.

Avoided primary production: Due to the circular flow of closed- or open-loop recyclate materials being available, the need for producing the primary material will be reduced. Different approaches to calculating the amount of avoided material (i.e., displacement factor) has been discussed in the literature (Mak & Heijungs, 2022). The approach to estimating the displacement factor is complex and beyond the scope of this work. As an approximation, for this case study we assume the availability of recyclate material will displace the same amount of primary production of the roofing membrane (in closed-loop) and flooring (in open-loop) scenarios. Exact carbon intensity factors of primary production of raw materials for roofing and flooring were also unavailable due to confidentiality reasons. However, after consulting with LCA experts who conducted an industry LCA study on PVC roofing membranes, 85% of Global Warming Potential (GWP) indicator value of the EPD's product stage (i.e., A1-A3 stages) was identified as a valid approximation for the carbon emissions due to material input (i.e., what's avoided) for the product. Therefore, the emissions factors of 3.13 $kgCO_2e$/kg (CFFA, 2020) and 2.64 $kgCO_2e$/kg (RFCI, 2019) were chosen for the primary production of roofing membranes and flooring respectively.

3.2.2. Environmental Impacts and Carbon Avoidance Estimation

Given the 60 mils (1.54 mm) bare-backed membrane with a typical density of 1.7 kg/m^2, the average commercial roof leads to an expected membrane weight of 3969 kg at a building site. Table 3 summarizes the input parameters and results of the different scenarios studied. It includes material weight, efficiency and other input parameters at different stages of each scenario. The low and high columns refer to the scenarios given the lower and upper bounds of the recyclable material percentage (section 3.2.1) for closed- and open-loop pathways. The carbon emissions section of the table details the emissions due to activities of transportation, recycling processing, and disposal. The avoided emissions section is estimated using the emissions factors and amounts of each primary material avoided in the respective scenario (i.e., roofing membrane for closed-loop and flooring product for open-loop). The results show the three scenarios have broadly similar net avoidances, with some differences depending on the recyclable percentages of the input materials. Given that all three scenarios show beneficial GWP reductions, strategizing allocation—based on grading of the incoming material—between closed- and open-loop pathways may provide opportunities for optimized carbon avoidance potential.

Table 3. Summary of input materials, system parameters, and potential carbon avoidance in recycling of a single commercial roof of average size (2323 m^2). Values are provided for Scenario 1: 100% open-loop, Scenario 2: 100% closed-loop, and Scenario 3: 50:50 split between closed- and open-loop pathways. All numbers are rounded to three significant figures.

Parameters	**Sc#1: Closed**		**Sc#2: Open**		**Sc#3: Split**	
	Low	High	Low	High	Low	High
MATERIALS						
Total membrane at site (kg)	3970		3970		3970	
Total membrane collected for recycling (kg)	3770		3770		3770	
Non-collected membrane (landfilled) (kg)	198		198		198	
CLOSED-LOOP:						
Allocated to closed-loop recycling	100%		0%		50%	
Closed-loop recyclable material	85%	90%	-	-	85%	90%
Closed-loop recycling efficiency	90%		-	-	90%	
Recyclate material output (kg)	2880	3050	-	-	1440	1530
Non-recoverable material (kg)	886	716	-	-	443	358
Avoided primary roofing membrane (kg)	2880	3050	-	-	1440	1530
OPEN-LOOP:						
Allocated to open-loop recycling	0%		100%		50%	
Open-loop recyclable material	-	-	85%	100%	85%	100%
Open-loop recycling efficiency	-	-	90%	90%	90%	90%
Recyclate material output (kg)	-	-	2880	3390	1440	1700
Non-recoverable material (kg)	-	-	886	377	443	189
Avoided primary flooring (kg)	-	-	2880	3390	1440	1700
CARBON EMISSIONS DUE TO…						
Recycling ($kgCO_2e$)	737	737	737	737	737	737
Disposal ($kgCO_2e$)	475	401	475	252	475	326
Transportation ($kgCO_2e$)	1090	1080	1090	1080	1090	1080
Scenario Total ($kgCO_2e$)	2300	2220	2300	2070	2300	2140
AVOIDED EMISSIONS (vs. BAU) FROM…						
Primary production ($kgCO_2e$)	9040	9570	7620	8960	8330	9270
Landfill ($kgCO_2e$)	1650	1650	1650	1650	1650	1650
Transportation ($kgCO_2e$)	71.1	71.1	71.1	71.1	71.1	71.1
Net avoided carbon vs BAU ($kgCO_2e$)	**8460**	**9070**	**7040**	**8620**	**7750**	**8850**
Net avoided carbon per 1m^2 membrane ($kgCO_2e$)	**3.64**	**3.91**	**3.03**	**3.71**	**3.34**	**3.81**

