POLITECNICO DI TORINO

Master of Science in Engineering and Management

Master's Degree Thesis

Development of a sustainable circular economy system in the roofing and geo composites industries

Tutor: **Candidate:**

Giulia Bruno ***Loris Lodi***

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Abstract ITA

L'imperativo globale di affrontare il degrado ambientale e la scarsità di risorse ha catalizzato un cambiamento di paradigma verso modelli economici sostenibili e circolari in tutti i settori. I settori delle coperture e dei geo compositi, parte integrante dell'edilizia e delle infrastrutture, non fanno eccezione. Questo studio vuole approfondire la complessa interazione tra sostenibilità e circolarità in queste due importanti realtà industriali, offrendo un'analisi completa dello stato dell’arte e sviluppando due casi studio incentrati sull’operato della SD Polymers, azienda leader del riciclaggio di materie plastiche post-industriali nel sud-est degli Stati Uniti.

Dopo una prima esplorazione del modello economico lineare tradizionale, evidenziandone caratteristiche e criticità, l’attenzione è spostata sulle radici del concetto di economia circolare approfondendo sfide e benefici legati allo sviluppo e all’implementazione di tale paradigma con particolare attenzione alle linee guida e alle normative emanate dai governi mondiali.

La ricerca si concentra poi in modo specifico sull'industria della plastica, con un approfondimento sulle sue applicazioni e impatti nella gestione di scarti e rifiuti. Particolare attenzione è posta al riciclaggio dei polimeri di cui vengono dettagliatamente definiti processi meccanici e chimici. Segue un’approfondita analisi del mercato delle plastiche riciclate con attenzione ai contesti territoriali, importazioni & esportazioni e ai numeri relativi a materiali ed applicazioni predominanti.

Un ampio approfondimento è dedicato alle industrie delle coperture e dei geo compositi, con focus sulle dinamiche locali e sulle sfide specifiche del sud-est degli Stati Uniti. Il tutto con l’obbiettivo di esaminarne l’ancora arretrata situazione attuale e capire come il riciclo possa svolgere un ruolo chiave nella promozione della sostenibilità e della circolarità in queste industrie.

Colonna portante del lavoro è l’analisi di due progetti di economia circolare sviluppati dalla SD Polymers LLC. di Macon, Georgia. Il primo caso studio descrive la collaborazione con un’azienda produttrice di rotoli di geo composito allo scopo di riciclare scarti e prodotti non conformi o difettosi per reintrodurli nelle linee produttive come materia prima. Il secondo affronta, invece, la progettazione e la messa in opera di un nuovo processo produttivo aziendale (definizione degli step di lavorazione, ricerca dei macchinari e prove di produzione) per il riciclo delle membrane in TPO, utilizzate per l'isolamento dei tetti.

L’elaborato offre quindi un'analisi completa e dettagliata sulla possibile transizione verso un sistema di economia circolare sostenibile nel settore delle industrie delle coperture e dei geo compositi nel sud-est degli Stati Uniti fornendo uno spunto concreto per promuovere la sostenibilità e la circolarità.

Abstract ENG

The global imperative to tackle environmental degradation and resource scarcity has catalysed a paradigm shift towards sustainable and circular economic models in all sectors. The roofing and geo-composite industries, an integral part of construction and infrastructure, are no exception. This study aims to delve into the complex interplay between sustainability and circularity in these two important industries, offering a comprehensive analysis of the state of the art and developing two case studies focusing on the work of SD Polymers, a leading post-industrial plastics recycling company in the southeastern United States.

After an initial exploration of the traditional linear economic model, highlighting its characteristics and criticalities, the focus shifts to the foundations of the circular economy concept, delving into the benefits and challenges related to the development and the implementation of this paradigm with particular attention to the guidelines and regulations issued by world governments.

The research then focuses specifically on the plastics industry, with an in-depth look at its applications and impacts in waste management. Special attention is paid to polymer recycling. The mechanical and chemical recycling processes are defined in detail, followed by an extended analysis of the recycled plastics market, covering territorial contexts, imports & exports and data about materials and applications.

Extensive coverage is devoted to the roofing and geo-composite industries, with a focus on local dynamics and challenges specific to the Southeast of the US. All with the aim of examining their still underdeveloped situation and understanding how recycling can play a key role in promoting sustainability and circularity in these industries.

The backbone of the paper is the analysis of two circular economy projects developed by SD Polymers LLC. of Macon, Georgia. The first case study describes the collaboration with a manufacturer of geo composite rolls to recycle waste and non-conforming or defective products and reintroduce them into production lines as raw material. The second deals with the design and implementation of a new company production line for the recycling of TPO membranes, used for roof insulation (definition of processing steps, research of machinery and production trials).

The paper thus offers a comprehensive and detailed analysis of the possible transition to a sustainable circular economy system in the roofing and geo-composite industries in the south-eastern United States, providing a concrete way to promote sustainability and circularity.

List of Terms and Abbreviations

CE	Circular Economy
PP	Polypropylene
PE	Polyethylene
EP	Ethylene Propylene
HDPE	high-density polyethylene
LDPE	low-density polyethylene
PET	Polyethylene terephthalate
TPO	Thermoplastic Polyolefin
IPP	Isotactic polypropylene
APP	Atactic Polypropylene
SBS	Styrene-butadiene-styrene
MBP	Membrane Bitume Polimero
EPS	Expanded Polystyrene
EPDM	Ethylene Propylene Diene Monomer
PVC	Polyvinyl chloride
CO_2	Carbon Dioxide
EU	European Union
USA	United States of America
UK	United Kingdom
UN	United Nations
UNI	Ente Nazionale di Unificazione
EN	European Normalization
ISO	International Organization for Standardization
EPR	Extended Producer Responsibility
UV	Ultraviolet
CAGR	Compound Annual Growth Rate
USD	United States Dollar

Introduction

Background

The past two centuries has been characterized by an abundance of material resources. Throughout this period, humanity's capacity to discover, extract, refine, and utilize materials has grown, resulting in increased availability and affordability of materials. The prevailing business approach followed a linear pattern: acquire, produce, utilize, and dispose, all while focusing on economic expansion through heightened consumption. Material supply rarely posed a significant challenge, except during times of conflict. International trade primarily remained within national borders rather than on a global scale, little emphasis was placed on regulating material usage or managing end-of-life processes for products. In terms of real value, material prices generally remained stable or even declined.

Nowadays, the situation presents a contrasting picture. The global population has surpassed eight billion and continues to rise, especially in the most densely populated regions. It's becoming increasingly apparent that the Earth's ecosystems have limitations in coping with the demands currently imposed upon them, environmental issues such as urban air pollution, water contamination in rivers, and chemical pollution of land often appear beyond our control despite the knowledge to contain them. The intricate nature of modern products has led to a greater reliance on a broader array of elements, some of which are relatively scarce. These elements are sourced globally and integrated into products traded on an international scale. The era of easily accessible oil reserves is ending, pushing us to explore oil reserves located kilometres beneath both land and sea. Countries with significant manufacturing capabilities are now in competition to secure exclusive rights to essential mineral resources worldwide, ensuring their domestic production capacities. Previously open trade of these resources is now constrained by nations seeking to safeguard their own consumption or pursuing geo-economic and political goals, evolving laws are imposing stricter regulations on various aspects of manufacturing, including corporate responsibility, product design, material usage, and material disposal. Beyond mere financial metrics, corporate success is increasingly evaluated based on environmental stewardship, workforce well-being, and contributions to the local economies of the communities they operate within.

The concept of sustainable development arises from the necessity to navigate this evolving landscape, the inescapable reality is that energy, water, and materials are indispensable for human existence and prosperity. The challenge is to manage these resources in a manner that satisfies present needs while ensuring that future generations can fulfil their requirements. This is why, in recent years, Circular Economy has gained significant traction as a sustainable alternative to the prevailing linear economic model. To appreciate the value of circularity, it is essential to delve into the characteristics and drawbacks of the linear model that preceded it.

Before Circular Economy: The Linear Model

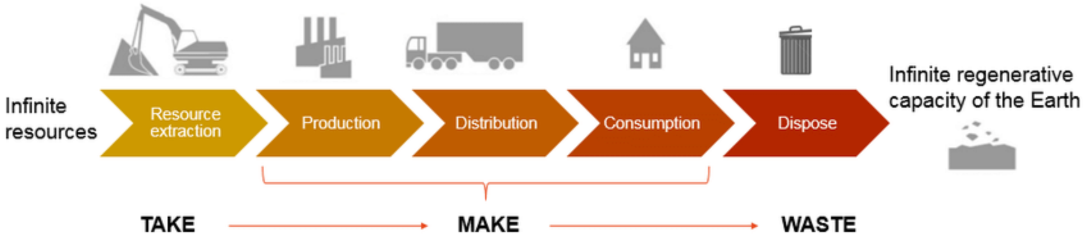

Figure 1 Linear Economic Model

The linear model [fig. 1], also known as the *take-make-dispose* model, revolve around the notion of extracting finite resources, transforming them into goods, and ultimately discarding them as waste after their useful life had ended. This route basically consists of 5 phases: *extraction* of the raw materials, *production* of the finish good by means of manufacturing processes, *distribution* to the end-user, *consumption* or use-phase and *disposal* in landfills after the completion of its purpose.

Linear economic thinking has been around for centuries, it was the dominant economic model for most of the 20th century. It is based on the desire to make products and offer services for the lowest price: raw materials are extracted from nature at the lowest cost, turned into products with the least amount of labour, and sold at the highest price. In this framework, the emphasis is on continuous growth, which often lead to rampant resource consumption and environmental degradation. Industries flourish by maximizing production and minimizing costs, often at the expense of natural resources and ecosystem health. This approach seems viable as long as resources appear abundant and waste disposal manageable. However, as the global population surged and industrialization accelerated, the flaws in this linear model became increasingly evident. One of the glaring issues of the linear model is its inherent unsustainability. Operating on a finite planet with finite resources, it leads to concerns about resource depletion. If non-renewable resources are extracted at an unsustainable rate, the potential for future generations to meet their needs will be under jeopardy. Moreover, the linear model's reliance on a constant influx of raw materials put immense pressure on ecosystems, contributing to deforestation, habitat destruction, and biodiversity loss. Waste emerges as another critical problem: products are created without much thought about their end-of-life fate. This approach result in overflowing landfills, increase greenhouse gas emissions from decomposing waste, and pollution of land, water, and air. In addition, the linear model inadvertently promoted a throwaway culture that disregarded the environmental consequences of excessive consumption.

Furthermore, the economic benefits are often short-lived: while rapid production and consumption lead to economic growth, this growth is fragile and vulnerable to market fluctuations. The model's reliance on constant resource inputs makes industries susceptible to resource price volatility, geopolitical tensions, and supply chain disruptions. This economic fragility is still witnessed during times of resource scarcity or sudden price spikes, like the Oil Crisis in 1973 or the Covid-19 pandemic.

Figure 2 Linear Model. Source: www.europarl.europa.eu

Circular Economy

Concept and Origins

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."

J. Kirchherr. *Conceptualizing the circular economy: An analysis of 114 definitions*. 2017

The concept of Circular Economy represents a revolutionary approach to economic and environmental sustainability, aiming to redefine our patterns of production and consumption. Unlike the traditional linear model that follows a *take-make-dispose* trajectory, CE seeks to create a closed-loop system where resources are continuously reused, regenerated, and recycled, minimizing waste and environmental degradation while fostering economic growth. [fig. 3]

The origins of this concept can be traced back to a combination of historical events, environmental concerns, and visionary thinkers. While the concept gained significant attention in recent years, its foundations were laid decades ago. In the mid-20th century, as post-World War II industrialization accelerated, the limits of Earth's resources began to come into focus. Economist Kenneth Boulding's *Spaceship Earth* metaphor and Rachel Carson's seminal book *Silent Spring* highlighted the fragility of the planet and the unintended consequences of unchecked growth. [1][2] These ideas set the stage for a growing environmental consciousness that would later intersect with the Circular Economy concept.

A pivotal figure in the early development of CE thinking was Walter Stahel, a Swiss architect and economist. In the 1970s, Stahel coined the term *service economy* and advocated for a shift from the prevalent ownership-based economy to one focused on delivering services and experiences. [3] His ideas laid the groundwork for extending the lifespan of products through repair, remanufacturing, and refurbishment. Stahel's work was instrumental in shaping the notion that a Circular Economy could be achieved by decoupling economic prosperity from resource consumption.

Another influential concept that dovetailed with Circular Economy principles was the *cradle-to-cradle* design philosophy introduced by William McDonough and Michael Braungart in the early 2000s. This approach emphasized the design of products and systems that mimic natural cycles, ensuring that materials remain in use indefinitely. Rather than relegating materials to waste, the *cradle-to-cradle* model envisions materials as nutrients in a closed-loop system, where they can be perpetually recycled and repurposed without loss of quality. [4][15]

The term circular economy was first used in an explicit manner by Pearce and Turner. In their book called *Economics of Natural Resources and the Environment*, they discussed the negative aspects of the traditional economy with its open-ended concept and proposed an alternative in the form of a closed system. [5]

As environmental concerns intensified and scientific evidence of climate change and resource depletion mounted, governments and businesses began recognizing the urgency of transitioning to a more sustainable economic model. The European Union's adoption of the *Circular Economy Action Plan* in 2015 marked a significant milestone, outlining strategies to promote resource efficiency, sustainable product design, and waste reduction across member states. Businesses also recognized the economic advantages of embracing circular practices, such as reduced reliance on virgin materials, decreased waste disposal costs, and enhanced brand reputation.

In recent years, the CE has gained remarkable momentum. Innovations in technology, such as 3D printing, advanced recycling methods, and digital platforms for sharing resources, have enabled new avenues for circularity. Collaborative initiatives between industries, governments, and academia have further accelerated the adoption of circular principles. These efforts are driven by the understanding that a Circular Economy not only mitigates environmental degradation but also generates economic opportunities and long-term resilience.

As proposed by Blomsma and Brennan in their article [6] we can divide the emergence of circular economy into three stages. The first stage, between 1960 and 1985, is called preamble period. Within that period the discussion about waste and resources grew and strategies such as recycling, composting or waste-to-energy have been developed. Industries and governing bodies faced pressure to support the emerging concept and discussions in other academic areas, such as physics or biology, has further driven the debate. However, during that early stage, waste was associated with costs and therefore interpreted negatively. Hence, no clear solutions had been developed and the taken initiatives such as recycling had not been matured at this time.

The second phase, the excitement period, occurred between 1985 and 2013 and is characterized by a positive view on waste. With strategies such as product-service systems, urban mining, recycling, remanufacturing or upgradability, the use period of resources should increase and disuse as well as landfilling should be avoided. Further, sustainable development received growing attention and was seen as an opportunity to save costs or for innovation. [7] In 1996, Germany was the first country that implemented circular economy in the form of a new law which should regulate waste management. In addition to that, the Chinese government started to make use of circular economy in that stage as an economic model to tackle environmental problems.[8][15][22]

From 2013 until now, the validity challenge period occurs. Although the number of academic publications considerably increased since 2015, there is still some uncertainty associated with the topic and interpretations are being made. One issue, for example, is the relationship of sustainability and circular economy as well as a lack of tools and appropriate language in some areas within CE. Hence, there is still a lot of work to do to clarify the concept and many opportunities for future research are available. [9][15]

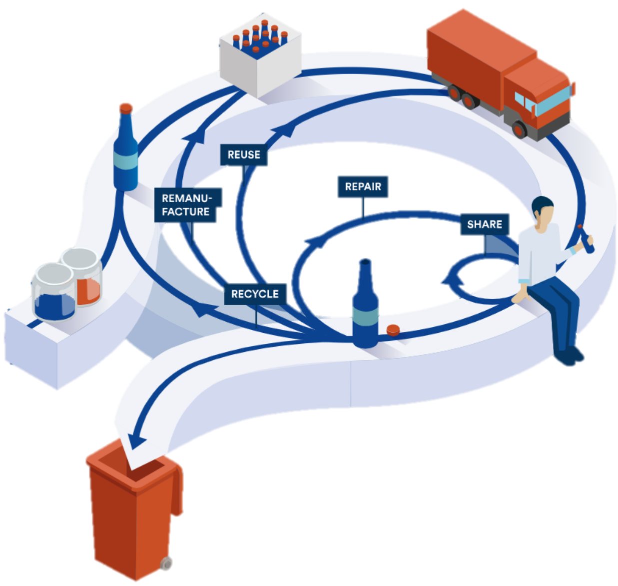

Figure 3 Circular Economic Model. Source: www.europarl.europa.eu

Benefits and Challenges

Circular Economy offers a plethora of benefits that span over environmental, economic, and social domains, but it also presents certain challenges that necessitate careful consideration and strategic planning. This transformative economic approach holds the potential to reshape industries, reduce waste, and enhance sustainability, but its successful implementation requires overcoming hurdles and ensuring widespread engagement.

One of the most notable benefits of CE is its potential to significantly mitigate environmental degradation. By reducing the reliance on virgin resources, circular systems minimize the extraction and depletion of non-renewable materials, subsequently decreasing the strain on ecosystems and conserving biodiversity positively affecting land productivity and soil health. In Europe, for the consumption of primary materials that could mean a decrease of 32% by 2030 and 53% by 2050. [11] Additionally, the emphasis on product durability, repairability, and remanufacturing helps curb the proliferation of discarded items in landfills and oceans. This, in turn, reduces pollution, lowers CO_2 and other greenhouse gas emissions, and contributes to the fight against climate change.

From an economic standpoint, Circular Economy holds immense promises as well. By reimagining the value chain and promoting the reuse and refurbishment of products, businesses can tap into new revenue streams and markets. Adopting circular practices often requires a shift toward service-based business models, where companies offer services instead of selling products outright. This encourages longer-lasting products and fosters customer loyalty. GDP is expected to increase considerably because of higher revenues from circular activities and lower costs due to a more efficient use of input factors, as a side-effect the income of households will grow because of higher salaries, spending and savings. For Europe, GDP is expected to grow by 11% by 2030 and 27% by 2050 compared to 4% and 15% without a circular economy approach, which allows benefits of up to €1.8 trillion by 2030. [10][22]

Moreover, circular economy has the potential to create jobs because recycling and remanufacturing requires qualified employees and promotes innovation through new products, networks, and systems. For companies, new profit opportunities emerge because input costs decrease, and completely new profit streams might arise due to a demand for new services such as collection and reverse logistics, product remarketing and sales platforms as well as parts and component remanufacturing and product refurbishment.

Circular solutions lead to a higher number of interactions with customers throughout the lifetime of a product and consequently to an improved customer loyalty and satisfaction. CE systems require fewer virgin materials, lowering volatility and making cost calculations easier for businesses. At the same time, it makes the supply chain less vulnerable to natural disasters or geopolitical imbalances. [9] [10][15]

On a societal level, it can bring about positive social impacts. The emphasis on local production, repair networks, and resource sharing can enhance community resilience and foster stronger social connections. Additionally, by prioritizing ethical sourcing and responsible consumption, circularity promotes awareness about the true cost of products and encourages more conscious consumer behaviour. This will lead to reduced overconsumption and a shift toward more sustainable lifestyles. Furthermore, as discussed within the economic benefits, closing loops has the potential to create jobs (even if some services or productions would be stopped), and make families save money due to lower costs for primary resources. Customers also benefit from lower costs of ownership due to higher lifetimes of products. [12][15][22]

However, the transition to a circular economy is not without challenges. One of the primary obstacles is changing deeply ingrained patterns of production and consumption (like customer perception towards reused components or lack of public awareness and enthusiasm towards sustainability). Shifting away from the convenience of disposable goods toward durable and repairable products may require a cultural shift, educating consumer to value quality over quantity. Additionally, CE relies on effective waste management infrastructure and recycling systems. Insufficient recycling facilities, lack of standardized collection methods, and inadequate waste separation can hinder the efficient flow of materials through circular loops. [9][13]

Another challenge lies in the design phase. Products must be intentionally designed for circularity, incorporating considerations like modularity, ease of disassembly, and use of recyclable materials. Achieving these design principles requires collaboration among designers, engineers, and manufacturers, as well as adjustments to existing regulations and standards. In addition, circularity face two other technical challenges: recyclability of different materials and products and energy consumption of recycling processes. [13]

Furthermore, the Circular Economy's success hinges on collaboration among stakeholders across industries, governments, and communities. Creating closed-loop systems demands cross-sector cooperation to establish efficient reverse logistics, share best practices, and develop innovative technologies. Achieving regulatory alignment incentivizing circular practices, and harmonizing policies across borders are complex tasks that require global cooperation. [9][14][15]

Implementation

The implementation of the CE represents a multifaceted endeavour that necessitates collaboration among governments, industries, and society at large. Transitioning from the linear model to a circular framework requires a comprehensive approach that spans economic, industrial, and societal dimensions.

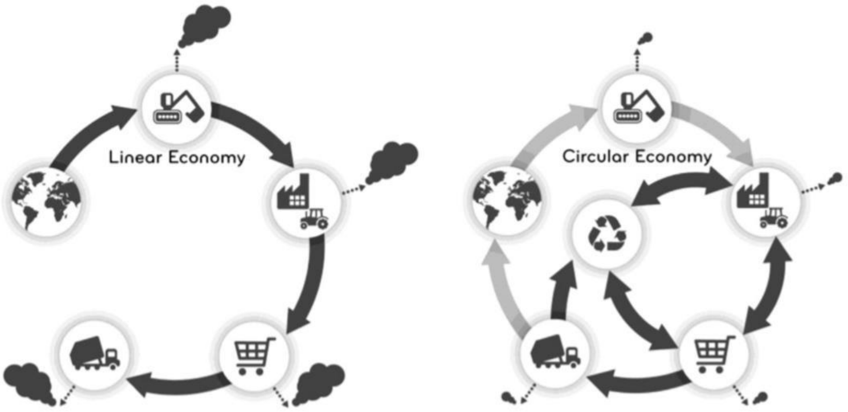

Figure 4 Linear vs Circular Economy

Researchers deals with two approaches regarding the implementation:

1. An economy-wide implementation with a system approach on the macro, meso and micro level.
2. Implementation targeted on groups of sectors, products, materials as well as substances.

Examples for the second case are the action plan developed by the European Commission proposing measures for the waste management sector or other legislations about eco-design and initiatives in areas like plastic, food waste and construction. Historically, governments measures tend to prioritize products such as electric and electronic equipment, textiles, furniture, packaging, and tires as well as raw materials such as plastic, metals, paper, and glass. [17][22]

From a societal perspective (meso & macro level), embracing the Circular Economy demands a shift in attitudes and behaviours towards consumption and waste. Education and awareness campaigns play a crucial role in informing the public about the environmental impact of their choices and encouraging more conscious consumption. By promoting the importance of repair, reuse, and responsible disposal, individuals can actively participate in reducing waste and extending the lifecycle of products. Communities can foster a culture of sharing, enabling resource pooling through platforms for tool-sharing, clothing swaps, and collaborative consumption. Additionally, supporting local artisans and businesses that prioritize sustainable practices can stimulate the circular local economy while building a sense of community resilience. [22][18]

At an economic (meso & macro) level, governments and businesses need to take a proactive role in enabling and incentivizing circular practices. Governments can establish policies that reward companies for adopting circular approaches, such as tax incentives for products designed for longevity and ease of repair. They can also implement extended producer responsibility regulations, where manufacturers are responsible for the end-of-life management of their products, encouraging design for durability and recyclability. Creating a conducive regulatory environment and harmonizing standards across industries can facilitate the integration of circular principles into business operations.

From an industrial standpoint, the implementation of the CE requires a rethinking of production and supply chains. On a company (micro) level, it becomes crucial to adopt a different supply chain and redesign the business model. These two aspects are closely connected as changing business models affects the way a company creates and delivers value through its supply chain. [19] The result of incorporating circular economy into business should therefore be a circular business model within the company and a circular supply chain within the value network the company is part of. [20] Those supply chains are structured as closed, short and cascade loops focusing not on efficiency but rather on a collaborative value capturing approach beyond industrial boundaries. This implies regional and local structures instead of global ones, the consideration of technical and biological cycles and the application of leasing and service-based strategies. [21] Businesses can adopt strategies that prioritize resource efficiency, such as lean manufacturing and closed-loop systems. Collaborative partnerships along the value chain can facilitate the exchange of materials, reducing waste and optimizing resource use. The adoption of circular business models, such as product-as-a-service and leasing, incentivizes companies to design products for durability and ease of maintenance. [18][16][22]

In manufacturing, adopting modular design principles allows for components to be disassembled and replaced. Remanufacturing, a process where used products are restored to their original condition, offers both economic and environmental benefits. Additionally, implementing digital, information and communication technologies can enable better tracking of product lifecycles, optimizing maintenance schedules and facilitating the identification of materials for recycling. [4][9][18]

In the realm of waste management, CE calls for a shift from end-of-pipe solutions to a more holistic approach. Recycling should be optimized through improved sorting and collection systems, as well as the development of innovative recycling techniques that can handle complex materials. Organic waste can be transformed into valuable resources through composting and anaerobic digestion, reducing landfill burden and greenhouse gas emissions.

Collaboration across sectors is key for successful circular implementation. Public-private partnerships can drive innovation, research & development of circular technologies. Industry associations and standards organizations can establish guidelines for sustainable practices, fostering consistency and scalability. Cross-sector dialogues can promote knowledge sharing, fostering a deeper understanding of the challenges and opportunities in the Circular Economy landscape.

To address the research gap on this matter, professors Lieder and Rashid have developed a model, recommending following a simultaneous approach: top-down and bottom-up [18] [fig. 5]. The top-down view is based on the so-called *national effort*, composed by all the individuals, governmental bodies and policy makers that are concerned about environmental and social impacts leading to legislations and policies regarding waste, emissions, and resource usage. On the other hand, the bottom-up approach is based on the *individual company effort*, composed by manufacturing companies which are focused on economic benefits and growth. Although many businesses take the environment into account, competition forces them to carefully assess the economic benefits of circular economy initiatives. The aim of the model is to balance the interests of public and business actors focusing on both, environmental and economic aspects. [22]

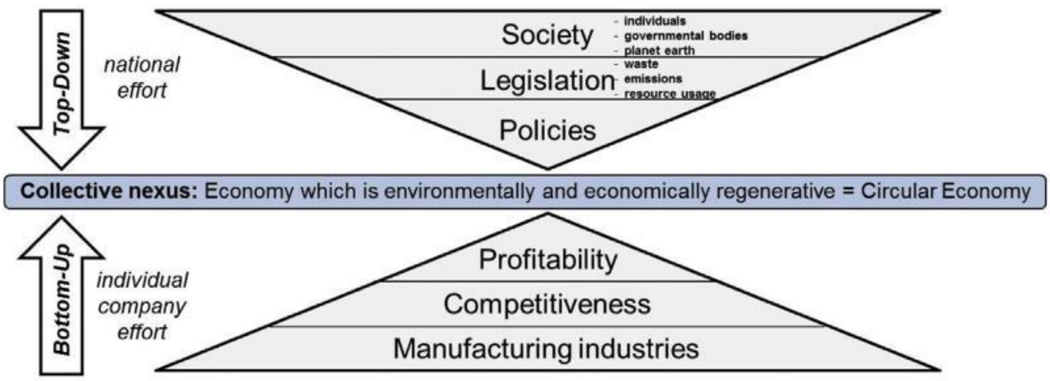

Figure 5 National Effort and Individual Company Effort. Source: www.researchgate.net

Embracing circularity also calls for innovative financial mechanisms. Investment in circular startups, research, and infrastructure development can create a supportive ecosystem. Moreover, businesses can explore alternative revenue streams, such as take-back programs, where customers return used products for refurbishment or recycling; this not only reduces waste but also strengthens brand loyalty.

In conclusion, the implementation of Circular Economy is a complex and transformative process that requires concerted efforts across society, economics, and industry. By fostering a cultural shift towards conscious consumption, governments and individuals can work together to reduce waste and extend product lifecycles. Economic incentives, regulatory frameworks, and circular business models can incentivize companies to adopt sustainable practices. Redesigning production processes, embracing modular design, and exploring innovative waste management strategies are essential steps for industries. Collaboration among stakeholders is critical for driving innovation, standardization, and knowledge exchange. As the Circular Economy gains momentum, societies can collectively move towards a more sustainable, regenerative, and prosperous future.

Circular Economy and World Regulations

Several principal legislations and initiatives have been established globally to promote circular economy and sustainability. These laws and regulations vary by region and focus on different aspects of the circular economy, including waste reduction, resource conservation, and sustainable practices. Here are some notable examples from different parts of the world:

1. ***European Union***

In 2019 all 27 EU Member States committed to turning the EU into the first climate neutral continent by 2050. To get there, they pledged to reduce emissions by at least 55% by 2030, compared to 1990 levels. They signed the so-called *Green Deal*.

The *New Circular Economy Action Plan*, adopted in 2021 as an integral part of the Green Deal, aims to accelerate the transition to a circular and regenerative economy, increase resource efficiency and double the percentage of circular material use over the next decade. Among the actions envisaged, of particular importance are those concerning:

- the *eco-design of products*: extending the design directive and eco-design criteria aiming at durability and reusability of products and increasing the use of recycled materials, limiting single-use products.
- the *circularity of production processes*: facilitating industrial symbiosis, developing the regenerative and circular bioeconomy, promoting the use of digital technologies for the traceability of resources, increasing the use of green technologies, supporting circularity through the revision of the directive on industrial emissions and the definition of BAT (Best Available Techniques), promoting circularity in small and medium-sized enterprises.
- *consumption circularity*: developing the sharing economy by ensuring that consumers receive reliable information on the lifespan and reparability of products and ensuring minimum requirements for sustainability labels. Ensuring minimum mandatory targets for green public procurement (GPP) and combating the so-called green washing.

