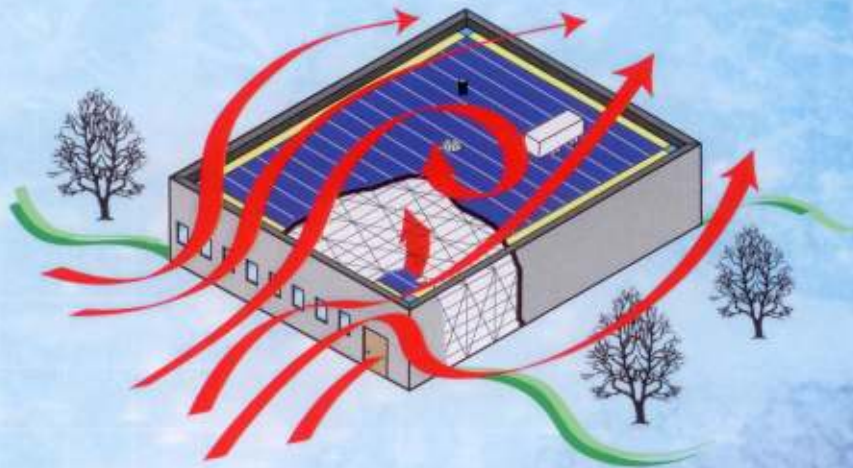


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SUSTAINABILITY OF THERMOPLASTIC VINYL ROOFING MEMBRANE SYSTEMS

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ABSTRACT

The term sustainability is fast becoming ubiquitous in the construction industry. Unfortunately interpretations of the word vary widely in practice. Although the more common, high level, definitions are beneficial in a conceptual sense, they are of only minimal assistance practically. When regards to construction materials, this has led many to associate sustainability with a single product attribute (e.g. recyclability, membrane radiative properties, etc.), which, although simple and practical in use, may ultimately be misleading. The International Council for Research and Innovation in Building and Construction (CIB-RILEM) developed a frame work for sustainable roofing based on a series of tenets divided into three key areas: preservation of the environment, conservation of energy and extended roof life. Using these guidelines and the relevant tenets for roof system selection, the paper will assess the sustainability of thermoplastic vinyl roof membranes.

1. INTRODUCTION

The term “sustainability” is fast becoming ubiquitous in the global lexicon. Most languages now have a word for it. However despite the broad awareness of the concept, there is far from universal agreement as to

exactly what the word means, in any language. One of the first widely accepted definitions of the term was proposed by the Brundtland Commission of the United Nations in 1987: “sustainable development that meets the needs of the present without compromising the ability of future

generations to meet their own needs". Wikipedia proposes a simple, broad description of it as "the capacity to endure". In both cases, the concepts are difficult to grasp concretely. Maybe the term is the epitome of those words that fall into the category, of "you cannot quite explain it, but you know it when you see it"! That is of course problematic, particularly as it relates to construction materials. Without clear guidelines, designers, contractors, building owners, etc. are left to their own devices to decide exactly what sustainability means to them. This can be difficult and confusing, particularly with the profusion of "sustainability" or "green" guidelines, standards and rating systems that have come into being over the past decade or so, many of which are based on a single product or system attribute such as recycle content, raw material type, urban heat island mitigation, etc. Although each one of these is to some degree beneficial, without a more holistic approach, there is always the risk of focusing on a single attribute at the expense of other, possibly more environmentally important criteria. Recognizing these challenges, CIB RILEM developed a series of tenets to be used in the selection, design and construction of roof assemblies to guide practitioners to sustainable construction in this specific industry segment.

The tenets are divided into three categories: minimize the burden on the environment, conserve energy and extend roof lifespan. The following outlines the assessment of thermoplastic vinyl roof membrane systems against these criteria. For the purposes of this paper only tenets directly related to the membrane systems will be addressed (i.e. issues specific to designers such as provide slope to drain, minimize penetrations through the roof, etc. are not considered in detail).

2. MINIMIZE THE BURDEN ON THE ENVIRONMENT

Key tenets falling within this category include the use of raw materials whose extraction is least damaging to the environment, minimize wastage, avoid hazardous waste, and use products that can be re-used or recycled.

From the very beginning, oil and more recently natural gas, have been the key raw materials in the production of low slope roofing materials. This is not likely to change in the foreseeable future. Tremendous progress has been made in the development of plant based polymers. However current generations of poly lactic acid and other non-fossil fuel polymers are bio-degradable and they exhibit short life expectancies when exposed to ultra violet radiation. Intuitively, the former is appealing, however both properties are serious disadvantages for an application where materials are expected to last decades exposed to intense solar radiation, temperature extremes, water, snow and ice, etc. Although we cannot avoid the use of oil or natural gas in the production of low slope roofing materials, we can use them optimally to minimize consumption and achieve the longest possible life span in the finished product.

