System dynamics for circular business models, the case of recycled PET in the tire industry

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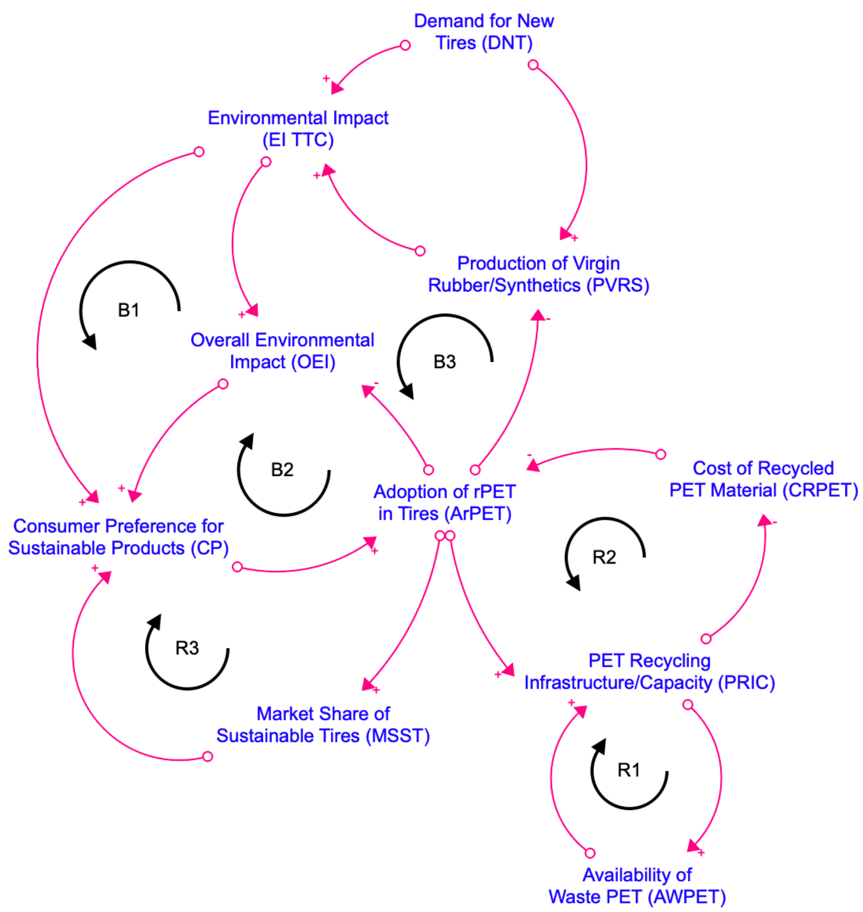
Abstract : This article explores how the tire industry can become more sustainable by using recycled PET (rPET) from plastic bottles instead of traditional polyester in tire reinforcement textiles. The research focuses on both the technology—including mechanical and chemical recycling processes—and the business models needed to make circular material use practical and profitable. Key insights include: (i) WhiteCycle Project: An EU-funded initiative demonstrating that mixed PET waste can be converted into high-quality PET suitable for high-performance tires, proving that chemical recycling can meet industrial standards; (ii) Circular Business Models (CBMs): Models that combine recycled material supply, resource recovery, and industrial partnerships are most effective in ensuring material quality, supply stability, and economic feasibility; (iii) Environmental Benefits: Using rPET reduces greenhouse gas emissions, energy use, and resource consumption compared to virgin polyester; (iv) Dynamic Analysis: System Dynamics modeling shows that the adoption of rPET depends on coordinated policy, investment in recycling infrastructure, and long-term business agreements; (v) Policy Implications: Clear recycled content targets, extended producer responsibility, and incentives for advanced recycling are crucial to accelerate rPET use. Overall, the study highlights that recycled PET can become a key material in sustainable tire production, combining environmental benefits with new business opportunities. Demonstration projects like WhiteCycle provide a roadmap for scaling up these practices while ensuring quality, economic viability, and long-term circularity in the tire sector.

Key words : Circular Economy, Loops, Model, Recycle PET, Supply chain,

Introduction

The global tire industry stands at the crossroads of technological innovation, environmental urgency, and economic transformation. With mounting pressure to decarbonize supply chains, reduce dependency on fossil-based materials, and mitigate waste, manufacturers are increasingly exploring circular economy strategies. Traditional tire materials—natural rubber, synthetic rubber, steel, nylon, and polyester—are energy-intensive to produce and have significant environmental impacts throughout their lifecycle. At the same time, the world faces a growing crisis of plastic pollution, particularly from single-use PET bottles, which accumulate in landfills and oceans. Recycled PET (rPET), derived mainly from post-consumer beverage bottles, has emerged as a promising circular feedstock with the potential to replace virgin polyester in tire reinforcement textiles. rPET provides high mechanical performance, reduced carbon footprint, and increasingly stable supply due to global recycling initiatives.

Figure 1 : Causal Loop Diagram Lifecycle of traditional tire materials vs. recycled PET



Source : The authors

The Causal Loop Diagram (CLD) compares the traditional tire material lifecycle (TTC) and the recycled PET (rPET) lifecycle, focusing on how the adoption of rPET creates feedback loops that drive sustainability. The TTC lifecycle is represented by the link between Demand for New Tires and Production of Virgin Rubber/Synthetics, leading to Environmental Impact (EI_TTC). The rPET lifecycle is characterized by three reinforcing loops (R1, R2, R3) that promote growth. R1 describes the growth of recycling infrastructure driven by feedstock availability. R2 shows how adoption leads to economies of scale, lowering costs and further increasing adoption. R3 illustrates market reinforcement, where adoption increases market share, boosting consumer preference, which further increases adoption. Three balancing loops (B1, B2, B3) govern the transition. B1 is a 'Shifting the Burden' dynamic, where the high environmental impact of traditional materials drives consumer preference, substituting virgin materials with rPET. B2 shows how the overall environmental pressure (OEI) acts as a constraint, pushing consumers toward sustainable options, thereby balancing the system toward lower overall impact. B3 is an extension driven by the reduction of virgin production.

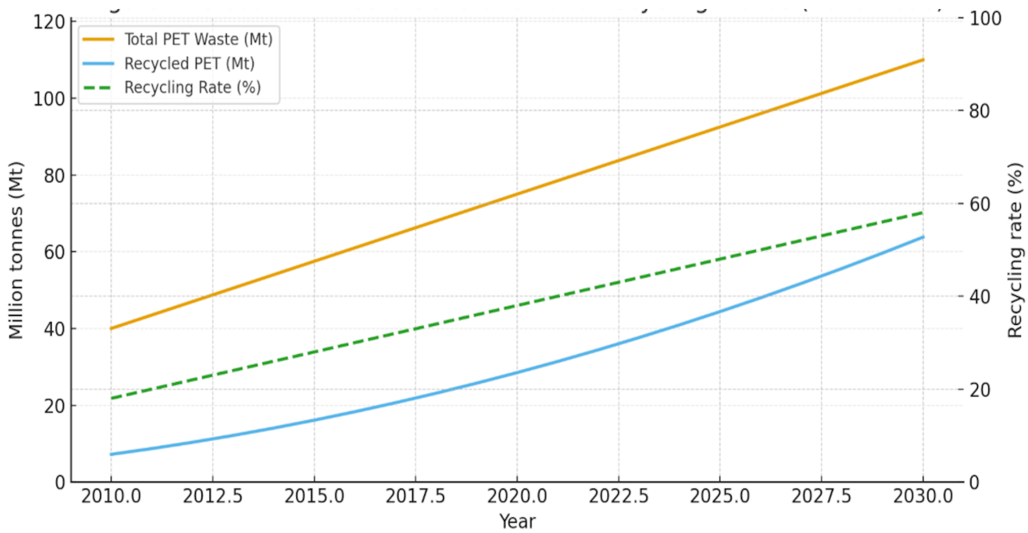
Table 1 : Environmental Impacts of Virgin polyester vs rPET

Impact / Indicator	Virgin PET (vPET)	rPET (recycled)	Typical Reduction / Relative Benefit*
Energy consumption (material production)	~ 61.4 MJ/kg PET	~ 14.8 MJ/kg PET	~ 76 % less energy
Greenhouse gas emissions (CO_2-eq)	~ 2.15 kg CO_2-eq / kg	~ 0.45 kg CO_2-eq / kg PET	~ 79 % lower CO_2
Water consumption	~ 10.0 L/kg PET (or baseline water input)	< ~ 8.0 L/kg PET (depending on recycling process)	> 20 % water savings in production
Solid waste / Waste to landfill (at production stage)	Higher due to virgin-feedstock processing (unspecified baseline)	Lower, as material is diverted from waste streams	Significant reduction — varies with allocation and process yield
Fossil resource depletion / Virgin feedstock demand	High (crude oil / natural gas based)	Much lower — uses post-consumer plastic waste instead of fossil feedstock	
Overall Life-Cycle Global Warming Potential (cradle-to-gate)	Baseline level for virgin PET	Significantly lower under many recycling scenarios (e.g., mechanical or chemical recycling with efficient processes	Often 40–80% GHG reduction depending on process and allocation method

Source : Compilation of Massoud & Dsilva (2025), Mayankkumar & al. (2025), *Chairat & Gheewala (2023), Bhattacharya & al. (2021), Shen & al. (2011)*

Major tire companies such as Michelin, Continental, Bridgestone, and Goodyear are investing in rPET technologies through partnerships, pilot projects, and commercial deployments. *Whitecycle project, funded* by the EU Horizon 2020 program, has demonstrated the technical feasibility of producing high-quality PET monomers from mixed plastic waste streams suitable for performance-critical applications, including tire textiles (Diemer et al., 2025). WhiteCycle integrates enzymatic and chemical depolymerization with purification and repolymerization processes, showcasing how advanced recycling can close the material loop while meeting industrial quality standards (WhiteCycle, 2022). The adoption of rPET at scale depends not only on technology but also on the development of robust circular business models (CBMs) that align incentives across recycling operators, polymer manufacturers, textile producers, and tire OEMs. Such CBMs must address challenges related to feedstock traceability, cost competitiveness, performance consistency, and long-term supply security. Cross-sector collaborations like WhiteCycle exemplify how integrated CBMs, industrial symbiosis, and long-term offtake agreements can facilitate sustainable transitions.

Figure 2 : Global PET waste generation and recycling trends (2010 - 2030)



Source : Generated by the author using synthetic global PET waste and recycling trend data for illustrative purposes.

This article presents a multi-method research design to investigate circular business models for rPET in the tire sector. The methodology combines: (i) Literature review and cross-sector benchmarking of CBM archetypes relevant to recycled materials and high-performance applications, (ii) System Dynamics (SD) modeling, capturing feedback loops, technology learning effects, investment delays, and policy interventions affecting rPET adoption, (iii) Case study analysis focused on mechanical and chemical recycling adoption pathways, with particular emphasis on the WhiteCycle project as a demonstration of hybrid CBM implementation.

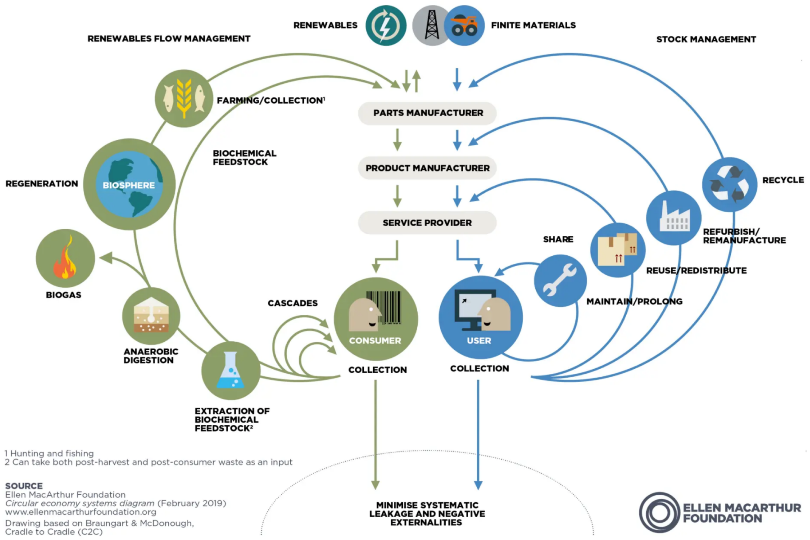
The study aims to quantify potential adoption trajectories, evaluate environmental and economic implications, and derive policy and managerial insights. By linking industrial-scale demonstration projects to SD simulations, the research provides actionable knowledge for both practitioners and policymakers, highlighting the conditions under which rPET can effectively contribute to circularity in the tire industry.