The Plan also foresees specific actions in certain sectors: plastics, textiles, construction and building, electronics, batteries and vehicles, packaging, food, and water. [23][24]

2. ***United States of America***

The United States does not have a comprehensive federal framework for circular economy regulations similar to the European Union. However, there have been initiatives and discussions at both the federal and state levels aimed at promoting circular economy principles and practices. At the federal level, certain sectors have witnessed efforts to address specific aspects of circularity: the *Resource Conservation and Recovery Act (RCRA)* and the *Environmental Protection Agency (EPA)* oversee waste management and recycling regulations. Several states have also implemented recycling programs and regulations, but these efforts vary significantly. Some states, such as California and Washington, have implemented EPR laws for specific products like electronic waste and paint. These laws require manufacturers to take responsibility for the end-of-life disposal or recycling of their products.

3. ***China***

The *Circular Economy Promotion Law* came into force in 2009 and focuses on encouraging resource conservation, waste reduction, and the efficient utilization of resources. It includes provisions related to eco-design, waste recycling, and the promotion of circular production methods. China's 13th Five-Year Plan (2016-2020) and subsequent development plans have emphasized the importance of circular economy development. The plans outline targets for resource efficiency, pollution reduction, and sustainable production and consumption. In addition to that, the country banned the import of certain types of foreign solid waste, which has had implications for global recycling markets.

4. Japan

Japan is famous for his *3Rs* approach that stands for *Reduce, Reuse, Recycle*. This approach emphasizes minimizing waste generation, promoting the reuse of materials and products, and increasing recycling rates. Japan during the years implemented some important polices: the *Law for the Promotion of Effective Utilization of Resources* (2000) aims to promote sustainable resource management and waste reduction. It includes measures to encourage recycling, establish recycling targets, and promote eco-friendly product design. The *Eco-Town Program* (1997), which designates certain areas as eco-towns and eco-parks, these areas focus on sustainable waste management, recycling, and resource-efficient practices. The Home Appliance Recycling Law (2001) and the *Containers and Packaging Recycling Law* (1995) that require manufacturers to take responsibility for recycling and end-of-life management of their products. Finally, the country introduced the *Eco Mark Progr*am (2018) that certifies products that meet specific environmental criteria, encouraging consumers to choose more sustainable products. [9]

5. United Kingdom

In 2020, the UK nations collectively unveiled *The Circular Economy Package (CEP)*, a significant policy statement. This package introduces a revamped legal framework aimed at outlining measures to reduce waste and establish an ambitious, credible long-term strategy for waste management and recycling. Many of the topics and provisions within the CEP are closely tied to aspects of resource and waste management policy that the UK nations were already actively engaged in, either through existing measures or ongoing efforts to fulfil commitments made in their respective domestic waste strategies.

The *Resources and Waste Strategy (RWS)* for England, launched in 2018, is a crucial component of the UK government's commitment, as outlined in the 25 Year Environment Plan, to leave the environment in a better condition than it was inherited. Meanwhile, the Welsh Government's strategy, known as *Beyond Recycling*, outlines its vision of transforming Wales into a circular, low-carbon economy. It lays out a series of key actions aimed at achieving the goal of zero waste by the year 2050. The Scottish Government, in its circular economy strategy titled *Making Things Last*, published back in 2016, presents a clear vision and a set of high-priority actions to advance toward a more circular economy. Scotland has also established ambitious targets to drive the adoption of circular practices. In Northern Ireland, the *Department of Agriculture, Environment & Rural Affairs (DAERA)* is currently in the process of developing the Environment Strategy for Northern Ireland. This strategy will address the primary long-term environmental priorities for the region, reflecting the commitment to environmental sustainability.

The UK Government has also been taking steps to tackle plastic waste, including bans on certain single-use plastics, introduction of plastic bag charges, and commitments to eliminate avoidable plastic waste by 2042.[28] The start of these commitments is the implementation of the *Plastic Packaging Tax 2022*, which mandates the use of 30% recycled material in packaging products adopted in markets.

6. India

In 2016, the country issued the *Plastic Waste Management Rules* which focus on reducing plastic waste through regulations on the manufacture, use, collection, and recycling of plastic products. The rules, amended in 2022, mandate the responsibilities of local bodies, gram panchayats, waste generators, retailers, and street vendors to manage plastic waste. The PWM Rules cast Extended Producer Responsibility on producers, importers, and brand owners for to both pre- and post-consumer plastic packaging waste.

7. Australia

Australia's *National Waste Policy*, released in 2018, sets out a vision for a circular economy by reducing waste generation and increasing recycling rates. It aims to improve resource recovery, reduce landfill, and promote sustainable practices. These policies were followed in 2019 by the *National Waste Action Plan*, which drives the implementation of their ambitious targets, including:

- Regulate waste exports.
- Reduce total waste generated by 10% per person by 2030.
- Recover 80% of all waste by 2030.
- Significantly increase the use of recycled content by governments and industry.
- Phase out problematic and unnecessary plastics by 2025.
- Halve the amount of organic waste sent to landfill by 2030.
- Provide data to support better decisions. [30]

8. South Africa

In 2008, the South African government issued the *National Environmental Management: Waste Act*. This legislation provided a framework for waste management and promotes the principles of the circular economy. It established guidelines for waste minimization, recycling, and the responsible management of waste. Based on this legislation, in 2011 and again in 2020 the government published the *National Waste Management Strategy*. NWMS provides government policy and strategic interventions for the waste sector and is aligned and responsive to the *Sustainable Development Goals* of Agenda 2030 adopted by all UN member States.

9. Canada

Each province and territory in Canada have its own waste management, recycling, and environmental legislation. These laws may include requirements for recycling, hazardous and non-hazardous waste disposal, and obligations for companies in terms of waste management The most strict one in the Ontario's *Resource Recovery and Circular Economy Act (2016)*, that implements a producer responsibility framework for products and packaging in Ontario by making brand holders and other persons with a commercial connection to products and packaging accountable for recovering associated resources and reducing associated waste. Canada also has environmental laws at the federal level, such as the *Canadian Environmental Protection Act (CEPA)* and the *Corporate Environmental Responsibility Act (CERCLA)*. To be noted is the *Canadian Council of Ministers of the Environment (CCME)*, which is composed by the 14 federal, provincial, and territorial environmental ministers. This intergovernmental forum meets at least once a year to discuss collective action on national and international environmental issues.

10. United Nations

The *2030 Agenda for Sustainable Development* is an action programme for people, planet and prosperity signed in September 2015 by the governments of the 193 UN member states. It incorporates 17 Sustainable Development Goals [fig. 6] into a grand programme of action with a total of 169 targets or goals. The official launch of the SDGs occurred in 2016, guiding the world on the road ahead over the next 15 years: countries have committed to achieving them by 2030. The Development Goals follow up on the achievements of the Millennium Development Goals that preceded them and represent common goals on a range of important development issues like fighting poverty, eradicating hunger, and combating climate change. [32]

Figure 6 Sustainable Development Goals. Souce: ONU

A remarkable initiative is the establishment of the *Global Alliance on Circular Economy and Resource Efficiency (GACERE)*, promoted by the EU in cooperation with the United Nations Organisations for the Environment (UNEP) and Industrial Development (UNIDO). In addition to the members of the European Union, this initiative, which aims to promote resource efficiency and the transition to a circular economy, involves 11 other countries: Canada, Kenya, Colombia, Japan Chile, Nigeria, Norway, Peru, New Zealand, Rwanda and South Africa. GACERE was launched in February 2021, during the fifth United Nations Environment Assembly.

The main working areas of the initiative are:

- Map the domestic policies on sustainable management of natural resources.
- Identify infrastructural gaps that hinder circular transitions, biodiversity loss, greenhouse gas emissions and possible opportunities for making global value chains greener.
- Advocate for a global transition to a resource efficient and circular economy.
- Identify research needs and possible global governance improvements.
- Help and support partnerships for the circular economy transition.
- Facilitate more global conversations on the governance of natural resources. [31]

These legislations and initiatives represent a fraction of the global efforts to promote circular economy and sustainability. As awareness of environmental challenges grows, more countries and regions are likely to enact laws and regulations that encourage responsible resource management, waste reduction, and the adoption of circular practices.

The Future

If in 2020 and 2021 the pandemic had strongly influenced the economic and social environment, a new dramatic event, the war in Ukraine, deeply marked the international picture in 2022. The economic recovery that had characterised 2021 was held back by difficulties in the supply of energy and raw materials, while rising costs induced a rise in inflation. In 2021, the global economic recovery had led to a sharp increase in demand and commodity prices. In 2022, Russia's aggression against Ukraine and the resulting geopolitical tensions, economic sanctions and speculative pressures slowed supplies and increased prices. This made the vulnerability of countries like Italy, poor in raw materials and too dependent on geopolitically unstable or unreliable regions, even more evident.

This difficult international context has made the need to accelerate both transitions to green energy and circular economy even more urgent, for obvious geopolitical as well as environmental and economic reasons.

The problems of supply and price volatility of raw materials are connected not only to the difficult economic situation, but also to a more structural trend, linked to the growing global demand for raw materials in the face of their not unlimited availability on the planet. Decoupling economic growth from the consumption of virgin materials through the development of circular economy is, therefore, more than ever a strategic objective for the European Union and all other countries that are poor on raw materials. The transition to circular production and consumption models is confirmed as an indispensable condition both for achieving climate neutrality goals and for ensuring sound and sustainable economic development.

The transition towards circular models offers multifaceted benefits. It remains a linchpin for achieving the ambitious goals of climate neutrality, providing an avenue to mitigate environmental impact while invigorating sustainable economic evolution. This paradigm shift aligns harmoniously with the broader vision of fostering resilient economies that withstand the shocks of an unpredictable world. As the global community navigates the intricate web of challenges woven by recent history, the resolute march towards circularity stands as a testament to human innovation and adaptability, offering a beacon of hope and progress amidst uncertainty.

Plastics

Plastics comprise a diverse array of synthetic or semi-synthetic compounds that exhibit flexibility, allowing them to be moulded into solid objects. They are organic polymers with high molecular mass, but often contain other substances. Raw materials utilized to produce plastics are natural products such as crude oil, cellulose, coal, and natural gas: they contain carbon and hydrogen elements, and they may also contain other elements such as oxygen, nitrogen, chlorine, or fluorine. As mentioned before, plastics are compounds of large molecules, called polymers. Polymers are formed by monomers which are joined together in a chain and are named after their elastic and plastic properties. Plasticity is the general property of all materials that results in permanent deformation without breakage. [33]

Usually synthetic and derived from petrochemicals, they can also come from renewable materials. Today's concern for the environment has led to an increase in number of *bioplastics*, such as polylactic acid from maize or cellulosic from cotton linters.

Plastics are conventionally divided into two different categories: thermoplastics and thermosets. [fig.7] [Table 1]

1. *Thermoplastics* are a group of polymers that can be melted when heated and hardened when cooled. These characteristics are reversible. They can be reheated, reshaped and frozen repeatedly.
2. *Thermosets* are plastics that undergo a chemical change when heated, creating a three-dimensional network. When heated and formed these polymers cannot be re-melted and reformed.

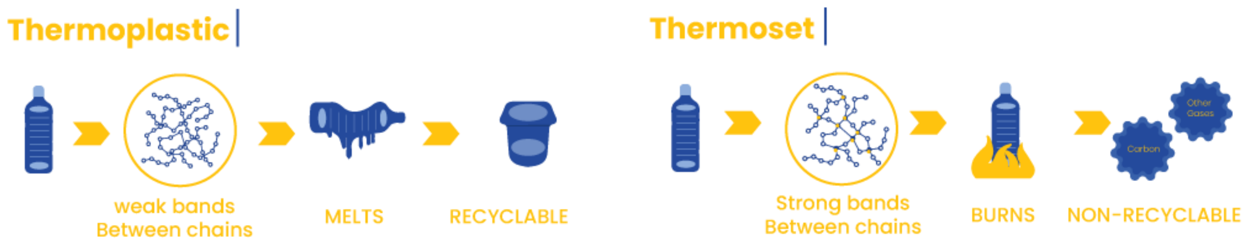

Figure 7 Thermoplastics and Thermosets characteristics

Materials engineers generally further classify plastics according to the chemical structure of the polymer backbone and side chains. Some important groups of these classifications include:

1. *Acrylics*
2. *Polyesters*
3. *Silicones*
4. *Polyurethanes*
5. *Halogenated plastics*

Plastic's versatility and widespread use have transformed industries and lifestyles. The diverse range of plastic types serves various purposes, from packaging to medical devices, driving economic growth and innovation. However, the persistence of plastic waste in the environment, including microplastics, has led to ecological harm, biodiversity loss, and potential risks to human health. Addressing the plastic problem requires a comprehensive approach involving responsible production, effective waste management, and sustainable alternatives.

Table 1 Thermoplastics and Thermosets

Thermoplastics	**Thermosets**
Polyethylene (PE)	Epoxy resins
Polystyrene (PS)	Unsaturated polyesters
Polyvinyl chloride (PVC)	Acrylic resins
Thermoplastic elastomers (TPE)	Melamine resins
Polyetheretherketone (PEEK)	Polyurethane (PUR)
Acrylonitrile butadiene styrene resin (ABS)	Phenol - formaldehyde resins
Polypropylene (PP)	Vinyl esters
Polyethylene Terephthalate (PET)	Urea - formaldehyde resins
Styrene-acrylonitrile copolymer (SAN)	Phenolic resins
Polyamides (PA)	Silicone
Poly methyl methacrylate (PMMA)	
Polyoxymethylene (POM)	
Polyarylsulfone (PSU)	
Polybutylene terephthalate (PBT)	
Expanded polystyrene (EPS)	
Polycarbonate (PC)	
Fluoropolymers	
EVOH	

History

Due to their adaptability and high resource efficiency, plastics have emerged as essential materials in critical industries, like packaging, construction, transportation, renewable energy, medical devices, and even sports. Plastics have fuelled innovation across various sectors, enabling the creation of products and solutions that would be inconceivable today without the use of these materials.

Considered a recent and modern material, plastic has a history that can be traced back to the earliest times. Since ancient times, man has in fact used natural polymers, such as amber, tortoise shells or horn.

The history of plastic began in the 19th century, when, between 1861 and 1862, the Englishman Alexander Parkes, developing his studies on cellulose nitrate, isolated and patented the first semi-synthetic plastic material, which he called Parkesine (later known as Xylonite). This was an early type of celluloid, used to produce handles and boxes, but also flexible items such as cuffs and shirt collars. [38]

The first real affirmation of the new material came a few years later, when in 1870 the American brothers Hyatt patented the celluloid formula. With the aim of replacing expensive and rare ivory in the production of billiard balls, celluloid met immediate success among dentists as a material to be used for dental impressions. Chemically, it was cellulose nitrate, very flammable and so unsuitable for high-temperature moulding. The problem was overcome with the advent of the new century, when cellulose acetate was developed, used to reinforce, and waterproof the wings and fuselage of the first aeroplanes or to produce film.

The *century of plastics* is the 20th century. In 1907 the Belgian chemist Leo Baekeland obtained the first thermosetting resin of synthetic origin by condensation between phenol and formaldehyde, which he patented in 1910 under the name Bakelite. The new material was an overwhelming success and Bakelite quickly became the most widespread and widely used plastic material.
In 1912, a German chemist, Fritz Klatte, discovered the process to produce polyvinyl chloride (PVC), which would have great industrial developments only many years later. In 1913, it was the turn of the first flexible, transparent, and impermeable material that immediately found application in the field of packaging: the Swiss Jacques Edwin Brandenberger invented Cellophane, a cellulose-based material produced in very thin, flexible sheets.

With the 1920s, plastics found a rigorous theoretical basis thanks to Hermann Staudinger, from the University of Freiburg, who initiated studies on the structure and properties of natural and synthetic polymers.
The 1930s and the Second World War marked the creation of the *Plastic Industry*: oil became the raw material from which to produce and processing techniques, starting with moulding, were improved and adapted to mass production. In 1935, Wallace Carothers was the first to synthesise nylon (polyamide), a material that was to spread with the war in the wake of the American troops, finding a multitude of applications: from women's stockings to parachutes, the rise of synthetic fibres began.
Building on Carothers' work, Rex Whinfield and James Tennant Dickson patented polyethylene terephthalate (PET) in 1941, together with their employer, the Calico Printers' Association in Manchester. After the war, this polyester had great success in the production of man-made textile fibres, a sector in which it is still widely used today. Its entry into the world of food packaging dates back to 1973, when Nathaniel Wyeth (Du Pont) patented the PET bottle as a container for carbonated drinks. Lightweight, impact-resistant, and transparent, the bottle invented by Wyeth is now the standard for packaging mineral water and soft drinks. [38]

The war stimulated the need to find substitutes for unavailable natural products, polyurethanes were developed to replace rubber, especially in Germany, where in 1939 the first vinyl chloride-acetate copolymers were industrialised. After the war, discoveries dictated by military needs invaded the civil world. The 1950s saw the discovery of melamine-formaldehyde resins, which made it possible to produce laminates for furniture and to print tableware at low prices. Synthetic fibres (polyester, nylon) experienced their first boom, a modern and practical alternative to natural ones. Those same years were marked above all by the irresistible rise of polyethylene, which found full success only two decades after its invention, exploiting its higher melting point to enable applications so far unthinkable. [38]

Very important to mention is Giulio Natta's discovery in 1954 of isotactic polypropylene, the crowning achievement of his studies on ethylene polymerisation catalysts which earned him the Nobel Prize in 1963 together with the German Karl Ziegler, who had isolated polyethylene the year before. Polypropylene would be produced industrially from 1957 under the brand name Moplen, revolutionising homes all over the world but above all entering the Italian mythology of the *economic boom*.

The 1960s saw the definitive establishment of plastic as an irreplaceable tool in everyday life and as a new frontier also in the fields of fashion, design and art. The material burst into the everyday life and imagination of millions of people, into kitchens, living rooms, allowing ever-widening masses to access consumption previously reserved for the privileged few. Polymers simplified an infinity of daily gestures, colouring homes, revolutionising habits consolidated for centuries and contributing to the creation of the modern lifestyle.

The following decades are those of great technological growth, of progressive affirmation for increasingly sophisticated and unthinkable applications, thanks to the development of so-called engineering plastics: Polymethylpentene (TPX) used mainly to produce tools for clinical laboratories, resistant to sterilisation and with perfect transparency. Polyimides, thermosetting resins that do not alter when subjected to temperatures of 300°C for even very long periods and which are therefore used in the automotive industry for engine components or microwave ovens. Acetal resins, polyphenylene oxide, ionomers, polysulphones, polyphenylene sulphide, polybutylene terephthalate, polycarbonate used, among other things, to produce astronauts' space helmets, contact lenses and bulletproof shields. Engineering plastics have such characteristics of both thermal and mechanical resistance (which are still partly unexplored) that they are often superior to special metals or ceramics, so much so that they are used in the production of turbine blades and other components of jet engines, or in the production of pistons and piston rings for cars. [38]

Plastic Types

The most common types of plastics are listed below:

Acrylonitrile Butadiene Styrene (ABS) is a terpolymer formed through the polymerization of styrene and acrylonitrile while incorporating polybutadiene. Most ABS can withstand temperatures between -20 and -80 °C, which make them perfect for applications like automotive parts, 3D printing, and housings for electronic equipment such as computer monitors, printers, keyboards, and drainage pipes. [33]

Polyamide (PA) exist naturally, for example with wool and silk, and synthetically as *nylon*, aramid, and sodium poly-aspartate. Industries such as the fashion, automotive, carpet or sportswear use synthetic polyamides in textiles for their durability and strength properties. It is estimated that the transport industry consumes 35% of polyamide worldwide. Some key applications include fibres, toothbrush bristles, pipes, fishing lines and low-strength machine parts in engines or gun frames.

Polycarbonates (PC) belong to the group of thermoplastic polymers containing carbonates. Their solidity, rigidity and transparency make them perfect for engineering purposes. In addition, their elasticity makes them easy to machine, mould and thermoform. Many applications, such as compact discs, glasses, riot shields, security windows, traffic lights and lenses, therefore, use polycarbonates.

Polyester (PES) may be present in nature, in plant cuticles, or synthetically through step-growth polymerisation, like polybutyrate. Natural ones and some synthetic polyesters are biodegradable, while most synthetic ones are not. PES are widely used in the textile and clothing industry.

Polyethylene (PE) stands as the most used polymer, boasting a global annual production of approximately 80 million tonnes. It finds extensive use in the packaging industry for crafting plastic bags, plastic films, geomembranes, and various types of containers, including bottles.

High-density polyethylene (HDPE) offers an exceptional strength-to-density ratio. It is primarily utilized for manufacturing detergent bottles, milk jugs, moulded plastic crates, plastic bottles, corrosion-resistant pipes, geomembranes, and plastic lumber. In the context of pipes, it is often referred to as "alkaline" or "polythene."

Low-density polyethylene (LDPE) was first developed by Imperial Chemical Industries (ICI) in 1933 and continues to be produced using the same method today. It finds enduring applications in outdoor furniture, floor tiles, shower curtains, and clamshell packaging.

Polyethylene terephthalate, often abbreviated as PET or PETE, represents the predominant thermoplastic polymer resin within the polyester category. It is extensively employed in various industries, serving as the material of choice for fabricating fibers used in clothing and to produce liquid and food containers. PET also finds application in thermoforming processes, and it is commonly combined with glass fibers to create engineering resins.

Polypropylene (PP), alternatively known as polypropene, represents a sturdy and corrosion-resistant addition thermoplastic polymer. Following polyethylene, it ranks as the second most widely manufactured synthetic plastic. Its versatility allows for a broad spectrum of applications, including but not limited to packaging, labels, textiles, stationery, plastic components, reusable containers, laboratory apparatus, loudspeakers, automotive parts, and the production of polymer banknotes.

Polystyrene (PS) is a synthetic aromatic polymer derived from the styrene monomer that can exist in both solid and expanded forms. PS is a cost-effective resin that is transparent, rigid, and somewhat brittle. While it is naturally clear, it can also be tinted or coloured. As one of the most extensively utilized plastics, with production reaching millions of tonnes annually, industrial enterprises employ it to create expanded pellets for purposes such as packaging, food containers, plastic tableware, disposable cups, plates, cutlery, compact disc (CD) cases, and cassette tapes.

High-impact polystyrene (HIPS) is a graft copolymer created by blending polystyrene with the more flexible polybutadiene rubber during the polymerization process. Frequently advertised as high-impact plastic, HIPS is utilized in injection molding to manufacture items such as toys, refrigerator liners, food packaging, and cups for vending machines.

Polyurethane (PUR and PU) is a polymer constructed from organic units linked by carbamate bonds, commonly referred to as urethane. While most polyurethanes are thermoset polymers that retain their form when heated, there are also thermoplastic polyurethanes available. Typical applications encompass cushioning foams, thermal insulation foams, surface coatings, and printing rollers. It stands as the most extensively employed plastic material in the automotive industry.

Polyvinyl chloride (PVC), alternatively known as polyvinyl or vinyl, ranks as the third most manufactured synthetic plastic polymer, trailing behind polyethylene and polypropylene. PVC is offered in both rigid (RPVC) and flexible forms. Rigid PVC finds its way into applications like plumbing pipes, gutters, doors, window frames, and items such as bank or membership cards. Flexible PVC, on the other hand, is commonly utilized for shower curtains, flooring materials, faux leather products, signage, phonograph records, inflatable goods, and serves as a substitute for rubber in various applications.

Thermoplastic Polyolefins (TPO) compounds represent a resin mixture consisting of polypropylene (PP), un-crosslinked EPDM (Ethylene-Propylene Diene Monomer) rubber, and polyethylene. They are distinguished by their notable attributes, including high impact resistance, low density, and commendable chemical resistance. These materials are very responsive to various processing methods, including injection molding, extrusion, and blow molding. TPOs find application in scenarios where heightened toughness and durability are prerequisites, surpassing what conventional PP copolymers can offer. Some notable applications include automotive bumpers, dashboards, as well as roofing insulation and waterproofing. [38]

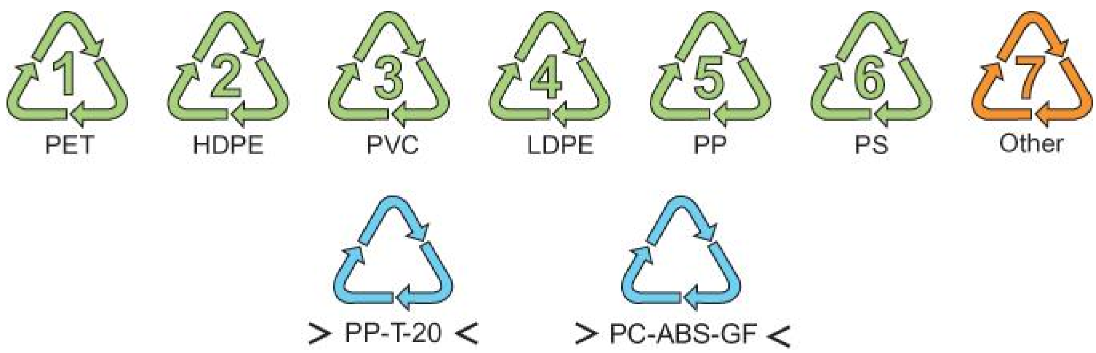

Figure 8 Recycle marks for the most used commodity polymers.

Plastic Production: from petrochemicals to polymerization

Plastic production involves a complex and multi-stage process that transforms petrochemical raw materials into a wide range of products, 99% of the feedstock is fossil fuel-based, accounting for 8-9% of global oil and gas consumption. [36] This intricate journey exemplifies the innovative engineering and chemistry that have revolutionized our world, while also highlighting the environmental challenges associated with plastic manufacturing.

1. *Raw Materials and Petrochemicals*

The journey begins with the extraction of fossil fuels, such as crude oil or natural gas, from deep within the Earth's crust. These hydrocarbon-rich resources serve as the primary feedstock for plastic production. Crude oil is processed in refineries to yield a variety of fractions, including naphtha, which contains hydrocarbons suitable for producing plastics. Alternatively, natural gas can be broken down into its component hydrocarbons through processes like steam cracking.

2. *Cracking and Chemical Conversion*

Once obtained, naphtha or ethane (derived from natural gas) undergoes a process known as cracking, where larger hydrocarbon molecules are broken down into smaller fragments called *monomers*. One of the most common monomers derived from these processes is ethylene, which serves as a building block for various types of plastics.

3. *Polymerization*

The monomers obtained from cracking are then subjected to polymerization, a chemical process that involves linking these smaller molecules together to form long chains, the polymers. Polymerization can be accomplished through various methods, such as high-pressure or low-pressure processes. For example, in the production of high-density polyethylene, ethylene molecules are polymerized under high pressure and elevated temperatures, resulting in a polymer with a high density and strong molecular structure.

4. *Additives and Blending*

To tailor the properties of the resulting polymer, various additives are introduced during polymerization. These additives can include colorants, stabilizers, plasticizers, and flame retardants, carefully selected based on the desired characteristics of the final plastic product. The polymer resin obtained is often processed into pellets for ease of handling and transportation.

5. *Processing and Manufacturing*

The polymer pellets are then transported to manufacturing facilities where they undergo processing to create the final plastic products. Processing methods include extrusion, injection molding, blow molding, and more. During *extrusion*, the plastic pellets are melted and forced through a die to create continuous shapes like pipes or sheets. *Injection molding* involves melting the pellets and injecting the molten plastic into molds to form complex shapes like bottles or automotive parts. *Blow molding* is used to create hollow objects such as containers by inflating molten plastic inside a mold.