More than half (approx. 57%) of the polyvinyl chloride molecule, the base polymer in vinyl membranes, comes from salt (sodium hydroxide), a practically inexhaustible resource, with the balance being ethylene from oil or natural gas (Figure 1).

To compare the total consumption of non renewable resources in the production of various low slope roofing materials, their total primary energy demand (TPED) was evaluated. The TPED is made up of two components: feedstock and process energy. The former includes energy content within the final product (including raw materials), while the latter includes all process energy from raw

material extraction, transportation and all manufacturing steps. For 1.5 mm (60 mil) single ply membranes, thermoplastics (PVC and TPO) were found to be statistically similar in TPED, in part due to TPO's lower unit weight (1.5 kg/m²) compared to PVC (1.9 kg/m²), with both having lower TPED than EPDM (due primarily to its higher process energy). As can be seen in Figure 2, with the results expressed in "barrels of oil equivalents", two ply modified bituminous and 4 ply BUR membranes had the highest TPED due largely to their higher raw material consumption.

In addition to using fuel based feedstocks efficiently, thermoplastic PVC membrane production scraps and trimmings are readily recycled back into new membranes. In modern production facilities these materials are reprocessed to separate the polyester reinforcement and to granulate the residual PVC membrane. The PVC granulate is re-integrated into the new membrane feedstock stream and the residual polyester fluff into other uses such as filler/ reinforcement in the manufacturing of concrete landscaping blocks. The net result is essentially a 100% conversion of raw materials into finished goods.

Some limited success has been achieved collecting contractor trimmings from the construction site and recycling in the same manner as those generated in the manufacturing facility.

What happens with these materials at the end of a roofing membrane's service life is even more important when considering environmental burdens. Traditionally, aged roofing materials, including vinyl membranes, have been sent to landfill. Studies have confirmed that PVC is not a hazard in landfills, and in fact has been used to as a liner in landfills to protect groundwater. In

considering the use of C-PVC for piping, the state of California concluded that even under the extreme conditions of landfill fires, the material is not a concern.

Although they can safely be sent to landfills, the better alternative is of course to recycle them. PVC roof membranes were first recycled at the end of their service life in Europe in the early 1990s. In North America post consumer recycling of PVC membranes began commercially in 2005. One manufacturer of PVC membranes has recycled about half a million square meters (approximately 5 million square feet) of PVC roofs at the end of their service life since that time, while diverting more than 8 million kilograms (18 million pounds) of PVC membrane waste from landfills. The reprocessed material is being used in the production of a variety of sheet goods including walkway materials, protection sheets for vegetated roof assemblies and new roofing/ waterproofing membranes. The process is putting these materials back into use in products that will last as long as the original membranes. The program has been proven to be economically viable and typically does not result in additional costs to the building owner. The European experience going back more than 15 years has shown that the products incorporating the post consumer recycled material are not performing any differently in the field than products manufactured solely with virgin raw materials. Thermoplastic PVC roof membranes are the only commercial roofing product being recycled back into new material at the end of their service in North America.

At this time, only loose laid or mechanically attached membranes can be recycled at the end of their service life, supporting the CIB-RILEM tenet to use designs that ease the sorting and salvage of materials. Adhered systems are however an important segment of

the industry, as in many instances it is not practical or it may even be impossible to mechanically attach a membrane. Development work is ongoing to develop a solution to recycle adhered membranes back into roofing membrane products. European processors have been able to recycle PVC membranes from adhered roofs into non-roofing products such as mats used in stables. Development work is ongoing in North America, and a solution to the post consumer recycling of adhered membranes is anticipated within a few years.

3. CONSERVE ENERGY

The most obvious way to conserve energy as it relates to roofing construction is through the use of thermal insulation. As energy costs have risen, often dramatically, over the past decades, there has been a move to increase the thickness of thermal insulation used in roof construction. In the most recent ASHRAE guidelines, minimum R-values for most climates increased from R-15 to R-20. There are numerous initiatives in various jurisdictions calling for even higher levels of thermal insulation, with minimum R values as high as 25 being proposed. This topic, although very important, generally applies more or less equally to all low slope commercial roofing systems, and is beyond the scope of this paper.

Light colored thermoplastic roof membranes, with their high levels of solar reflectivity and emissivity, can contribute to energy savings through reductions in cooling loads in conditioned buildings. Reports on the potential for energy savings resulting from the use of “cool roofing surfaces” began to appear in the late 1990s. Additionally, researchers have found that by reducing rooftop surface temperatures, cool roofs can help mitigate the “Urban Heat Island Effect” (UHIE). A number of locations have mandated the use of cool roofing materials, in efforts to reduce

building energy consumption and/or as a component of their UHIE mitigation strategies. U.S. Energy Secretary, S. Chu, identified the broad implementation of cool roofs and paving as important measures in the current administration’s “new revolution” regarding energy usage.