These results highlight the potential of PVC roofing recycling. The average life expectancy of a roofing system is 20 years. Two decades ago, approximately 30 million square meters of single-ply PVC roofing were installed in the U.S., with roughly 50% being adhered roofing (which is difficult to remove and subsequently recycle). If around 10 million square meters could be available for recycling annually, there is a potential to avoid about 37 million kg of carbon dioxide equivalent in a conservative scenario. Furthermore, PVC roofing has become more popular in the last decade along with the percentage of PVC roofs that are mechanically attached (i.e., ideal candidates for recycling). Therefore, opportunities for recycling are expected to increase annually.

4. Discussion

While the results show the carbon benefits of PVC recycling, the study does rest on assumptions that can be significantly challenging in practice, particularly in the areas of measurement uncertainty and the need for standards as discussed below. Nevertheless, progress is being made towards addressing these challenges as described below.

4.1. Uncertainty in carbon intensity of PVC recycling

One of the main uncertainties in this estimation is the carbon intensity of the PVC recycling process. A recent study (Ye et al., 2017) on the PVC recycling in process in China provides an emissions factor of 0.65 $kgCO_2e/kg$. While this study provides important lifecycle inventory data, our conversations with the North American industry representatives indicate the published emissions factor is higher than expected for the North American region. This discrepancy is likely due to specific processing used and differences in the electricity grid supply mix. Nevertheless, we recalculated the above scenarios using this emissions factor to get estimates of possible lower bounds for the carbon avoidance values. For scenarios 1 through 3, the net avoided ranges of emissions per roof of 2323 m^2 were estimated to be 6760 to 7370, 5340 to 6920, and 6240 to 7220 $kgCO_2e$ respectively. Even using this lower factor, the scenarios still show positive net carbon avoidances, compared to their BAU instances.

Additionally, different closed-loop processing techniques and other open-loop paths (e.g., landscaping products) are available to EOU membranes. These other applications for the PVC recyclate can add variability to the actual carbon avoidance possible. Therefore, further work can be done to implement those as additional scenarios and provide additional dimension to the above results.

4.2. Challenges to implementing recycling in PVC roofing membranes.

This case study demonstrates the value of recycling PVC roofing membranes with respect to carbon avoidance (i.e., in terms of GWP benefits). However, several barriers limit the expansion of PVC roofing recycling in the near term. Table 4, highlights these challenges by life cycle stage (ISO, 2017), revealing the complexities that must be addressed by stakeholders.

Table 4: Challenges to increased recycling of PVC roofing membrane by life cycle stage

Life Cycle Stage	**Challenges for Recycling PVC Roofing Membranes**
Product	• EOU PVC membranes may contain incompatible additives for new applications
Construction	• Adhesives for adhered roofs can remove substrate materials reducing the quality of reclaimed material and limiting the recovery rates
Use	• Chemical contamination from pollutants can pool on the roof membrane • Degradation from environmental exposure may render some recovered material unsuitable for recycling
End-of-Use (EOU)	• Limited number of PVC recycling facilities reduces access for stakeholders • High logistics costs may be uneconomical when the quantity of recovered material is low • Lack of storage for the post-removal membrane that avoids material deterioration

PVC membranes that have been in service for several decades are now ready for reclamation, however as it relates to the product stage, these membranes may have been manufactured with additives that are incompatible with formulations that are used today. Therefore, especially with older roofs, screening may need to be done to ensure best value recovery pathway.

One key challenge in the construction stage that reduces the amount of quality material available for recycling, is the use of adhesives to install the roofing membranes. These adhesives often pull up insulation faces and other substrate materials, impacting recycled feedstock quality. Although mechanically fastened roofing membranes comprise about 75% of new thermoplastic installations (Taylor, 2020), EOU membranes being recovered for recycling currently are likely to be both adhered and mechanically fastened. Should recycling PVC roofing membranes become a common practice, it can become another reason for opting for mechanical fastening of PVC roofing membranes. By implementing building operational energy modeling at the detailing stage, implications of mechanical fastening and tradeoffs, such as thermal bridging from fasteners vs recyclability of roofing, can be better assessed.