Production and Consumption

Since the 1950s, the production of plastic has outpaced that of almost every other material. In 2021, after a stagnation in 2020 due to the Covid-19 pandemic, global production reached approximately 390.7 million metric tons, with an annual increase of four percent. [40] [fig. 9] Polyethylene and polypropylene are the most widely produced types, accounting for a significant portion of global production. [fig. 11] Asia is the largest producer in the world, China alone accounted for 31% of global production in 2021, producing between 6 and 12 million metric tons of plastic products each month. North America ranks second worldwide, with a share of 19%, while Europe is not far behind, at 16%. [42] [fig.10]

Together, the plastic raw materials producers, converters, recyclers, and machinery manufacturers (the European Plastics Industry - EU27), represent a value-chain that employs over 1.5 million people in Europe, through more than 55,000 companies. In 2019, these companies created a turnover of over 350 billion euros and contributed to more than 30 billion euros to European public finances. In 2021, EU27 had a positive trade balance of 14.4 billion euros, which ranks them 8th in Europe in industrial value-added contribution, positioned after the manufacturing of electrical equipment. [36][37]

Global consumption of plastic is accelerating. Over half of the plastic production ever manufactured has been produced since 2000 and the current global annual production is set to double by 2050. In western Europe, the average annual plastic consumption is around 150 kg per person, the global average is 60 kg/person. [41]

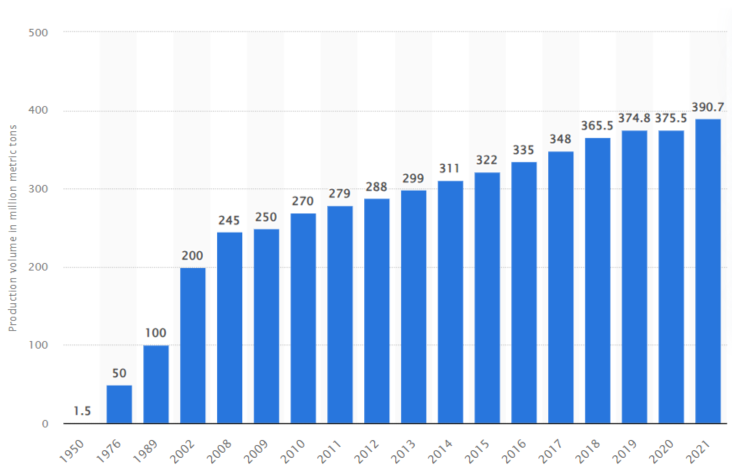

Figure 9 Annual production of plastics in million metric tons (1950 – 2021). Source: www.statista.com

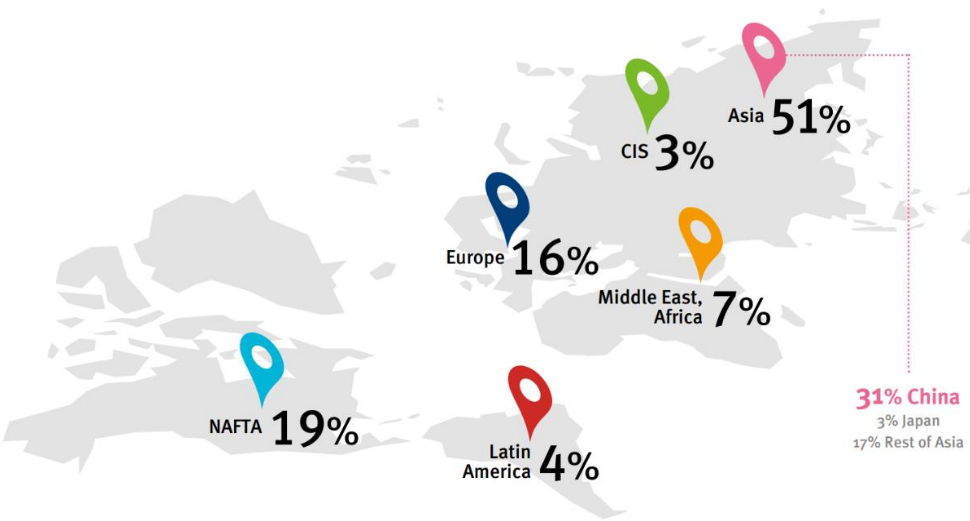

Figure 10 Distribution of global plastic production. Source: PlasticsEurope

In 2021, 90.2% of the world plastics production was fossil based. Post-consumer recycled plastics and bio-based/bio attributed plastics respectively accounted for 8.3% and 1.5% of the world plastic production.

Packaging (44%) and construction (18%) are the two sectors that are primarily dependent on polymers. The growth of the packaging industry was largely an effect of the trend to use single-use containers. This range of numerous types of plastics with different substances used for their manufacturing, has made sorting and recycling of plastics extremely challenging. [fig. 11]

Single-use plastics, such as plastic bags, bottles, and packaging, have short usage lifespans but can persist in the environment for hundreds of years. Today, 60% of plastic products and parts have a use phase between 1 and 50 years, or even more. This lapse of time determines when they will potentially become waste. This is why, in a single year, the quantity of collected plastic waste does not match the quantity of production or consumption.

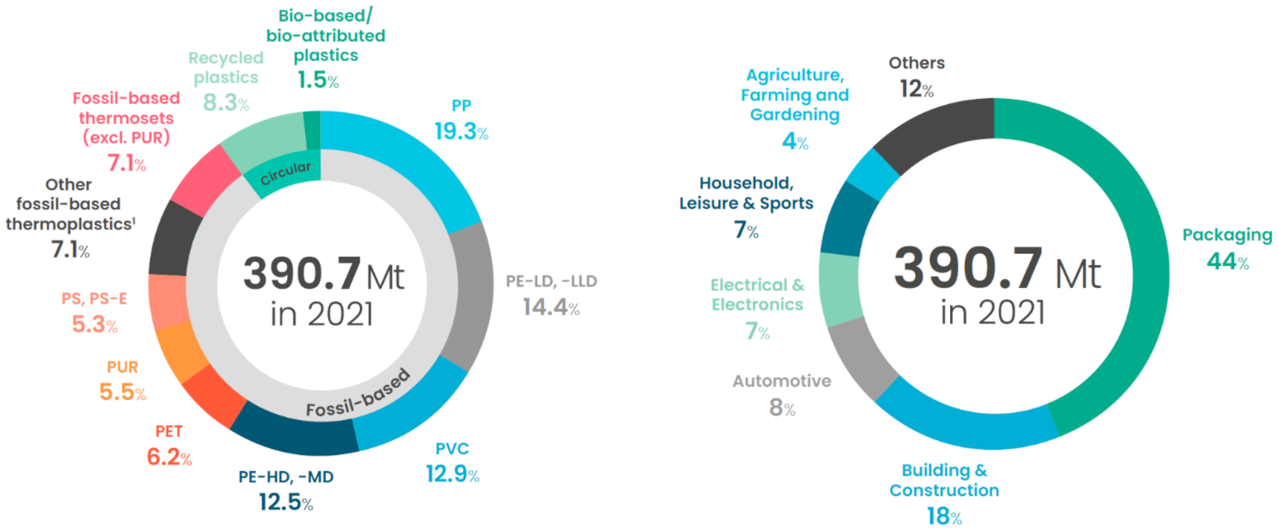

Figure 11 Plastics Market by Type and Application. Source: PlasticEurope

While plastic production has fuelled technological advancements and economic growth, it also poses significant environmental challenges. The extraction of fossil fuels for petrochemical feedstocks contributes to carbon emissions and resource depletion. Additionally, the durability of plastic, while beneficial for its applications, leads to persistent waste that accumulates in landfills, water bodies, and ecosystems. Mismanaged plastic waste has far-reaching ecological consequences, including harm to wildlife, soil, and water quality.

Efforts are underway to address the environmental impact of plastic production. One avenue is the development of bio-based plastics, which use renewable resources like corn starch or sugarcane as feedstocks. Recycling initiatives are also gaining momentum, aiming to divert plastic waste from landfills by turning it back into useful products. Furthermore, innovative technologies are being explored to break down plastics into their original monomers, allowing for closed-loop recycling.

Plastic Waste Management

Waste management encompasses a series of activities involving the handling of materials that result from human activities. The primary goal of waste management is to prevent these materials from causing harm to human health and the environment, and to recover resources from them. Typically, local governments are responsible for managing household and municipal waste, while companies directly manage the waste they generate, except for hazardous materials, which require specialized treatment.

Plastic waste management is a global challenge, the proliferation of polymers products has led to an alarming increase in waste generation, presenting complex issues that require comprehensive solutions both before and after consumer use. Various methods are employed for waste management: landfilling, incineration, gasification, pyrolysis, and recycling.

Landfilling

Landfilling involves burying waste in designated areas around cities. Waste is transported to landfills and deposited in trenches or cells, layers of garbage are compacted and covered with soil or other materials to reduce odors, prevent litter, and minimize environmental impacts. Landfills can accommodate large volumes of waste over extended periods, and they can also capture methane gas emissions for energy generation. Poorly designed or managed landfills, however, can result in high costs for governments and significant environmental/health impacts: they may generate leachate, a liquid by-product that can contaminate groundwater, release debris scattered by the wind or gases in the atmosphere that can produce odors, harm vegetation, and contribute to greenhouse effects. Even if is still the most widespread practice, countries around the world are starting to pass legislations against landfilling. The first of her kind, the Landfill Directive, was introduced by the European Commission in 2001; it mandates Member States to reduce the percentage of waste sent to landfills. [41][45]

Incineration

Incineration, also known as waste-to-energy, is a thermal treatment process that involves combusting waste materials at high temperatures to generate heat and ultimately electricity. Garbage is burned in incinerators, where it is reduced to ash, gases, steam, and heat; steam and heat can then be harnessed for electricity generation or district heating. Producing energy and reducing volume and mass of waste (typically by 95% and 80-85% respectively) it is a resource-efficient method, particularly suitable for hazardous waste. [43] Not all plastics, however, are good candidates for combustion; some are resistant to oxygen heating or explosives. Furthermore, this process can lead to emissions of pollutants and harmful organic compounds, including dioxins and acid gases, both carcinogens. Thanks to improved technology, catalytic fabrics and strict emission limits, the emissions of these agents is reduced to a minimum: nowadays a modern incinerator facility burning 200 tonnes of municipal waste a day emits just 1/5 of the dioxins that one family would produce using a barrel to burn household trash in their backyard. [44]

Gasification

Gasification is a thermochemical process that converts organic materials into a gas called syngas (synthesis gas). It involves heating the feedstock, at 500 – 1300 °C, in a controlled environment with gasifying agents and limited oxygen or air supply, which prevents complete combustion. As a result, the feedstock breaks down into its constituent gases, primarily hydrogen (H_2) and carbon monoxide (CO), along with other gases like methane (CH_4) and carbon dioxide (CO_2). The syngas produced can be used for various applications, including electricity and heat generation, as well as the production of synthetic fuels and chemicals. Gasification offers several advantages, including high energy efficiency, flexibility in feedstock selection, and reduced greenhouse gases emissions. It also allows for the recovery of valuable by-products, such as biochar, which can be used for soil enhancement. Challenges associated with gasification include the need for sophisticated and well-maintained equipment, high capital costs, and the potential for tar and particulate matter formation in the syngas, which can require additional processing steps for cleanup.

Pyrolysis

Pyrolysis is another thermochemical process that involves the thermal decomposition of organic materials in the absence of oxygen or with limited oxygen supply. This process results in the breakdown of feedstock into three main products: biochar (a carbon-rich solid), bio-oil (a liquid), and syngas (like the one produced in gasification). The specific product distribution depends on factors like temperature, pressure, and feedstock type. Biochar can be used as a soil conditioner, bio-oil as a source of renewable chemicals, and syngas for heat and power generation.

Recycling

Recycling is the process of collecting, sorting, and processing waste to produce new products or materials. It aims to reduce the consumption of virgin resources and minimize waste. Recycling conserves resources, reduces energy consumption, and lowers greenhouse gas emissions, it also supports the circular economy by closing the materials loop.

Recycling is often linked to the 3R method (Reduce, Reuse, and Recycle), a set of principles and practices aimed at minimizing waste generation, conserving resources, and promoting sustainable consumption and production.

Only about an estimated 9% of the plastics ever produced have been recycled while 12% have been incinerated, the remainder is either still in use or has been disposed of in landfills or released into the environment. [42] In 2020, more than 29 million tonnes of plastic post-consumer waste were collected only in the European Union, where each person generates in average 480 kg of municipal waste per year: 35% is sent to recycling, 23% to landfills, and 42% to energy recovery facilities. [37] [fig. 12]

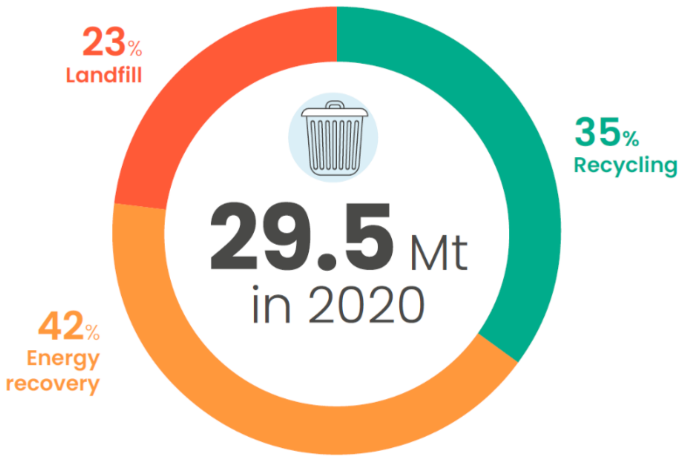

Figure 12 Plastic Waste Management in 2020. Source: PLASTICS - THE FACTS 2022

Globally, 26% of wastes is recycled, 15% composted, 31% landfilled, and 26% incinerated. [45]

Single-use plastics, such as bags, bottles, and disposable cutlery, are a significant contributor: packaging accounts for about half of the plastic waste in the world. Most of it is generated in Asia, while America, Japan and the European Union are the world's largest producers of plastic packaging waste per capita. [42][45]

Before digging deeper into the recycling process, it is crucial to define the characteristics and differences between pre- and post-consumer waste.

Pre-consumer / Post-industrial Waste

“Post-industrial material refers to material that is separated from the waste stream during a manufacturing process”.

UNI EN ISO 14021:2016

Pre-consumer waste, also known as post-industrial or manufacturing waste, refers to materials and by-products generated within the manufacturing process before a product reaches the consumer. This waste originates within factories, production facilities, and supply chains and typically consists of scraps, off-cuts, rejects, excess raw materials, defective parts, or components that do not meet quality standards. The most important characteristics of post-industrial waste are that it’s *clean* and *homogeneous* because it hasn't been exposed to consumer use. It also often consists of similar materials, making it easier to recycle or repurpose.

Pre-consumer waste is managed within the manufacturing and industrial sectors. Excess raw materials, scraps and off-cuts can quite often be recycled within the manufacturing facility or repurposed into other products, while defectives and off-quality goods are usually sent to landfills or incineration. Effective waste reduction strategies, such as optimizing production processes to minimize scraps, are essential. Manufacturers can implement quality control measures to reduce such waste and, where possible, recover and recycle defective items and production surplus.

Post-Consumer Waste

Post-consumer waste refers to materials and products that have been used and discarded by consumers. This waste originates from households, businesses, and other end-users. This type of plastic waste is inhomogeneous and includes a wide range of different materials. It’s usually contaminated with food residue, dirt, or other substances, that make sorting, processing, and recycling very challenging. The collection and management of post-consumer waste typically involve municipal programs, recycling centres, and consumer responsibility.

The focus of this thesis will be exclusively on the treatment of post-industrial/pre-consumer waste with the aim of creating a circular economy system in the commercial roofing and geocomposites industries.

Plastic Recycling

"Material recycling is the process where some material is recovered from the plastic waste in order to be used to produce new products".

Worrell & Reuter, 2014

There are two broadly distinguishable approaches to material recycling from plastic waste:

- Mechanical recycling
- Chemical recycling

Mechanical recycling

Mechanical recycling encompasses processes that focus on reclaiming plastics through mechanical methods like grinding, washing, separating, drying, re-granulating, and compounding. This results in recyclable materials that can replace virgin polymers in the production of finished goods. Mechanical recycling applies to both pre-consumer (post-industrial) materials and post-consumer plastic waste. In Europe and North America, it stands as the predominant approach for recycling post-consumer plastic waste. This method exclusively targets thermoplastic materials, which are polymers capable of being re-melted and reprocessed into products using techniques like injection molding or extrusion. It is a well-established technology for recovering plastic materials such as polypropylene, polyethylene, or polyethylene terephthalate.

Post-consumer plastic waste typically represents a highly diverse and contaminated waste stream. It encompasses a wide variety of material types, including multilayer films, blends, and composites, characterized by varying shapes, colours, and sizes. In contrast, post-industrial waste, originating from the manufacturing process, is often clean and devoid of contamination, essentially in a pre-contaminated state. Pre-consumer plastics consist of input resin types that are well-known and controllable, simplifying the recycling process to produce high-quality pellets for reuse. Whenever feasible, companies engage in internal reprocessing of post-industrial plastic waste, a practice known as in-house recycling.

Sorting

In the initial phase, plastic waste undergoes thorough manual or automated sorting processes. Accurate material identification is crucial for achieving the highest possible purity of recyclable materials. Various technologies such as near-infrared (NIR), laser, or x-ray-based methods are available. NIR units are widely adopted and represent the cutting edge in several European countries for sorting mixed post-consumer packaging. Despite advancements in sorting technology, achieving 100% efficiency remains unattainable due to occasional separation imperfections and challenges posed by laminated or blended products. Sorting process quality also hinges on the effectiveness of collection systems, which can vary significantly, even within EU member states or US federal jurisdictions.

To obtain adequately pure material streams, most companies employ a combination of different techniques, tailoring the sorting facility's design to the incoming stream of plastic waste. The level of purity attainable represents a trade-off between energy costs and market requirements: the maximum achievable purity when separating mixed plastic waste typically ranges between 94% and 95%. For high-quality recycled materials a minimum purity of 98% is required. Consequently, additional refining steps are necessary in subsequent phases of processing. [50]

Induction sorting. Materials travel along a conveyor belt equipped with a sequence of inductive sensors. These sensors detect the presence of metal contaminants that are isolated through rapid bursts of compressed air.

Eddy current separation. An *eddy current* refers to an electrical current generated when there are changes in the magnetic field within a conductor. It is employed to distinguish non-ferrous metals from the bulk of polymer materials.

Drum separation/screening. Waste is introduced into a sizable rotating drum that features perforations of various diameters. Particles smaller than the hole diameter fall through, while larger ones remain within the drum.

Sink float separation. Plastic waste undergoes separation based on its specific weight compared to the surrounding fluid. In water, certain plastics like PET, PVC, and PS will sink, while others such as PE, PP, and EPS will float.

X-ray technology. X-rays are employed to differentiate between various materials by assessing their density differences.

Near infrared sensor. NIR sensors have the capability to discern different materials based on their light reflection properties. Air jets are employed to separate these fractions from the mixed stream. Currently, this method is the industry's preferred choice for accurately identifying the numerous polymer types.

Shredding and Cleaning

Collected and sorted waste plastics are shredded and ground generally in two stages to achieve suitable particle size for further processing. Typical particle size of grounded material is around 5 x 5 mm flakes. These flakes are washed to remove dirt, impurities, and labels from the plastic fraction, followed by thermal treatment to remove moisture from the plastics.

Grinding Process

The plastic material intended for grinding is introduced into a granulator [fig. 13] via a dedicated loading system. Upon reaching the cutting chamber, a rotating body known as the rotor, fitted with blades, shreds the material. Fixed blades (counter blades) are positioned diametrically opposite within the chamber to facilitate the cutting process. Beneath the rotor, a perforated grid or sieve directs the ground plastic material into the discharge hopper. The size of the holes on the grid's surface determines the final size of the ground material. Grinding can be either dry or wet, contingent upon the type of plastic waste being processed. Water is only added during the process when dealing with post-consumer materials, where it indirectly serves as a pre-wash step. [49]

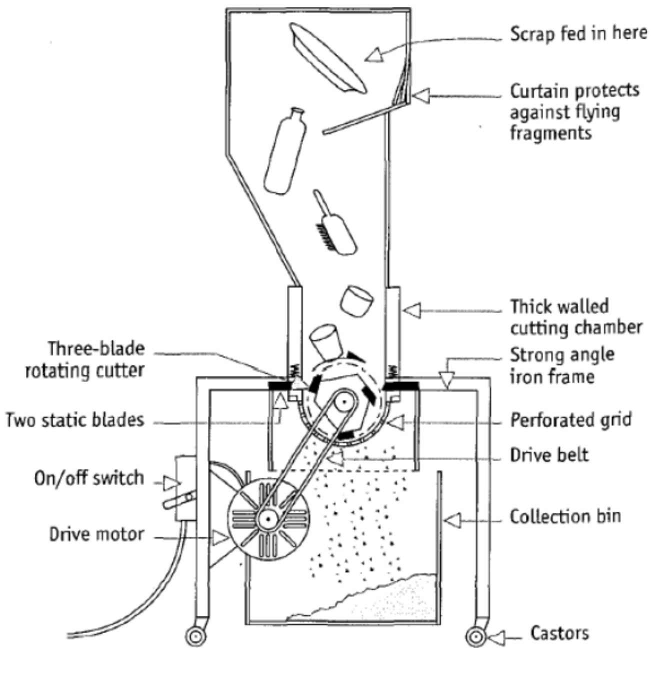

Figure 13 Granulator. Source: www.researchgate.net

Washing

After post-consumer plastics are ground, they are washed. In rare cases, some regrind or even agglomerate is processed instantly, a normality for pre-consumer polymer scraps. The washing operations are done by vibratory plates, compressed air systems, or centrifuges, using cold or hot water, up to 60 °C. Cold water processes are characterised by a higher mechanical energy consumption and the use of chemicals additives (sodium hydroxide). The wastewater is often treated internally for internal reuse and the washed plastic flakes are dried using centrifuges until they contain less than 0.1 wt% moisture and are ready for reprocessing. [50]

1. Reprocessing

Following the cleaning and grinding procedures, the materials are recovered through remelting and regranulation, resulting in pellets that are compatible with all common technologies for plastics conversion. It's important to note that during the reprocessing stages, the elevated temperatures and shear forces involved can lead to thermal and mechanical degradation. This can affect factors such as polymer chain length and distribution, subsequently impacting material properties like crystallinity and mechanical strength. If the recycled materials meet the necessary quality standards, they can be reintegrated into similar products. If quality falls short, they may find application in lower-value uses, a practice often referred to as *down-cycling*.

Densification

The Agglomerator or Densifier [fig. 14,15] is a cylinder, called *pot*, with 5 to 12 stationary blades welded on the side and two rotating ones at the bottom. The plastic is fed into the chamber and cut into small chips by the crushing function of the rotary and fixed knifes. During the process, the material absorbs a lot of heat due to the friction created by the blades; the temperature rises rapidly to a semi-plasticized state, making the particles adhere to each other into small pieces. Cold water is then sprayed on the mass before it reaches the melting point, right before the material agglomeration which would lead to the blocking of the machine. When the cold water meets the hot mass, it quickly vaporizes taking away the surface heat of the material, preventing agglomeration. The *shocked* high-density bulk is then shredded into granules by the action of the blades and discharged. [51] [52]

During the process, the material is first dried, then broken by the energy of the blades, heated up, made viscous, and finally densified by the inflow of cold water. Densification machines are used for physically transform loose plastic materials, like film or fiber, into chips suitable to be fed in the hopper of an extruder. The agglomeration process is very energy intensive (300-700 kWh/t of plastic). [50]

Figure 14 Inside of a densifier

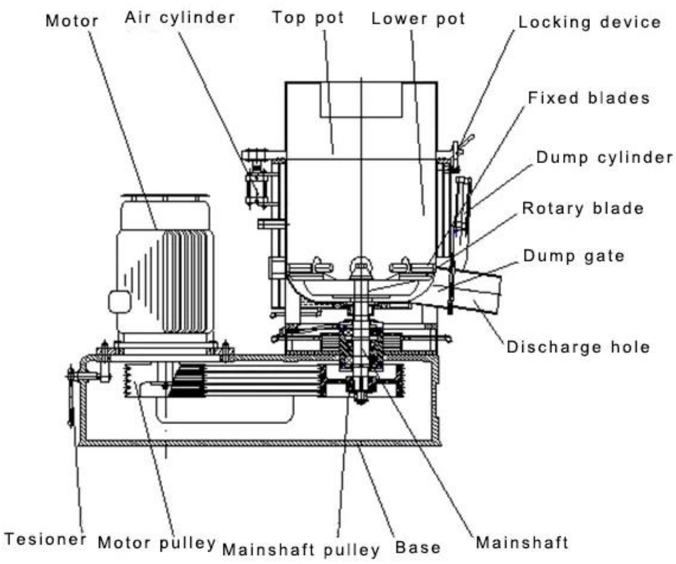

Figure 15 Densifier Source: www.wanrooerecycle.com

Extrusion (Pelletising)

The material in the form of granulates or flakes is gravity fed into the hopper [1] and, through the feed throat, drops on a rotating screw, operated by an electric motor. [fig. 16] The screw design varies on the polymer type and on the final specification sought. The rotation forces the plastic forward into a heated barrel at the desired melt temperatures, ranging from 200 to 275 °C. As the plastic is conveyed through the barrel the channel or thread of the screw decreases, thus compressing the plastic. The pressure created allows the material to mix and melt gradually; the temperature in the chamber is normally higher than set in the controllers, the additional heat is generated through a combination of compressive force and shear friction (shear heat). The melt is degassed [6] to remove oils, waxes, and lubricants. The molten plastic is pushed through a screen pack, supported by a breaker plate [5], filtering contaminants, and removing the materials rotational memory. The filtered product is then pushed through a die, which gives the final desired profile and shape (*spaghetti* form), and finally cut by rotating knifes. Exiting the extruder, the pellets meet a flow of cold water, the impact cools them down and give them their typical rounded shape. The water pushes them into a centrifuge tower [8] that cools and dries them completely before dumping them on a vibrating sieve [9]. Only those with the correct shape and size pass through, ready to be re-melted or bagged. Depending on the diameter of the holes, the screw design and number (single or twin-screw extruders) and the rotational speed of the blades, it's possible to obtain pellets with variable diameter, composition, and length.

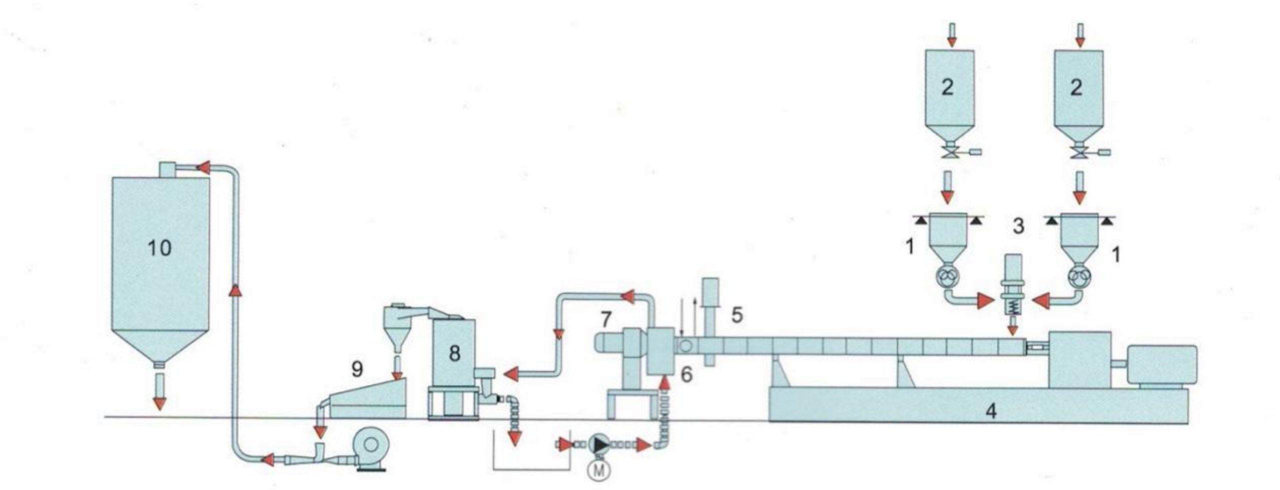

Figure 16 Extrusion line. Source: www.cowinextrusion.com

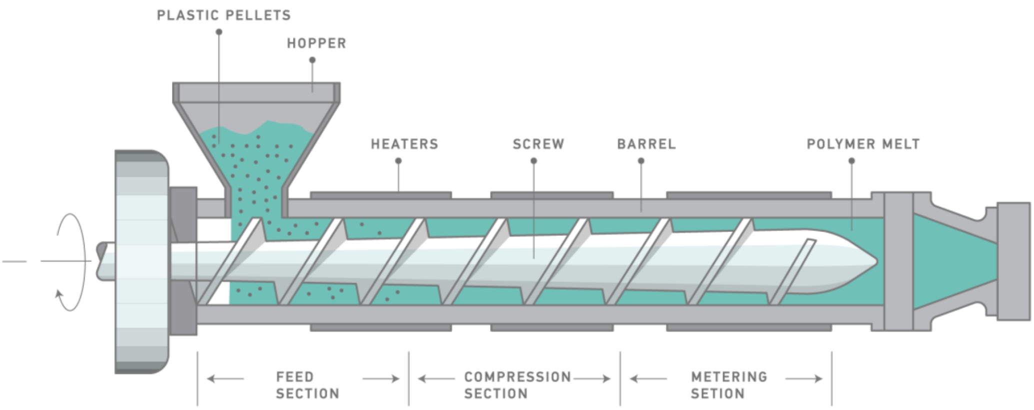

Figure 17 Inside of an extruder. Source: www.elastron.com

Agglomerates or pellets can serve as feedstock in any manufacturing line or final processing step, with the selection contingent upon the intended final product:

Injection molding. The initial phase of this process mirrors that of extrusion. The pellets are melted and then pressed into a split mold. The mixture is compressed within the mold until it fills completely, and after a cooling period to solidify the plastic, the mold is opened, and the finished product can be extracted.

Blow molding. The spiral screw within the extruder propels the plasticized polymer through a die. A brief hollow tube, activated by compressed air, is employed to expand the matrix until it completely fills the mold and attains the desired shape. This method is commonly employed for producing bottles and containers.

Film blowing. Film blowing is a technically intricate manufacturing process utilized to produce items like plastic bags. It demands top-notch raw materials and involves inflating a narrow polymer tube with compressed air until it transforms into a thin film tube.

Fiber extrusion. The molten polymer, typically polyester, is directed to a spinneret where the filaments are spun. The spun filaments then pass through a denier setter before entering the finishing steps where they are drawn, dried, cut into staple fibre and finally baled for sale.