Lawrence Berkeley National Laboratory (LBNL) has been a major contributor to the study of the impacts of cool roofing. In a 2009 study, LBNL simulated the potential impact of substituting cool roofs for conventional dark-colored roofs on commercial buildings in 236 U.S. cities.

They considered a broad inventory of types, occupancies and ages of conditioned buildings (i.e. air conditioned in the summertime). They calculated the impact of substituting aged conventional materials (assumed to be grey, with weathered solar reflectance of 0.20), with reflective roofs (assumed to be white, with a weathered solar reflectance of 0.55).

Using the DOE-2.1E building energy model, LBNL simulated for each prototype building, in each city the hourly heating and cooling energy used during a typical meteorological year, first with a weathered conventional roof, and then with a weathered cool roof. Savings and penalties were determined by comparing performance with a cool roof to performance with a conventional roof. State and national average rates of savings and penalties were then determined by weighting these results according to local building inventories (types, ages, and densities of construction). The following results are state or national averages per square meter of conditioned roof area (area of roof surface over a conditioned space) (CRA), for the stock of commercial buildings, and are not intended to be used to represent any given single building.

Three key metrics in assessing the relative performance of cool roofs compared to conventional roofs are cooling energy savings, heating energy penalties, and overall energy cost savings.

Not surprisingly, the greatest impact from a change from a conventional grey roof surface to a cool roof is achieved in hot states (see Table 1 for a representative cross section of results by state). However, as can be seen, even the coldest states can clearly benefit from significant reductions in cooling energy through the use of cool roofs.

If reflective roofs are beneficial in cooling dominated climates, one would intuitively assume that they would be disadvantageous in heating dominated climates. Presumably, in such climates, dark-colored, minimally reflective materials, that absorb large amounts of the sun's energy should heat up, resulting in a reduction in the heating energy required to keep the occupied space below the roof's surface at the desired temperature. There should, in effect, be a "heating energy penalty" associated with the use of cool roofs in such climates. According to the paper, there can be, although the magnitude is small. There are a number of reasons for this, the most important of which is that a horizontal surface in the northern states receives about 3 to 5 times more daily sun in the summer than in the winter. The authors found that the average reduction in annual cooling load exceeded the average increase in annual heating load everywhere in the U.S. except the most remote areas of Alaska. Results presented as net energy cost savings per square meter of conditioned roof area are also shown in Table 1.

An alternative approach to achieving the benefits of a cool roof, both energy cooling energy savings and a reduction in the UHIE, is through the use of green or vegetated roofs.

A detailed analysis of this type of roof design is beyond the scope of this paper, other than to note that PVC membranes are amongst the few able to pass the severe FLL root resistance test without the need for a root barrier. Vegetated roofs over PVC membranes have been in service problem free for up to 40 years in Europe, even under the most aggressive of plant/ root types.

It should be noted that the benefits of cool roof systems should not be used as a basis to "value engineer" other aspects of a roof assembly. The benefits of cool roofs should be additive to the other elements of the roof's construction such as required levels of thermal insulation, rather than a reason to reduce R value.

By lowering rooftop temperatures, cool roof materials such as thermoplastic vinyl membrane can contribute directly and indirectly to reductions in greenhouse gases. Significant amounts of greenhouse gases and other pollutants in our environment are the byproducts of smog formation in Urban Heat Islands and energy generation and usage. In its paper, LBNL estimated the reduction in a variety of emissions that could be achieved by substituting traditional darker colored roofing materials with reflective roofing surfaces. Their results for the same selection of states are shown in Table 2.

Climate is a key driver in the magnitude of the energy savings. However, the types of energy generation in a given location have a significant impact on the emission reductions for a given level of energy savings. For example, the impact per unit of energy is less in areas with "cleaner" sources of power such as hydro generation, than in areas with "dirtier" sources of power such as coal generation.

LBNL estimates that converting 80% of all commercial buildings in the U.S.A. to cool roofs could result in a reduction of 6.23 Mt of CO₂ emissions, which equals the annual CO₂ emissions of 1.2 million cars.

LBNL's evaluation focused on the green house gas reductions that could be achieved by switching from traditional darker colored membranes to "cooler" materials. They do not consider the creation of green house gases resulting from these materials. A manufacturer of reflective thermoplastic PVC roof membranes, commissioned a study to establish the amount of CO₂ emissions generated in the production of its roof membranes. The assessment was made on a "cradle-to-gate" basis: from raw material extraction, to chemical precursor production, to membrane manufacturing.