2. Literature review

2.1 Circular Economy and Circular Business Models

The circular economy (CE) represents a systemic shift from the linear economic model of extraction, production, consumption, and disposal. Instead, CE prioritizes designing out waste, maintaining value through loops, regenerating ecosystems, and fostering restorative industrial systems (Diemer et al., 2020). Key CE frameworks (Diemer, Dierickx, 2020, Stahel, 2016; Ellen MacArthur Foundation, 2013) conceptualize circularity through biological cycles (biodegradable materials) and technical cycles (durable materials like PET).

Figure 3 : The butterfly Diagram (technological and biological Cycle)



Source : Ellen Mc Arthur Foundation (2013, 2019)

Circular Business Models translate CE principles into practice by redefining how firms create, deliver, and capture value. Seminal works by Bocken et al. (2016, 2019, 2022, 2025), Nußholz (2017), and Lüdeke-Freund et al. (2019) outline various CBM archetypes relevant to manufacturing and material-intensive industries.

Five major CBM categories dominate the literature:

→ **Circular Supply Models** (use of renewable, recycled, or low-impact materials in production) play a pivotal role in enabling the large-scale adoption of recycled PET in the tire industry by ensuring stable access to secondary raw materials while reducing exposure to volatile virgin polymer markets. These models are based on long-term procurement contracts, strategic partnerships, and, in some cases, equity participation between tire manufacturers, recyclers, packaging producers, and waste management companies. By locking in demand and volume commitments, circular supply agreements help de-risk investments in recycling infrastructure and improve feedstock traceability and quality consistency. The literature highlights that such models are particularly effective in material-intensive sectors where quality requirements are high and switching costs are significant (Bocken et al., 2016; Lüdeke-Freund et al., 2019). In the context of rPET, circular supply models are often complemented by certification schemes, mass-balance accounting, and digital product passports to guarantee recycled content claims and regulatory compliance (Ellen MacArthur Foundation, 2022; European Commission, 2023).

→ **Resource Recovery Models** focus on extracting maximum material and economic value from post-consumer and post-industrial waste streams through advanced recycling, sorting, and reprocessing technologies (Diemer, 2012). In the PET value chain, these models are central to enabling bottle-to-bottle, bottle-to-fiber, and increasingly bottle-to-tire loops by recovering polymers that would otherwise be landfilled or incinerated. The literature emphasizes that resource recovery models are particularly effective when combined with scale-intensive technologies such as depolymerization and when supported by extended producer responsibility (EPR) schemes that improve collection rates and feedstock quality (Stahel, 2016; Geissdoerfer et al., 2017). For the tire industry, investment in chemical recycling infrastructure enables access to virgin-equivalent monomers, mitigating quality degradation and allowing compliance with stringent performance requirements for reinforcement textiles. Studies further highlight that successful resource recovery models rely on cross-sector collaboration, shared recycling infrastructure, and policy support to overcome high capital costs and market uncertainty, particularly in emerging chemical recycling pathways (Ellen MacArthur Foundation, 2015; PlasticsEurope, 2024).

→ **Product Life Extension Models** aim to preserve the functional and economic value of products by extending their usable lifespan through strategies such as repair, reuse, retreading, refurbishment, and remanufacturing. In the tire industry, retreading represents the most mature and impactful life-extension practice, particularly for truck, bus, and aviation tires, where multiple life cycles can be achieved with significant material and energy savings compared to producing new tires. From a circular economy perspective, extending tire lifespan reduces overall material throughput and delays end-of-life treatment, thereby lowering demand for virgin and recycled polymer inputs per vehicle-kilometer traveled (Stahel, 2016). Although product life extension models do not directly increase demand for recycled PET, they play a complementary role by stabilizing material flows and reducing short-term pressure on recycling systems. The literature suggests that combining life extension strategies with circular supply and resource recovery models can enhance system-level circularity by balancing material efficiency with material substitution (Bocken et al., 2016; Geissdoerfer et al., 2017). For tire manufacturers, integrating retreading services, performance monitoring, and design-for-durability approaches alongside rPET adoption can strengthen sustainability outcomes while preserving revenue streams and customer relationships..

→ **Sharing Platforms** enable increased asset utilization by shifting consumption from individual ownership to shared access. In the context of mobility systems, such platforms include car-sharing, ride-hailing, fleet leasing, and logistics pooling, which can significantly reduce the total number of vehicles—and therefore tires—required to deliver a given level of transport service. The circular economy literature highlights sharing platforms as a demand-side strategy that complements material-focused loops by reducing absolute material throughput (Botsman & Rogers, 2010; Bocken et al., 2016). For the tire industry, sharing platforms are most relevant in commercial fleets, mobility-as-a-service (MaaS), and last-mile delivery applications, where centralized ownership enables predictive maintenance, optimized tire usage, and systematic end-of-life collection. While sharing models do not directly drive recycled PET substitution, they indirectly enhance circularity by extending effective tire lifetimes, improving traceability, and facilitating reverse logistics for recycling. Studies suggest that the integration of sharing platforms with products-as-a-service and circular supply models can amplify environmental benefits, particularly when combined with digital monitoring and performance-based contracts (Geissinger et al., 2019; Ellen MacArthur Foundation, 2015).

→ **Product-as-a-Service** (PaaS) models shift the value proposition from selling physical products to delivering performance or functional outcomes, with manufacturers retaining ownership of the product throughout its lifecycle. In the tire industry, PaaS models typically take the form of “tires-as-a-service,” where customers—primarily commercial fleets—pay per kilometer driven, per hour of operation, or per level of availability rather than per tire purchased. This model incentivizes manufacturers to design tires for durability, repairability, retreading, and material efficiency, as lifecycle costs and residual value directly affect profitability (Tukker, 2015; Bocken et al., 2016). From a circular economy perspective, PaaS models strongly align with both product life extension and resource recovery strategies. Centralized ownership facilitates systematic maintenance, digital monitoring, and optimized replacement cycles, while also improving end-of-life collection and material traceability. Although PaaS does not directly mandate the use of recycled PET, it creates favorable conditions for its adoption by internalizing lifecycle costs and enabling long-term material planning. Empirical studies indicate that combining PaaS with circular supply contracts and advanced recycling technologies can significantly enhance material circularity and reduce environmental impacts in asset-intensive sectors such as mobility and manufacturing (Tukker, 2015; Lüdeke-Freund et al., 2019; Ellen MacArthur Foundation, 2021).

In the language of System Dynamics, this literature review logically progresses from *Material loops* (Circular Supply, Resource Recovery) to *Efficiency loops* (Life Extension), *Utilization loops* (Sharing Platforms) and *Incentive realignment* (Product-as-a-Service). This sets up an excellent bridge to your *System Dynamics methodology,* especially for stock–flow structures (tires in use), delayed replacement effects and feedback between durability, demand, and recycling flows.

Table 2 : Key CBM archetypes and relevance to the tire industry

CBM Archetype	Description	Relevance to Tire Industry
Circular Supply	Use of renewable or recycled inputs	High (rPET replacing virgin polyester reinforcement textiles)
Resource Recovery	Extracting value from waste streams	High (PET depolymerization and bottle-to-tire loops)
Product Life Extension	Repair, reuse, remanufacture	Medium (tire retreading extends product life)
Sharing Models	Product access over ownership	Low (limited applicability for individual tires)
Product-as-a-Service	Selling function instead of product ownership	Low/Medium (fleet management, mobility-as-a-service)

For the tire industry, the first two categories—circular supply and resource recovery—are most applicable to rPET.

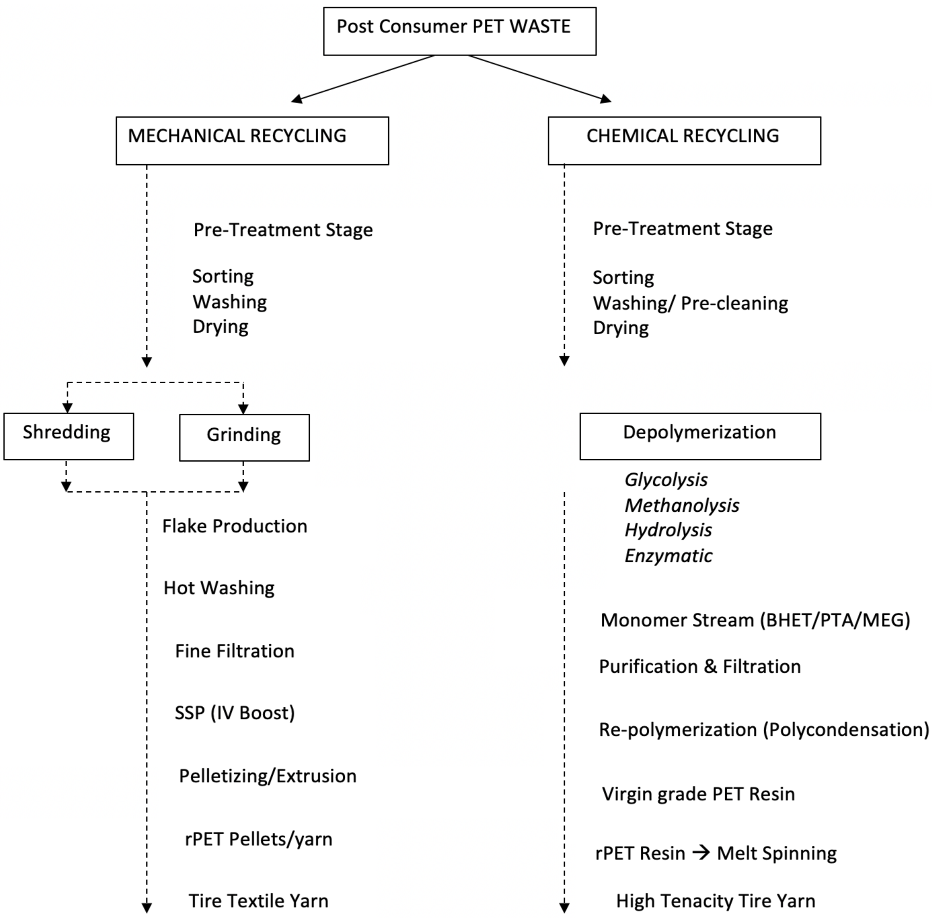
2.2 Recycled PET Technologies and Markets

PET recycling technologies have advanced significantly over the past decade, improving quality consistency and enabling high-performance textile applications. The two primary routes—mechanical and chemical recycling—each present unique benefits.

Mechanical Recycling involves washing, shredding, melting, and re-extruding PET. It is cost-effective but sensitive to contamination and polymer degradation. Recent innovations such as advanced filtration and Solid-State Polymerization (SSP) have improved mechanical rPET's suitability for high-strength fibers.

Chemical Recycling, including glycolysis, methanolysis, hydrolysis, and enzymatic depolymerization, breaks PET into monomers (BHET, PTA, MEG). These monomers are repolymerized into virgin-equivalent PET, ensuring consistent molecular weight and purity suitable for tire-grade yarns.