Figure 138 Virgin vs Recycled PP pellets

Chemical recycling

Chemical recycling, also known as advanced recycling or feedstock recycling, is an emerging method that involves breaking down plastic polymers into their chemical constituents for reuse. To grasp the concept of chemical recycling, it's crucial to remember that all plastics consist of one or more fundamental molecules known as monomers. These monomers repetitively combine to form lengthy chains, referred to as polymers. Typically, monomers are derived from gases or oils produced during oil refining.

There are three primary categories of technologies used to chemically recycle plastics: Conversion, Depolymerization, and Dissolution. While each of these technologies is distinct, they convert polymers into raw materials for the petrochemical industry.

Conversion. Conversion is a process that facilitates the transformation of plastic waste into hydrocarbons. Using heat with minimal or no oxygen, plastic waste is *cracked* to yield either oil (through *pyrolysis*) or gas (via *gasification*). After purification, the oil and gas can be supplied to refineries or cracking plants, where their products are utilized to manufacture new plastics and various other materials. This technique is suitable for a wide range of waste types, particularly those comprising multiple polymers or materials, such as certain multi-layer food packaging. It is also highly effective in removing impurities from polymers.

Depolymerisation. Depolymerization involves breaking the chemical bonds within the polymer to re-obtain the monomer. This can be achieved using chemical agents like solvents, water, or alcohols, as well as through heat. The resulting monomers are then purified and polymerized once more and can be integrated into traditional production processes as raw materials.

Dissolution. Dissolution is a process in which polymers are dissolved in a solvent bath. This technology doesn't alter the chemical structure of the polymer but allows it to be separated from additives, impurities, and other materials. The recycling principle is grounded in the solubility of polymers, which are the sole components to dissolve, while other elements remain in a solid state. Similar to mechanical recycling, the recovered plastic can be used to produce new items without the need for pre-polymerization.

All these innovative technologies help to reduce the environmental footprint of plastics, but they are often still at the industrial pilot stage and require major investments. As a result, they need to be optimised and reach a larger scale of production to demonstrate their full potential in terms of technical and economic performance. The EU has planned a significant increase in chemical recycling investment: €2.6 billion in 2025 and €8 billion in 2030, with an estimated rise in production of 0.9 Mt in 2025 and 2.8 Mt in 2030. These investments are part of the European Commission's Circular Plastics Alliance target of 10 Mt recycled plastics used in European products by 2025. Conversion to feedstock technologies (pyrolysis, gasification) represents 80% of the planned capacities. [47][48]

Plastic Recycling Markets

The global recycled plastics market reached a valuation of USD 47.60 billion in 2022 and is anticipated to experience growth from USD 50.78 billion in 2023 to USD 88.96 billion by 2030, representing a compound annual growth rate of 8.3% over the forecast period. The rising use of plastics in the manufacturing of lightweight components across various industries such as building and construction, automotive, electrical and electronics is anticipated to drive the demand for recycled plastics in the foreseeable future. [53][55]

The market exhibits a fragmented landscape, comprising various small and medium-sized enterprises. Despite its fragmented nature, characterized by limited market volumes, liquidity, and relatively small trade flows compared to total plastics waste generation, this market holds substantial potential. Key industry players are actively involved in expanding their plastic recycling facilities, enhancing infrastructure, investing in research and development capabilities, and exploring opportunities for vertical integration throughout the value chain.

The Recycled Plastics Market by Application

The packaging application segment dominated the market, contributing to over 37% of the global revenue in 2022. This substantial share can be attributed to the increased demand for packaged food and beverages, electrical and electronics components, personal care products, as well as protective equipment like gloves and face masks. These heightened demands are, in part, a residue of the global COVID-19 pandemic situation.

Personal hygiene products, such as electronic trimmers, shavers, along with automotive components, and clothing produced from recycled plastics are the major emerging products in the market. In particular, the automotive (12%) and textile (8%) industries are pushing towards a large use of recycled plastics to meet certain sustainability requirements imposed both by governments and themselves. [53] [fig. 19]

In 2022, the building and construction market constituted 21% of the global recycled plastics market. [53] This share is noteworthy, and the demand within this sector is expected to grow, primarily due to the expansion of the construction industry in emerging economies like Brazil, China, India, and Mexico. This growth is likely to drive the demand for recycled plastics in the production of various components, including insulation, fixtures, structural lumber, windows, and fences.

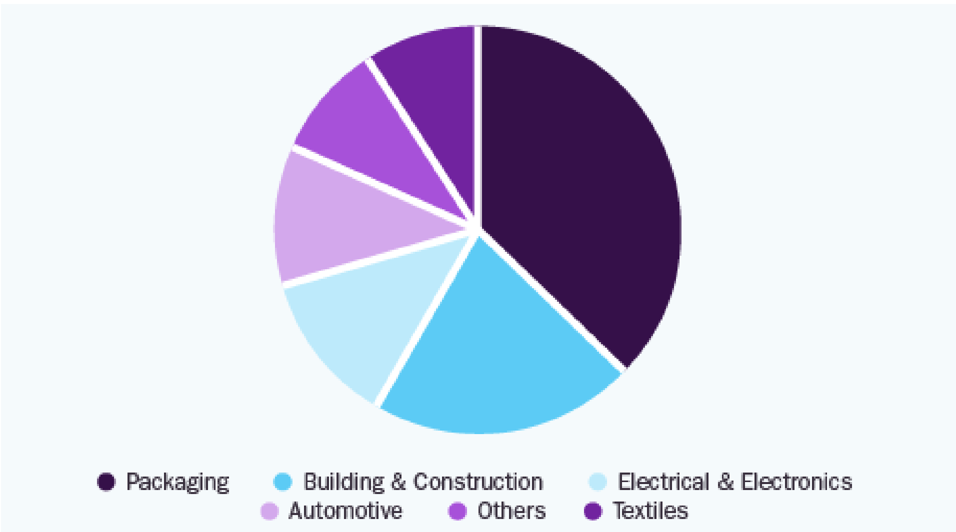

Figure 19 Recycled Plastics Market share by Application, 2022 (%).   Source: www.grandviewresearch.com

Recycled Plastics Market by Material

Polyethylene took the lead in the market, representing over 26% of the global revenue share in 2022. [53] This notable share can be attributed to the increasing demand for packaging materials across diverse industries such as consumer goods, food and beverage, and industrial sectors. PE is also commonly employed in the production of packaging for items like laundry detergents, milk cartons, cutting boards, and garbage bins.

Polypropylene, ranking second in popularity with a 19% share, finds extensive application in the manufacturing of automotive components, packaging and labelling, medical devices, and various laboratory equipment due to its exceptional chemical and mechanical properties. It boasts resistance to a wide range of chemical solvents, acids, and bases, along with high mechanical strength, making it one of the most widely used plastics globally. Components made from polypropylene are also fatigue-resistant, which is why it is prominently utilized in the building and construction sector for producing plastic hinges, piping systems, insulations, mats, carpets, rugs, and everyday consumer products. Anticipated growth in the automotive, packaging, and building and construction industries is expected to drive the demand for recycled polypropylene during the forecast period. [53][55]

PVC secured the third position among polymers, accounting for a 13% share of the global recycled plastics revenue in 2022. [53] PVC is recognized for its cost-effectiveness, durability, ease of integration into existing systems, and its suitability for recycling. It can be melted down and reformed without compromising its structural integrity, making it well-suited for recycling processes. Consequently, PVC is extensively utilized in the building and construction industry for the production of pipes, window frames, and siding.

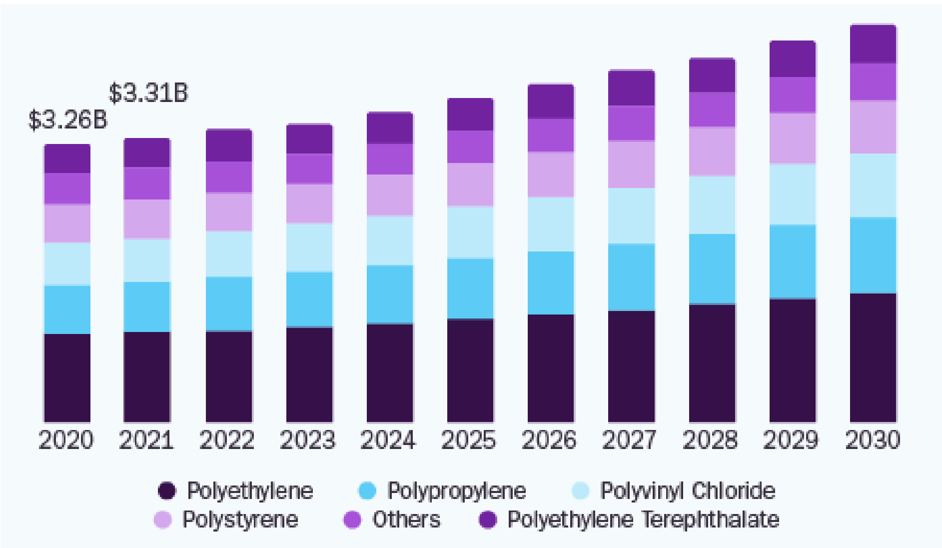

Figure 20 U.S. Recycled Plastics Market size by Product, 2020-2030 (Billion$). Source: www.grandviewresearch.com

Recycled Plastics Market by Region

Asia Pacific dominates the market accounting for over 47% share of global revenue. [53]

The Eastern construction industry is poised for significant growth, primarily fuelled by the rising need for non-residential construction projects like hospitals, schools, and colleges. This surge in construction activity is expected to drive demand for various plastic products, including roofing tiles, insulation, fences, floor tiles, and carpets, thus contributing to market growth. Moreover, the packaging industry in the region is being propelled by the robust demand for building and construction products, consumer goods, and electrical and electronics, particularly from countries such as China, India, and Southeast Asia. Additionally, a flexible regulatory environment in the Eastern markets is anticipated to help mitigate constraints often observed in Western markets.

The Asia Pacific region is expected to experience significant market growth, driven by the increasing expenditure on electronics in countries such as China, India, and Japan. Furthermore, the presence of numerous technology companies engaged in research and development (R&D) activities in the region, including names like ASE Electronics Malaysia, Foxconn Technology Group, Honeywell International Inc., SAMSUNG, Lenovo, Bajaj Electronics, Huawei Technologies Co., Havells Group, and Haier Inc., is poised to propel the expansion of the industry over the next decade. [53][56]

Europe holds the second position in terms of revenue in the recycled plastics market. This market is primarily driven by the adoption of circular economy strategies and legislation aimed at reducing the carbon footprint associated with traditional plastic production. The European plastics industry is undergoing a transition to align with its 2050 net-zero and circularity targets. Landfill bans and high disposal taxes in several European Union countries have led to a situation where recycling becomes a more cost-effective option compared to dumping waste. This circumstance is encouraging greater participation from the population in the collection of plastic waste and its recycling efforts.

In 2021, packaging (39,1%) and building & construction (21,3%) by far represented the largest markets for plastics in the EU, the third biggest market is the automotive sector (8,6%). In the same year, the use of post-consumer recycled plastics by European converters reached 5.5 Mt, representing a 9.9% recycled content, an increase of about 20% compared to 2020. [37]

North America ranks third in terms of revenue in the recycled plastics market, following Europe. The market here is primarily driven by major end-use industries, including electrical and electronics, construction, and packaging. The increasing demand for packaged and processed food, as well as the growing construction industry in the United States, Mexico, and Canada, is expected to fuel market growth in the coming years. The U.S. dominates the market, accounting for over 90% of the revenue share in 2020. It's worth noting that a significant portion of plastic waste generated in the United States is exported to other countries for recycling. Following China's recent ban on plastic waste imports, the U.S. has started exporting its plastic waste to Southeast Asia. Within North America, the packaging end-use segment leads the market, constituting over 36% of the total capital, and it is projected to maintain its dominance in the years ahead.

Several major companies such as Adidas America Inc., Everlane, Rothy, Vivobarefoot, United by Blue, and Nike Inc. are engaging the manufacturing of products from recycled plastics. In addition, rising demand for electric vehicles is likely to augment the need for lightweight and durable components to enhance the efficiency and reduce the carbon footprint associated with vehicle manufacturing.

Plastic waste trade flows

The recycling rate for plastics exhibits significant variation among countries and remains at approximately 9% worldwide. A substantial portion of plastic waste is disposed of through export, sent to landfills, incineration plants, or mismanaged. In the 21st century, the global plastic waste trade from high-income to low-income countries has gained popularity due to the environmental risks involved and the economic benefits it offers.

The volume of plastic waste trade is relatively small when compared to the total generation of plastic waste. In 2018, out of the 350 million tonnes of plastic waste generated, only approximately 14 million tonnes, which is equivalent to around 4%, were exported outside their country of origin. [57][58] Imports of these materials are concentrated in a limited number of countries, with China accounting for roughly 8 million tonnes, constituting approximately 60% of plastics waste imports in 2016. [58]

The concentration of demand for recycled plastics in a limited number of countries makes these markets susceptible to shocks. A notable example is the implementation of restrictions on the import of specific types of waste by China in 2017, which resulted in substantial disruptions. Reduced access to the Chinese market for waste plastics has led to the accumulation of growing stockpiles in numerous countries. Furthermore, there are concerns that diverting these materials to countries with comparatively weaker treatment and environmental standards could give rise to new health and environmental challenges.

Even though the free trade flow of plastic waste could increase global recycling rate because without trade barriers, plastic scrap would be exported to countries where recycling is cheaper, global trade in plastic waste is deemed modest, overall. Both import and export data are concentrated in a few countries: USA accounts for 13,2% of total exports (coherently with the estimated low rate of internal recycling), Germany reaches 12,2% and Japan 11,6%. [Table] The same holds for imports. In fact, the first seven countries account for more than half of global imports (53,1%, in terms of volume), as summarized in the table below [Table]. [58][59]

*Table 2 List of the six major countries **exporting** plastic scrap (ranked by exported value in 2018). Source: UN Comtrade, 2019*

Exporting country	Exported value $	% on total
USA	446.473	13,2%
Germany	414.691	12,2%
Japan	393.628	11,6%
Belgium	176.862	5,2%
France	172.178	5,1%
Netherlands	162.202	4,8%

*Table 3 List of the seven major countries **importing** plastic scrap (ranked by imported volume in 2018). Source: UN Comtrade, 2019*

Importing country	Imported tons	% on total
Malaysia	872.531	11,8%
Hong Kong	598.046	8,1%
Netherlands	555.419	7,5%
Thailand	552.727	7,5%
Germany	468.022	6,3%
USA	442.291	6,0%
Turkey	436.910	5,9%

As regard imports, the current scenario is the result of the recent regulatory turmoil in China (the same applies to various south-eastern Asian countries) that imposes heavy restrictions on imports. Until 2017, China showed a clear supremacy with respect to imports, but year 2018 marks the start of the enforcement of the *National Sword* policy. This was a severe and permanent ban on plastic waste and other materials import, which, by the beginning of the year shocked the global market.

COVID-19 Impact

The pandemic had a significant impact on the recycled plastics market, affecting various aspects of the industry both temporarily and permanently.

One of the most immediate effects was the disruption in supply chains: many recycling facilities faced challenges in collecting, sorting, and processing recyclables due to lockdowns, reduced workforce, and transportation restrictions. This disruption led to a decrease in the availability of post-consumer plastics for recycling. The pandemic also resulted in decreased demand for certain types of products, particularly those in industries like automotive, construction, and hospitality. With lower demand for new plastic products, there was less demand for recycled plastics as feedstock. [60]

COVID-19 led to changes in consumer behaviour, including an increased reliance on single-use plastics like packaging, masks, and personal protective equipment (PPE). This shift raised questions about the long-term environmental sustainability of increased plastic waste. Renewed discussions about the need for more sustainable packaging solutions and recycling infrastructure improvements pushed companies and governments to invest in the creation of more resilient and sustainable supply chains.

The price of virgin plastics is closely linked to the price of oil. During the early stages of the pandemic, oil market value experienced extreme volatility. When crude tariffs dropped significantly, it made virgin plastics cheaper than recycled ones, which impacted the economic competitiveness of recycled plastic materials. [60]

The Russia-Ukraine war disrupted the chances of global economic recovery from the COVID-19 pandemic, at least in the short term. The war has led to economic sanctions on multiple countries, a surge in commodity prices, and supply chain disruptions, causing inflation across goods and services and affecting many markets across the globe. The only positive outcome related to this conflict is seen in the recycled plastic industry: oil prices are at sky-high levels and because of that virgin polymers are becoming unaffordable for many manufacturing companies. The result is a huge interest in recycled materials.

Roofing Industry

Introduction to Roofing

Roofing refers to the construction and installation of the uppermost surface of a building, commonly known as roof. The primary purpose of a roof is to provide shelter and protection from various environmental elements, including rain, snow, wind, sunlight, and extreme temperatures. Roofing involves the selection and installation of the materials needed to create a weatherproof and durable barrier for the building.

The specific layers of a roofing structure can vary depending on type and climate, a typical roofing system consists of the following layers from the bottom up:

1. ***Structural Roof Deck***

The structural roof deck is the base layer and serves as the foundation for the entire roof. It is usually made of materials like plywood, oriented strand board (OSB), or concrete. The deck provides structural support to the roof and distributes the weight evenly to the building's framing.

2. ***Roofing Underlayment***

The roofing underlayment is placed directly on top of the structural deck and serves as a secondary barrier against moisture infiltration. Underlayment materials include asphalt-saturated felt (roofing felt), synthetic sheets, rubberized asphalt rolls, or ice and water shield.

3. ***Roof Insulation (Optional)***

In some roofing systems, insulation is installed on top of the underlayment and beneath the roof deck to provide thermal resistance and improve energy efficiency. Types of insulation can include fiberglass batts, rigid foam boards, or spray foam insulation, depending on the desired R-value (thermal resistance).

4. ***Roof Ventilation (Optional)***

Proper roof ventilation is essential for maintaining temperature and moisture control within the attic or roof space. It helps prevent moisture buildup, which can lead to mold growth and damage to the roof structure. Ventilation components include ridge vents, soffit vents, gable vents, or mechanical ventilation systems.

5. ***Roofing Material***

The roofing material is the outermost layer of the roof and is the most visible part of the roofing system. It provides protection against the elements and contributes to the building's aesthetics. Common roofing materials include asphalt shingles, metal panels, wood shingles or shakes, clay or concrete tiles, slate, or single-ply membrane like TPO (Thermoplastic Polyolefin) or EPDM (Ethylene Propylene Diene Monomer).

6. ***Flashing***

Flashing is used to waterproof vulnerable areas of the roof, such as edges, valleys, chimneys, vents, and skylights. It is typically made of metal or engineered polymers.

7. ***Ridge Cap***

The ridge cap is a specialized component installed at the ridge of the roof (the peak). It covers and seals the ridge, preventing water penetration and contributing to the roof's overall structural integrity.

8. Gutters and Downspouts

Gutters and downspouts are installed along the roof edges to collect and channel rainwater away from the building's foundation. They help prevent water damages and they are usually made of copper or PVC.

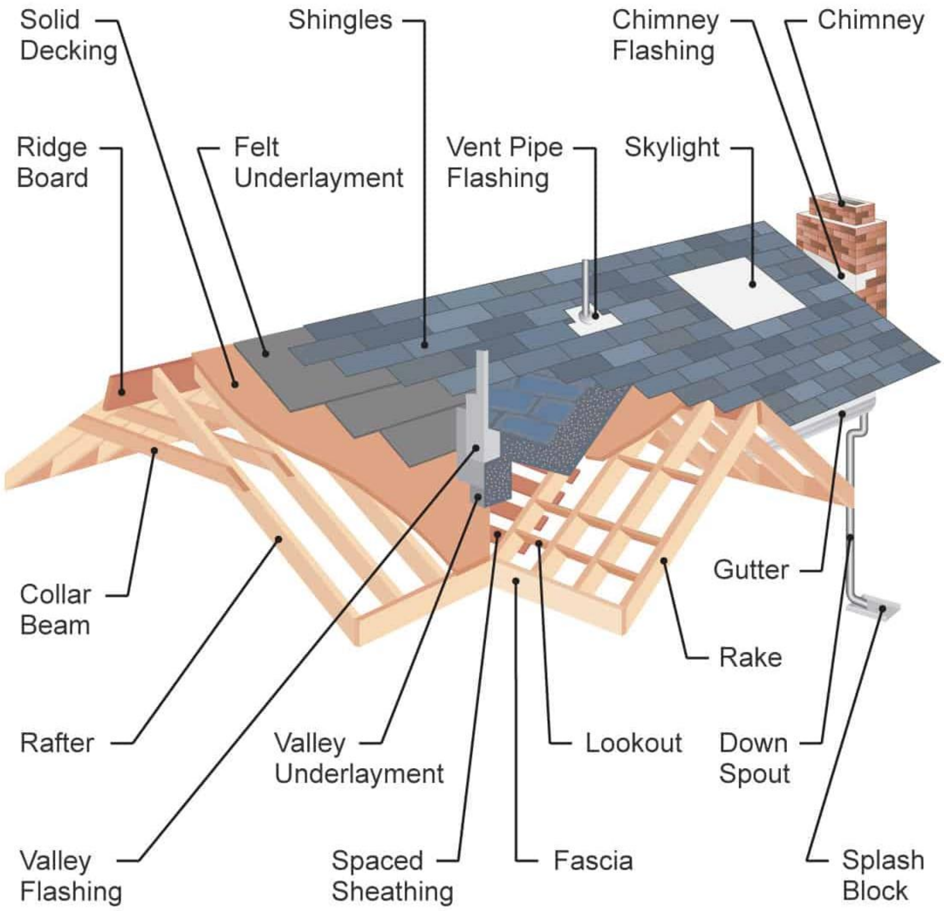

Figure 21 Anatomy of a roof. Source: www.homestratosphere.com

Roofing Materials

Asphalt Shingles

Asphalt shingles [fig. 22] are made of a base mat, typically fiberglass or organic felt, coated with asphalt, and covered with mineral granules. The asphalt provides waterproofing, while the granules offer UV protection and aesthetic appeal. They are cost-effective, relatively lightweight, easy to install and widely available in various styles and colours to suit different architectural designs. They are commonly used in residential roofing and can last 15 to 30 years but may not perform well in extreme conditions.

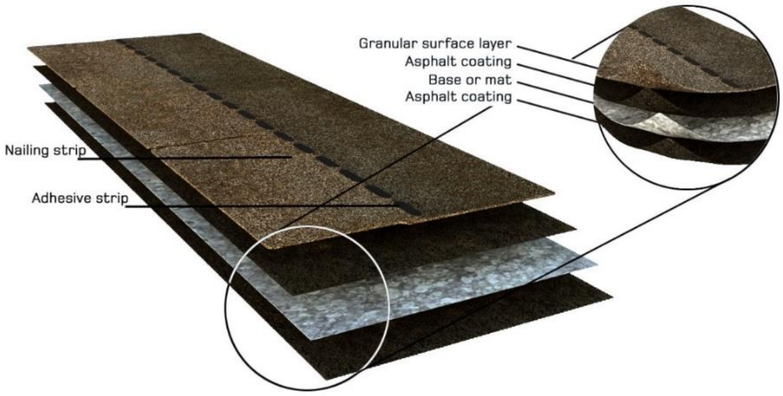

Figure 142 Asphalt Shingle. Source: www.rona.ca

Metal Roofing

Metal roofing materials can be made from steel, aluminium, copper, or zinc. They are typically formed into sheets or shingles and can last 50 years or more, often outlasting other materials. They are lightweight (put less stress on the structure compared to other materials) and highly resistant to weather, fire, and pests. Metal roofs are used in both commercial and residential applications and are becoming increasingly popular because they can improve energy efficiency when covered by reflective coatings.

Wood Shingles and Shakes

Wood shingles and shakes [fig. 23] are sawn or hand-split from lumber, cedar and redwood are common choices. Wood roofing has a natural, rustic appearance, provides good insulation and ventilation and is environmentally friendly when sustainably sourced. Wood shingles and shakes are used in residential roofing for a traditional and natural look. They are most popular in regions with mild climates and have a lifespan of 20 to 30 years with proper maintenance.

Figure 153 Wood shakes vs wood shingles. Source: www.cedur.com

Clay and Concrete Tiles

Clay tiles [fig.24] are made from natural clay, while concrete ones are a mixture of cement, sand, and pigments. Both offer a distinct and attractive appearance, are very long-lasting and highly resistant to fire and pests. These tiles are heavy and require robust roofing structures, they are used for residential and commercial roofing, particularly in regions with warm and Mediterranean climates. They provide excellent insulation and weather resistance. Traditional clay tiles have a more limited colour range than concrete ones.

Figure 164 Clay Tiles Roof, typical of the South of Europe

Slate Roofing

Slate roofing consists of natural stone tiles that are split into thin sheets. [fig. 25] They have a classic and luxurious appearance but can last 100 years or more. They are highly fire-resistant and environmentally friendly. Slate is heavy and requires a robust roof structure; it is primarily used in high-end residential and historic roofing projects, especially in areas with abundant slate resources.

Figure 25 Slate Roof

Bituminous Membranes (Modified Bitumen)

Modified bitumen made its debut in the commercial roofing industry in Europe during the mid-1960s. Prior to its introduction, the conventional system used on most commercial buildings was built-up roofing (BUR), which involved a complex arrangement of alternating layers of asphalt and fabric, topped with gravel. Although BUR was a well-established method, it had its drawbacks: it was heavy, expensive to install, challenging to repair, and often struggled to withstand extreme temperatures. The solution came in the form of modifying bitumen by incorporating polymers and fiberglass into a single, straightforward membrane.

In 1954, the first isotactic polypropylene was synthesized by Giulio Natta, an Italian chemical engineer and Noble Price winner. In the years after the invention, polypropylene production plants widespread in Italy, producing discrete quantities of a waxy by-product, the so-called polypropylene waxes. This material consists of an attactic polymer with a low molecular weight, not conforming to commercial specifications. In 1963, Ervinio Breitner, Italian entrepreneur and founder of Vetroasfalto, had the ingenious idea to use this product, which among other things was a major waste management problem, to improve the rheological characteristics of bitumen; in other words, to improve its softening point and cold flexibility. In 1964, at the

Vetroalfalto plant in Concorezzo (MI), Breitner built the first plant for the production of Bitumen-Polymer-APP waterproofing membranes reinforced with glass fiber, MBP (Membrane Bitume Polimero) in Italian. [63]

Modified bitumen, with its ease of installation and improved protection, outperformed BUR systems even in extremely cold temperatures. By 1975, Modified Bitumen Roofing (MBP) had established dominance in the global waterproofing market, playing a pivotal role in fuelling the *Italian economic boom*. [63]

Modified bitumen roofing is typically available in the form of membranes, which come in rolls and are installed directly onto the substrate using an adhesive. These membranes are known for their flexibility, allowing them to expand and contract in response to temperature fluctuations, and they exhibit high resistance to UV rays and chemicals. Modified bitumen roofing systems often comprise multiple layers, including a base sheet, reinforcement layer, and cap sheet, contributing to their durability. These roofs have a lifespan of approximately 30 to 35 years. Installation methods may involve heat welding (torch-applied), cold-adhesion, or, in certain cases, self-adhesion.

There are two varieties of MBP: APP and SBS.

APP Membranes

Commonly nicknamed *plastic asphalt*, APP membranes consist of asphalt blended with plasticized atactic polypropylene, a polymer that become elastic under high temperatures.

This type of plastic begins to melt at a point of 300F (149 °C), where it become a liquid wax-like substance which acts as an almost free-flowing liquid that can be mopped across a surface. This ease of melting and high temperature tolerance makes APP bitumen user-friendly for installers and popular on smaller roofs such as residential properties and commercial flat roofs. [63][65]

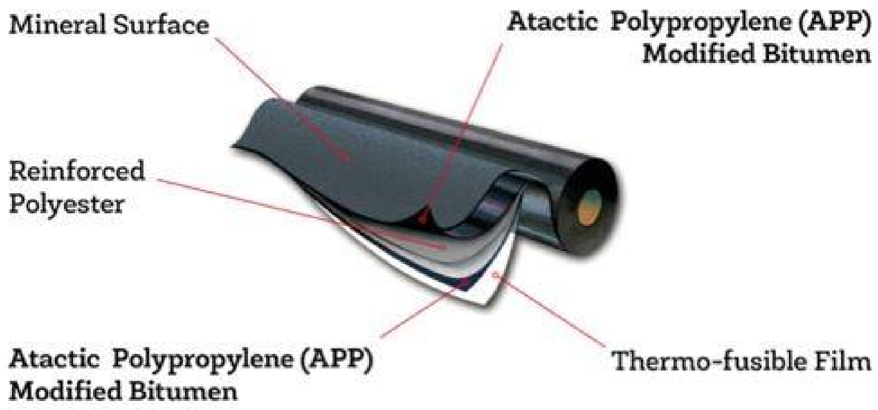

Figure 176 APP-Modified Bitumen Membrane. Source: www.iko.com

SBS Membranes

SBS-Modified bitumen consists of bitumen with a synthetic rubber modification, adding styrene-butadiene-styrene (SBS). This does not melt in the same way as APP, instead offering a ‘sticky’ melt which increases the hotter it gets. This lack of liquid flow means it takes less heat to install and allows a faster installation compared to APP. SBS systems can also be installed with cold adhesive on projects where open flames are not permitted. [64][65]

Because of the rubber used in its construction, SBS-bitumen is more flexible when compared to the plastic used in APP. This flexibility means it has recovery properties, making it capable of withstanding stresses created by wind, temperature fluctuation and expansion and contraction.