Taking into account the local product mix (type and thickness), the CO₂ emissions resulting from the production of the membranes sold into each state were calculated. The average CO₂ generated per m² of membrane produced varied from about 4.0 kg/m² of membrane to less than 5.0 kg/m² by state. Comparing these values to the data in Table 2, it is clear that the CO₂ generated on a unit-of-production basis exceeds the energy saving CO₂ reduction calculated by LBNL for cool roofs.

However, the CO₂ generated in the production of the materials is a one-time event. The energy savings evaluated by LBNL are incurred annually, throughout the service life of the membrane. It is helpful to consider an environmental "pay-back" period for CO₂. Analogous to any financial model, the CO₂ pay-back period is the time it takes to recover our "environmental investment" (CO₂ generated producing membrane), through our "annual environmental return" (CO₂ reductions associated with energy savings).

Payback periods ranged from a low of 0.9 years in Hawaii, to a high of 4.3 years in Alaska. Results for the states previously highlighted are shown in Table 3. The national average is 1.7 years.

Looking at it another way, assuming a life expectancy of 20 years for the membrane, on average, across the USA, the CO₂ investment would pay for itself almost twelve times over a 20 year service life. Similar results for the selected states are shown in Table 3.

It should be noted that the projected energy and CO₂ savings are relative values based on the basic premise of a substitution from dark colored roofs. The CO₂ emissions are absolute values applicable to the vinyl membranes only. For a complete assessment, the CO₂ emissions related to the production of the traditional materials would also need to be calculated. Based on the TCED analysis referenced previously, it is safe to assume that the CO₂ payback periods for the bituminous materials would be significantly longer.

Minimizing green house gases is clearly an important mechanism for "minimizing burden on the environment", although due to its close correlation with energy production, it was included in this section rather than the previous.

4. EXTEND ROOF LIFESPAN

Arguably the intent of this tenet in the CIB-RILEM document is the most important. The sustainability of a building system is heavily dependent on its service life. The longer the system stays in place, the less frequently new raw materials, energy and other resources are consumed to replace it.

Roofing material manufacturers can broadly impact a roof's lifespan in three ways: a) the training and support of specifiers in the design of roof systems incorporating the

manufacturer's products, b) the training and support of contractors installing the products and c) the supply of high quality, proven, long lasting materials.

All three are equally important. As highlighted in the CIB-RILEM document, failure to insure a properly supported structure, to provide for effective drainage, to minimize the number of penetrations and insure that high maintenance roof mounted equipment is accessible for repair and maintenance at the design stage can severely curtail even the best roof system's service life. Similarly, allowing materials to be installed by untrained and/ or unskilled roof mechanics can result in unfulfilled performance expectations.

Manufacturers of low slope commercial roofing systems in North America offer a variety of training tools, documentation and literature, technical and other field support in order to address these issues as effectively as possible. Fundamentally however, it all starts with having a product that under a variety of rooftop conditions can provide a building with long lasting protection, often despite the roof being subjected to a number of the shortcomings noted above.

As the noted roof consultant and researcher C. Cash was fond of noting, "The only rational procedure for selecting a roofing system is its past performance on the roof in the same climate as the new project".

In order to assess the long term performance of their membrane systems, a major international manufacturer of PVC membranes conducted a survey of 44 of its oldest roofs in Europe (Austria, England, Germany, Switzerland) and in North America. The North American roofs were distributed amongst all climatic areas of the USA and Canada. The oldest roof studied was 34 years

old, and the average age of all the roofs was 20.3 years.

Samples from each roof were sent to the manufacturer's laboratory in Switzerland for testing. Additionally, samples from the North American roofs were also sent to the National Research Council Canada. The samples were tested according to the relevant material standards: ASTM D4434 in North America, and SIA V280 in Switzerland. As could be expected, all samples tested exhibited some loss of physical properties, although they generally held up very well compared to the minimum values for new materials called for in the standards they were tested to. Detailed results are available in the reports noted in this paper's reference list.

The one property measured that is perhaps the best indicator of how well the materials are aging is plasticizer content. Plasticizers are blended with the polymer during the manufacturing of vinyl roofing membranes to make them flexible. Some plasticizer is lost as vinyl membranes age. The plasticizers that migrate from the sheet are bio-degraded. In the formulation of vinyl membranes, the choice of the appropriate types and grades of plasticizers, and their use in sufficient quantities, are critical to the long term performance of the finished product, as they determine the material's ability to resist thermal cycling, structural movement, hail, etc.

The residual plasticizer content is plotted against sample age in Figure 3. As expected, plasticizer content decreases with age. As can be seen, the data correlate quite well, despite the fact the samples were taken from roofs located in various European and North American climate zones, and that the roof

constructions and building occupancies vary appreciably. With one exception, even the oldest samples (up to 34 years old at the time of testing) still contain approximately 60% or better of their original plasticizer, and they were all found to be flexible when removed from the roofs.