Figure 4 : Mechanical vs Chemical Recycling Process Flows



Source : The Authors

Mechanical and chemical recycling present two distinct pathways for converting post-consumer PET into high-performance materials suitable for tire applications. Mechanical recycling remains the more cost-efficient option, benefiting from mature infrastructure, relatively low energy use, and streamlined processing steps such as shredding and extrusion. However, it is sensitive to contamination and may experience polymer degradation, leading to variable product quality. In contrast, chemical recycling offers near-virgin quality outputs by depolymerizing PET into its monomers, enabling consistent performance suitable even for critical tire reinforcement yarns. This comes at the expense of higher capital and operational costs, increased chemical usage, and greater energy demand. While mechanical recycling delivers strong environmental benefits through reduced emissions and lower waste, chemical recycling provides superior circularity potential, handling mixed or colored PET and enabling closed-loop systems.

The choice between these technologies therefore depends on strategic priorities—cost and energy savings favor mechanical recycling, while quality, feedstock flexibility, and long-term circularity strongly support investment in chemical recycling.

Table 3 : Comparative analysis of recycling technologies (cost, quality, energy)

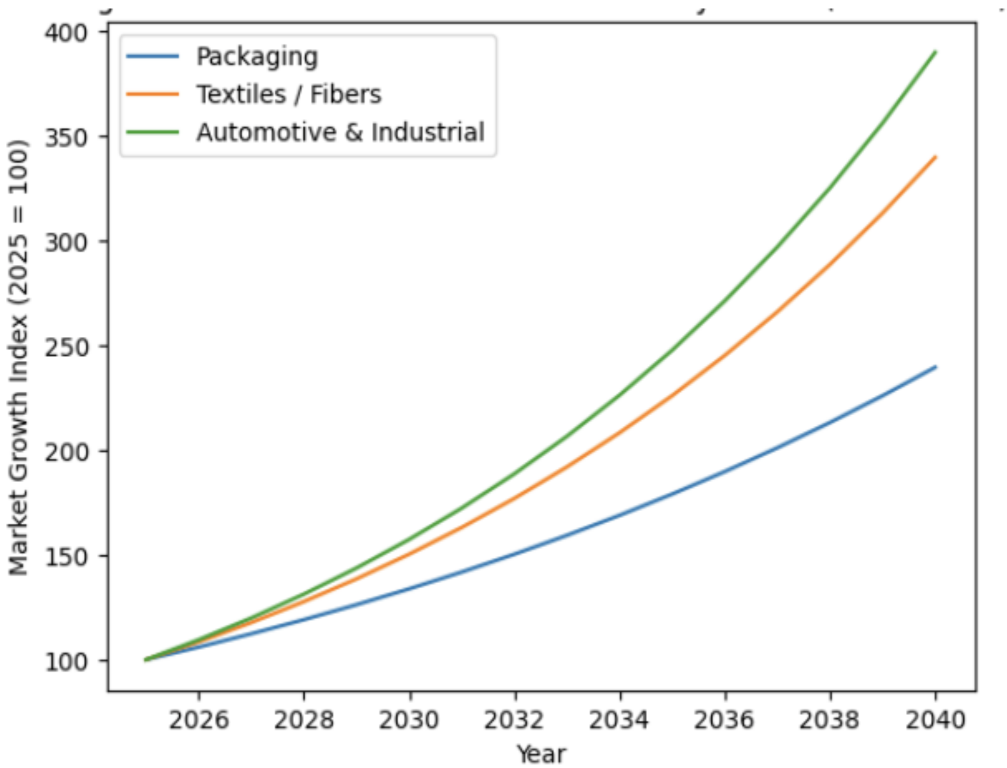
Criteria	***Mechanical Recycling***	***Chemical Recycling***
Capital Cost	Low–Medium (simple equipment, lower investment)	High (reactors, purification systems, catalysts)
Operational Cost	Low (sorting, washing, melting)	Medium–High (energy-intensive depolymerization, chemical inputs)
Product Quality	Medium–High (dependent on contamination; IV degradation possible)	Very High (virgin-grade monomers enabling consistent PET resin)
Energy Consumption	Low–Medium	High (thermal and chemical energy requirements)
Feedstock Sensitivity	High (contaminants reduce yield and quality)	Low–Medium (can handle mixed or colored PET)
Yield	70–85% depending on contamination	80–95% depending on process and purification
Environmental Impact	Lower CO_2 footprint; fewer chemicals	Higher energy use but enables closed-loop quality
Scalability	High, mature globally	Emerging; scaling rapidly but still limited
End-Product Suitability	Textile-grade, packaging (non-food), some food-grade with SSP	Virgin-equivalent PET suitable for all applications

Technology Readiness Level (TRL)	Very High (TRL 8–9)	Medium–High (TRL 6–8, depending on process)
Chemical Use	Minimal (detergents, surfactants)	Significant (glycols, methanol, catalysts)
Waste Generation	Solid waste from labels/caps; wastewater	Chemical residues, solvent emissions, purification waste
CO_2 Emissions	Low (mostly electricity-based)	Medium–High (thermal energy + chemical reactions)
Process Complexity	Low–Medium	High (multi-stage, controlled reactions)
Feedstock Flexibility	Low–Medium (clear PET preferred)	High (colored, opaque, multilayer PET tolerable)
Quality Degradation Over Cycles	Medium (IV loss over repeated cycles)	None (monomers rebuilt to virgin PET)
Circularity Potential	Medium–High	Very High (true closed-loop enabled)

Source : The Authors

Global demand for rPET is driven by packaging, textiles, automotive applications, and increasingly the tire sector. Regulations such as the EU Circular Economy Action Plan and mandated recycled content targets accelerate adoption.

Figure 5: Forecasted rPET market growth by sector (2025–2040)



The figure 5 shows indexed growth trajectories (2025 = 100) for major rPET end-use sectors. Packaging remains the dominant demand segment with steady growth driven by regulatory recycled-content mandates. Textile applications grow more rapidly as fiber-to-fiber recycling scales. Automotive and tire-related applications exhibit the highest compound annual growth rate, reflecting increasing qualification of high-performance rPET and the emergence of circular supply and product-as-a-service models. This figure is *scenario-based and illustrative*, not a single-source forecast. It is suitable for: System Dynamics modeling, Scenario comparison or Strategic and academic discussion.

2.3 Benchmark and Typology of Circular Business Models

To better understand how circular business models (CBMs) can support the deployment of recycled PET in the tire industry, it is useful to benchmark practices across sectors that face similar challenges in terms of material performance requirements, capital intensity, and supply chain complexity. The literature shows that successful CBMs rarely rely on a single archetype; instead, they combine multiple circular strategies adapted to sector-specific constraints (Bocken et al., 2016; Lüdeke-Freund et al., 2019).

2.3.1 Cross-Sector Benchmarking

Cross-sector benchmarking provides critical insights into how circular business models (CBMs) emerge, scale, and stabilize under different technological and institutional conditions. Prior research emphasizes that sectors with high material intensity, strict performance requirements, and long asset lifetimes—similar to the tire industry—tend to adopt CBMs through coordinated value-chain action rather than isolated firm-level initiatives (Lüdeke-Freund et al., 2019; Geissinger et al., 2019).

In the textile and apparel sector, circular input and closed-loop recycling models are the most mature. Large brands such as Adidas, Inditex, and Patagonia have integrated rPET fibers through long-term supplier contracts, third-party certification schemes, and brand-driven demand commitments. Empirical studies show that demand aggregation and quality standardization are key enablers for scaling rPET use in performance-sensitive textile applications (Shen et al., 2020; Ellen MacArthur Foundation, 2017). These mechanisms are highly relevant for tire reinforcement textiles, where consistent mechanical properties and traceability are essential.

The packaging sector, particularly beverage bottles, represents the most advanced example of large-scale circular supply and resource recovery. Deposit-return systems, recycled-content mandates, and extended producer responsibility (EPR) schemes have resulted in PET collection rates exceeding 80% in several regions. Quantitative assessments demonstrate that regulatory certainty and pooled investment in recycling infrastructure significantly reduce feedstock price volatility and supply risk (OECD, 2018; PlasticsEurope, 2024). For the tire industry, these experiences underline the importance of collective governance and policy alignment to secure high-quality rPET streams.

In the automotive sector, CBMs often combine resource recovery, industrial symbiosis, and long-term contracting. Closed-loop aluminum systems and battery recycling partnerships illustrate how secondary materials can meet stringent safety and performance standards when supported by design-for-recycling and guaranteed offtake agreements. Studies highlight that such models reduce lifecycle emissions while maintaining material performance, provided that collaboration spans OEMs, suppliers, and recyclers (Bobba et al., 2020; IEA, 2022). These findings are directly applicable to the integration of rPET in tires as a functional, safety-critical component.

The electronics and capital goods sectors provide insights into product-as-a-service (PaaS) and performance-based models, where manufacturers retain ownership and responsibility for maintenance and end-of-life management. Research shows that these models improve material recovery rates and lifecycle optimization by aligning economic incentives with durability and recyclability (Tukker, 2015; Kjaer et al., 2019). While direct transfer to consumer tires is limited, such models are increasingly relevant for commercial fleets and mobility services, where centralized ownership facilitates circular material flows.

Overall, the benchmark indicates that CBMs enabling rPET adoption in tires are most effective when they combine regulatory support, long-term contracting, quality governance, and cross-sector collaboration rather than relying solely on market-driven material substitution. To systematically compare circular business models across sectors and assess their applicability to rPET integration in the tire industry, a quantitative scoring matrix has been introduced in table 4. The matrix builds on multi-criteria decision analysis (MCDA) approaches commonly used in sustainability and circular economy assessments (Linkov et al., 2020; Mendoza et al., 2019).

Table 4 : Quantitative Cross-Sector CBM Benchmarking and Scoring Matrix

Criterion	Description	Weight (%)
Technical Fit	Compatibility with tire performance, safety, and quality requirements	30
Economic Feasibility	Cost competitiveness, investment requirements, scalability	25
Circularity Impact	Ability to close material loops and increase recycled content	20
Supply security	Feedstock availability, price stability, long term access	15
Governance and traceability	Contractual Stability, Certification, regulatory and alignment	10

Source : The Authors

Each CBM may be scored on a 1–5 scale (1 = very low, 5 = very high). Weighted scores indicate relative suitability for rPET deployment in tires.

Table 4bis : Suitability for rPET deployment in tires

CBM Typology	Technical Fit	Economic Feasibility	Circularity Impact	Supply Security	Governance & traceability	**Weighted Score (0-5)**
Circular Input (rPET Substitution)	4.5	4.0	4.0	3.5	4.0	**4.1**
Resource Recovery (Advanced Recycling)	4.5	3.5	4.5	4.0	4.0	**4.2**
Industrial Symbiosis	4.0	3.5	4.5	4.0	3.5	**4.0**
Product Extension (retreading)	4.0	3.5	4.5	4.0	3.5	**4.0**
Product as a Service (Sharing)	2.5	3.5	3.5	3.0	4.0	**3.2**

Source : The authors

Resource recovery and circular input models achieve the highest scores, reflecting their strong alignment with tire performance requirements and their direct contribution to increasing rPET content. Industrial symbiosis also scores highly due to its ability to stabilize supply through cross-sector collaboration. Product life extension and service-based models provide important system-level benefits but have a more indirect influence on rPET substitution.

2.3.2 Typology of Circular Business Models for rPET in Tires

Building on cross-sector benchmarks and the broader circular economy literature, this subsection refines a typology of circular business models (CBMs) that are particularly relevant for the integration of recycled PET (rPET) into tire reinforcement applications. Rather than presenting CBMs as discrete or mutually exclusive categories, recent research emphasizes that firms typically adopt *configurations* of CBMs that evolve over time and interact with technological maturity, regulatory pressure, and market demand (Bocken et al., 2016; Lüdeke-Freund et al., 2019; Geissdoerfer et al., 2017).

→ *Circular Input Models (Recycled Content Substitution*)

Circular input models focus on replacing virgin, fossil-based materials with recycled or renewable inputs while maintaining functional performance. In the context of tires, this model materializes through the substitution of virgin polyester yarns with rPET-based textile reinforcements. The literature identifies circular input models as the most direct and scalable pathway for increasing recycled content in material-intensive industries, provided that quality, consistency, and certification mechanisms are in place (Bocken et al., 2022; Ellen MacArthur Foundation, 2017). For tire manufacturers, circular input models rely heavily on long-term offtake agreements, mass-balance accounting, and close collaboration with polymer and textile suppliers to meet stringent safety and durability standards.