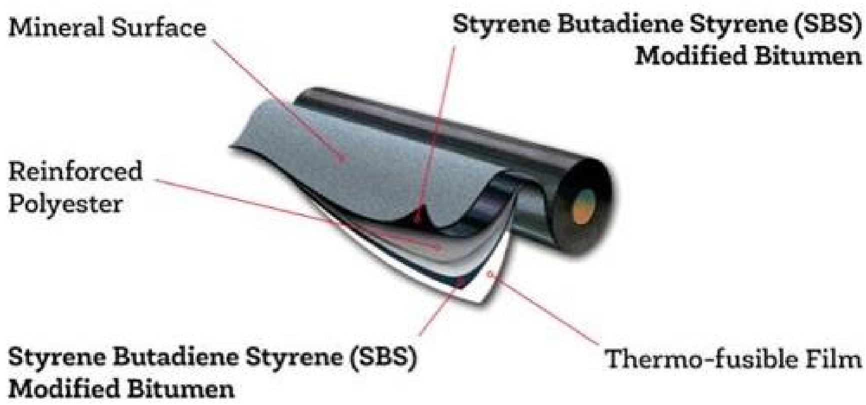

Figure 27 SBS-Modified Bitumen Membrane. Source: www.iko.com

Normally, APP membranes are more resistant to UV radiation and high temperatures and therefore suitable for hot climates. SBS, on the other hand, is more resistant to temperature fluctuations and wind force, perfect for colder northern climates. Ironically, however, SBS membranes are much more popular than APP ones in the southern United States, Mexico and Latin America, climates that are typically torrid. APP roofing, instead, is the most popular in the northern United States and Canada, areas characterised by very cold climates, subjected to high winds and temperature changes.

TPO (Thermoplastic Polyolefin) Membranes

Polyolefin membranes, abbreviated by various acronyms of which the most used are TPO (Thermoplastic Polyolefins) and FPO (Flexible Polyolefins), belong to the family of thermoplastic polymers, which react to heat by softening and regain rigidity when they cool down thanks to the sliding of the polymer chains. [62]

TPO membranes are a popular and versatile roofing material widely utilized in commercial and industrial roofing systems. These single-ply membranes consist of a thermoplastic compound, typically a blend of polypropylene and ethylene-propylene rubber with a fabric reinforcing scrim that stabilizes and strengthens them for improved and increased performance.

Unlike PVC, which, being inherently rigid, requires plasticisers to be flexible, TPO polymeric membranes owe their flexibility to the combination of ethylene-propylene (EP) and polypropylene (PP) or polyethylene (PE) copolymer particles in a nuclear reaction that creates a stable, balanced and permanent bond. TPO roofing membranes are highly resistant to UV radiation, ozone, and chemical exposure, making them reliable in various weather conditions. They often come in reflective or white formulations, effectively reducing heat absorption and cooling costs, which is especially valuable in hot climates.

TPO roofs are very lightweight and can last 20 or more years. Installation methods include heat welding or adhesive application, both quick and efficient solutions for flat or low-slope roofs. Overall, TPO membranes have become a preferred choice in the roofing industry, representing 60% of the commercial sector. They are valued for their long-lasting performance, energy-saving properties, and cost-effectiveness. [53]

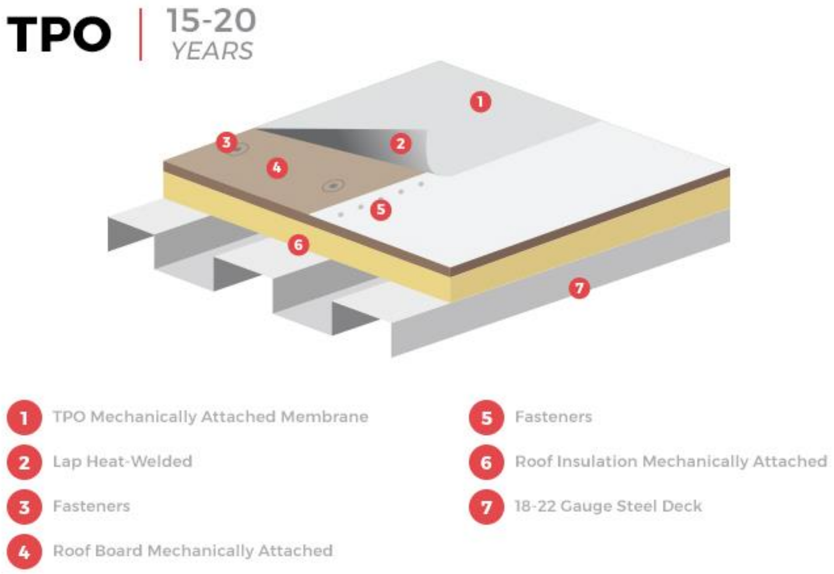

Figure 188 TPO ROOFING MEMBRANE Source: www.roofslope.com

EPDM (Ethylene Propylene Diene Monomer) Roofing

EPDM roofing consists of a single-ply synthetic rubber membrane that is made from a combination of ethylene, propylene, and diene monomers. EPDM sheets are known for their durability and resistance to UV radiation, ozone, and weathering. They remain flexible even in cold temperatures and can accommodate building movement. EPDM can be fully adhered, mechanically attached, or ballasted during installation, it requires minimal maintenance and is resistant to punctures and tears. This type of roofs can last 20 to 30 years and are widely used in both commercial and residential applications, particularly for low-slope or flat roofs. They are known for their cost-effectiveness, durability, and ease of installation. EPDM is especially popular in regions with moderate to cold climates.

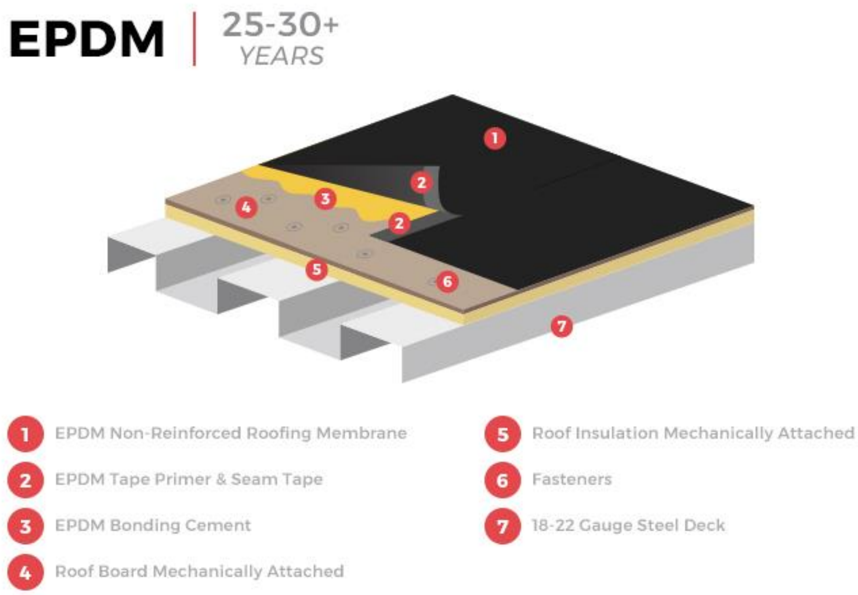

Figure 199 EPDM ROOFING MEMBRANE Source: www.roofslope.com

PVC Roofing

PVC roofing is made of a flexible and synthetic membrane composed of polyvinyl chloride. The membrane typically includes layers of PVC polymer, reinforcing polyester or fiberglass mesh, and protective additives.

This solution is highly durable and resistant to extreme weather, UV radiation, and chemical exposure. It has a long lifespan, often exceeding 20 years with proper installation and cure, and maintains its integrity in extreme temperatures, making it suitable for various climates. PVC membranes provide excellent waterproofing properties: the seams and joints are typically heat-welded to create a watertight seal, reducing the risk of leaks. Sheets or rolls are available in reflective or "cool roof" formulations, which can help reduce heat absorption and cooling costs in warm climates: the surface (white or light-coloured) reflects a significant portion of solar heat.

PVC is highly resistant to chemicals, making it particularly suitable for industrial roofs with potential exposure to pollutants or rooftop equipment. It is also lightweight and easy to install; it can be mechanically fastened, adhered with adhesive, or heat-welded, depending on the specific project requirements.

PVC roofing is commonly used in commercial and industrial applications, particularly for low-slope or flat roofs. It is suitable for various types of buildings, including office complexes, warehouses, retail centres, and manufacturing facilities. It is also used in residential buildings in areas with harsh weather conditions or when homeowners seek a long-lasting roofing solution.

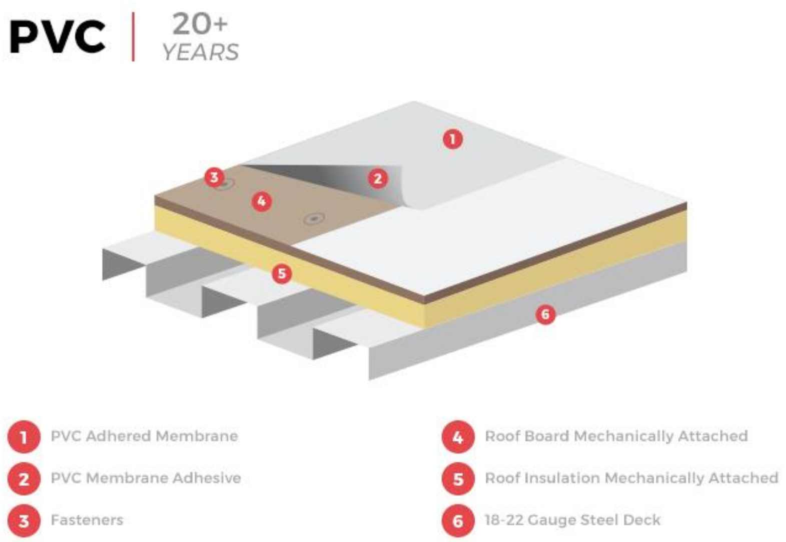

Figure 30 PVC ROOFING MEMBRANE Source: www.roofslope.com

Roofing Materials Market Analysis

The global roofing materials industry had a market value of USD 138.43 billion in 2022, and it is anticipated to expand to USD 173.23 billion by 2030, demonstrating a compound annual growth rate of 3.6%. The growth is driven by rising investments in the renovation and redevelopment of both commercial and residential buildings, rapid urbanization, and improving living standards in emerging economies. [55]

By Application

Based on applications, the roofing market is divided into *residential* and *commercial* sector.

Residential application segment leads the way and accounts for more than 55% of the global revenue. [53] This sector is projected to grow further in the next years, fuelled by the rapid urbanisation of emerging countries and the rising preference of consumers for single-family housing structures. Residential (single-family) roofs are often covered with a variety of materials, with asphalt shingles being the most common choice due to their affordability and ease of installation. Other materials, such as wood shakes, slate, metal, and clay or concrete tiles, are used for aesthetic appeal and durability. Roofing solutions for multi-family housing generally involve flat or low-slope roofing systems: here TPO, EPDM, or modified bitumen membranes are used due to their durability and ease of maintenance.

Commercial roofing encompasses a wide range of non-residential structures, including office buildings, shopping centers, industrial facilities, and schools. Unlike residential roofs, commercial roofs often have low-slope or flat designs, which require specialized materials like TPO, EPDM, and PVC to ensure durability and weather resistance. The global demand for these roofing products is expected to rise due to evolving business models, the emergence of new startups, and the increasing need for office spaces, as well as the renovation of manufacturing facilities worldwide.

From an institutional perspective, the growth of the commercial roofing industry is driven by substantial investments in Europe and North America for the renovation of hospitals, educational institutions, sports facilities, and governmental offices. Additionally, countries like India, China, and other developing nations in Asia Pacific, Latin America, and Africa are heavily investing in infrastructure development and the construction of commercial buildings such as multiplexes and shopping complexes.

By Area

Asia Pacific is the leading market with significant construction activities taking place in both the residential and commercial sectors. Countries like India, China, Indonesia, and Vietnam are experiencing robust growth in construction. In 2022, the roofing materials market in the Asia Pacific region was valued at USD 54.87 billion. [55] Of note, the Indian government has set an ambitious target of constructing 29.5 million houses by March 2024. This ambitious housing initiative is expected to have a substantial impact on the regional roofing materials market, further driving its growth.

The Middle East is another significant roofing materials market, driven by increased government expenditure on commercial and industrial construction projects. The region is expected to experience the highest CAGR over the next eight years, estimated at 5.3%. [55] The 2022 FIFA World Cup held in Qatar played a crucial role in boosting the roofing industry in the region. The event led to substantial investments in infrastructure, sports facilities, and hotels, contributing to the growth and development of the roofing materials sector in the Middle East.

In North America, the roofing industry holds significant economic importance, with an annual worth of USD 34 billion. Roofing contractors are a major segment within the construction industry, contributing approximately 6% to the total annual revenue in the region. [61] The roofing industry is a substantial employer, with over 3.0 million people employed in the roofing sector in the United States alone. Moreover, it is responsible for the installation of more than 1.7 billion square feet of roofing every year.

The North American construction industry faced challenges during the COVID-19 pandemic, including labour shortages and government-imposed shutdowns of various manufacturing plants. However, the roofing market in the United States and Canada is now in the recovery phase, driven by the increasing demand for re-roofing projects in the commercial, industrial, and residential sectors.

The roofing market in Europe is valued at USD 29 billion. [53][56] The member states of the European Union are experiencing increased tourism, retail trade, and business activity, which is expected to drive the construction of commercial buildings. Additionally, there is a growing emphasis on converting old, energy-consuming buildings into energy-efficient and sustainable structures. This shift towards sustainability is anticipated to further boost the demand for roofing materials in Europe.

The roofing industry in South America displayed resilience despite the economic challenges brought about by the pandemic. In 2022, the market was valued at USD 6.41 billion. However, there is ongoing uncertainty regarding economic policies and reforms in Brazil, and recent social unrest in countries such as Colombia, Chile, Bolivia, and Ecuador. These factors may have a negative impact on the economic growth of the region, potentially affecting the roofing industry in South America.

Africa is currently witnessing robust growth in the demand for roofing materials, primarily fuelled by the rapid expansion of the residential building sector in countries such as Nigeria, Egypt, Ethiopia and Kenya. The roofing materials market in Africa is valued at approximately USD 4 billion. Importantly, it has the second-highest forecasted CAGR of 4.7% from 2024 to 2030. This growth trend reflects the increasing construction activities and urbanization across the continent, making Africa a significant market for roofing materials. [55]

Key Companies

The global roofing materials market exhibits a moderate level of concentration and is characterized by the presence of numerous manufacturers. Many of these companies are headquartered in North America and Europe, with countries like Italy, France, and Germany being significant players. Additionally, some of these companies have manufacturing facilities in Mexico and Latin America.

Notably, the southeastern United States and northern Italy are the regions with the highest concentration of companies making them the key hubs for the production of roofing materials.

Some prominent players in the global market include:

GAF Materials Corporation

Johns Manville

Atlas Roofing Corporation

Owens Corning

TAMKO Building Products, Inc.

IKO Industries Ltd.

Carlisle Companies Inc.

CertainTeed Corporation (Saint-Gobain SA)

Polyglass S.p.A. (Mapei S.p.A.)

Dow Chemical Company

BASF SE

Vetroasfalto S.p.A.

Sika AG

Soprema Group

Roofing Industry in the Southeast of the United States

The Southeastern United States, which includes states like Florida, Georgia, North Carolina, South Carolina, Alabama, Mississippi, Tennessee, and West Texas has a thriving roofing industry due to its diverse climate and population growth. In this region there is a mix of roofing manufacturing companies, roofing contractors, distributors, and retailers serving both residential and commercial markets. Roofing materials that offer resistance to high winds, heavy rainfall, and UV radiation are commonly sought after in the Southeast due to the hurricane-prone climate, while reflective and energy-efficient products are gaining popularity, especially in the hot and sunny parts of the region, to reduce cooling costs.

The favourable economic and social policies pursued by the local governments combined with the climatic conditions and the geographical location (facing the Atlantic Ocean and close to Latin America) make of the southeastern USA a strategic industrial region. That is why almost all roofing materials companies have manufacturing plants in the area or are in the process of building one.

1. *GAF Materials Corporation*

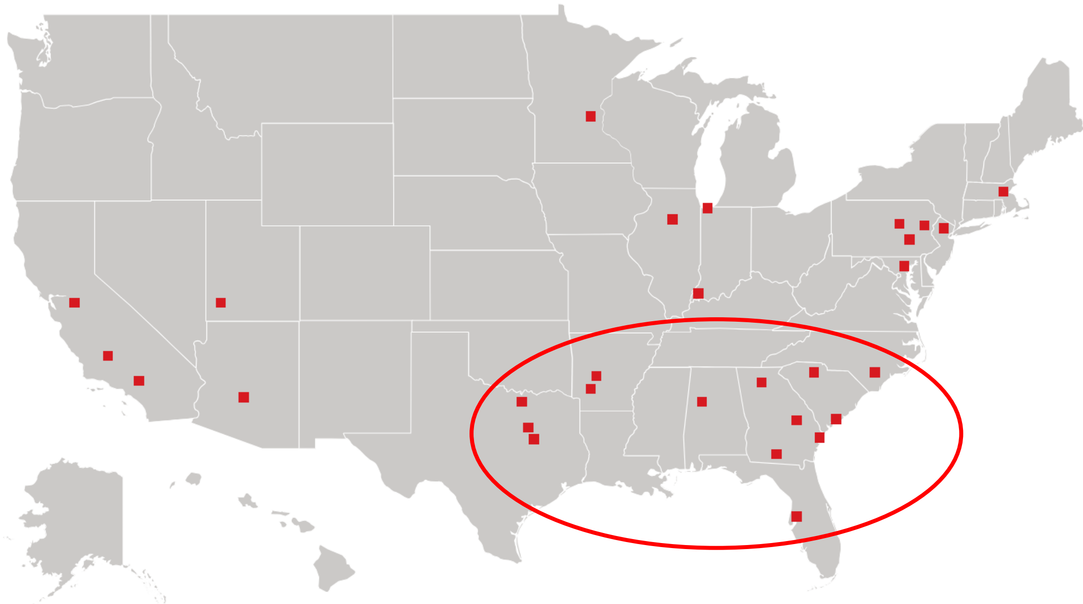

Figure 31 GAF manufacturing plants Source: www.gaf.com

Gainesville, TX – TPO membranes production
Dallas, TX – Residential roofing shingles production
Ennis, TX – R&D center
Arkadelphia, AR – Waterproofing product manufacturing
Tuscaloosa, AL – Residential roofing shingles production
Valdosta, GA – future TPO manufacturing plant
Savannah, GA – Multi-ply roofing production
Charleston, SC – Roof coatings production
Chester, SC – Non-woven fiberglass mat production
Burgaw, NC – ventilation products manufacturing
Tampa, FL – Residential roofing shingles production

General Aniline & Film is North America's largest roofing and waterproofing manufacturer. Founded more than 135 years, GAF is headquartered in Parsippany, NJ, and currently employs over 4,000 people nationwide with 35 manufacturing operations across 27 locations in the US (14 in the Southeast). [72]

2. Johns Manville

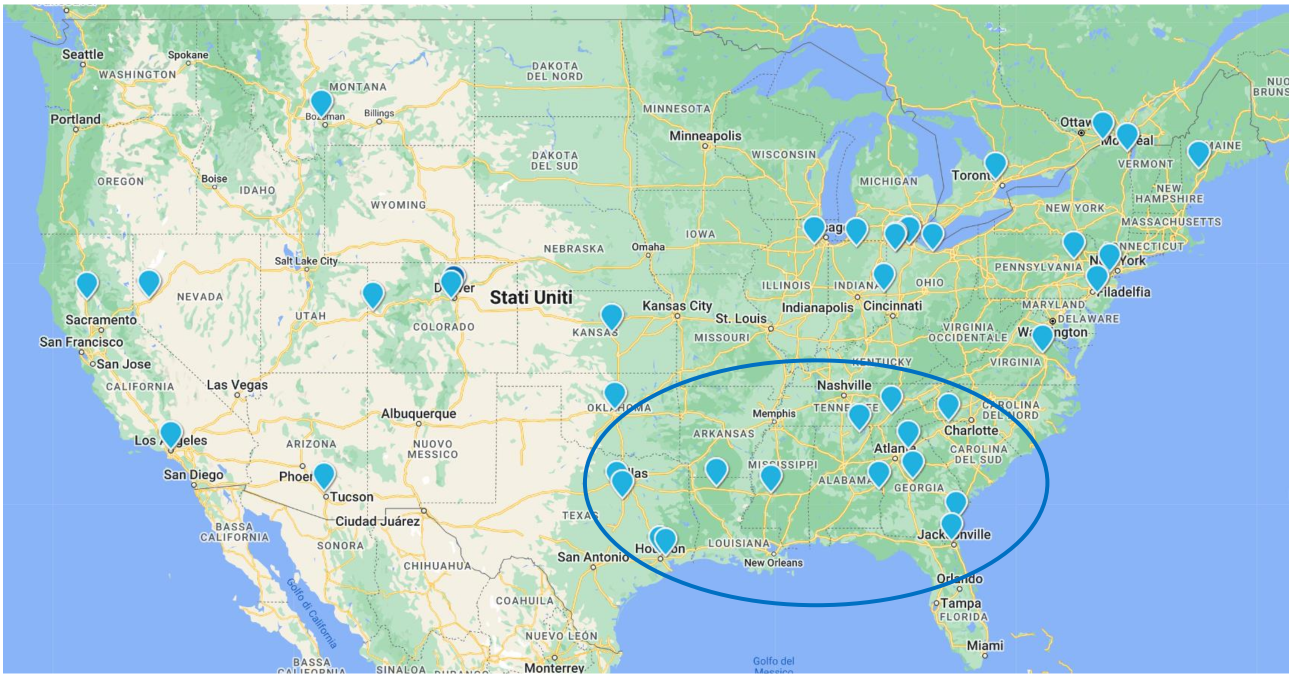

Figure 32 JM American production plants. Source: www.jm.com

Hillsboro, TX – Plant roofing systems
Cleburne, TX – Plant insulation systems
Houston, TX – Plant insulation systems
LaPorte, TX – Plant insulation systems
Ruston, LA – Plant insulation systems
Richland, MS – Plant engineered products
Scottsboro, AL – Plant roofing systems
Etowah, TN – Plant engineered products
Winder, GA – Plant insulation systems
Macon, GA – Plant roofing systems
Brunswick, GA – Plant insulation systems
Spartanburg, SC – Plant engineered products
Jacksonville, FL – Plant roofing systems
Phenix City, AL – Plant insulation systems

Johns Manville is a leading manufacturer and marketer of premium-quality insulation and commercial roofing, along with glass fibers and nonwovens for commercial, industrial and residential applications. It was founded in 1858, when the H.W. Johns Manufacturing Company began in New York City. Headquarters are now in Denver, Colorado. The company have 44 manufacturing facilities across North America and Europe, 14 production plants are located between Texas and South Carolina. [69]

3. Atlas Roofing Corporation

Figure 203 Atlas Roofing Corporation Manufacturing Locations. Source: www.atlasroofing.com

Atlas Roofing Corporation is a customer-oriented manufacturer of residential and commercial building materials. Atlas has grown from a single shingle-manufacturing plant into an industry leader with 24 facilities across North America (3 in Texas, 3 in Luisiana, 1 in Alabama and 3 in Georgia). [70]

4. Owens Corning

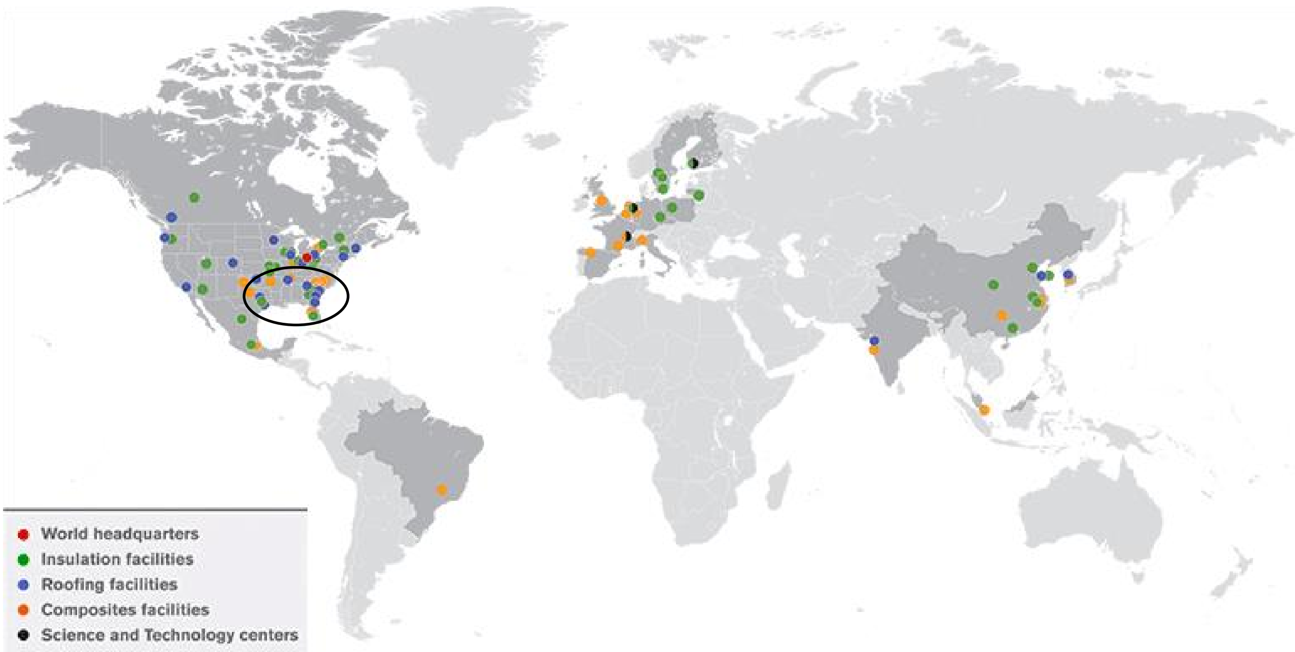

Figure 34 Owens Corning worldwide locations. Source: www.owenscorning.com

Founded in 1938, Owens Corning has approximately one hundred operations spread across North America, South America, Europe, and Asia Pacific. In the Southeast the company count 24 manufacturing plants: [67]

Aiken, SC	Houston, TX	Fairburn, GA
Amarillo, TX	Irving, TX	Fort Smith, AR
Atlanta, GA	Jackson, TN	Fresno, TX
Blythewood, SC	Jacksonville, FL	Gastonia, NC
Charleston, SC	Joplin, MO	Savannah, GA
Cleveland, TN	Kansas City, KS	Sedalia, MO
Concord, NC	Lakeland, FL	Springfield, TN
Duncan (Ridgeview), SC	Memphis, TN	Starr, SC

5. *IKO Industries Ltd.*

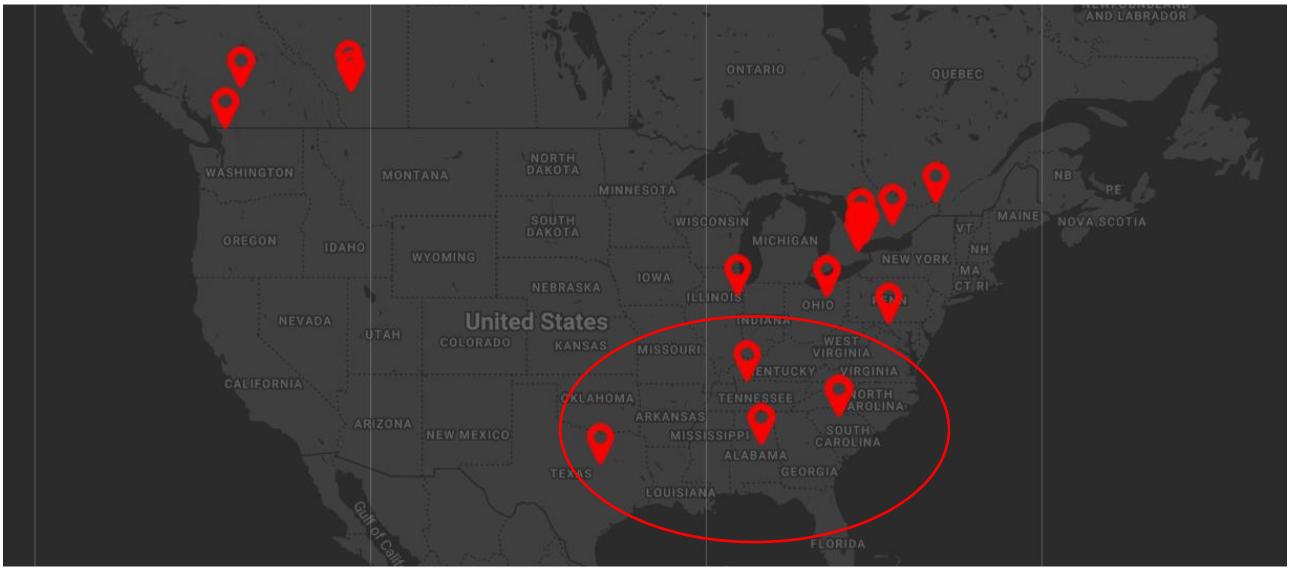

Figure 215 IKO Industries manufacturing plants. Source: www.iko.com

Clarksville, TN	Chester, SC
Sylacauga, AL	Hillsboro, TX

IKO is a worldwide enterprise with more than 3,500 employees and more than 25 manufacturing plants in Canada, United States, England, Belgium, Holland, France and Slovakia. The company ships roofing products to 96 countries around the globe. It was founded in Canada in 1951 as a manufacturer of building paper and then expanded to include coated roll roofing. IKO entered the U.S. marketplace in 1979 through various acquisitions and has since expanded its presence by building new plants across North America, 4 of which in the Southeast. The most recent plants to open were in Hillsboro, Texas and Hagerstown, Maryland. [68]

6. *Carlisle Construction Materials Inc.*

Figure 226 CCM manufacturing plants. Source: www.carlisleconstructionmaterials.com

CCM has 41 manufacturing facilities across the US, 14 of which located in the Southeast. [66]

Senatobia, MS - TPO
Houston, TX - Insulation
Spring, TX - Carlisle Polyurethane Systems
Tyler, TX - Metal roofing
Terrel, TX - Waterproofing
Garland, TX - Insulation
Wylie, TX - HQ

Cartersville, GA - TPO
Acworth, GA - Metal roofing
Lake City, FL - Insulation
Tampa, FL - Metal roofing
Bartow, FL - Waterproofing
Lakeland, FL - EPS (Expanded Polystyrene)
Chattanooga, TN

7. *CertainTeed Corporation*

Founded in 1904 as General Roofing Manufacturing Company, today, CertainTeed is North America's leading brand of exterior and interior building products, including roofing, siding, fence, decking, railing, trim, insulation, gypsum and ceilings. A subsidiary of Saint-Gobain, one of the world's largest and oldest building products companies, CertainTeed and its affiliates have more than 6,300 employees and more than 60 manufacturing facilities throughout the United States and Canada (12 in the south-east area). [71]

Insulation
Winter Haven, FL
Athens, GA

Roofing
Russellville, AL
Glenwood, AR
Little Rock, AR
Peachtree City, GA
Shreveport, LA
Gads Hill, MO
Jonesburg, MO
Oxford, NC
Charleston, SC
Ennis, TX

Roofing Industry and Recycling

The roofing industry, once synonymous with disposal challenges and environmental concerns, is undergoing a remarkable transformation towards sustainability and responsible waste management. Recycling roofing materials has emerged as a critical component of this revolution, reducing landfill waste, conserving resources, and contributing to a more eco-conscious construction sector. Roofing manufacturers and contractors are increasingly exploring ways to recycle or repurpose their products.