The analytical results simply quantified the most important observation made during the extensive survey. All the membranes had retained sufficient plasticizer to allow them to be hot air welded. On every roof studied, a roughly 1 m x 1m “patch” of new material, was welded to the existing membrane to seal the sample removal area. Weldability is critical to the long term performance of any thermoplastic roof as it allows permanent, watertight repairs or modifications to be made to the roof at any time during its service life. The survey and the data generated in the manufacturer’s laboratories and at the National Research Council Canada confirm that properly formulated and maintained reinforced PVC roof membranes can perform for decades in various climates throughout North America and Europe.

The data was included in a submittal package to the British Board of Agrément (BBA) during the Agrément Certificate renewal process for the manufacturer’s products. BBA issued Agrément Certificates are used to demonstrate product compliance within the United Kingdom’s Building Regulations. The BBA is somewhat unique amongst standards and testing agencies in that it provides a durability statement in its Agrément Certificates. The BBA conducts site assessments of the manufacturer’s oldest installations and tests the physical properties of the samples that are pulled during these inspections, both “as received” and after subjecting them to further conditioning (200 days at 80 C). After assessing the results of their own investigation, as well as having

thoroughly analyzed the data generated in the manufacturer’s study, they issued the following durability statement in the product’s BBA Certificate: “All available evidence suggests that the durability of {*the manufacturer’s specific product designations*} membranes when used in accordance with the relevant BBA Certificates should have a life in excess of 35 years”. At the time this paper is being written, this is the longest durability projection provided to any membrane roofing system holding a BBA Agreement Certificate.

5. LIFE CYCLE ASSESSMENT

CIB-RILEM’s tenets of sustainable roofing are a practical guide that can be used by any stakeholder in the roofing industry (owners, designers, contractors, etc.) to guide them to sustainable roofing solutions, or to assess various roofing options in a general or on a project specific basis. What the tenets do not do however is provide a quantitative framework for assessing the sustainability of roofing materials or systems.

Life Cycle Assessment (LCA) is a tool for quantifying a material or system’s environmental impacts throughout all phases of its life cycle: from raw material extraction right through to the end of its service life. LCA is increasingly being referenced in various environmental ratings systems and environmentally preferred product (EPP) purchasing policies, as it is an objective, science based approach that can be used to measure a wide variety of impacts. Fundamentally, an LCA analysis breaks down the high level criteria outlined in the CIB-RILEM document (burdens on the environment, energy and service life/ life span), and applies the appropriate metrics to them.

A LCA was commissioned to compare the most common North American low slope

roofing assemblies: 4 ply Built-Up (BUR), 2 ply modified bituminous, EPDM, TPO and PVC. In order to account for the importance of climate, particularly as it impacts a building's energy consumption throughout the roof's service life, the assessment was carried out considering three locations: Austin, TX, Boston, MA and Los Angeles, CA. The analysis was conducted using the US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). The impacts chosen for analysis were nonrenewable primary energy, global warming, acidification and photochemical smog.

The analysis involved calculating the impact for each assessment category for one square meter of roof area, over the estimated service life of the system, in each location. The results are then annualized. Metrics for each assessment criteria are different. For example, the "global warming" metric is "kg CO₂ equivalents", while the "nonrenewable primary energy metric is "MJ". In order to be able to present the data in a succinct manner, the highest value amongst the systems being analyzed for each criteria is assigned a value of 100. All other values are scaled and presented as a percentage of the highest value for each impact category. The aggregate results are presented in Figure 4.

The most important factors driving the LCA impact results are:

- consumption of non-renewable (primarily oil and gas) raw materials
- impact on a building's energy consumption throughout the service life of the roof assembly
- service life expectancy.

As noted throughout the paper, thermoplastic PVC membranes rate very well in all of these categories, which results in the overall favorable results in the LCA analysis as

shown in Figure 4. The study covered all life cycle phases from raw material extraction to end of service life: cradle to grave. Since the study was completed, post consumer recycling of PVC membranes at the end of their service life has been introduced. Considering this unique attribute of PVC roofing membranes, one could conduct a cradle to cradle analysis, which would further separate PVC from other materials on a LCA basis.

6. SUSTAINABILITY AND SAFETY

Sustainability is fast becoming a critical criteria in how we assess our design and construction practices. However, as with most "movements", we must be vigilant to avoid unintended negative consequences. Within the sustainable building movement one such area is fire safety. At their recent 25th anniversary symposium, the Fire Protection Research Foundation highlighted the intersection of fire protection and environmental sustainability as an emerging issue. There is a concern that fire safety may be compromised through restrictions on chemical substances used to retard or suppress the development of fire, and the shortage of naturally occurring materials with inherent fire protection features. The various environmental rating systems such as the United States Green Building Council's LEED do not account for component damage and the numerous other negative health and safety effects of unwanted fires in buildings.