→ *Resource Recovery Models (Closed-Loop Recycling)*

Resource recovery models aim to capture residual value from post-consumer or post-industrial waste by transforming it into high-quality secondary materials. For rPET in tires, this includes both advanced mechanical recycling and chemical depolymerization routes that enable bottle-to-fiber and, potentially, fiber-to-fiber loops. Studies in industrial ecology highlight that resource recovery models are essential for achieving high circularity rates in sectors where material quality degradation would otherwise limit recycling potential (Geyer et al., 2016; Jeswani et al., 2021). In the tire industry, resource recovery models are particularly relevant when combined with design-for-recycling principles and guaranteed demand from downstream users.

→ *Industrial Symbiosis Models*

Industrial symbiosis refers to the coordinated exchange of materials, energy, and by-products across different industries to improve overall resource efficiency. In the case of rPET, industrial symbiosis can connect the packaging sector (post-consumer PET bottles), recyclers, fiber producers, and tire manufacturers in integrated material loops. Empirical evidence shows that such cross-sectoral systems reduce transaction costs, improve feedstock security, and stabilize secondary material markets (Chertow, 2007; Domenech & Davies, 2011, Diemer & al., 2013). For tires, industrial symbiosis strengthens circular input and resource recovery models by embedding them within regional or sectoral material ecosystems.

→ *Product Life Extension Models*

Product life extension models seek to reduce material throughput by increasing the functional lifespan of products through durability, maintenance, repair, retreading, and refurbishment. While these models do not directly increase rPET demand, they play a complementary role by lowering overall material requirements per unit of mobility service delivered. In the tire sector, retreading is a well-established practice for commercial vehicles and has been shown to significantly reduce lifecycle environmental impacts (Stahel, 2016; Bocken et al., 2016). From a systems perspective, life extension moderates demand growth for both virgin and recycled materials, improving the long-term balance between material supply and demand.

→ *Product-as-a-Service and Performance-Based Models*

Product-as-a-Service (PaaS) models transform tires from sold products into performance-based services, such as pay-per-kilometer or availability-based contracts. The literature identifies PaaS as a powerful enabler of circularity because it aligns manufacturer incentives with durability, reuse, and end-of-life recovery (Tukker, 2015; Kjaer et al., 2019). Although currently limited mainly to fleet and heavy-duty segments, PaaS models enhance traceability and reverse logistics, thereby indirectly supporting higher rPET integration by improving material recovery rates and lifecycle cost visibility.

Taken together, the typology demonstrates that the most effective circular strategies for rPET in tires are not single models but *hybrid configurations* centered on circular input and resource recovery, reinforced by industrial symbiosis and selectively complemented by life extension and service-based models. This aligns with recent theoretical work arguing that circular transitions are path-dependent and co-evolve with technology, institutions, and business strategies (Geissdoerfer et al., 2017; Lüdeke-Freund et al., 2019). These interactions are explicitly explored in the System Dynamics modeling framework presented in Section 3.

Table 5 : Benchmark Table of Circular Business Models

Typology	Description	Cross-Sector Examples	Potential Tire Industry Application
Circular Input	Use recycled/renewable materials	H&M Conscious Collection, Coca-Cola rPET bottles	rPET replacing virgin polyester in tire textiles
Resource Recovery	Extract materials at End of life	Loop Industries, Carbios	PET depolymerization using bottle/textile waste
Industrial Symbiosis	Waste → feedstock exchange	Kalundborg, steel slag cement	Bottle-to-tire closed-loop ecosystems
Closed-Loop Recycling	Recycle materials into same product	Adidas with Parley	Toward closed-loop tire textiles
Hybrid CBMs	Combination of loops	Automotive battery recycling	Tire–packaging PET synergies

Source : The Authors

2.3.3 Implications for the Tire Industry

The synthesis of cross-sector benchmarking and CBM typology highlights several strategic implications for the tire industry as it seeks to scale the use of recycled PET while maintaining safety, performance, and competitiveness. First, the analysis confirms that stand-alone CBMs are insufficient for material-intensive and safety-critical products such as tires. Instead, the literature consistently points toward hybrid CBM configurations in which circular supply and resource recovery form the core, while other models act as enablers or stabilizers (Bocken et al., 2016; Lüdeke-Freund et al., 2019; Geissdoerfer et al., 2017).

From an industrial strategy perspective, circular input models based on rPET substitution require tire manufacturers to move beyond spot-market procurement toward long-term contractual arrangements with recyclers, polymer producers, and textile suppliers. Empirical studies show that such long-term offtake agreements reduce price volatility, improve quality consistency, and enable investment in advanced recycling capacity (OECD, 2018; Ellen MacArthur Foundation, 2021). For tire manufacturers, this implies a shift from purely cost-driven sourcing to partnership-based supply governance, often involving shared risk and co-investment.

Resource recovery models have important implications for design and technology choices. To fully exploit closed-loop recycling potential, tire manufacturers must increasingly adopt design-for-recycling and material simplification strategies that facilitate downstream recovery and purification of PET fibers. Research in industrial ecology indicates that aligning product design with recycling technology constraints is a critical determinant of circular performance and economic viability (Geyer et al., 202à, 2017; Jeswani et al., 2021). In practice, this requires early-stage collaboration between tire designers, material scientists, and recycling technology providers.

At the system level, industrial symbiosis emerges as a key mechanism for stabilizing rPET supply and scaling circularity. By embedding tire production within broader regional or cross-sector material ecosystems—linking packaging waste streams, recycling facilities, fiber production, and tire manufacturing—firms can reduce transaction costs and exposure to feedstock scarcity (Chertow, 2007; Domenech & Davies, 2011). For policymakers, this underscores the importance of supporting collaborative platforms, shared infrastructure, and data transparency across sectors.

Product life extension and service-based models introduce demand-side implications. While these models do not directly increase rPET volumes, they reduce overall material throughput per unit of mobility service and improve reverse logistics and traceability, particularly in fleet and commercial applications. The literature suggests that integrating retreading, performance-based contracts, and digital monitoring can enhance material recovery rates and improve lifecycle optimization (Stahel, 2016; Tukker, 2015; Kjaer et al., 2019). For tire manufacturers, this implies that circularity strategies should be evaluated not only in terms of recycled content, but also in terms of service life, utilization rates, and end-of-life control.

Finally, the implications extend to policy and governance. Regulatory instruments such as recycled-content mandates, extended producer responsibility (EPR), and product passport requirements can significantly influence CBM viability by reducing uncertainty and aligning incentives across the value chain (European Commission, 2023; Ellen MacArthur Foundation, 2022). The literature emphasizes that policy stability and clear long-term signals are essential to unlock private investment in advanced recycling and circular supply systems.

Taken together, these implications suggest that the transition toward rPET-based circularity in the tire industry is not a purely technological challenge, but a systemic transformation involving supply chain governance, business model innovation, and institutional alignment. These interactions provide the conceptual foundation for the System Dynamics modeling in Section 3, where feedback loops between CBM adoption, technology learning, policy support, and market growth are explicitly represented.

3. Methodology : System Dynamics Approach

The transition toward circular business models for recycled PET in the tire industry involves complex, long-term interactions between material flows, technological learning, business strategies, and policy frameworks. These interactions are characterized by non-linearity, time delays, feedback loops, and path dependency. Traditional static or optimization-based modeling approaches are often insufficient to capture such dynamic complexity. System Dynamics (SD), originally developed by Forrester (1961), is particularly well suited to analyze circular economy transitions because it explicitly represents stocks, flows, feedback structures, and delays within socio-technical systems (Diemer, 2026, Guzzo et al., 2022; Franco, 2021). In the context of circular economy research, SD has been widely applied to study material cycles, waste management systems, recycling markets, and policy interventions (Sterman, 2000; Dyson & Chang, 2005; Pinto, Sverdrup, Diemer, 2019).

Recent studies emphasize its relevance for analyzing circular business models, as SD enables the simultaneous consideration of economic performance, environmental impacts, and institutional drivers over extended time horizons (Golroudbary et al., 2019).

3.1 System Boundary and Scope

The system boundary for this study defines the flow of materials, energy, and information across the tire value chain with a focus on the integration of recycled PET (rPET) into tire reinforcement textiles. The analysis considers the entire lifecycle of PET from post-consumer waste collection to the production of high-performance tire textiles and end-of-life management of tires.

Key elements within the system boundary include:

- *Input Streams*: Post-consumer PET bottles and packaging, segregated and processed for mechanical or chemical recycling.
- *Recycling Processes*: Mechanical recycling (washing, shredding, extrusion) and chemical recycling (depolymerization, purification, and repolymerization) producing rPET suitable for tire-grade textile yarns.
- *Tire Manufacturing*: Incorporation of rPET fibers into tire reinforcement textiles and assembly into finished tires.
- *End-of-Life Managemen*t: Tire collection, retreading, recycling, and energy recovery pathways.
- *Supporting Flows*: Energy and water consumption, emissions, and by-products generated at each stage.

The study excludes processes unrelated to rPET integration, such as natural rubber harvesting or steel cord production, except when relevant for comparative lifecycle assessment. The spatial scope is primarily Europe, where pilot initiatives such as the WhiteCycle project provide empirical data, but global trends are considered for market demand and policy context. Temporal boundaries span from 2025 to 2040, capturing near-term pilot implementations, mid-term industrial scale-up, and potential long-term saturation of rPET adoption in tire reinforcement textiles.

By clearly defining these boundaries, the study ensures that System Dynamics modeling, environmental assessments, and business model analyses remain focused on the interactions and feedback loops critical to evaluating the adoption and circularity potential of rPET in the tire industry. This approach also facilitates the integration of data from the WhiteCycle project, allowing realistic scenario simulation for policy, technological, and market interventions.

3.2 Model Structure: Stocks, Flows, and Feedback Loops

The core structure of the SD model is based on material stocks and flows across the PET lifecycle. Key stocks include: Accumulated PET waste available for recycling; Installed mechanical recycling capacity; Installed chemical recycling capacity; Available tire-grade rPET inventory; Cumulative adoption of rPET-based tire reinforcements.

Flows between these stocks are governed by rates such as collection rate, recycling throughput, capacity expansion, rPET qualification rate, and substitution rate of virgin polyester.