Different roofing materials have varying levels of recyclability, and understanding these aspects can help in making environmentally conscious choices.

Asphalt Shingles

Asphalt shingles are the most popular and widely used residential roofing type and have been for decades because of the material's low price point and ease of installation. For a long time, they could not be recycled because of their oil-based petroleum composition. When an asphalt shingle roof was at the end of its lifecycle, the shingles were torn off and disposed of in a regular dumpster, which led to an abundance of shingles in landfills. Nowadays, they are totally recyclable: the process consists in repurposing them into an additive for hot-mix asphalt (HMA) or cold patch to fill cracks and potholes in roads. To do this, after the roofing waste is sorted to remove extraneous agents, the shingles are ground into smaller particles as per state and local regulations using specific grinders, designed to handle the abrasive material. [74]

In 2023, however, approximately 11 to 13 million tons of asphalt shingles still end up in landfills every year in the United States. This is a continuing issue, especially because it takes upwards of 300+ years for a shingle to completely break down. [73]

Metal Roofing

Metal roofing materials, such as steel and aluminium, are highly recyclable. When these roofs reach the end of their life cycle, the materials can be melted down and used to manufacture new metal products. The recycling process for metal roofing does not compromise the quality or integrity of the material.

Many metal coils and sheets used to fabricate metal roofing panels may already contain previously recycled metals. The most likely roofing material to be made of previously recycled metal is aluminium, in fact 95% of all aluminium roofing comes from recycled products. The best part of using an already recycled material is that it significantly cuts down on the amount of energy and resources required to produce it from virgin materials: recycled steel uses 26% of the original energy while recycled aluminium uses only 5%. [73]

Additionally, metal roofing materials can either be pre-consumer or post-consumer recycled content: scrap metal content produced during the initial manufacturing stage that has been recycled for future use or materials that have already been in the possession of a consumer at a point in time and have been recycled for reuse, like soda cans.

Single-Ply Membranes (TPO, PVC, EPDM)

Recycling options for single-ply roofing membranes like TPO, PVC, and EPDM are limited compared to some other roofing materials. Some manufacturers and recycling facilities have been exploring methods to recycle these materials, although it may not be as widespread as with asphalt and metal.

The only material of this type that is really being recycled is EPDM. The process was invented in 2006 by the EPDM Roofing Association (ERA) and consist in grinding the roofing sheets into a power-like substance, the powder is then devulcanized using an industrial autoclave which provide both heating and high-pressure steam. To aid the devulcanization process, 2-mercaptobenzothiazoledisulfide (MBTS) and tetramethyl thiuram disulfide (TMTD) devulcanizing agents, and aromatic and aliphatic oils are also used.

The devulcanized rubber can then be blended with virgin EPDM and used to produce automotive rubber strips. [75][76] Unfortunately, this practice is still very underdeveloped: it is estimated that there are upwards of 200,000 tons of EPDM in landfills available for recycling. [75]

The second case study presented in this article is dedicated to the creation and development of a TPO recycling process by SD Polymers, a discovery that could change the landscape of the industry.

Modified Bitumen Membranes

The recyclability of MBP is a complex issue due to the combination of bitumen, polymers, and reinforcement layers. While there are efforts to develop recycling methods for these materials, challenges remain in separating and recycling all components effectively. As of today, the disposal in landfills is the only way to manage MBP waste, no recycling activity is underway around the globe.

Concrete or Clay Tiles

Both concrete and clay tiles can easily be recycled, the process typically involves crushing the old tiles into smaller pieces or aggregates. Crushed concrete can then be used in various construction applications, as road base or as a component in new concrete products. Clay particles can be repurposed as additives in clay brick or tile manufacturing or used as lightweight aggregates in concrete products. [73] End of life tiles can also be reused as they are in landscaping design projects.

In addition to post-consumer recycling benefits, many clay and concrete roof tiles contain already recycled materials, thus adding to its sustainability.

As recycling practices evolve and expand, roofing professionals, property owners and policy makers increasingly recognise the importance of responsible waste management in the roofing industry, a sector that is undoubtedly lagging in this respect.

Geocomposites Industry

Introduction to geosynthetic materials

Geosynthetics are polymeric man-made products used to solve geotechnical problems in construction projects. They may be planar, strips or three-dimensional structures. The different types of geosynthetics are uniquely designed to deliver varying functions such as stabilisation, reinforcement, separation, filtration, drainage, erosion control or containment of liquids. Some products are designed to deliver a combination of functions. The purpose of geosynthetics can be derived easily from the word itself: *Geo* means earth, in the sense of ground or land, and *Synthetic* means manmade, in the sense of an artificial substance. [77][79]

There are seven different types of geosynthetics:

Geogrids

Geogrids [fig. 37] are structured as a regular, interconnected network of tensile elements known as ribs, which can be linked together through extrusion, bonding, or interlacing methods. The spaces between these ribs are larger than the individual constituents themselves. Typically, ribs are composed of robust polymeric materials like high-density polyethylene (HDPE), polypropylene, or polyester (PET). In the manufacturing process, the plastic may undergo stretching to align the molecular structure, thereby enhancing the strength and rigidity of the product.

The inherent stiffness of the ribs and the robust connections within a geogrid facilitate a high level of interaction between the geogrid and the surrounding soil. Soil particles can partially penetrate the openings and are either restrained by the ribs or confined within these apertures. Geogrids find particular utility in soil stabilization and reinforcement applications, including construction on weak soil foundations, road construction, and the construction of earth retaining structures. Consequently, they rank among the most widely employed geosynthetic materials in the industry. [78][79]

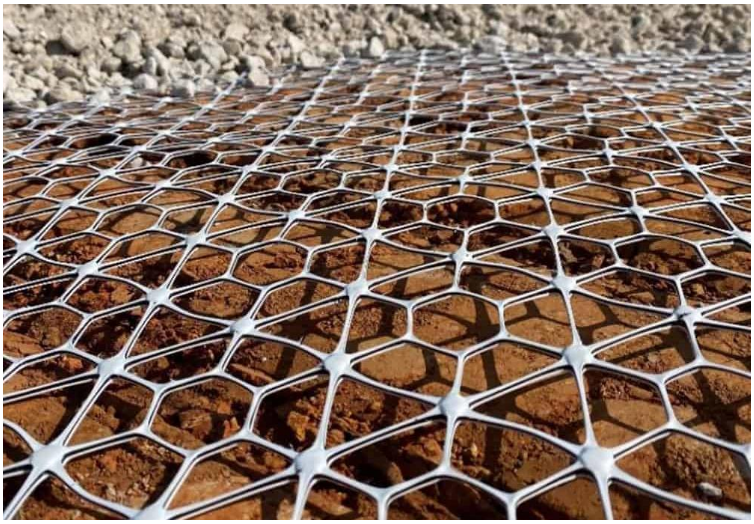

Figure 237 TENSAR INTERAX® GEOGRIDS Source: www.tensar.co.uk

Geotextiles

Geotextiles [fig. 38] represent the largest and one the firsts categories of geosynthetic materials to be created. They are porous fabrics composed of synthetic fibers like polyester or polypropylene and can be manufactured in woven, knitted, or non-woven forms. Non-woven geotextiles are created by mechanically or thermally/chemically bonding fibers or filaments that may be oriented directionally or randomly. These materials come in various strengths and weights, ranging from lightweight filtration products to robust reinforcement materials. When employed alongside soil, they serve diverse functions, including separation, filtration, drainage, protection, and reinforcement. While they are most used as separators before road construction or as filter in drainage applications, their versatility extends to various engineering projects and applications. [78][79]

Figure 248 Geotextile Source: www.bontexgeo.com

Geocells

Geocells [fig. 39] are three-dimensional geosynthetic products composed of ultrasonically welded polyethylene webs or geotextile strips, that expand into a honeycomb-like structure intended to be filled with soil, sand or gravel. The cellular structure contains and stabilises the infill material, minimising soil movement. This allows geocells to have multi-functional uses, including soil erosion protection, and stabilisation. [79]

Figure 39 HDPE Geocells – Cellular Confinement Systems (CCS). Source: www.industrialplastics.com.au

Geonets

Geonets are typically engineered with two sets of relatively thick polymeric ribs, often composed of polyethylene, arranged in parallel fashion. These ribs are securely bonded to create a distinctive diamond-shaped pattern, forming a network characterized by substantial porosity, facilitating efficient in-plane flow of fluids and gases. While geonets possess notable tensile strength, their primary role is in drainage applications. Initially, they found utility in environmental contexts, notably in hazardous waste containment and landfills, where they efficiently collected and directed leachate fluids while detecting potential leaks. Geonets have also demonstrated their effectiveness in establishing capillary breaks to counter moisture intrusion through capillary rise. Over time, their usage has expanded to encompass various applications, including drainage behind retaining walls, slope reinforcement, hydraulic structures like dams and canals, expansive horizontal surfaces such as golf courses and athletic fields, and as drainage underlays beneath surcharge fills and embankments. To safeguard against soil infiltration into voids, geonets are commonly used in conjunction with geotextiles and/or geomembranes. While traditional biaxial geonets [fig. 40] were primarily designed without the intent of supporting tensile or shear loads, newer triaxial [fig. 41] iterations have been developed to enhance flow capacity while providing increased load-bearing capacity in both compression and shear. The triplanar structure minimizes intrusion by geotextiles and offers improved flow capacity through longitudinal channels. With their heightened rigidity, tensile strength, and resistance to compression, they prove suitable for a diverse array of applications, including incorporation within roadway pavement systems, beneath highways and airfields, and beneath concrete building slabs. [77][78]

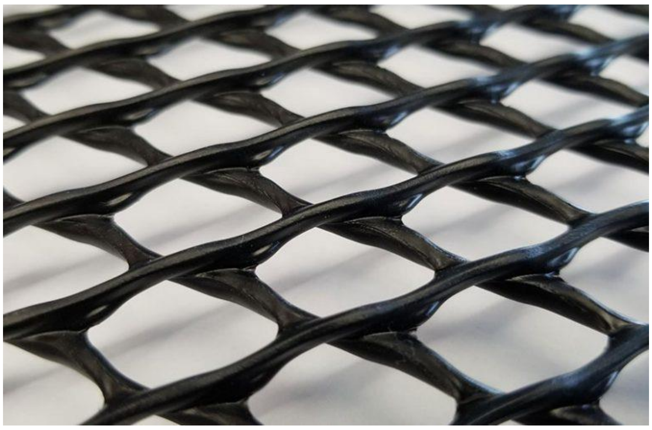

Figure 40 Biaxal Geonet. Source: www.layfieldgroup.com

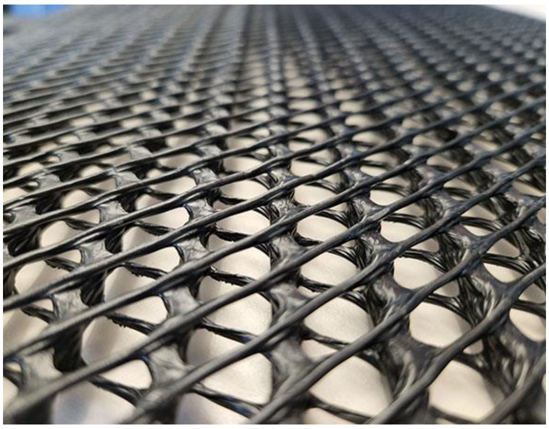

Figure 41 Triaxial Geonet. Source: www.layfieldgroup.com

Geopipes

Geopipes [fig. 42] are polymeric pipes, either perforated or solid wall, designed to facilitate the effective drainage of gases and liquids within construction projects. They are typically encased in a geotextile filter to ensure their drainage efficiency. Geopipes find utility in various scenarios, such as collecting leachate or gases in landfill applications and other situations requiring efficient drainage and containment. [79]

Figure 252 Single Wall (SW) HDPE Drainage Pipe. Source: www.geostar-tm.com

Geofoam

Geofoam, also referred to as Expanded Polystyrene (EPS), represents an exceptionally lightweight and durable material often employed as an alternative to soil backfill. Geofoam blocks are crafted through the expansion of polystyrene, resulting in numerous gas-filled, sealed cells within the block. This unique structure is the reason for their remarkably low density. [79] The inherent low density of geofoam renders it invaluable in engineering ventures, particularly as a filling material when dealing with soft or compressible foundation soils. When used as a lightweight core within an embankment, it effectively mitigates settlements and has the potential to eliminate the need for staged construction. [78]

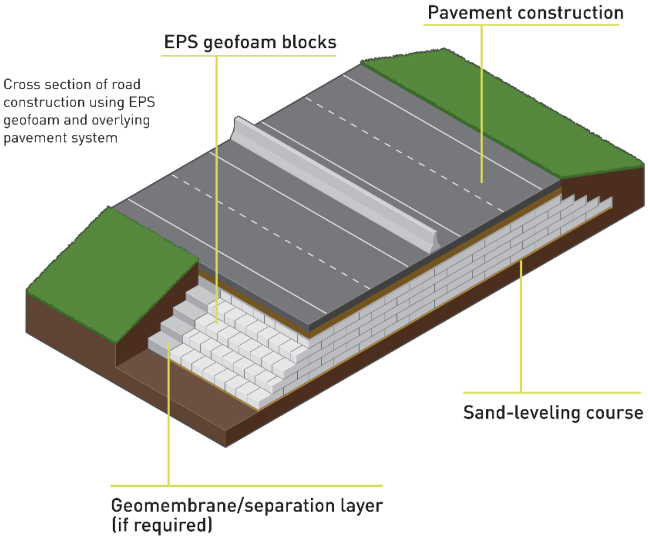

Figure 263 Geofoam in road application. Source: www.geofoam.org

Geomembranes

A geomembrane [fig. 44] is a synthetic membrane usually made of high-density polyethylene with low permeability. These specialized membranes serve as effective barriers against the passage of liquids or gases, exerting control over fluid movement and ensuring containment in geotechnical engineering endeavours. Geomembranes can be especially useful where there is the potential for leakage of hazardous contaminants as this geosynthetic offers chemical-resistant properties. They are commonly employed as liners in various sectors such as landfill management, mining operations, and agriculture, where their impermeable nature plays a pivotal role in maintaining environmental integrity. [77][78][79]

Figure 274 Geomembrane. Source: www.productsandsolutions.pttgcgroup.com

Geocomposites

Geocomposite is a generic name used to define a factory-fabricated product consisting of the combination of two or more geosynthetic types discussed above. Combining the features of each geosynthetic creates a product with more benefits than any individual product type, particularly useful in drainage and containment applications and some road foundation situations. [77]

Drainage Composites

Drainage composites are employed in cases requiring substantial drainage capacity. They are made up by associating a geonet or geomembrane (corrugated, *waffle* or *dimpled*) core, designed with high porosity, between two layers of geotextiles to provide filtration and prevent soil intrusion.

Geocomposite can take on various configurations. Geonet drains [fig. 45] feature an extruded high-density polyethylene net core with a non-woven filter fabric bonded to its ridges. The filter fabric retains soil or sand particles as well as freshly placed concrete or grout, allowing filtered water to pass into the form to irregular surfaces. Because of this crush-proof nature, geonet drainage composites can be used in the most extreme cases with heavy loads or heavy vehicular traffic, both horizontally and vertically.

Thin strip drains, often referred to as prefabricated vertical drains, combine a formed polymeric drainage core with a filter fabric bonded to one or both sides. They are utilized to aid ground consolidation and can be inserted directly into soft ground using specialized equipment.

Thicker versions with significantly larger core volumes serve as edge drains in roadway applications or for horizontal drainage within soil masses. Sizable sheet drains, featuring an impermeable waffle core with a geotextile filter on one side [fig. 46], are deployed adjacent to foundations and behind retaining walls to mitigate hydrostatic pressures beneath and behind these structures.

Geocomposite prefabricated sheet drains can also be composed of a dimpled polymeric core with a woven or nonwoven geotextile bonded to one or both sides. The geotextile allows water to pass through while retaining backfill materials.

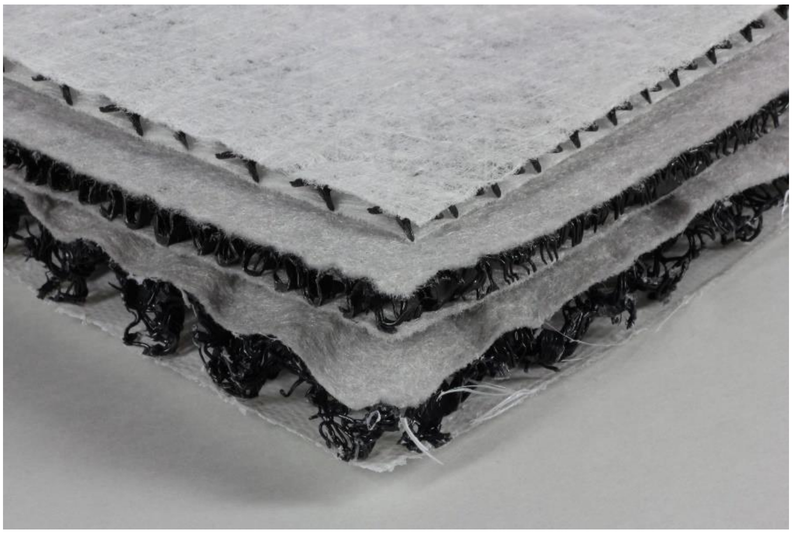

Figure 45 Geonet Drainage Composites. Source: www.maccaferri.com

Figure 286 Geocomposite waffle sheet drain. The filter fabric is bonded to each dimple to prevent soil intrusion into the core flow channels while allowing water to freely enter the drain core. Source: www.sciencedirect.com

Geosynthetic Clay Liners

Another significant category of geocomposites, created in the late 1980s, is *Geosynthetic Clay Liners*. [fig. 48] They consist of two non-woven geotextile sheets enclosing a layer of sodium bentonite clay (typically with water contents ranging from 10% to 18% and layer thicknesses of 4–6 mm), securely bonded together through techniques like stitching or needle punching and further heat-treated for layer consolidation. [fig. 47][78]

GCLs offer a more expedient and efficient alternative to the conventional compacted clay liners. The swelling properties of the sodium bentonite layer contribute to the self-sealing capabilities, ultimately reducing the risk of leakage, while the geotextile simplifies installation. are mostly used in landfill management as barriers in solid waste containment systems. [79]

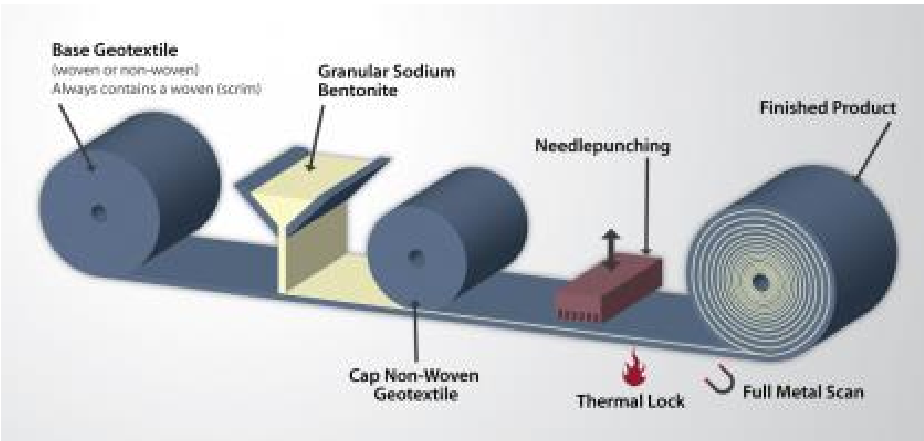

Figure 47 Geosynthetic clay liners manufacturing process. Source: www.terrafixgeo.com

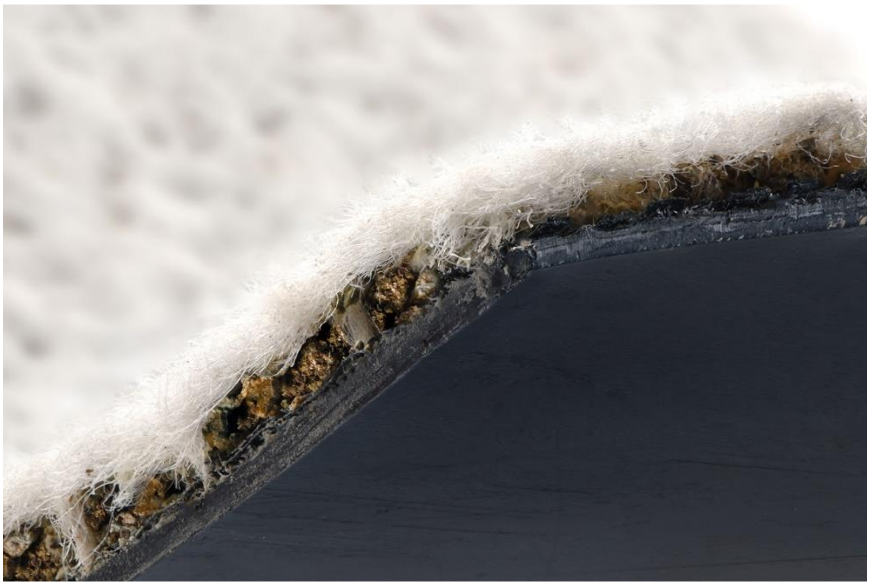

Figure 48 BENTOMAT Geosynthetic Clay Liners. Source: www.beco-bermueller.de

Earthquake Drains

A novel type of geocomposite, known as *earthquake drains*, involves the installation of a perforated pipe enveloped by a robust filtering geotextile. This innovative approach is employed to address liquefaction risks in loose sandy soils. [78]

Earthquake drains are installed by vibrating the insertion mandrel during penetration and removal. [fig. 49] The vibrations result in some densification of the granular soils, assisting in the liquefaction mitigation. The drain core is tightly wrapped with geotextile filter fabric, allowing free access of pore water into the tube while preventing the piping of fines from adjacent soils. The geotextile wrap is durable and can withstand handling and abrasion during installation. Several core designs and fabric types can be used to fit a variety of drainage applications and soil classifications.

Liquefaction mitigation achieved with earthquake drains can be valuable for support of embankments, reduction of lateral spreading from seismic loading, containment of densified ground, support of floor slabs in certain conditions, liquefaction mitigation of mine tailings, and reducing seismic deformations of pile groups. Combined with other ground improvement techniques, earthquake drains can be applied to big box stores, mid-rise buildings, tanks, ports, and hydraulic fills. [81]

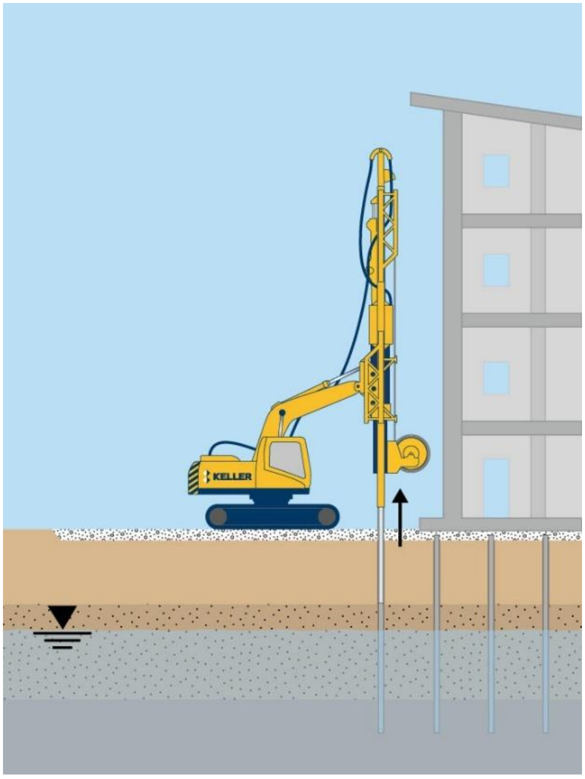

Figure 299 Earthquake drains installation. Source: www.keller-na.com

Geocomposites market analysis

The global geocomposites market is expected to expand from USD 447.1 million in 2023 and reach USD 681.4 million by 2030, exhibiting a compound annual growth rate of 6.2%. [55]

The reasons for this growth are the steady expansion of the construction industry boosted by the various large-scale infrastructure projects around the globe, the wide usage of geocomposites material in road and rail development, and the increasing demand for waste treatment, water containments and canaling projects. [53][82]

North America dominates the industry both in terms of value and volume, with a market share of 42,5%. Europe holds 29,5% and is anticipated to so until 2030 while Asia-Pacific is expected to be the highest growing area (at a GAGR of 13%) thanks to the unbelievable market potential of China and India. [82] The Latin American market is projected to experience modest growth, primarily due to the region's less developed construction sector. In contrast, the markets in the Middle East and Africa are poised for significant expansion, driven by a rise in the number of intricate construction and infrastructure projects. [55]

The market is basically divided between 14 major companies spread around the world:

GSE Holding, Inc. (US)

Tensar International Corporation (US)

TenCate Geosynthetics (Netherlands)

Terram Geosynthetics Private Limited (UK)

Officine Maccaferri S.p.A. (Italy)

Hanes Geo Components (US)

SKAPS industries (US)

Ocean Global (India)

ABG Geosynthetics (UK)

Freudenberg Group (Germany)

Thrace Group (Greece)

Crafco, Inc. (US)

Huesker Synthetics GmbH (Germany)

JDR Enterprises, Inc. (US)

Geocomposites and Southeastern United States

Of the 14 major manufacturers of geocomposite materials, 9 are headquartered and/or have production facilities in the Southeast of the US. In particular:

TenCate Geosynthetics

Founded in Hengelo, Netherlands in 1953, TenCate Geosynthetics is one of the world's leading providers of geosynthetics and industrial fabrics. To meet the growing demand for these products in the Americas, the company, in 1991, merged with Nicolon Corporation to form TenCate Geosynthetics Americas, headquartered in *Pendergrass, GA, United States*. [83]

GSE Holding, Inc.

GSE makes polyethylene-based geomembranes, geonets, geocomposites, geosynthetic clay liners, concrete protection liners and vertical barriers. The company is headquartered in *Houston, TX* and has manufacturing facilities in the US, Chile, China, Germany, Thailand, and Egypt. [84]

Thrace Group

Thrace Group is a market leader in the innovation, production and distribution of technical fabrics and packaging solutions consisting of 16 member companies and a growing sales network in over 80 countries. The company was established as Thrace Plastics Co S.A. in Xanthi, Greece.

Figure 50 Thrace Group locations. Source: www.thracegroup.com

In 2006 Thrace Group purchased a 50% equity share of Lumite Incorporated. In addition to giving Thrace a presence in the growing US filtration business this acquisition enhanced their distribution of horticultural products and gave them an entry into the erosion control and high strength geotextile markets.