Roofing membranes, just like any material, can face wear and degradation as they age, and this can be exacerbated by environmental factors such as local climate, thermal cycling, and solar radiation (Cash & Bailey, 1993). While recovery and recycling of these aged roofing membranes is possible, they must be reformulated with additives to rejuvenate their properties and assure proper performance for its next use.

Finally, PVC membrane recycling can be limited by infrastructure and logistics. Currently not that many recycling facilities exist in North America capable of processing PVC membrane material. The additional burden for transportation and disposal can lead to low participation rates in programs that do exist (Ait-Touchente et al., 2024).

Even if PVC recycling is available, without a robust reverse logistic system, roofing membranes may still be sent to landfill.

Considering the complexity and the different stakeholders involved, a system-level approach must be taken to address all these challenges at different life cycle stages and establish a robust infrastructure to enable efficient circular pathways for this material.

4.3. Opportunities in recycling PVC roofing membrane

The increased adoption of recycling PVC roofing membranes also presents several opportunities for stakeholders including manufacturers and building owners. As the building industry aims to be more sustainable, one strategy taken by building owners is the achievement of "green certifications" from rating systems such as Green Globes, LEED, and BREEAM (Holland, 2024). Each of the systems provides credits for certification when selecting new building products with recycled content and for recycling construction waste materials (Holland, 2024). For roof membranes in particular, these credits are awarded by selecting single-ply roofing membranes that have NSF 347 sustainability certification. Not only do green building certifications signal a commitment to building industry carbon reduction goals, these certifications also improve marketability, building occupancy rates, and financial value (Kaplow, 2009).

Business and economic drivers are increasing value in activities that add to Corporate Sustainability Reporting (CSR) and Environmental, Social, and Governance (ESG) reports. In June 2023, the International Sustainability Standards Board (ISSB) issued IFRS S1 *General Requirements for Disclosure of Sustainability-related Financial Information*, which includes provisions for building products and furnishings (ISSB, 2023). On this basis, recycling PVC roofing membranes and specifying roofing membranes/products with recycled content, are activities that can be reported in a CSR or ESG report.

4.4. Progress and Opportunities for Standardization

Consensus-based standards distill knowledge from manufacturers, regulating bodies, academia, end users, etc., into a common standard that can aid in product development and evaluation by communicating best practices and specifying performance metrics and values. The previously mentioned NSF 347 certification is dictated by the standard NSF/ANSI 347-2018 Sustainability Assessment for Single Ply Roofing Membranes, which provides a set of environmental and social impacts to evaluate these products and targets that must be met for a given certification level. NSF/ANSI 347 also provides points towards certification for incorporating recycled content into the manufacturing process. Other relevant standards efforts include the ASTM D8013-16(2021) Standard Guide for Establishing a Recycle Program for Roof Coverings, Roofing Membrane, and Shingle Materials (ASTM International, 2021), and the ASTM work item WK70992 New Practice for Sustainability Assessment for Single-Ply Roofing Membranes (ASTM International, 2019).

5. Conclusions & Recommendations

For decades, building construction debris has been disposed of in landfills due to convenience and low costs. However, as industry turns a more critical eye to the environmental impacts of building construction, several converging factors are limiting this practice including the closure of landfills, increased restrictions on materials that can be landfilled, and increased disposal and tipping costs. Most importantly, built environment stakeholders' interest is growing in reducing the detrimental impacts associated with construction waste and debris. This can drive industry-wide change towards the prioritization of reuse and recycling of construction materials.

This work demonstrated significant avoided emissions through the recycling of PVC roofing membranes. By quantifying and understanding the carbon benefits of recycling PVC roofing, this work can encourage stakeholders to work together to increase recycling of the EOU PVC roof membranes and to direct these materials to the most beneficial second life. This work summarized the major challenges to be overcome at each life cycle stage to increase roofing membrane recycling. Challenges in the completion of this analysis include a lack of standardized and publicly available data specifically on PVC recycling (as opposed to general municipal plastic waste recycling). This can be addressed by PVC manufacturers and recyclers quantifying and disclosing their impacts as available either through EPDs, or industry-wide LCA reports which provide average values and alleviate concerns about data privacy. The biggest practical challenge to implement recycling and break the old habits here is perception-related: there is a general lack of awareness on recycling option and its tangible benefits. Ultimately, we believe carbon avoidance quantification builds awareness of potential benefits of EOU alternatives to landfilling. This awareness can lead to improving waste management practices, planning and incentivizing effective reverse logistics, and developing better technology for sorting and recycling operations, making circular pathways for roofing membranes more enticing for building owners and managers.