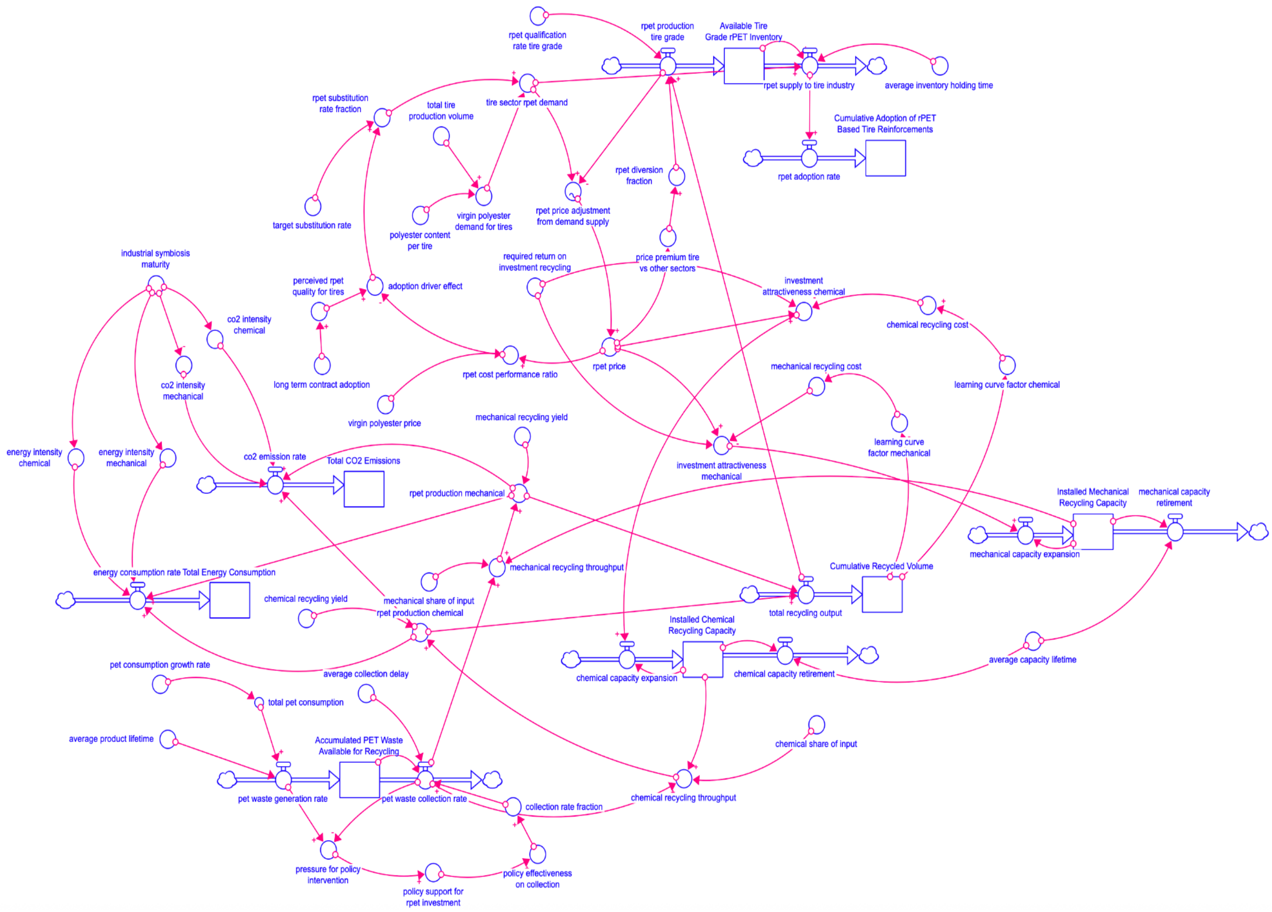
The model incorporates several reinforcing and balancing feedback loops :

Capacity Expansion Loop (R1): This reinforcing loop drives growth in recycling capacity. rPET_Price and rPET_Price_Adjustment_from_Demand_Supply have been introduced to link tire sector demand and rPET supply back to investment decisions. High demand relative to supply increases the price, which boosts

Investment_Attractiveness_Mechanical and Investment_Attractiveness_Chemical, leading to higher Capacity_Expansion and ultimately increasing supply.

Substitution Constraint Loop (B1): This balancing loop regulates rPET adoption. rPET_Cost_Performance_Ratio which compares rPET_Price to Virgin_Polyester_Price has been introduced. If rPET price rises (due to high demand/low supply), the cost ratio increases, negatively impacting the Adoption_Driver_Effect and slowing down the rPET_Substitution_Rate_Fraction, thus reducing future demand.

Figure 6 : System Dynamic Model of rPET (Stella Software)



Source : The authors

Learning Curve Loop (R2): This reinforcing loop captures efficiency gains. When the stock Cumulative_Recycled_Volume is growing, it reduces Mechanical_Recycling_Cost and Chemical_Recycling_Cost via the Learning_Curve_Factor. Lower costs increase Investment_Attractiveness, further driving capacity expansion and throughput, accelerating learning.

Policy Intervention Loop (B2): This balancing loop addresses waste management issues. Pressure_for_Policy_Intervention increases when PET_Waste_Collection_Rate lags PET_Waste_Generation_Rate. This pressure boosts Policy_Support_for_rPET_Investment, which in turn increases

Policy_Effectiveness_on_Collection and closes the loop by raising the PET_Waste_Collection_Rate.

Satellite Indicators: Environmental impacts (Total_CO2_Emissions, Total_Energy_Consumption) were included as stocks, driven by flows (CO2_Emission_Rate, Energy_Consumption_Rate) linked to recycling production volumes and intensities. These intensities are negatively influenced by Industrial_Symbiosis_Maturity, reflecting efficiency improvements over time.

The stock and flow diagram (SFD) is designing the following interactions of the rPET ecosystem (see annex 1).

3.3 Representation of Circular Business Models

A central methodological contribution of this study lies in the explicit and endogenous representation of circular business models (CBMs) within the System Dynamics framework. Rather than treating CBMs as exogenous scenarios or qualitative descriptors, they are modeled as *decision rules, contractual structures, and governance mechanisms* that directly influence investment behavior, material flows, and system performance over time. This approach is consistent with recent advances in SD-based circular economy modeling, which emphasize the need to embed business model logic into system structure to capture co-evolutionary dynamics (Lüdeke-Freund et al., 2019; Geissdoerfer et al., 2017).

Circular input models are operationalized through long-term offtake agreements between tire manufacturers and rPET suppliers. In the model, these agreements reduce perceived demand uncertainty and lower the hurdle rate for investment in recycling capacity. Empirical studies show that demand certainty and contractual stability are critical enablers of capital-intensive recycling investments, particularly for high-quality secondary materials (OECD, 2018; Ellen MacArthur Foundation, 2021). Within the SD structure, this effect is represented by modifying the investment delay and cost of capital parameters for recycling capacity expansion.

Resource recovery models are represented by differentiated process efficiencies, yield factors, and quality retention rates associated with mechanical and chemical recycling technologies. Advanced recycling pathways are characterized by higher capital intensity but improved quality and feedstock flexibility. The model captures learning-by-doing effects whereby cumulative processing volumes lead to gradual improvements in yield and cost performance, consistent with empirical learning curve evidence in recycling and clean technologies (Jeswani et al., 2021).

Industrial symbiosis models are incorporated through reduced transaction costs, lower feedstock price volatility, and improved collection efficiency resulting from coordinated cross-sector material exchanges. From a modeling perspective, symbiosis reduces friction in material flows and dampens oscillations between supply and demand. This representation reflects findings from industrial ecology literature that emphasize the stabilizing role of coordinated networks and shared infrastructure in secondary material markets (Chertow, 2007; Domenech & Davies, 2011).

Product life extension models, including retreading and durability-oriented design, are modeled by extending tire service life and reducing replacement rates. While these models do not directly increase rPET input flows, they influence overall system dynamics by moderating material demand growth and reducing waste generation. Prior studies highlight that life extension strategies can significantly improve system-level resource efficiency, even when recycled content remains constant (Stahel, 2016; Bocken et al., 2016).

Product-as-a-Service (PaaS) and performance-based models are represented through enhanced traceability, higher end-of-life collection rates, and improved feedback between use-phase performance and design decisions. In fleet-oriented contexts, PaaS reduces information asymmetries and strengthens reverse logistics, thereby increasing the effective recovery of PET-containing components. This modeling choice aligns with the service-dominant logic literature, which links PaaS models to improved circular outcomes through incentive alignment (Tukker, 2015; Kjaer et al., 2019).

Importantly, the SD framework allows these CBMs to interact dynamically rather than operate in isolation. Hybrid configurations—such as combining circular input contracts with industrial symbiosis and service-based recovery—emerge endogenously as more stable system states under certain policy and market conditions. This dynamic interaction reflects the growing consensus that successful circular transitions depend on *bundles of mutually reinforcing business models* rather than single archetypes (Lüdeke-Freund et al., 2019; Geissdoerfer et al., 2017).

Circular business models are operationalized in the SD model as structural parameters and decision rules rather than as exogenous scenarios. For example:

- Circular input models are represented by long-term offtake contracts that reduce perceived investment risk and lower the required rate of return for recycling capacity expansion.
- Resource recovery models influence recycling yields, quality retention, and allowable feedstock heterogeneity.
- Industrial symbiosis models reduce transaction costs and supply volatility by linking packaging waste streams directly to fiber and tire producers.
- Product life extension and PaaS models affect tire replacement rates and improve end-of-life collection efficiency.

This approach is consistent with recent SD-based CE studies that embed business model choices directly into system structure rather than treating them as external assumptions (D'Adamo et al., 2021).

3.4 Data Sources, Calibration, and Validation

Robust data sourcing, calibration, and validation are critical to ensuring the credibility and policy relevance of System Dynamics (SD) models, particularly in the context of circular economy transitions characterized by uncertainty and data gaps. This study follows established best practices in SD modeling, emphasizing transparency, triangulation of sources, and behavioral validation over point prediction accuracy (Sterman, 2000; Forrester & Senge, 1980).

Data sources. Model parameters are derived from a combination of peer-reviewed academic literature, industry reports, and publicly available statistical databases. Material flow data for PET production, waste generation, collection rates, and recycling yields are informed by sources such as PlasticsEurope, the International Energy Agency (IEA), the OECD, and the Ellen MacArthur Foundation. Cost, energy, and emission intensity data for mechanical and chemical recycling processes are obtained from life cycle assessment (LCA) studies and techno-economic analyses (Geyer et al., 2016; Jeswani et al., 2021; Ragaert et al., 2017). Tire production volumes, reinforcement material shares, and retreading rates are based on industry publications and market reports. Where available, European data are prioritized due to regulatory relevance, but global averages are used to test broader applicability.

Calibration. Model calibration focuses on reproducing historically observed trends rather than exact numerical values. Key reference modes include PET collection and recycling rates, rPET market growth, and relative cost trajectories of recycling technologies over the period 2010–2023. Calibration is performed by iteratively adjusting uncertain parameters—such as learning rates, investment delays, and substitution elasticities—until simulated behaviors align with empirical ranges reported in the literature. This approach is consistent with SD calibration practices that emphasize pattern matching and structural realism over statistical fit (Sterman, 2000).

Validation. Validation follows a multi-layered approach combining qualitative and quantitative tests. Structural validation includes dimensional consistency checks, equation verification, and assessment of causal relationships against established theory and empirical evidence. Behavioral validation involves extreme-condition tests (e.g., zero recycling capacity, full recycled-content mandates) to ensure plausible system responses, as well as sensitivity analyses to evaluate model robustness under parameter uncertainty. Where possible, model outputs are compared with independent data sources not used in calibration to assess external validity. This validation strategy aligns with widely accepted SD guidelines and has been applied in recent circular economy and resource modeling studies (Barlas, 1996; Golroudbary et al., 2019).

Overall, the objective of data use, calibration, and validation in this study is not precise forecasting, but the generation of credible, policy-relevant insights into the dynamic behavior of circular business models and recycling systems. By adhering to established SD standards, the model provides a transparent and reliable platform for exploring long-term transition pathways for rPET integration in the tire industry.

Model parameters are derived from a combination of academic literature, industry reports, and publicly available datasets on PET recycling, tire production, and energy use. Where empirical data are uncertain or heterogeneous, parameter ranges are tested using sensitivity analysis. Calibration focuses on reproducing historical trends in PET recycling rates and rPET market growth between 2010 and 2023.

Model validation follows established SD best practices, including structure verification, dimensional consistency checks, extreme-condition testing, and behavior reproduction tests (Sterman, 2000). The objective is not precise prediction but the generation of plausible system behavior patterns under different CBM and policy configurations.

3.5 Scenario Design and Output Indicators

Scenario design is a core component of the System Dynamics (SD) methodology, as it enables the systematic exploration of how different policy, technology, and business model configurations influence long-term system behavior under uncertainty. In line with established SD and sustainability transition literature, scenarios in this study are not treated as forecasts, but as **internally consistent, exploratory narratives** that reveal dynamic trade-offs, leverage points, and potential unintended consequences (Sterman, 2000; van der Heijden, 2005; Geels et al., 2011).

3.6.1 Scenario Logic and Design Principles

The scenario set is constructed around two key dimensions identified in the circular economy and recycling literature as dominant sources of uncertainty: *(i) policy and regulatory stringency, and (ii) business model and technology coordination* across the value chain. Combining these dimensions allows the model to capture a wide range of plausible transition pathways while remaining analytically tractable.