Lumite, Inc. leads the industry in monofilament and multifilament engineered fabrics for liquid filtration and erosion control applications. The company based in *Alto, GA* produces three dimensional fabrics for shock absorption in applications where cushioning, weight, breathability, and stability are important. Lumite is also an industry leader in the horticultural market, offering highly stabilized shade material to protect plants and livestock from harmful exposure to ultraviolet rays and heat as well as durable ground cover fabric to inhibit weed growth. [85]

SKAPS Industries

SKAPS Industries is a leading manufacturer and supplier of various extrusion based geosynthetic products & technical textiles. The company hold a strong market presence in over 60 countries with 13 manufacturing facilities spread across North America, India and Brazil. Established in 1996 in *Commerce, GA* and headquartered in *Athens, GA* the firm has 3 productions sites in the *Peach State* (Commerce, *Pendergrass*, and Athens) with a capacity to manufacture 24 million sq. m of geonets and 180 million sq. m of non-woven fabric per year. [86]

HUESKER Inc.

The company was founded in 1861 in Gescher, Germany under the name *H.&J. Huesker & Co*. It began as a cotton fabric producer and rapidly expanded thanks to the German industrial growth of that period. In 1958 HUESKER realised the enormous potential of synthetics and started production of technical textiles by manufacturing waxed cloth and sandbags. The continuous increase in the number of products offered and their degree of specialisation led to the establishment of HUESKER Synthetic GmbH in 1973 to expand marketing beyond the German borders. In 1991 the company opened its first foreign branch in *Shelby, NC, United States*. The company now has an extensive worldwide network of subsidiaries and sales partners. [87]

Tensar

Tensar, founded in Blackburn (UK) in 1959, is a manufacturer and provider of ground stabilization and soil reinforcement solutions. Its world-leading position in the sector was established in the 1980s when, the company invented the first polymeric geogrids. Tensar patented the process of geogrid manufacture in 1978, and in 1980 launched the first uniaxial geogrid, used to build a temporary retaining wall supporting a railway. In 2022, Tensar became a division of Commercial Metals Company, which is headquartered in *Irving, Texas, USA*. [79]

The company has 4 manufacturing locations around the world:

- *Morrow, Georgia, United States*
- Blackburn, England, United Kingdom
- Wuhan, China
- St. Petersburg, Russia

Hanes Companies, Inc

Hanes Companies is a leading supplier for woven and nonwoven materials, division of Leggett & Platt, an American diversified manufacturer that designs and produces various engineered components and products that can be found in homes and automobiles.

In 2005, Hanes Companies acquired Webtec (*North Carolina*) and picked up the TerraTex® and TerraGrid® brand names, creating the Hanes Geo Components division to service the geosynthetic and erosion control market in North America. The Hanes Geo network now includes 12 facilities located in the Southeast: [88]

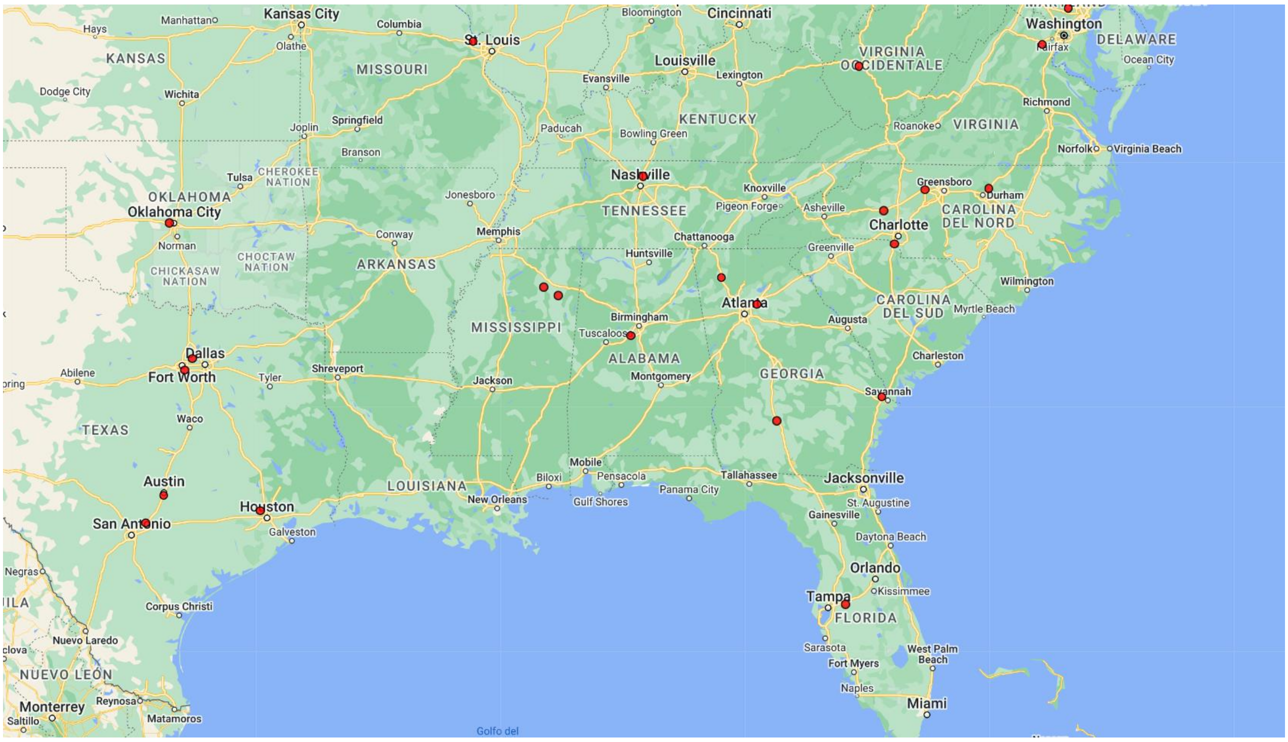

Figure 51 Hanes Companies locations in the Southeast. Source: www.hanescompanies.com

Butner, NC
Winston-Salem, NC
Fort Mill, SC
Lawrenceville, GA
Ashburn, GA
Savannah, GA.
Pontotoc, MS
Houston, TX
New Braunfels, TX
Austin, TX
Plant City, FL
Bessemer, AL

Freudenberg Group

The Freudenberg Group operates as a supplier across diverse sectors, including automotive, machinery, textile mechanics, construction, and telecommunications. Founded by Carl Johann Freudenberg in 1849, is headquartered in Weinheim, Germany, and have a workforce of 40,000 employees spread across 60 countries. The group has been present in North America for almost 160 years making it its second largest market after Europe. Through the years, Freudenberg's operations in the region have evolved into a family of companies. They supply a broad cross-section of industries with advanced product solutions including gaskets and seals, vibration control technology, filters, nonwovens, release agents, lubricants, expansion joints and household products. [89]

Freudenberg Performance Materials, one of the German group's companies, is a leading global supplier of innovative technical textiles. The firm is entirely based in the Southeast with manufacturing facilities in *Durham, NC* and *Macon, GA*.

JDR Enterprises, Inc.

JDR Enterprises, Inc. is a manufacturer of geonets, sub-surface drainage composites, sheet drains, and strip drains for residential and commercial applications. Founded in 1982, JDR has developed a comprehensive line of advanced drainage composites called J-DRAIN. The company is entirely based in *Georgia*, USA with corporate office in *Alpharetta* and manufacturing facility in *Madison*. [80]

Geocomposites Recycling

Geocomposites are a relatively new type of products, developed in the last 20 years and designed to last at least 50. For these reasons they do not represent an imminent waste management problem and the recycling of these materials is a totally unexplored field.

Recycling geosynthetics like geonets or geogrids should not create major problems because it would consist of the same process as other polyethylene, polypropylene or PET material: basically, grinding and extrusion.

The matter is completely different for geocomposites, hybrid products composed of layers of different materials. To date, there are no established processes for the recycling of these materials: production waste, defective and off-quality products are simply dumped in landfills. The first case study proposed in this paper is dedicated to the development of an efficient recycling process for J-DRAIN factory rejected rolls and production scraps.

SD Polymers LLC

Company History and Overview

SD Polymers is a family-owned business founded in 1998 in Macon, Georgia, by Italian entrepreneur Marco Danese, pioneer of the roofing industry.

Danese started his career in 1962, when he founded CA.BI.VE. (Cartoni Bitumati Veneto). Marco's father and grandfather, who already owned a dozen of spinning mills and a basalt quarry, had started a production of stone wool, from which they made insulating mats quilted with bituminous cardboard. The young Marco, intrigued by the fact that in addition to the use that his father made of it, bituminous felt board was requested by local *asphalt workers* for use in *hot coating*, decided to start production. Since the family also owned a transport company, with the opportunity to pick up the boxes, Marco began to attend the world of *bitumers*, such as Panfilli in Trieste and Benassi in Milan, curious about the production cycle.

The CA.BI.VE. plant was built in Bussolengo (VR), in an old shed of a spinning mill abandoned by the family. The production line was designed and manufactured internally, including the retractor to roll the membranes. In the wake of the success of the CA.BI.VE. initiative, Marco and his partner Luigi Carlon (future founder of Index S.p.A., now owned by Sika AG) founded Nord Bitumi in 1968. The company soon became one of Europe's leading bitumen membranes manufacturers and began to expand its horizons beyond the Atlantic. Nord Bitumi U.S. built the first of its plants in 1982 in Plattsburgh, New Jersey, followed in 1984 by a second one in Macon, Georga, and a third in 1986 in Kansas City, Kansas. Marco Danese did not just operate in the United States but created Nord Bitumi Mexico in 1994 with a plant in Tampico. Today this plant belongs to the Swiss Sika Group, after having been owned for some time by Johns Manville. All the Nord Bitumi plants were equipped with machinery manufactured in Bitumec, a Danese's company founded in 1978 in Ala (VR) with the aim of transferring know-how and selling equipment. [63]

Following the success of MBP membranes in the US, Danese partnered with Politex (now a Freudenberg Group company) to form Politex USA, which built its first plant in Macon in 1995. In 1993 he had also founded General Industrial Polymers in Baytown, TX to process and supply thermoplastic rubber for SBS membranes production, the most popular roofing material in the South. In 1996 Marco sold all the US and Mexican manufacturing operations to Johns Manville Corp., as well as Nord Bitumi Italia and Bitumec. Drawing on decades of roofing experience Danese realised before anyone else the importance of external services, including polymer recycling, and foresaw the future of the industry. Following his vision, he founded SD Polymers in 1998. [63][90]

The company initially focused on supplying nonwoven polyester mat and densified polypropylene to a wide range of commercial roofing manufacturers, mainly in Latin America. Over time, it expanded its offering to include fibreglass mats and materials for TPO membrane roofing applications. Today, managed by Marco's son Stefano Danese, SD Polymers specializes in plastic extrusion and industrial polymers recycling, custom blended polymer compounds for APP membrane production, roll converting services and rubber recycling. It has over 160,000 square feet of material storage and processing facilities, as well as a chemical laboratory for testing raw materials and finished products. [90]

Company Structure

SD Polymers has diversified into three business segments, headed by its core Plastics Extrusion division, which focuses on closed-loop recycling and compounding. The other two divisions are Industrial Rubber Recycling and Roll Converting Services.

Industrial Rubber Recycling

The work of this division basically consists of procuring truckload quantities of rubber materials from both tire and non-tire manufacturers, arranging the efficient collection of surplus rubber sheets, tires, and industrial scrap. The materials are then catalogued and sold in South America to gaskets or rubber hoses manufacturers. [90]

Materials

- A/B Compound [fig. 52]
    - Tread
    - Wigwag
    - Strips
- C/D Compound [fig. 53]
    - Masterbatch
    - Mixed
- Fabric Friction Rubber
- Textile Chord
- Green Tires (Green Tyres)
- Uncured EPDM [fig. 54]

Solutions

- Surplus or scrap rubber purchasing
- Uncured rubber processing
- Warehouse storage and quality assessment
- Waste rubber recycling program implementation

Figure 312 A/B Compound - Wigwag Source: www.sdpolymers.net

Figure 323 C/D Compound - Masterbatch Source: www.sdpolymers.net

Figure 304 Uncured EPDM Sheets Source: www.sdpolymers.net

Roll Converting Services

Roll converting is a process in which large rolls of material, such as nonwoven fabrics, paper, plastic film, or other continuous sheet materials, are transformed into smaller rolls or sheets of specific dimensions and configurations. This process is often used in various industries to customize and prepare materials for specific applications.

SD Polymers offer 4 types of rolls converting services: slitting, splicing, rewinding, printing, and inspecting. Slitting involves cutting the large master roll into narrower ones, typically of different widths. Precision is crucial to ensure that the resulting rolls meet the required specifications. Splicing is the process of joining two rolls of material together, while Rewinding consists of winding material from a large roll onto a smaller core, creating a more manageable roll size for specific applications. Rewinding is called Inspecting when used to check the fabric thickness and homogeneity and eventually remove defects or imperfections. Printing services allows for customization, branding, labelling, or adding essential information to the material.

The company possess 2 rewinding/inspecting/cutting lines [fig. 56] as well as 2 flexographic printing machines used mainly to impress the manufacturer's logo on the nonwoven rolls. [fig. 57]

Materials

- Polyester nonwoven
- Polypropylene nonwoven
- Fiberglass mat nonwoven
- Fiberglass
- Spunbond Polyester
- Staple Fiber Polyester

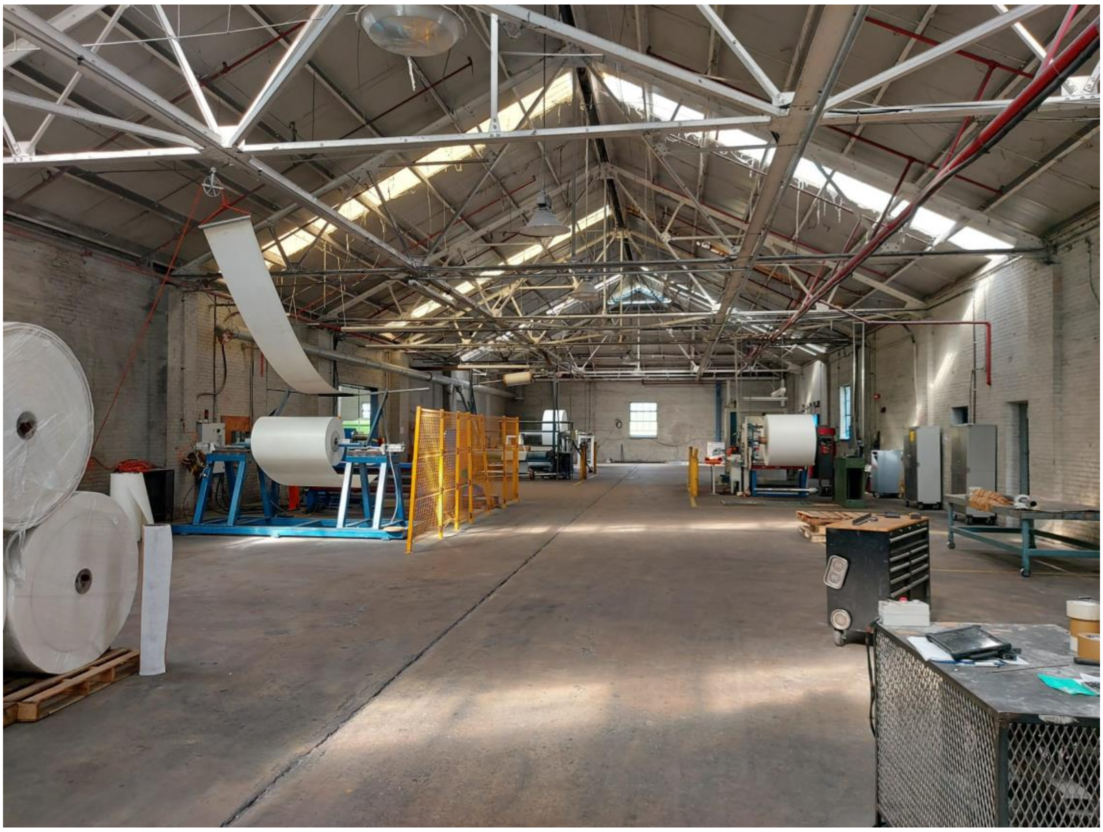

Figure 335 SD Polymers Roll Converting Division Shed #1

Figure 346 Roll Converting Line

Figure 357 Printing Line

Plastic Extrusion

Plastic recycling is the core business of the company and is divided into IPP compound manufacturing and toll services.

1. ***IPP Compound Manufacturing***

SD Polymers specialize in custom blended IPP (Isotactic Polypropylene) compounds for membrane production. [fig. 58] The company engineered a single polymer solution, made from recycled raw materials, allowing lower polymers costs in hot asphalt roll mix. Unlike other suppliers that use four or more raw materials, their pelletized single formula melts more quickly, reducing mixing time and increasing efficiency. The product substitute costly APP and APAO (Amorphous Poly Alpha Olefin) polymers. Customers can produce premium APP modified bitumen membranes using 100% recycled polymer compounds. [90]

Figure 368 IPP Compound Pellets

2. ***Toll Services***

SD Polymers offers a complete suite of toll services for plastic industry manufacturers. Using high-capacity machinery for size reduction, the company handle production scrap and process it according to the customer specifications so that can be reused in molding, compounding or other manufacturing processes. Services include pelletizing, blending, size reducing, compounding, densifying, sifting and packaging. Materials processed include PP, HDPE, LDPE, TPO, EP and PET. [90]

Recycling and compounding capabilities include:

- Two single-screw extrusion lines with a 130 mm and 180 mm diameter extruder [fig. 59].
- 48 × 87 in. hydraulic guillotine [fig. 60].
- Densifying line composed by shredder, double pot densifier and a final grinder [fig. 61].
- Grinding line with shredder and grinder placed in series [fig. 62].
- New hybrid densifying/grinding line, initial shredder with two-way conveyor belt system capable of sending the material to a densifier or grinder placed in parallel [fig. 63, 64].

Figure 379 Extruders.

Figure 6038 Guillotine.

Figure 6139 Densifying line.

Figure 402 Grinding line.

Figure 413 hybrid line under construction

Figure 424 hybrid line under construction

Case Study: Recycling Geocomposite Scraps

The geocomposites industry, as previously discussed, is relatively young and experiencing robust growth. Manufacturers in this sector, inundated with demand for their products, often pay limited attention to production efficiency and the quantity of scraps generated. On average, in the geocomposite factories of the southeastern United States, approximately 20-25% of the production ends up as waste, a concerning statistic, especially when considering that this surplus is typically disposed of in landfills. Companies find themselves lacking the time and resources to invest in recycling systems for their products, opting instead to dispose of them quickly to free up warehouse space.

This situation raises important questions about sustainability and resource utilization. As the demand for these products continues to soar, it becomes imperative for businesses to explore more environmentally friendly practices, such as recycling, to reduce waste and minimize their ecological footprint.

SD Polymers, in collaboration with JDR Enterprise, has pioneered a circular economy system [fig.] for recycling the production waste from J-DRAIN. The surplus generated at the JDR facility in Madison, GA is transported to Macon, GA, where it undergoes sorting, grinding, and densification processes. The densified material flakes are then shipped back to Madison, where they are reintroduced into the production line as feedstock for the extruders, effectively closing the loop.

This innovative approach not only reduces waste and minimizes the environmental impact but also sets a commendable example for the industry by demonstrating that responsible resource management can coexist with industrial growth and innovation.

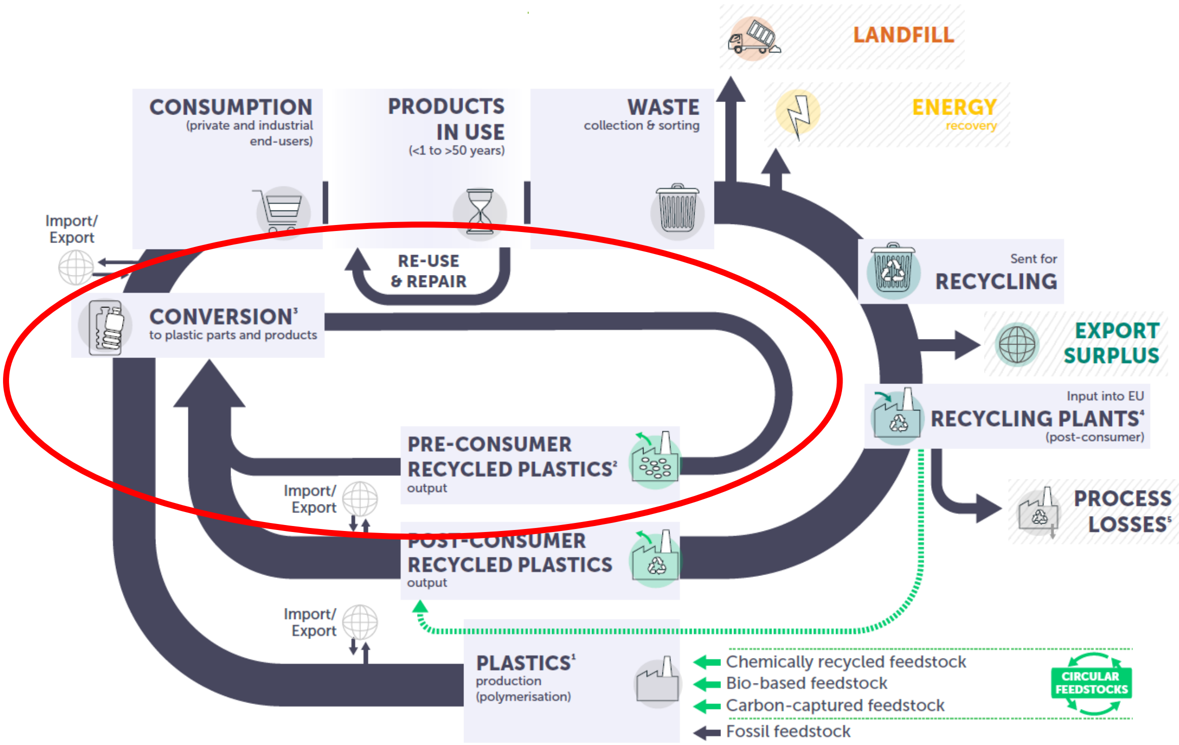

Figure 65 Plastic Material Lifecycle (Circular Economy Framework)

Recycling Project

JDR Enterprise offers an extensive range of geocomposite products grouped under the J-DRAIN brand, each possessing unique characteristics and compositions. The challenge at hand revolves around finding an efficient method to recycle these diverse product types. During the project's developmental phase, specific efforts were dedicated to study and test a processing method for each material.

Once the production flow, including the quantity of material produced for each type and the associated figures for waste and non-conformities, was comprehended, the rolls were categorized into 4 groups based on their composition and chemical-physical structure:

1. **J•DRAIN 300 – 302**

Consists of a heavy-duty, high-density polyethylene geonet drainage core with its ridges heat fused to a layer of non-woven filter fabric, on one (J-DRAIN 300) or both sides (J-DRAIN 302). [80] [fig. 66, 67]

Figure 446 J-DRAIN 302

Figure 437 J-DRAIN 300

SD Polymers' name: BLACK AND WHITE

Composition: 99.5% HDPE (black geonet), 1.5% PP (white non-woven fabric)

Percentage of JDR waste stream: 15%

2. J•DRAIN 200 – 700 – 780

J-DRAIN 200 consists of a light-duty impermeable polymeric sheet cuspated under heat and pressure to form a high-flow dimpled drainage core. The core is then bonded to a layer of non-woven filter fabric. [80][fig. 70]

J-DRAIN 700 is made of a heavy-duty impermeable polymeric sheet cuspated under heat and pressure to form a high-flow dimpled drainage core. The core is then bonded to a layer of woven filter fabric [80][fig. 69].

J-DRAIN 780 is composed of a heavy duty impermeable polymeric cuspated sheet, with identical properties of J-DRAIN 700 core, bonded to a layer of heavy duty non-woven filter fabric (8 oz/sq yd.). [80][fig. 68]

Figure 468 J-DRAIN 780

Figure 459 J-DRAIN 700

Figure 70 J-DRAIN 200

SD Polymers' name: BLACK NO PLASTIC

Composition: 97% HDPE (dimpled core), 3% PP (woven or non-woven fabric)

Percentage of JDR waste stream: 35%

3. J•DRAIN GRS

A high strength pre-assembled drainage composite consisting of a perforated or dimpled core with root resistant ECO fabric (film) attached to the top layer and non-woven fabric attached at the bottom. [80] [fig. 71]

Figure 71 J-DRAIN GRS

SD Polymers' name: BLACK WITH PLASTIC

Composition: 98% HDPE (dimpled/perforated core), 2% PP (film and non-woven)

Percentage of JDR waste stream: 15%

The fourth group is represented by all other J-DRAIN products, characterised by large quantities of *polymer foam* in their composition, and representing 35 % of JDR waste stream. The foam makes them not suitable for densification and single-screw extrusion. This category is referred to as ***FOAM 50/50*** within SD Polymers and is simply ground and returned to JDR.

Process Definition

The initial idea was to take the geocomposite rolls, shred them roughly, then densify and extrude them into pellets. However, this three-step process was quickly discarded due to its high processing cost, which was estimated to be around 24 cents per pound. Implementing this approach would have significantly squeezed SD Polymers' profit margin and led to an upward adjustment in the toll service price. Considering that the average price for HDPE virgin pellets stood at 50 ¢/pound and the proposed service price was 36 ¢/pound, any increase would have been unsustainable. This was especially concerning given the highly volatile nature of the virgin polymers market.

Extrusion was deemed redundant since, at the JDR plant, the pellets undergo extrusion to be melted and subsequentially pressed and formed into dimpled sheets or geonets. Furthermore, every time a polymer is melted it loses a bit of its mechanical properties. Saving an unnecessary extrusion cycle means increasing the life of the material, which can be recycled once more.

The choice was made to exclusively engage in shredding and densification, yielding plastic flakes of the appropriate size for JDR's extruders. Subsequently, these flakes would undergo screening via a vibrating sieve to remove dust particles, which could negatively impact pneumatic conveying systems.

Densification Insight

The densification process is a highly delicate one. First, the material must be absolutely dry. Secondly, it's crucial to determine the right densification cycle, which involves empirically finding the optimal loading time into the densifier pots, the first processing time (dry material machined by the stationary and rotary blades), the right moment to introduce water, and the seconds of water injection. After that, the subsequent second processing time (wet material), and the moment to finally discharge.

Leaving too much time into the blades' action can cause the material to melt and block the system [fig. 72], resulting in hours or even days of downtime for cleaning. Conversely, if too little water is added, the outcome remains the same, while an excess of water leaves the flakes wet, leading to several complications during subsequent extrusion (maximum moisture accepted is generally 2.5%).

Figure 72 "Melted Pot" during JDR Trial #1

Each material reacts differently to the action of the machine and many times the same exact product but placed differently (ground or shredded, wet or dry) lead to completely different results. In essence, the densification process is a precise and intricate operation that requires a fine balance between operator's skills, defined instructions, and environmental conditions. To obtain a stable and efficient production it's essential to carry out tests to define the processing cycle in detail.

First Trial

JDR Trial #1

Conducted on April **19, 2023**, using Densifier 1 (left pot) ***NO VIBRATOR***

Objective:	Establishing the densifiability of JDR rolls	
Material:	BLACK AND WHITE (99.5% HDPE, 1.5% PP)	480 lbs
	BLACK NO PLASTIC (avg. 97% HDPE, 3% PP)	1464 lbs
	BLACK WITH PLASTIC (98% HDPE, 2% PP)	200 lbs

Process composed of a sequence of eight steps [fig. 73]:

- ***Step 0:*** Rolls are loaded onto the box dumper by an operator.
- ***Step 1:*** Shredding of the rolls, loaded in the shredder by the box dumper under the operator's command.
- ***Step 2:*** Transportation of the shredded pieces (in continuous as they are created) by the conveyor belt to the densifier. The belt remains in operation until the densifier pots are loaded with the desired quantity.
- ***Step 3:*** Densification process.
- ***Step 4:*** Discharge of the densified material into a screw conveyor that transports it to the grinder.
- ***Step 5:*** Grinding to obtain flakes of specific dimensions (based on the screen installed on the machine).
- ***Step 6:*** Aspiration of the flakes and initial screening conducted by a cyclone, which captures a significant portion of the dust (filtration).
- ***Step 7:*** Discharge into boxes of the finished product.