6. References

Ait-Touchente, Z., Khellaf, M., Raffin, G., Lebaz, N., & Elaissari, A. (2024). Recent advances in polyvinyl chloride (PVC) recycling. *Polymers for Advanced Technologies*, *35*(1), e6228. https://doi.org/10.1002/pat.6228

Aljamal, D., Salem, A., Khanna, N., & Hegab, H. (2024). Towards sustainable manufacturing: A comprehensive analysis of circular economy key performance indicators in the manufacturing industry. *Sustainable Materials and Technologies*, *40*, e00953. https://doi.org/10.1016/j.susmat.2024.e00953

Annibaldi, V., Cucchiella, F., De Berardinis, P., Rotilio, M., & Stornelli, V. (2019). Environmental and economic benefits of optimal insulation thickness: A life-cycle cost analysis. *Renewable and Sustainable Energy Reviews*, *116*, 109441. https://doi.org/10.1016/j.rser.2019.109441

Architecture2030. (2023). *Why the Built Environment*. https://www.architecture2030.org/why-the-built-environment/

ASTM International. (2019). *WK70992 New Practice for Sustainability Assessment for Single-Ply Roofing Membranes*. https://www.astm.org/workitem-wk70992

ASTM International. (2021). *ASTM D8013-16(2021) Standard Guide for Establishing a Recycle Program for Roof Coverings, Roofing Membrane, and Shingle Materials*. https://www.astm.org/d8013-16r21.html

Bendig, D., Wagner, A., & Lau, K. (2023). Does it pay to be science-based green? The impact of science-based emission-reduction targets on corporate financial performance. *Journal of Industrial Ecology*, *27*(1), 125–140. https://doi.org/10.1111/jiec.13341

Cash, C., & Bailey, D. (1993). *Predictive Service Life Tests for Roofing Membranes: Phase 1*. US Army Corps of Engineers. https://apps.dtic.mil/sti/citations/ADA278910

CFFA. (2020). *Industry average EPD for white, single-ply polyester reinforced (SPPR) PVC roofing membranes*.

CFFA. (2024). *Avoiding the Landfill: The Recycling of PVC Roof Membranes*. Chemical Fabrics and Film Association (CFFA). https://vinylroofs.org/wp-content/uploads/RecyclingWhitePaper.pdf

CFFA. (2025a). *Pathway to Zero*. Chemical Fabrics and Film Association (CFFA). https://vinylroofs.org/sustainability/pathway-to-zero/

CFFA. (2025b). *Post-consumer recycling of PVC roofing membranes*. Chemical Fabrics and Film Association (CFFA). https://vinylroofs.org/sustainability/post-consumer-recycling/

CFFA. (2025c). *Unpublished information based on internal voluntary surveys performed monthly by CFFA during 2023 and 2024.* Chemical Fabrics and Film Association (CFFA).

Contarini, A. (2012). *Flat roofs renovation: A life cycle approach for environmental impact assessment and economic effectiveness*. University of Bologna.

ecoinvent. (2021). *Treatment of waste polyvinylchloride, sanitary landfill, RoW.* (Version 3.3) [Dataset].

Gonçalves, M., Silvestre, J. D., De Brito, J., & Gomes, R. (2019). Environmental and economic comparison of the life cycle of waterproofing solutions for flat roofs. *Journal of Building Engineering*, *24*, 100710. https://doi.org/10.1016/j.jobe.2019.02.002

Hapuwatte, B. M., Mathur, N., & Morris, K. C. (2023). Emissions Avoidance Quantification and Allocation Framework for Secondary Materials Marketplaces Supporting the Circular Economy. *Proceedings of the ASME 2023 18th International Manufacturing Science and Engineering Conference*. https://doi.org/10.1115/MSEC2023-104125

Holland, M. J. (2024). *Green Building Certification System Review: Findings Report*. U.S. General Services Administration. https://www.gsa.gov/system/files/GBCS_Findings%20Report%20June%202024-508-v1.1.pdf

IRP. (2018). *Re-defining Value – The Manufacturing Revolution*. A report of the International Resource Panel (IRP), United Nations Environment Programme (UNEP). https://www.resourcepanel.org/reports/re-defining-value-manufacturing-revolution

ISO. (2017). *ISO 21930:2017 Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services. International Standards Organization (ISO)* (Version 2).