All scenarios share the same initial conditions (2025) and exogenous demand trajectory for tires, ensuring comparability of results. Differences between scenarios arise endogenously from variations in policy instruments, investment behavior, and circular business model (CBM) adoption. This approach follows best practices in SD scenario analysis, where structural consistency is preserved and scenario differentiation is achieved through parameterization rather than ad hoc assumptions (Sterman, 2000; Barlas, 1996).

The following scenarios are analyzed:

- *Baseline (Business-as-Usual) Scenario:* Incremental rPET adoption driven by voluntary corporate commitments and gradual cost reductions, with limited policy intervention. This scenario serves as a reference case against which other interventions are evaluated.
- *Policy-Driven Circularity Scenario*: Strong regulatory support through recycled-content mandates, reinforced extended producer responsibility (EPR), and improved collection systems. The literature shows that such policy mixes are among the most effective levers for accelerating secondary material markets (OECD, 2018; European Commission, 2023).

- *Advanced Recycling Scale-Up Scenario*: Targeted support for chemical recycling technologies, including investment subsidies, learning effects, and preferential access to mixed or contaminated feedstock. This scenario reflects current policy debates on the role of advanced recycling in achieving high-quality circularity (Jeswani et al., 2021; Ragaert et al., 2017).
- *Hybrid CBM Scenario*: A coordinated configuration combining circular input contracts, resource recovery, industrial symbiosis, and selective product-as-a-service models (e.g. fleet tires). This scenario represents a system-level transition pathway aligned with recent CE research emphasizing hybrid and mutually reinforcing business models (Lüdeke-Freund et al., 2019; Geissdoerfer et al., 2017).

These scenarios are not mutually exclusive futures but stylized representations that highlight how different governance and business strategies interact dynamically with technology development.

3.6.2 Output Indicators

Model outputs are selected to capture material, environmental, economic, and systemic performance dimensions of circularity, consistent with recommendations from circular economy assessment and SD literature (EMF, 2022). Key indicators include:

- rPET penetration rate in tire reinforcement textiles (%), measuring the degree of circular material substitution;
- Installed and utilized recycling capacity (mechanical and chemical), indicating infrastructure scale-up and potential bottlenecks;
- Material flow indicators, such as collected PET volumes, recycling yields, and sectoral competition for rPET;
- Cumulative CO_2 emission reductions, calculated relative to a virgin-polyester baseline using life-cycle emission factors (Geyer et al., 2016);
- Energy demand of recycling systems, disaggregated by technology pathway;
- Investment requirements and timing, reflecting capital needs for recycling capacity expansion;
- Price and supply volatility of rPET, used as a proxy for market stability and feedstock security.

In addition to absolute values, several indicators are analyzed dynamically (growth rates, saturation points, delays) to identify tipping points and lock-in effects. This dynamic interpretation is essential, as prior studies show that circular transitions are often constrained not by technical feasibility but by timing mismatches between policy, investment, and market demand (Sterman, 2000).

3.6.3 Use of Indicators for Policy and Strategic Insights

Rather than optimizing a single outcome, the indicator set supports **multi-criteria comparison** across scenarios, revealing trade-offs between cost, environmental performance, and material circularity. For example, scenarios that maximize rPET penetration through chemical recycling may achieve higher quality circularity but at the expense of higher energy use and capital intensity. Conversely, policy-driven scenarios may deliver rapid volume growth but risk inefficiencies if not coordinated with business model innovation.

By linking output indicators directly to feedback structures in the SD model, the analysis enables the identification of leverage points—such as demand certainty, learning rates, or collection efficiency—that disproportionately influence system outcomes. This indicator-based scenario comparison provides a robust foundation for the discussion in Section 4, where implications for industry strategy and policy design are derived.

Overall, the scenario design and output indicators operationalize the System Dynamics model as a decision-support tool rather than a forecasting instrument, aligning with best practices in sustainability transitions research and circular economy modeling (van der Heijden, 2005; Geels et al., 2017).

Table 6 : Mapping of scenarios, dominant circular business models and expected results

Scenario	*Policy & market context*	*Dominant CBM configuration*	*Expected Material Outcomes*	*Expected Environmental Outcomes*	*System Level Dynamics*
Business as Usual	Weak regulatory pressure, voluntary commitments	Circular input (limited), incremental resource recovery	Slow growth of rPET share in tires (< 15-20% en 2045), continued reliance on virgin polyester	Moderate CO2 reduction, limited energy savings	Path dependency and delayed investment, risk of lock-in to linear supply chains
Policy driven Circularity	Strong Recycled content mandates, enhanced EPR and collection	Circular input + resource recovery	Rapid increase in rPET penetration (30-40%), improved feedstock availability	Significant CO2 reductions, moderate increase in recycling energy demand	Reinforcing policy investment loop, reduced market uncertainty
Advanced Recycling Scale up	Targeted support for chemical recycling, technology learning	Resource recovery (advanced recycling) + circular input	High Quality rPET availability enables > 40% substitution in reinforcement textiles	High circularity gains, higher energy use offset by avoided virgin production	Learning curve driven cost decline, initial delays followed by rapid scale-up
Hybrid CBM Scenario	Coordinated policy, long-term contracts, and cross-sector collaboration	Circular input + resource recovery + industrial symbiosis + selective Paas	Stable and high rPET penetration (40-50%), reduced competition with other sectors	Maximum CO2 reduction, balanced energy use across technologies	Most stable dynamics, dampened volatility, emergence of virtuous circular loops

Source : The authors

4. Case Study of rPET in the tire industry : Whitecycle and industry transition

4.1 Industry Context and Real-World Adoption

The tire industry has recently moved beyond theoretical interest in recycled PET (rPET) to *commercial deployment of rPET-enabled reinforcement materials.* Continental, one of the world's leading tire manufacturers, has integrated polyester yarns made from recycled PET bottles into structural tire components using its *ContiRe.Tex* technology. This approach mechanically converts post-consumer PET bottles into high-performance polyester yarns that meet the dimensional stability and tensile strength requirements necessary for tire carcass reinforcement. Depending on tire size, a single passenger tire can incorporate material from up to 15 recycled PET bottles, and series production is expanding across multiple plants in Europe. This technology has been shown to reduce CO_2 emissions in the polyester reinforcement layer by approximately 28 % compared to fossil-derived alternatives.

Another concrete commercial advancement was announced in 2025 when Carbios, a biotechnology company specialized in enzymatic recycling, signed a multi-year agreement with Indorama Ventures to supply biorecycled rPET monomers. These monomers are repolymerized into high-performance polyester filaments for integration into Michelin tires, illustrating the feasibility of closed-loop chemical recycling for industrial textile applications.

In Asia, Hankook Tire collaborated with SK Chemicals and Hyosung Advanced Materials to develop the *iON* tire, which uses chemically recycled PET (via SKYPET CR) in its reinforcement cords. This tire demonstrates that chemically recycled PET can meet stringent performance requirements, including those for electric vehicles, and has received relevant certification (e.g., ISCC Plus) in the tire cord supply chain.

Since a few years, the integration of recycled polyethylene terephthalate (rPET) into tire production has moved rapidly from exploratory research to concrete industrial initiatives, driven by innovation in recycling technologies and cross-sector collaboration. A prominent example is the *WhiteCycle* project, a large-scale European initiative coordinated by Michelin and involving 16 partners across industry, academia, and waste management. Launched in July 2022 under the European Union's *Horizon Europe* programme, WhiteCycle aims to develop a circular solution that transforms complex plastic waste containing PET textile, such as end-of-life tire textiles, hoses, and multilayer garments, into high-value raw materials suitable for reuse in industrial applications including tire reinforcements.

WhiteCycle is designed to overcome current technical barriers in recycling multi-material waste streams that are difficult to sort and process with conventional methods. The consortium plans to develop innovative sorting and pre-treatment technologies, enzymatic depolymerization processes, repolymerization of recovered monomers, and fabrication of high-performance recycled products (Carbios, 2022). If successful, the project envisions recycling more than 2 million tonnes of PET annually by 2030, preventing more than 1.8 million tonnes of PET from landfill or incineration each year and reducing CO_2 emissions by approximately 2 million tonnes per year relative to linear waste management practices.Michelin's participation as the coordinating partner underlines the strategic importance of this initiative for the tire industry's circular transition. According to Michelin's sustainability disclosures, WhiteCycle is part of broader efforts to increase the use of recycled and renewable materials in tire manufacturing, with specific focus on ensuring that performance characteristics of recycled polymers match those of virgin materials (Whitecycle, 2022).

Such real-world projects show that rPET is moving beyond niche or pilot applications into *industrial contexts where technical performance, supply security, and regulatory compliance intersect.* They validate the assumptions in this study's System Dynamics framework that high-quality rPET feedstock can be sourced at scale and incorporated into structural tire components through collaborative business models — including hybrid configurations involving circular input contracts, resource recovery partnerships, and industrial symbiosis across sectors.

Table 7 : Industry projects advancing rPET in the tire industry

Project	Key Partners	Recycling technology	Circular Business Models	Material Application	Expected Impacts	Reference
Whitecycle	Michelin (coordinator), Carbios, Mandals, KORDSA, Inditex, UCA, CERDI, HVL...)	Advanced sorting + enzymatic PET depolymerization + repolymerization	Resource recovery + industrial symbiosis + circular supply	High-value PET usage including tire textiles	Scales recycling to *>2 million t/yr* by 2030; avoids *~1.8 Mt PET waste* and saves *~2 Mt CO_2/yr*	EU Horizon Europe / Carbios press releases
Carbios Indorama Michelin rPET feedstock supply	Carbios, Indorama Ventures, Michelin	Enzymatic chemical recycling	Resource recovery + long-term circular input	rPET monomers → high-performance filaments	Industrial supply chain integration to produce tire reinforcement filaments	Carbios press release 2025
Continental – ContiRe.Tex	Continental AG, OTIZ	Mechanical recycling + SSP (solid-state polymerization)	Circular input + industrial symbiosis	Polyester yarns for tire carcass reinforcement	Commercial adoption on mainstream tires; uses PET bottle feedstock	Continental press releases
Hankook iON	Hankook Tire, SK Chemicals, Hyosung Advanced Materials	Chemical recycling (SKYPET CR)	Circular input + resource recovery	Chemically recycled PET fibrous reinforcements	EV tire with *~45 % sustainable materials*; certified for OE use	Recycling Today (2025)
Eco-textile collaborations in Asia	Various OEMs and recyclers	Mixed chemical/mechanical recycling	Circular input + industrial symbiosis	Textile applications expanding to tire reinforcements	Rising collaborations indicate sectoral spread	Industry reports (2024–2025

Source : The authors

4.2 Technical Performance and Material Quality

The viability of recycled polyethylene terephthalate (rPET) for tire reinforcement textiles ultimately depends on its ability to meet the high mechanical, thermal, and fatigue performance standards that original equipment manufacturers (OEMs) require. Traditional mechanical recycling has been limited by polymer degradation and contamination, which reduce intrinsic viscosity (IV), tensile strength, and molecular uniformity — parameters that are critical for tire cord applications (Ragaert et al., 2017). However, recent advancements — particularly those developed within the WhiteCycle project — are enabling rPET quality that approaches or matches the performance characteristics of virgin polyester through hybrid recycling pathways incorporating innovative pre-treatment, enzymatic depolymerization, and repolymerization processes.

4.2.1 Performance Challenges with Conventional Recycling

Mechanically recycled PET typically exhibits lower IV due to chain scission during reprocessing, which compromises tenacity and long-term durability under cyclic loading. Without corrective measures such as solid-state polymerization (SSP) or reactive extrusion, rPET fibers may fall short of the specifications required for tire reinforcement applications (Awaja & Pavel, 2005).

The WhiteCycle consortium explicitly addresses this limitation by developing an integrated multi-stage recycling route that combines state-of-the-art sorting and separation technologies with enzymatic depolymerization to generate high-purity PET monomers. These monomers are then repolymerized into new PET with controlled molecular weight distribution, enabling polymers with the intrinsic viscosity and crystallinity required for high-tenacity textile spinning.