The growth of PVC in many construction applications such as wire and cable was in large part due to its inherent fire resistance properties. PVC generally does not support combustion and self extinguishes when the source of a flame recedes or extinguishes. In building fire situations, PVC roofing membranes have in numerous instances prevented the spread of flames across the roof surfaces. The roof mounted lighting system

of a major athletic stadium short circuited on a number of occasions, causing fires. The fires were never able to propagate across the surface of the stadium's PVC roof, thereby limiting the damage and preventing a potentially very dangerous situation from developing. Similar experiences have been reported on a variety of commercial and industrial facilities where fires originating inside the building and propagating up through roof penetrations, or initiated on the roof by other trades, etc. have been prevented from spreading across the roof surface by the highly fire resistant PVC membranes, protecting the building and its occupants from serious harm.

One area that has been specifically highlighted for concern by the National Fire Protection Agency (NFPA) is the use of rooftops as a platform for solar photovoltaic (PV) installations. Fires resulting from PV systems present unique and dangerous challenges to fire fighters due to the fact that the PV panels continue to generate electricity as long as they are exposed to sunlight, increasing the risk of rapid fire spread across the underlying roof surfaces. With their superior ability to minimize the spread of flame and to self extinguish, PVC membranes provide important life safety benefits on roofs upon which PV arrays are to be installed.

7. CONCLUSIONS

Taking a very practical approach to a topic that is generally viewed in almost philosophical terms, CIB-RILEM outlined a series of tenets for sustainable roofing. Thermoplastic PVC roofing membranes fulfill all relevant tenets, as well as, or better than available alternatives:

- Minimize the burden on the environment through efficient use of non-renewable raw materials, the only post consumer recycling program which allows membranes at the end of their service life to be recycled back into new membranes, and mitigation of greenhouse gases.
- Conserve energy through the reduction of cooling energy consumption over conditioned spaces.
- Extend the lifespan of all components in the roof assembly by providing very long lasting membranes which can easily and effectively be maintained and repaired, insuring longevity.

The tenets are captured similarly in a qualitative manner in Life Cycle Assessment evaluations, where PVC membrane systems have been shown to have less impact on the environment across a series of environmental metrics than competing systems.

This high level of sustainability of PVC roofing materials is complimented by superior fire resistance, a life safety issue that will only grow in importance as rooftops are increasingly used for other purposes such as the generation of renewable energy.

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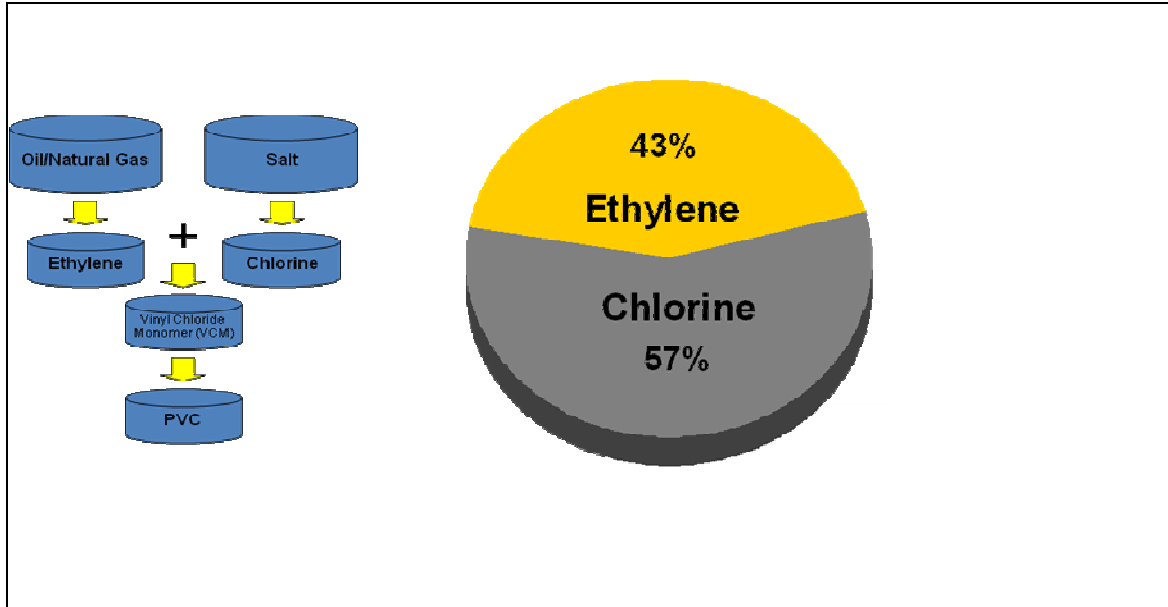