Figure 473 Processing Steps in the Densification Line

Results

BLACK/WHITE

Cycle	Loading time	1^{st} Run	H_2O	2^{nd} Run	Drop	Total cycle time	Quality	Notes
1	50''	3.5'	5''	28''	15''	5' 8''	GOOD	¾ of a pot
2	65''	5'					BAD	clought up
3	48''	4'	6''	35''	20''	5' 49''	DECENT	full pot
4	45''	3.5'	5''	30''	15''	5' 5''	GOOD	¾ of a pot
5	51''	3.5'	5''	30''	15''	5' 11''	GOOD	¾ of a pot

Total Production *435 lbs*
45 lbs of waste
5% powder
1.9 % moisture

BLACK NO PLASTIC

Cycle	Loading time	1^{st} Run	H_2O	2^{nd} Run	Drop	Total cycle time	Quality	Notes
1	45''	7'	8''	1.5'	15''	9' 38''	DECENT	¾ of a pot
2	40''	6'					BAD	half a pot, clought up, 8 min cleaning
3	46''	7'	8''	1.5'	15''	9' 39''	DECENT	¾ of a pot
4	46''	7'	8''	1.5'	15''	9' 39''	DECENT	¾ of a pot
5	44''	7'	8''	1.5'	15''	9' 37''	DECENT	¾ of a pot
6	58''	9'					BAD	full pot, clought up, 20 min cleaning

Total Production *907 lbs*
557 lbs waste
6% powder
3.7% moisture

BLACK WITH PLASTIC

Cycle	Loading time	1^{st} Run	H_2O	2^{nd} Run	Drop	Total cycle time	Quality	Notes
1	56''	6'					BAD	¾ of a pot, clought up
2	60''	6'					BAD	¾ of a pot, clought up, *trial abandonment*

Total Production 0 lbs

From the initial test, the team discovered that it's possible to efficiently process the BLACK AND WHITE rolls, producing high-quality flakes [fig. 74] through a fast cycle (around 5 minutes) with an excellent production rate and moisture level. However, processing the other two types of materials proved to be unsustainable. The BLACK NO PLASTIC type takes too long to be processed, with cycles lasting 9-10 minutes producing ugly shaped and too wet flakes, while the BLACK WITH PLASTIC melt before the operator can introduce water, resulting in a complete blockage of the operation.

Figure 484 BLACK/WHITE Densified Flakes (JDR Trial #1)

Laboratory analysis of the three different materials reveals a striking similarity in their chemical composition: 97-99% HDPE and 3-1% PP. This implies that the challenges encountered during densification are not attributed to the chemical nature of the materials but rather to their physical form. The presence of polymer films or woven fabrics significantly elevates the complexity coefficient of the densification process. The next logical step, therefore, is trying to grind the rolls before the densification step to obtain a more homogeneous material, this was the purpose of the second trial.

Second Trial

JDR Trial #2
Conducted on **May 12, 2023**, using Densifier 1 (left pot)

Objective:	Establishing the densifiability of ground JDR rolls	
Material:	3 boxes of ground BLACK WITH PLASTIC (98% HDPE, 2% PP)	1180 lbs
	2 boxes of ground BLACK AND WHITE (99.5% HDPE, 1.5% PP)	860 lbs
	1 and a half boxes of BLACK NO PLASTIC (avg. 97% HDPE, 3% PP)	685 lbs

Process composed of a sequence of 14 steps divided in 2 parts (*grinding* and *densifying*):

- ***Step -6:*** Geocomposite rolls are dumped into the shredder.
- ***Step -5:*** Shredding.
- ***Step -4:*** Transportation from shredder to grinder via automated conveyor belt regulated according to the grinder's capacity.
- ***Step -3:*** Grinding.
- ***Step -2:*** Aspiration and filtration of grinded material (blower and cyclone)
- ***Step -1:*** Discharge.
- ***Step 0:*** Box of ground material loaded into the shredder thanks to a box dumper.
- ***Step 1:*** Passage through the shredder (simple connection because the pieces are already too small)
- ***Step 2:*** Loading of the densifier.
- ***Step 3:*** Densification.
- ***Step 4:*** Discharge.
- ***Step 5:*** Grinding.
- ***Step 6:*** Aspiration and filtration.
- ***Step 7:*** Final discharge (finished product in boxes).

Steps -6 to -1 performed in the grinding line [fig. 75] and steps 0 to 7 in the adjacent densifying line.

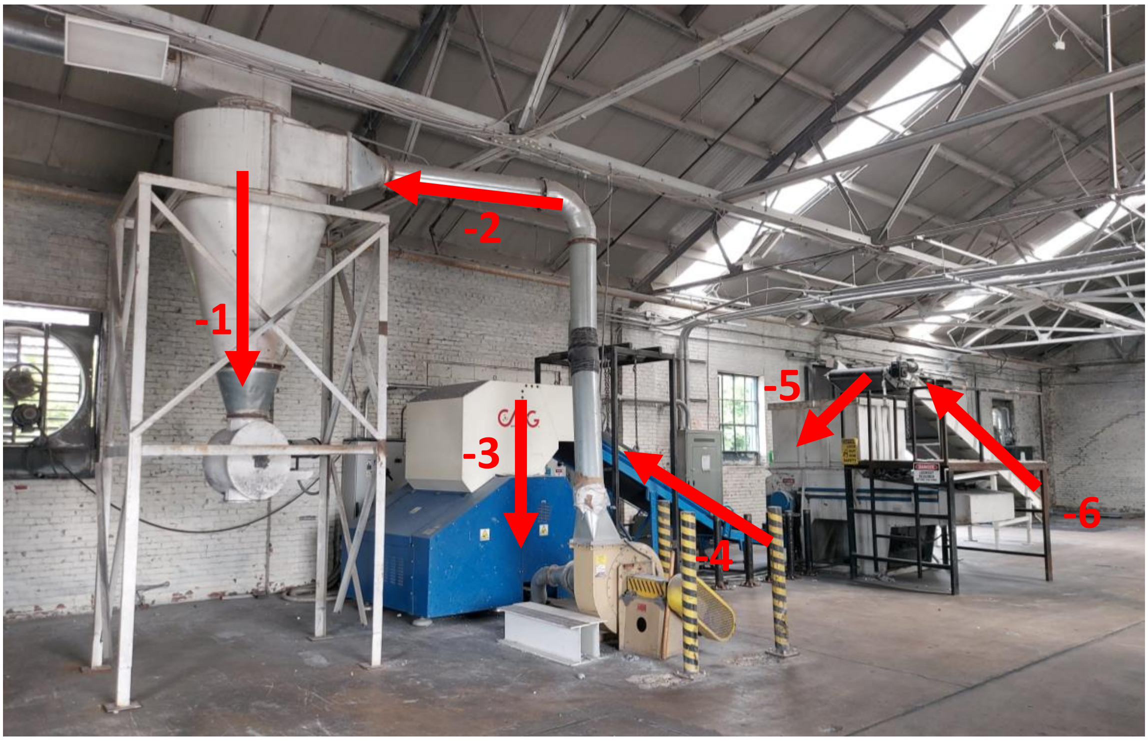

Figure 495 Grinding line.

Results

BLACK WITH PLASTIC

Cycle	Loading time	1st Run	H_2O		2nd Run	Drop	Total cycle time	Quality	Notes
1	62''	5 ' 45''	5''		50''	15''	8' 40''	GOOD	¾ of a pot
			5''	after 38''					
2	41''	5' 41''	5''		1' 35''	20''	9' 20''	BAD	½ a pot, clought up
			2''	after 26''					12 min cleaning
			2''	after 28''					
3	50''	5' 48''	8''		15''	16''	7' 17''	GOOD	½ a pot
4	45''	5' 52''	6''		10''	15''	7' 08''	GOOD	½ a pot
5	42''	5' 37''	9''		12''	15''	6' 55''	GOOD	½ a pot
6	51''	5' 39''	8''		8''	16''	7' 02''	GOOD	½ a pot
7	58''	5' 28''	7''		4''	18''	6' 55''	GOOD	¾ of a pot
8	49''	5' 35''	7''		4''	15''	6' 50''	GOOD	¾ of a pot

		Vibrator	Notes
Total Production	*1110 lbs*	YES	39 lbs of dust expelled
	1.8% moisture		

BLACK/WHITE

Cycle	Loading time	1st Run	H_2O	2nd Run	Drop	Total cycle time	Quality	Notes
9	38''	6'					BAD	IMPOSSIBLE TO DENSIFY
								melts and jams immediately

		Vibrator	Notes
Total Production	*0 lbs*	/	

BLACK NO PLASTIC

Cycle	Loading time	1st Run	H_2O		2nd Run	Drop	Total cycle time	Quality	Notes
10	43''	8' 20''	7''		20''	35''	10' 05''	GOOD	½ a pot
11	96''	7' 48''	6''		33''			BAD	¾ of a pot, *clought up*,
			6''	after 2'					cleaned
12	28''	7' 51''	7''		11''	26''	9' 03''	GOOD	½ a pot
13	9''	7' 32''	7''		24''	25''	8' 37''	GOOD	½ a pot
14	57''	6' 31''	7''		11''	18''	8' 04''	GOOD	¾ of a pot
15	48''	6' 43''	7''		15''	19''	8' 12''	GOOD	¾ of a pot

		Vibrator	Notes
Total Production	*673 lbs*	YES	17 lbs of dust expelled
	2% moisture		

Upon reviewing the results of the second trial, it became evident that the BLACK NO PLASTIC and BLACK WITH PLASTIC rolls should be ground before densification to achieve favourable outcomes in terms of both quality (flake shape and moisture content) [fig. 76] and production rate (reducing the densification cycle time by 2-3 minutes). Grinding homogenizes the material, eliminating the presence of large pieces of film or woven fabric in the densifier pots, which can be challenging for the blades to handle. Additionally, as the material is relatively lightweight, grinding makes it denser, enabling more efficient pot filling.

In contrast, grinding proves to be unfeasible for the BLACK AND WHITE rolls. These materials are inherently dense enough for proper pot filling, a critical factor in ensuring sufficient material compression and therefore friction between the blades. Furthermore, when these products are ground, the black of the geogrid and the white of the attached fabric blend, create a greyish mass. Based on feedback from the initial trial, the operator heavily relied on the white pieces as a reference point within the mixture to determine precisely when to introduce water.

Figure 506 Densified JDR BLACK NO PLASTIC rolls (JDR Trial #2)

In the end, considering the results obtained from the tests, the following processing cycles have been established for the three materials:

BLACK/WHITE		**BLACK NO PLASTIC**		**BLACK WITH PLASTIC**	
		Grinding		*Grinding*	
Cycle		***Cycle***		***Cycle***	
fill ¾ of a pot	≈ 50''	*fill ¾ of a pot*	≈ 50''	*fill ¾ of a pot*	≈ 50''
1st Run	3' 30''	1st Run	6' 30''	1st Run	5' 30''
Water	5''	Water	7''	Water	7''
2nd Run	30''	2nd Run	15''	2nd Run	5''
Drop	15''	Drop	20''	Drop	15''
Total cycle	***≈ 5'***	***Total cycle***	***≈ 8' (+ grinding)***	***Total cycle***	***≈ 7' (+ grinding)***

Final Considerations

This collaboration represents a significant milestone in the geocomposites sector. It is the first of its kind, displaying a groundbreaking method that not only produces recycled materials with identical chemical and physical properties to virgin ones but also does so at a substantially reduced cost. Moreover, the material is processed entirely locally, reducing the transportation footprint to just 74 miles (120 km) and avoiding the usual overseas shipping. The process allows JDR to reintroduce over 30% of the material used in each production cycle, partially recovering lost margins, and avoiding the heavy socio-economical costs associated with disposal or international shipments. Through this cooperation, it will be possible to recover tons of perfectly intact plastic every year, reintroducing it into the system and effectively creating a sustainable circular economy.

It is crucial to acknowledge that a significant portion of the broad American geocomposite industrial sector has yet to fully embrace these environmentally responsible practices. The potential for this model to be replicated and scaled across the industry cannot be overstated. It must serve as an inspiration and a blueprint for other companies to follow suit. This example should not remain an isolated case but rather become the standard in the industry.

Although the collaboration between the two Georgia-based companies focuses exclusively on processing post-industrial material, it will be of fundamental importance in 5 or 10 years when the first installed geocomposites will reach the end of their lifespan and disposal challenges will emerge. SD Polymers recycling process will serve as the cornerstone upon which to build concrete solutions to address the disposal issue and create a sustainable model for the entire industry.

Case Study: Recycling TPO Roofing Membranes

Introduction and Problem Definition

TPO (thermoplastic polyolefin) membrane is the largest segment in the commercial roofing industry, over 60% of roofing materials sold annually in North America are TPO based. [53]

A TPO membrane is a unique product created by incorporating ethylene-propylene rubber into a polypropylene matrix with a distinctive polyester reinforcement fabric embedded within it [fig. 77]. This hybrid composition makes it flexible, lightweight, and exceptionally durable, a perfect choice for the roofing industry. However, its unique structure also presents a significant challenge when it comes to recycling.

Figure 517 TPO Roofing Membrane

Rubber, polypropylene, and polyethylene react differently to mechanical recycling processes. The most significant challenge arises from the polyester fabric network enclosed between the layers of PP and EP. Under normal conditions, it accounts for 5% in volume; when the rolls are shredded, the value goes up to about 15%, but when the membrane is ground up, the percentage increases to as much as 50%. [fig. 78]

Figure 528 Shredded TPO (SX) and Ground TPO (DX)

The grinding mill shreds the PET fabric into fluffy cotton-like material. This *cotton* hinders the extrusion process because PET melts at much higher temperatures than PP (260°C as opposed to 165°C), causing it to clog the machine's filter and block the entire operation [fig. 79].

Figure 539 Extruder die after filter blockage during TPO trials.

The only way to successfully recycle TPO is, therefore, to separate the cotton from the matrix.

Numerous studies are currently underway to address the recyclability of TPO membranes, but no company has yet successfully developed an efficient recycling process for this material. Several industry giants have invested significantly in research and trials aimed at separating the PET fabric from the TPO matrix. Johns Manville has come close through a method known as *elutriation*.

Elutriation is a separation process that involves suspending a mixture of particles in a liquid or gas and allowing gravity or a current to carry lighter particles away while heavier ones settle [fig. 80]. In the context of TPO recycling, the process relies on the fact that polyester has a lower density than the other materials. When the mixture is agitated, the lighter PET particles are carried away by the fluid, leaving behind the heavier PP/EP flakes.

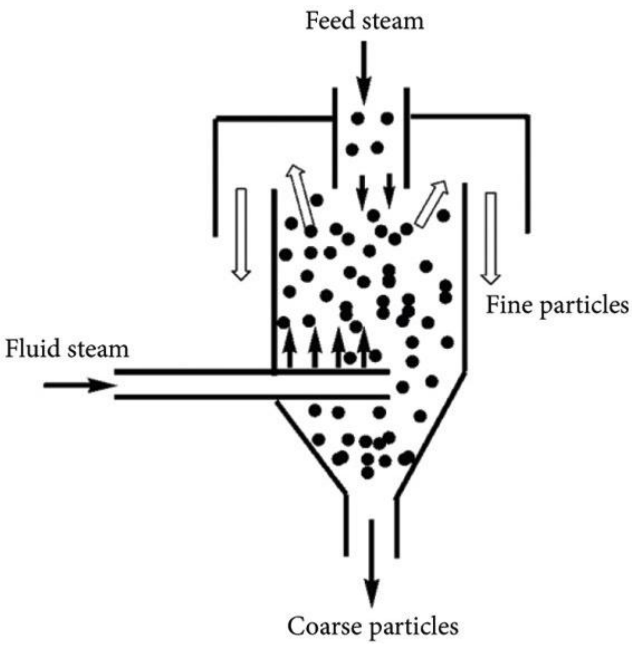

Figure 54 Elutriation. Source: www.sciencedirect.com

While elutriation holds promise for separating TPO components, it suffers from high inefficiency, necessitating three repetitions for effective separation [fig. 81]. This results in prolonged processing times and substantial costs, compounded by the already significant equipment expenses. Additionally, elutriators are bulky machines with a substantial energy demand. For these reasons, numerous roofing companies in the Southeast have turned to recyclers such as SD Polymers to find a solution and establish partnerships aimed at the creation of a circular economy system.

Figure 8155 TPO elutriated 3 times

SD Polymers’ Solution

Driven by market demand for an innovative solution in TPO recycling, SD Polymers has developed a four-stage production process and is in the final phase of installing a specially designed recycling line entirely dedicated to TPO membranes, for which it expects a workload of more than three truckloads per week.

Guillotine

The *first* step involves cutting the rolls using a guillotine. TPO rolls (production scraps, or those that have not passed quality control) arrive at the company on trucks and are generally three meters long. Operators, assisted by forklifts, take them and make an initial cut with the guillotine to create 50 cm rolls. Then the rolls pass once more under the guillotine, this time to be cut crosswise into squares of material.

Grinding

The *second* phase is grinding. The TPO squares are thrown first into a shredder and then into a mill (connected in series by an automated conveyor belt) that grinds them into confetti ranging in size from 0.5 to 1 cm. It’s in this phase that the PET reinforcement armour breaks down into bulky cottony flakes that entrap the PP and EP confetti [fig. 82].

Figure 82 TPO after Grinding Step

Screening

The *third* step is the pivotal one that sets SD Polymers apart from other companies, enabling efficient separation of the cotton from the pellets. The secret lies in the use of a ROTEX® Industrial Separator [fig. 83], food industry standard for the separation of grains such as rice, wheat, barley, or coffee from their husks. [91]

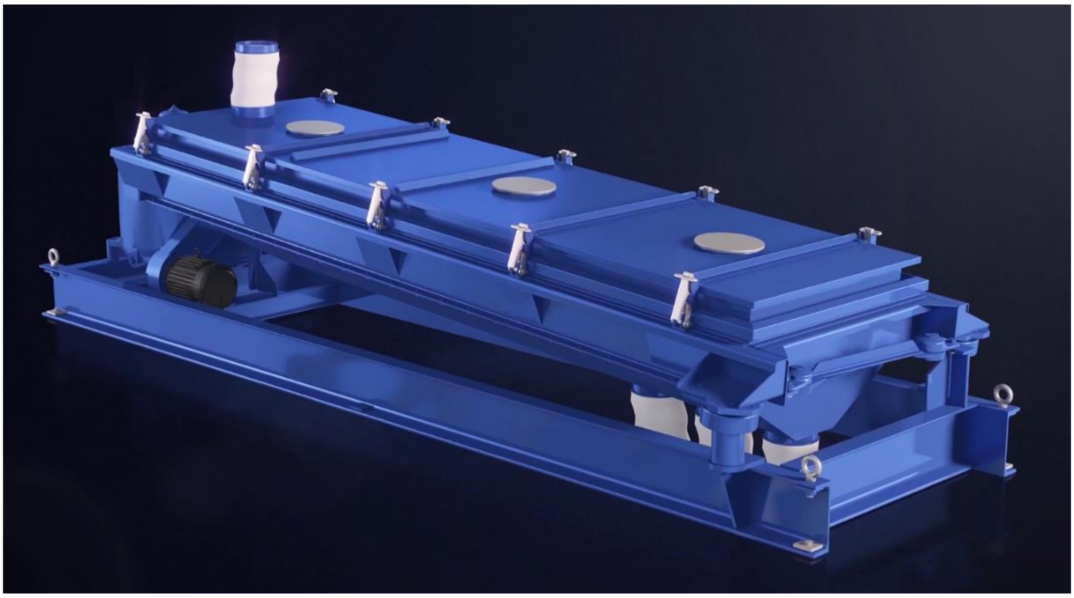

Figure 563 ROTEX® Industrial Separator. Source: www.rotex.com

The screener comprises two overlapping decks, each equipped with screens of varying sizes and containing polymer balls to enhance the separation process. [fig. 84] This configuration allows for the material to be sorted into different size fractions in a single pass. ROTEX® Separator use the so-called *Gyratory Reciprocating Motion*. The movement gradually transitions along the length of the screening machine, starting off as purely gyratory motion at the head, then moving to elliptical movement in the center and reverting back to reciprocating toward the end. The circular motion at feed end spreads the material across the full width of the screen surface, stratifies it and aggressively conveys it forward. The change to elliptical motion at center enhances product stratification and helps conveying it with high capacity. The reciprocating motion at discharge end, finally, removes near-size particles and improves screening efficiency. The absence of vertical movements ensures that the material is in constant contact with the screen surface.

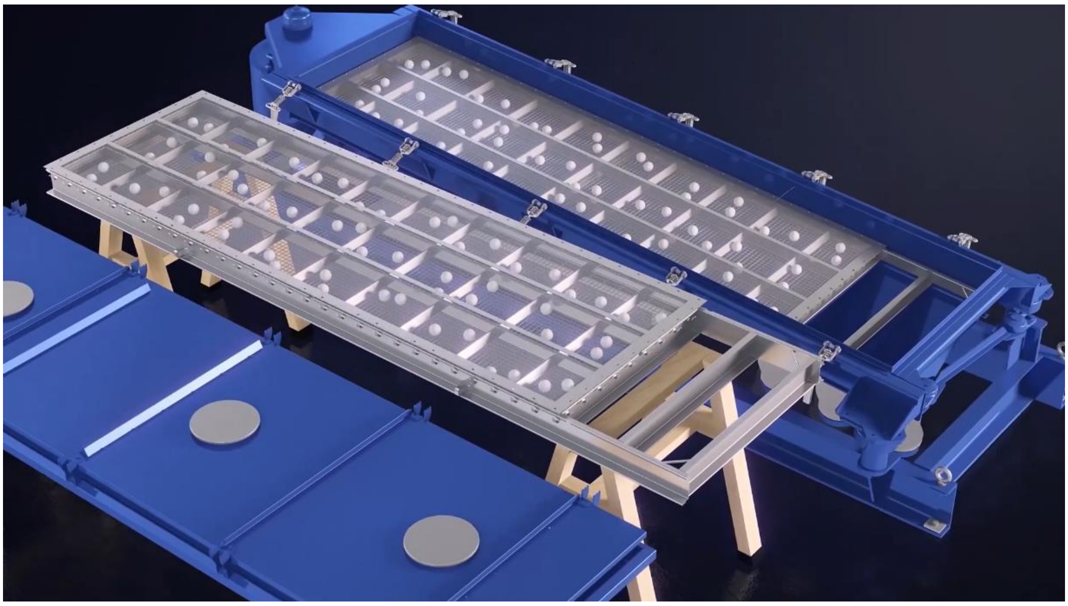

Figure 574 ROTEX® Industrial Separator, opened. Source: www.rotex.com

The material enters from the top opening and is separated into three distinct parts:

- *Overs*. Most of the PET cotton is unable to pass through the screens and falls into the first discharge hole. [fig. 87] On average, Overs consist of 96% PET and 4% TPO matrix.
- *Product*. The appropriately sized PP/EP confetti remain on the second layer, dropping into the intermediate hole. [fig. 86] Product is 94.5% PP/EP confetti, 2.5% PET cotton and 3% PET dust.
- *Fines*. The micro-PP/EP particles and cotton dust pass through both screens and descend through the third hole. [fig. 88] Fines may contain a maximum of 2% of acceptable-sized PP/EP confetti.

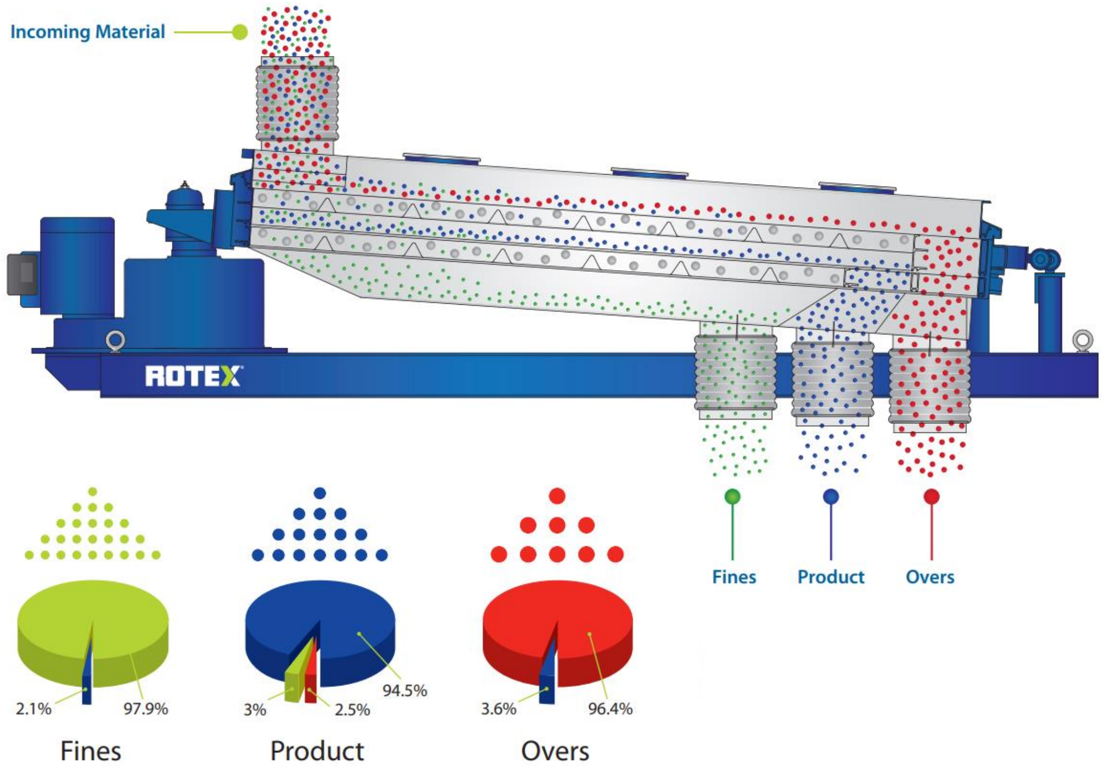

Figure 585 Rotex® industrial separator, material flows. Source: www.rotex.com

Figure 596 Product

Figure 607 Overs

Figure 618 Fines

The mill is linked to the screener in continuous, meaning that the output flow of ground material exiting the mill immediately becomes the input flow of the screener. Both machines are calibrated and sized to maintain an equal production rate. If the screener operates too slowly, it becomes necessary to reduce production to prevent overloading the mill, resulting in financial losses. Conversely, if the mill operates too rapidly, the screener becomes overloaded and struggles to effectively separate the TPO.

SD Polymers possesses two Rotex screens of different sizes. The first one is relatively compact (39 inches by 66 inches) and designed to be mobile, serving as a backup for the *old* grinding line when needed, such as during surplus processing or when conducting tests for new clients. It maintains a production rate aligned with the mill, ranging from 1100 to 1300 pounds per hour. The second screen [fig. 89] measures 58 in by 83 in and is capable of filtering 2000-2200 lbs/h. This larger screen was acquired to be installed in series with the new hybrid line, taking charge of daily production requirements.

Figure 629 58'' x 83'' Rotex screener

Extrusion

The *fourth* and final step in the process is extrusion. Here, the confetti, which are nearly entirely free from the PET cotton, are extruded at a temperature of ≈170°C. At this specific point, PP and EP are liquid while PET is still solid. The last screening is then obtained thanks to the extruder's filter that captures the remaining polyethylene filaments. The result of the process are pure PP/EP pellets, bagged and ready to be shipped back to the roofing manufacturers.

The journey of PET, however, remains an open question. Currently, it is either discarded or sold in its cotton form at a significantly reduced price. An ongoing effort involves the exploration of an efficient method for compressing the Overs and Fines mixture into an extrudable product. This, in turn, would enable high-temperature extrusion at approximately 270°C to separate the PET from the residual PP-EP components and obtain pure polyethylene pellets.

Final Considerations

This process enables the recycling of TPO in a simple and continuous manner, using one-third of the energy and half the time compared to elutriation.

Production waste and non-conforming membranes, whether because not uniform, unusually coloured, or damaged, can be efficiently reintroduced into the production cycle, fully minimizing waste. While this approach might seem commonplace in Europe, where recycling has been a focal point for years, and production lines are meticulously designed to yield waste levels not exceeding 5%, it is undeniably innovative in the North American context. Recycling remains a relatively unexplored field in this region, where raw materials are so abundant and cheap that companies often neglect the need to limit production waste, which, on average, exceeds 20% in roofing material manufacturing facilities.

In the next three years, the first TPO membranes installed in the late 1990s will become obsolete and require replacement. By adding a fifth phase at the beginning of the process dedicated to cleaning it will be possible to recycle recently removed dirty sheets. This will provide an opportunity to expand the circular economy system including post-consumer materials, encompassing end-of-life products, and exponentially expanding the volumes of recycled material in the industry. For the first time in history, the North American construction sector is prepared to address an emergency in a positive and sustainable manner.

Conclusions

This thesis work offers a significant analysis of the challenges and opportunities associated with the adoption of sustainable and circular economic models in the roofing and geocomposites sectors. The emergence of environmental degradation and resource scarcity has catalysed a growing awareness of the need to shift away from the traditional economic paradigm. This awareness is gradually taking hold even in the North American context, typically characterized by high levels of waste and seemingly endless natural resources.

The research has highlighted that adopting a circular approach can not only significantly contribute to mitigate environmental impacts but can also offer substantial economic opportunities. SD Polymers LLC provides a concrete example of how businesses can innovate and contribute to sustainability while simultaneously increasing their profits.

The two case studies proposed demonstrates that recycling can be advantageous both environmentally and economically. The collaboration with JDR Enterprise allows for the recovery of tons of perfectly good plastic and consequently helps the geo composite manufacturer save millions of dollars. Similarly, the development of the recycling process for TPO membranes represents a tremendous opportunity for profit and innovation for roofing materials manufacturers. Trough recyclers services, manufacturing companies can reduce waste and promote efficiency as well as the two industries can address the future issue of post-consumer waste disposal. SD Polymers' initiatives, although not yet fully developed and primarily local in character, should serve as examples to make recycling one of the fundamental pillars of the construction industry.

In conclusion, this study provides a significant contribution to understanding how sustainability and circularity can be successfully integrated into the roofing and geocomposites sectors. The results indicate that a circular approach is not only possible but can also be profitable, thereby contributing to the global goal of addressing the environmental challenges the world faces today. The transition to a sustainable circular economy system represents the only promising path for the future of these industries and the preservation of our planet.

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