ISSB. (2023). *IFRS S1 General Requirements for Disclosure of Sustainability-related Financial Information. International Sustainability Standards Board (ISSB)*.

Kaplow, S. (2009). Does a Green Building Need a Green Lease? *University of Baltimore Law Review*, *38*(3).

Mak, M., & Heijungs, R. (2022). Environmental Externalities of Secondhand Markets—Based on a Dutch Auctioning Company. *Sustainability*, *14*(3), Article 3. https://doi.org/10.3390/su14031682

Mathur, N., Hapuwatte, B. M., & Morris, K. C. (2023). A proposed integrated model to assess product recovery pathways: The case of solar photovoltaics. *Procedia CIRP*, *116*, 83–88. https://doi.org/10.1016/j.procir.2023.02.015
Oblock, J., Thomas, J., Krock, R., Hapuwatte, B. M., & Mathur, N. (2023). *Increasing Sustainability in the Low Slope Roof Market through PVC (Vinyl) Membrane Recycling*. IIBEC International Convention & Trade Show, Houston, TX.
RFCI. (2019). *Environmental Product Declaration: Homogeneous Vinyl Flooring. Resilient Floor Covering Institute (RFCI) Industry-wide EPD.*
Roof Resources LLC. (2024). *Estimates based on various industry statistics*.
Sika Corporation. (2023, July 14). *Environmental Product Declaration Cradle-To-Grave: Sarnafil S 327*.
Taylor, T. J. (2020). Eliminating Fastener Thermal Bridging in Low Slope Roofs: Energy Efficiency Savings versus Installation Costs. *Open Journal of Energy Efficiency*, *09*(02), 94–110. https://doi.org/10.4236/ojee.2020.92007
Taylor, T. J., Willits, J., Hartwig, C. A., & Kirby, J. R. (2018). Optimizing Single-Ply Low-Slope Roofing Assemblies for Insulation Value. *Buildings*, *8*(5), 64. https://doi.org/10.3390/buildings8050064
United Nations Environment Programme. (2024). *2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector*. United Nations Environment Programme. https://doi.org/10.59117/20.500.11822/45095
US EPA. (2023). *GHG Emissions Factors Hub*. United States Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-03/ghg_emission_factors_hub.pdf
VinylPlus. (2017). *PVC Recycling Technologies*. https://vinylplus.eu/wp-content/uploads/2017/02/VinylPlus_PVC_recycling_tech_20092017.pdf
WBCSD, & WRI (Eds.). (2005). *The greenhouse gas protocol: The GHG protocol for project accounting*. World Business Council for Sustainable Development (WBCSD); World Resources Institute (WRI). https://ghgprotocol.org/sites/default/files/standards/ghg_project_accounting.pdf
Ye, L., Qi, C., Hong, J., & Ma, X. (2017). Life cycle assessment of polyvinyl chloride production and its recyclability in China. *Journal of Cleaner Production*, *142*, 2965–2972. https://doi.org/10.1016/j.jclepro.2016.10.171

7. About the Authors

Dr. Buddhika Hapuwatte is a PREP Research Fellow at the National Institute for Standards and Technology (NIST) and a Postdoctoral Researcher at the University of Maryland. His research includes product design for circular economy and carbon avoidance quantification of secondary materials.

Dr. Ashley Hartwell is a mechanical engineer and researcher at the National Institute for Standards and Technology (NIST), where she works developing methods and metrics to design products for the circular economy.

Richard Krock, P.E., has 37 years in PVC, retired from Vinyl Institute and formed VyChlor Advisors, which consults for the CFFA and other organizations on recycling, sustainability, and regulatory affairs.

Brian Whelan has a degree in architectural technology and is a graduate of Harvard Business School's PMD Program. Mr. Whelan recently retired from his Executive role with Sika Sarnafil in their commercial roofing and resinous flooring business. His company, Roof Resources LLC consults for the CFFA.

Tribuwan (Tribu) Persaud has been recycling plastics in North America since 1989. He was named a Plastics News 'Rising star' in 2014 and 'Notable Name in Sustainability' in 2023. He is a Director at Norwich Plastics, current Secretary of the Vinyl Institute of Canada and Chair of Vin-Finity Sustainability Steering Committee.