Figure 1: Raw material composition, polyvinyl chloride

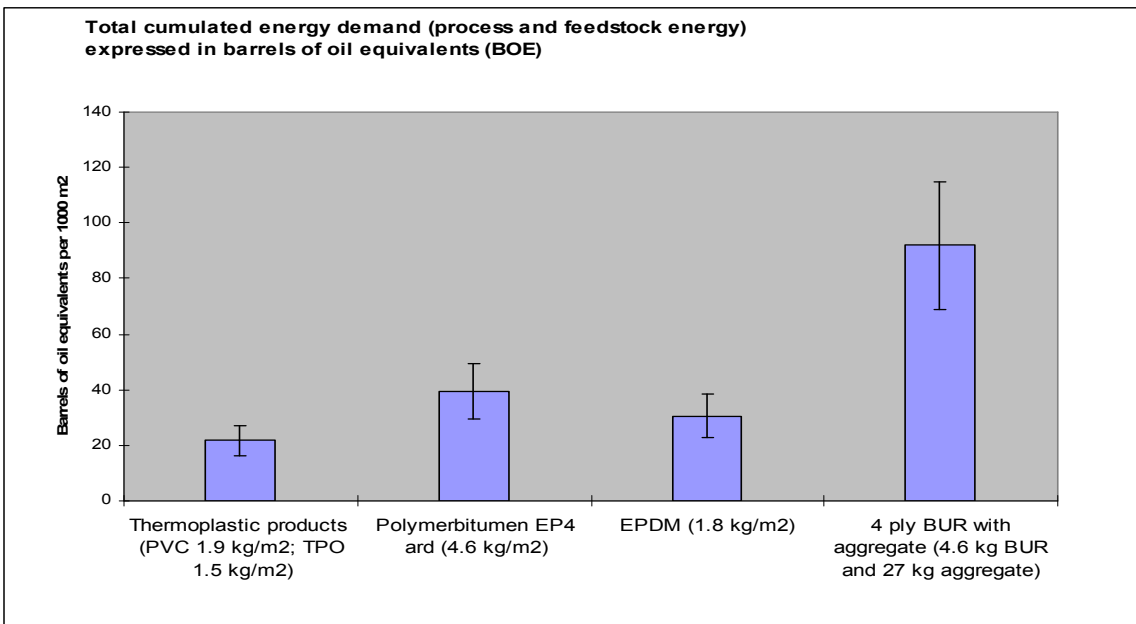


Figure 2: Total Cumulated Energy Demand expressed as “barrels of oil equivalents

State	Cooling Energy Saving kWh/m ² CRA	Heating Energy Penalty therm/m ² CRA	Energy Cost Saving (\$/m ² CRA)
CA	6.13	0.0292	0.699
NV	6.86	0.0737	0.570
FL	5.72	0.0115	0.448
NH	5.35	0.121	0.482
MN	4.17	0.137	0.136
IL	4.22	0.0994	0.217
US	5.02	0.0645	0.356

Table 1: Calculated average annual results for selected states (Source LBNL)

state	CO ₂ reduction kg/m ² CRA	NO _x reduction g/m ² CRA	SO ₂ reduction g/m ² CRA	Hg reduction µg/m ² CRA
CA	2.58	2.31	1.79	61.2
NV	3.64	6.37	4.74	71.8
FL	3.77	6.45	11.1	29.7
NH	1.82	2.14	6.36	21.6
MN	3.09	7.45	12.4	89.5
IL	2.97	5.48	19.6	89.9
US	3.02	4.81	12.4	61.2

Table 2: Calculated annual average emission reductions for selected states (Source LBNL)

State	CO ₂ Pay-Back Period (years)	CO ₂ Pay-Back multiple over 20 year service life
CA	1.8	11.1
	1.2	16.7
FL	1.2	16.7
NH	2.4	8.3
MN	1.3	15.4
IL	1.6	12.5
US	1.7	11.8

Table 3: Average CO₂ pay-back periods, and pay-back multiples for selected states (Source: Carbotech).