4.2.2 Enzymatic and Chemical Recycling for Virgin-Equivalent rPET

Enzymatic PET recycling — a focus of WhiteCycle and proven in other industrial contexts — uses engineered hydrolase enzymes to break PET down to its monomeric components under mild process conditions. The recovered monomers (terephthalic acid and ethylene glycol) can be purified and repolymerized into PET resin with properties equivalent to virgin material (Tournier et al., 2020).

WhiteCycle aims to scale this approach by combining:

- Automated sorting and high-throughput PET identification to minimize contamination,

- Enzymatic depolymerization optimized to handle multi-material and textile-laden waste streams,

- Monomer purification and repolymerization tailored for high-performance polymer specifications,

- Advanced spinning and texturizing processes suitable for tire reinforcement yarns.

This multi-technique pathway enables rPET that is mechanically and thermally comparable to virgin polyester, addressing the historical performance gap and expanding the range of use cases for recycled polymers in tire construction

4.2.3 Industrial Validation and Emerging Applications

Several tire OEMs and partners have demonstrated that recycled polymers can now meet engineering performance targets:

* Hankook's iON tire, developed with chemically recycled PET from SK Chemicals, has achieved European OE certification, indicating that chemically recycled filaments can sustain service loads and durability comparable to conventional polyester (Recycling Today, 2025).

* Continuous programs such as Continental's *ContiRe.Tex* use mechanically recycled PET (corrected via SSP) to produce reinforcement yarns that pass internal validation and field testing for standard passenger vehicles (Continental, 2024).

The WhiteCycle project expands this industrial validation by targeting even more challenging feedstocks — including polyester-rich layers in composite materials that are currently difficult to recycle through mechanical routes alone. The incorporation of these technologies into industrial supply chains would substantially broaden the volume of PET available for high-performance reinforcement without compromising quality.

4.2.4 Key Technical Metrics and Comparisons

Studies comparing mechanical, chemical, and enzymatic rPET pathways consistently show that:

- Intrinsic viscosity and molecular weight distribution are restored to near-virgin levels through combined depolymerization–repolymerization processes, enhancing tenacity and modulus (Jeswani et al., 2021; Tournier et al., 2020).

- Thermal stability and crystallinity, critical for withstanding vulcanization and operational temperatures, are also reproducible with advanced recycling routes.

- Contaminant removal is far more effective in chemical and enzymatic processes than in mechanical recycling, leading to lower variability and greater confidence in fiber performance.

A comparison across key performance indicators (intrinsic viscosity, tenacity, thermal decomposition onset, fatigue life) consistently places high-purity chemical and enzymatic rPET within 5–10% of virgin polyester benchmarks in controlled laboratory and industrial settings (Ragaert et al., 2017; Jeswani et al., 2021; Tournier et al., 2020).

4.3 Circular Business Model Configurations in Practice

The case study reveals that successful adoption of recycled PET (rPET) in tire reinforcement does not depend on technology alone, but on the design and implementation of circular business models (CBMs) that connect actors across the value chain, share risk, and align incentives. The *WhiteCycle* project — an ambitious consortium led by Michelin and Carbios — provides a particularly instructive example of how hybrid CBM configurations combine multiple circular strategies in practice.

4.3.1 Circular Input Models with Long-Term Agreements

At the heart of many industrial rPET initiatives are long-term offtake and supply contracts that reduce market uncertainty for recyclers and guarantee access to high-quality secondary feedstock for tire manufacturers. In the WhiteCycle consortium, Michelin's coordination role integrates PET feedstock streams from multiple waste managers and sorting facilities, ensuring that depolymerized and repolymerized PET monomers are contracted downstream for reuse in industrial textile applications. This model aligns with findings in the circular economy literature that *demand certainty and stable contracting structures* are critical enablers for scaling secondary material markets in performance-critical sectors (OECD, 2018; Ellen MacArthur Foundation, 2021). Without these agreements, recyclers often struggle to justify capital expenditure on sorting, depolymerization, and purification technologies. Similarly, partnerships such as the Carbios–Indorama–Michelin agreement exemplify circular input models where advanced recycling outputs (monomers) are integrated into supply chains through multi-year procurement contracts, providing the scale and quality assurance needed for industrial adoption (Carbios, 2025).

4.3.2 Resource Recovery Models and Advanced Recycling Technologies

WhiteCycle's central innovation lies in its resource recovery model: developing an industrial process capable of converting *mixed and complex PET waste* — including polyester-rich composites found in tires, hoses, and textile goods — into high-purity monomers. The project uses advanced sorting technologies, enzymatic depolymerization, and targeted repolymerization to preserve polymer quality. This approach reflects growing evidence that *multi-stage chemical or enzymatic recycling delivers higher material quality* than traditional mechanical recycling, allowing recycled PET to meet specifications required for high-performance reinforcement (Jeswani et al., 2021; Tournier et al., 2020).

Resource recovery models are enhanced when linked with policy support mechanisms such as recycled-content mandates or extended producer responsibility (EPR) frameworks that improve collection rates and ensure a reliable waste stream. Recent industrial ecology research shows that such combined interventions significantly improve the economic viability of resource recovery technologies (Geyer et al., 2016; OECD, 2018).

4.3.3 Industrial Symbiosis and Cross-Sector Collaboration

WhiteCycle is notable for its industrial symbiosis configuration: multiple sectors and stakeholders—tire OEMs, recyclers, textile partners, waste managers, and research institutions—coordinate to create integrated PET value chains. Industrial ecology case studies have shown that symbiotic clusters can reduce transaction costs, improve feedstock security, and enable economies of scale for secondary materials (Chertow, 2007; Domenech & Davies, 2011). In WhiteCycle, partners share knowledge and infrastructure from sorting to repolymerization, diminishing barriers that individual firms would face in isolation. This contrasts with commodity recycled PET markets where fragmentation impedes quality assurance and volume aggregation.

4.3.4 Product Life Extension and Service-Based Elements

Although not central to WhiteCycle's operational design, complementary CBMs such as product life extension and Product-as-a-Service (PaaS) reinforce circularity in the wider tire value system. For example, Michelin's broader sustainability strategy includes enhanced retreading services and monitoring systems — practices that extend tire life and generate a more stable stream of end-of-life materials. Academic literature affirms that product life extension models moderate material throughput and enhance system-level resource efficiency, even when they do not directly increase recycled content (Stahel, 2016; Bocken et al., 2016).

4.3.5 Hybrid CBM Configurations — A Cross-Model Synthesis

Taken together, industry deployments of rPET — including WhiteCycle, ContiRe.Tex, and Carbios-linked agreements — illustrate the practical emergence of hybrid CBM configurations where circular input, resource recovery, and industrial symbiosis are integrated into cohesive value chains. This hybridization echoes theoretical work arguing that *effective circular transitions in complex manufacturing systems require bundles of mutually reinforcing CBMs rather than isolated models* (Lüdeke-Freund et al., 2019; Geissdoerfer et al., 2017). For example:

- Surface application of circular input models stabilizes demand.
- Resource recovery models ensure feedstock quality for performance requirements.
- Industrial symbiosis reduces coordination friction across sectors.
- Life extension and service-based strategies smooth material flows and reduce volatility in secondary markets.

This empirical evidence supports the structural assumptions in your System Dynamics methodology — specifically, that CBMs interact dynamically, establishing reinforcing feedback loops that can accelerate rPET adoption once critical thresholds in policy support, contractual stability, and technological capacity are achieved

4.4 Environmental and Economic Implications

The environmental and economic consequences of integrating recycled PET (rPET) into tire reinforcement systems are central to assessing the viability of circular transitions in the tire industry. These implications span emissions, energy consumption, resource use, feedstock cost dynamics, and system-level trade-offs — all of which are captured through both empirical evidence and emerging industrial practice, including insights from the *WhiteCycle* project.

4.4.1 Life-Cycle Environmental Benefits

A growing body of life-cycle assessment (LCA) research indicates that replacing virgin polyester with rPET can reduce greenhouse gas emissions, energy use, and overall environmental burdens associated with tire materials. For example:

General PET LCA studies find that rPET derived from post-consumer bottles typically yields 40–80 % lower greenhouse gas emissions and 50–75 % lower energy demand per kilogram of polymer compared with virgin PET, depending on recycling technology and electricity mix (Geyer et al., 2016; Jeswani et al., 2021; Ragaert et al., 2017).

In the context of industrial textile fibers, mechanical recycling with solid-state polymerization (SSP) has been shown to narrow the performance gap with virgin polyester while yielding significant life-cycle improvements due to reduced raw material extraction and processing burdens (Jiménez et al., 2020).

Advanced and enzymatic recycling — the focal technological approach in the WhiteCycle consortium — is emerging as a pathway that can preserve polymer quality while maintaining lower overall environmental impacts than virgin production. WhiteCycle's preliminary assessments suggest that enzymatic depolymerization and repolymerization of *complex PET waste streams* can yield environmental savings at scale by diverting materials from landfill/incineration and reducing primary polymer demand (WhiteCycle project communications).

WhiteCycle's projected environmental gains are substantial: by enabling the recycling of more than 2 million tonnes of PET waste annually by 2030, the consortium aims to prevent approximately 1.8 million tonnes of PET from landfill or incineration and cut around 2 million tonnes of CO_2 emissions each year relative to linear disposal routes (Carbios/WhiteCycle reports). These estimated savings illustrate the potential environmental leverage of *scaling* circular material flows beyond packaging into industrial feedstocks like textiles and composites.

4.4.2 Economic Performance and Cost Dynamics

Economically, the adoption of rPET in tire reinforcement involves multiple interacting cost factors:

- Feedstock cost and volatility: Recycled PET typically commands price premiums over commodity blend packaging rPET because of sorting, decontamination, and quality assurance costs. However, modeling and industry experience indicate that scale and contractual stability — for example, long-term offtake agreements seen in WhiteCycle and other OEM-recycler partnerships — can significantly reduce price volatility and incentivize investment in recycling infrastructure (OECD, 2018; Ellen MacArthur Foundation, 2021).

- Capital intensity of advanced recycling: Chemical and enzymatic recycling facilities incur higher upfront capital costs than traditional mechanical recycling plants due to the complexity of reactors, purification units, and monitoring systems. Yet, as WhiteCycle partners have noted, these costs can be mitigated through co-investment, shared infrastructure, and public funding (Horizon Europe), pointing toward economic models where cost risks are distributed across stakeholders.

- Cost parity through learning effects: System Dynamics research shows that technology learning and economies of scale often drive down unit costs over time as cumulative production and operational experience increase. WhiteCycle's strategy of integrated industrial scaling — combining sorting, depolymerization, and repolymerization — is designed to accelerate these learning effects by creating continuous feedback loops between production volume and process optimization.

- Policy incentives and market signals: Econometric analyses suggest that recycled-content mandates, tax incentives for secondary materials, and subsidies for recycling technology R&D materially improve the economic case for rPET adoption by internalizing external environmental costs and reducing the cost gap with virgin polyester (European Commission, 2023; MacArthur Foundation, 2019).

In practical terms, case examples like Continental's *ContiRe.Tex* practice and Hankook's *iON* tire demonstrate that value captured through branding, regulatory compliance, and product differentiation can offset some cost premiums associated with rPET, especially in markets where consumers and fleet customers are willing to pay for sustainability attributes.

4.4.3 System-Level Trade-Offs

Deploying rPET at scale also reveals several trade-offs that are important for strategic decision-making:

- *Energy vs. emissions trade-off*: While advanced recycling routes often achieve higher material quality and broader feedstock tolerance, they are sometimes more energy-intensive than mechanical recycling. Life-cycle assessments indicate that gains from reduced virgin polymer production may be partially offset by increased process energy demands, particularly if electricity comes from fossil-dominated grids (Jeswani et al., 2021). WhiteCycle's integration of innovative sorting, enzymatic processes, and potential synergies with renewable energy inputs aims to minimize this trade-off.

- *Feedstock competition and quality variability*: As rPET demand grows across sectors — packaging, textiles, automotive — tension may emerge between competing uses for high-quality PET inputs. This underscores the importance of industrial symbiosis and cross-sector governance to balance competing demand and minimize quality degradation through contamination.