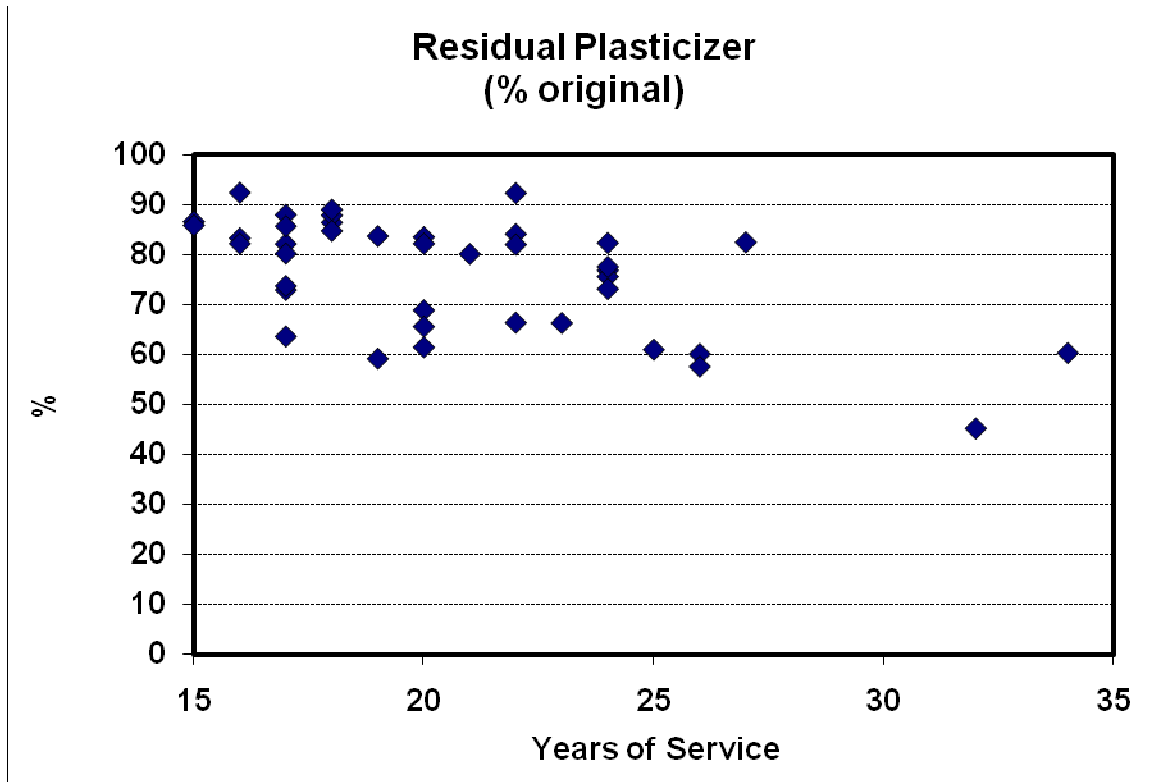


Figure 3: Residual Plasticizer Content vs. Years of Service

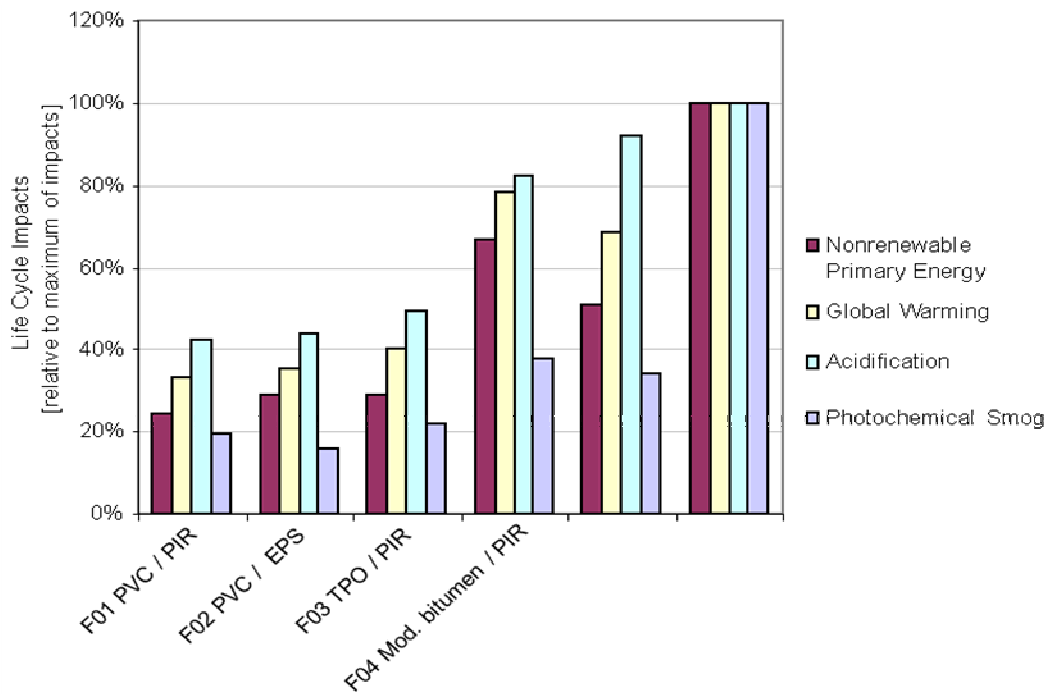


Figure 4: Comparative Life Cycle Assessment (LCA) results for 5 North American Roofing Assemblies