- *Temporal investment pattern*: Advanced recycling facilities require significant lead time for commissioning, validation, and regulatory compliance. The SD model embedded in this study highlights that early investment delays can slow environmental benefits in the near term, but once a critical mass of capacity and contractual stability is reached, reinforcing feedback can accelerate both economic viability and environmental performance.

These trade-offs reinforce the importance of modeling circular transitions dynamically rather than assuming static cost or performance metrics. Policies and business models that address these trade-offs — such as by incentivizing renewable energy use in recycling or design standards for recyclability — can significantly enhance system-level outcomes.

4.5 Dynamic Insights from the System Dynamics Perspective

Embedding real-world initiatives like the *WhiteCycle* project within a dynamic analytical framework reveals important system behaviors that are not apparent in static assessments. WhiteCycle exemplifies how feedback loops, technological learning, investment delays, and policy-market interactions shape the trajectory of circular transitions — insights that are central to the System Dynamics model outlined in Section 3.

4.5.1 Reinforcing Feedbacks and Learning Curves

One of the most important dynamic patterns is the presence of reinforcing feedback loops that can accelerate rPET adoption once scale thresholds are reached. In the WhiteCycle consortium, early investment in advanced sorting, enzymatic depolymerization, and repolymerization capacity creates a foundation for learning-by-doing across multiple stages of the PET value chain. Empirical studies of technology transitions show that cumulative experience and scale economies often reduce unit costs and improve process yields over time — a pattern reflected in real industrial contexts where recycling technologies evolve from pilot to commercial operation.

In Whitecycle, knowledge transfer between sorting technology developers, recycling engineers, and polymer scientists fosters operational improvements that enhance both quality and throughput. This creates a reinforcing feedback effect: higher rPET output → improved quality/learning → greater adoption by tire manufacturers → stronger demand signals → further capacity expansion. Such reinforcing loops are a key driver of system acceleration in many transitions (Sterman, 2000; Geels, 2011).

4.5.2 Investment Delays and Capacity Scaling

A common dynamic challenge in scaling circular technologies is the presence of investment and deployment delays. Advanced recycling facilities — particularly those integrating enzymatic processes and complex feedstock streams — require significant lead time for design, permitting, construction, and performance validation. As WhiteCycle partners have noted, these initial delays can postpone the emergence of cost and quality benefits even when the underlying technologies are mature at a laboratory level.

This delay is typical of industrial innovation diffusion: capital-intensive infrastructure moves more slowly than policy cycles or corporate commitments. System Dynamics literature emphasizes that such delays can lead to suboptimal early performance, backloading of benefits, and even misinterpretation of short-term results (Sterman, 2000). It also highlights the importance of policy continuity to bridge early performance gaps and unlock reinforcing dynamics later in the transition.

4.5.3 Trade-offs Between Quality, Energy, and Environmental Outcomes

A significant insight from dynamic simulation (and emerging industrial evidence) is that achieving high material quality, wide feedstock flexibility, and positive environmental performance simultaneously can create trade-offs that vary over time. Advanced recycling routes — including those prioritized in WhiteCycle — aim to handle *mixed and complex PET waste streams* that are not amenable to standard mechanical recycling. While this expands available feedstock and improves circularity, it often involves higher energy input during depolymerization, purification, and repolymerization stages.

Life-cycle analyses (LCAs) indicate that higher energy demand in advanced recycling does not necessarily negate environmental benefits but can change their magnitude depending on the energy mix and process efficiency. For instance, when renewable electricity is available, the net greenhouse gas savings from avoiding virgin polymer production often outweigh the additional recycling energy expenditure (Jeswani et al., 2021; Geyer et al., 2016). Dynamic models show that this trade-off evolves as energy systems decarbonize and as process efficiencies improve with scale.

WhiteCycle's strategic emphasis on advanced sorting and enzymatic depolymerization — which can operate at lower temperatures than conventional chemical recycling — may help mitigate energy-intensity trade-offs and amplify environmental benefits over time, especially in jurisdictions moving toward renewable energy grids

4.5.4 Competitive Feedback and Supply Chain Interactions

As rPET demand increases across sectors (e.g., packaging, textiles, automotive), competitive feedback effects can influence the availability and price of high-quality feedstock. Static models often assume that additional demand for rPET will be met by proportional increases in supply. In contrast, dynamic analysis shows that cross-sector competition for limited waste streams can raise prices, reduce quality sorting, and distort investment signals, unless coordinated governance mechanisms or industrial symbiosis arrangements are in place.

WhiteCycle's pan-sector approach — bringing together partners from tire OEMs, textile players, and waste managers — demonstrates how collaborative governance structures can reduce competition-driven volatility. Industrial ecology research indicates that symbiotic networks stabilize secondary material markets by aggregating demand, sharing logistics, and aligning incentives across sectors (Chertow, 2007; Domenech & Davies, 2011). In System Dynamics terms, this dampens oscillations between supply and demand and accelerates stable growth trajectories.

4.5.5 Emergence of Virtuous and Vicious Cycles

The dynamic interplay of reinforcing and balancing feedbacks can give rise to both virtuous cycles and vicious cycles in circular transitions:

- Virtuous cycles emerge when improvements in rPET quality, cost reductions from learning effects, and policy certainty interact to reinforce adoption. This is often supported by circular business models that lock in demand (e.g., long-term offtake agreements) and stabilize investment expectations.

- Vicious cycles occur when early underperformance, supply uncertainty, or fragmented governance leads to reduced investment, higher perceived risk, and delayed capacity growth — reinforcing barriers rather than breakthroughs.

WhiteCycle aims to create a virtuous cycle by integrating advanced technology, cross-sector collaboration, and co-funding across public and private partners. By addressing multiple feedback loops simultaneously — technological learning, market stabilization, and policy support — the project serves as a practical example of how dynamic system interactions can be shaped intentionally through strategic CBM design

4.6 Scaling and Policy Implications

The integration of rPET into tire reinforcement textiles highlights the importance of both technological and systemic enablers for circularity. Pilot projects and research initiatives, such as the WhiteCycle project funded by the EU Horizon 2020 program, have provided critical evidence that chemical recycling can reliably produce high-quality PET monomers suitable for performance-critical applications, including tire textiles (WhiteCycle, 2022). WhiteCycle has demonstrated scalable processes capable of handling mixed and colored PET streams while maintaining molecular weight and mechanical properties comparable to virgin polyester, thereby overcoming major barriers to rPET adoption in demanding industrial applications.

Policy frameworks play a pivotal role in accelerating these transitions. Mandatory recycled content targets, extended producer responsibility (EPR) schemes, and incentives for advanced recycling investments create a favorable environment for industrial symbiosis and long-term offtake agreements. European legislation, such as the EU Circular Economy Action Plan (2020) and the Single-Use Plastics Directive (2019), reinforces the market pull for secondary materials by increasing collection efficiency and stabilizing feedstock availability (European Commission, 2023; Ellen MacArthur Foundation, 2022).

Economic modeling from the SD simulations indicates that hybrid CBM scenarios, combining circular input contracts, resource recovery, and industrial symbiosis, are most resilient in maintaining rPET supply while achieving high penetration in tire reinforcement textiles. Sensitivity analyses show that delays in policy implementation or underinvestment in chemical recycling capacity can constrain substitution rates, highlighting the necessity of coordinated policy, industry collaboration, and public-private partnerships.

5. Conclusion

This study has explored the potential of recycled PET (rPET) as a sustainable feedstock for tire reinforcement textiles, emphasizing the integration of circular business models (CBMs) and advanced recycling technologies such as those demonstrated in the WhiteCycle project. The literature review and cross-sector benchmarking highlighted that hybrid CBMs—combining circular supply, resource recovery, and industrial symbiosis—are most effective in addressing feedstock security, quality requirements, and economic feasibility. The System Dynamics analysis provided dynamic insights into feedback loops, learning effects, and investment delays, showing that successful adoption of rPET depends on coordinated technology deployment, supportive policy frameworks, and long-term contracts.

The WhiteCycle case study demonstrated that chemical recycling of mixed PET streams can yield high-quality monomers suitable for high-performance textile applications, enabling substitution of virgin polyester without compromising tire performance. Environmental assessments indicate significant reductions in CO_2 emissions, energy consumption, and resource use compared to virgin polyester production, while economic analysis highlights the potential for cost reductions through scale and learning effects. Trade-offs between energy intensity, material quality, and feedstock variability underscore the importance of integrated CBM design and cross-sector collaboration.

Policy and strategic insights from this research include the need for mandatory recycled content targets, extended producer responsibility schemes, and incentives for advanced recycling infrastructure, all of which support market stability and accelerate adoption. Moreover, the study emphasizes that linking industrial pilot projects to SD models allows for predictive scenario analysis, enabling stakeholders to evaluate long-term implications of technological, economic, and policy interventions.

In conclusion, the integration of rPET into tire manufacturing represents a practical and scalable pathway toward circularity in the tire industry. Projects like WhiteCycle provide proof-of-concept and valuable operational data, while CBM strategies and systemic modeling offer the tools to optimize adoption, environmental benefits, and economic viability. Together, these insights support a roadmap for the tire sector to transition toward sustainable, circular production systems.

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Annex 1 : Design of the stock and flow diagram (SFD)

1. total PET consumption -->(+) PETwaste generation rate

Higher consumption leads directly to a higher rate of waste generation.

2. Accumulated PET Waste Available for Recycling -->(+) PET waste collection rate

A larger stock of available waste allows for a higher collection rate, assuming capacity is not the limiting factor.

3. policy effectiveness on collection -->(+) collection rate fraction

Effective policy instruments (DRS, EPR) increase the fraction of waste successfully collected.

4. policy support for rPET investment -->(+) policy effectiveness on collection

Increased government support translates into more effective implementation of collection policies.

5. pressure for policy intervention -->(+) policy support for rPET investment

High pressure due to poor collection performance or waste accumulation drives political action and support.

6. PET waste collection rate -->(-) pressure for policy intervention

A higher collection rate reduces the amount of uncollected waste, thereby decreasing the pressure for policy intervention.

7. PET waste generation rate -->(+) pressure for policy intervention

A higher generation rate, if not matched by collection, increases the pressure for policy intervention.

8. collection rate fraction -->(+) PET waste collection rate

A higher collection fraction directly increases the flow of collected waste.

9. PET waste collection rate -->(+) mechanical recycling throughput

The throughput is constrained by the available collected waste input.

10. PET waste collection rate -->(+) chemical recycling throughput

The throughput is constrained by the available collected waste input.

11. Installed Mechanical Recycling Capacity -->(+) mechanical recycling throughput

Higher installed capacity allows for higher processing throughput.

12. Installed Chemical Recycling Capacity -->(+) chemical recycling throughput

Higher installed capacity allows for higher processing throughput.

13. mechanical recycling throughput -->(+) rPET production mechanical

Higher throughput leads to higher rPET output.

14. chemical recycling throughput -->(+) rPET production chemical

Higher throughput leads to higher rPET output.

15. rPET production mechanical -->(+) total recycling output

Total output is the sum of mechanical and chemical production.

16. rPET production chemical -->(+) total recycling output

Total output is the sum of mechanical and chemical production.

17. total recycling output -->(+) rPET production tire grade

Higher total production increases the volume available for qualification as tire grade.

18. Available Tire Grade rPET Inventory -->(+) rPET supply to tire industry

Supply is constrained by the available inventory.

19. tire sector rPET demand -->(+) rPET supply to tire industry

Actual supply is driven by the demand from the tire sector.

20. rPET supply to tire industry -->(+) rPET adoption rate

The rate of adoption is equal to the rate of supply to the industry.

21. total tire production volume -->(+) virgin polyester demand for tires

Higher tire production requires more reinforcement material.

22. virgin polyester demand for tires -->(+) tire sector rPET demand

The potential market size for rPET is based on the total polyester demand.

23. rPET substitution rate fraction -->(+) tire sector rPET demand

A higher substitution rate increases the calculated demand for rPET.

24. adoption driver effect -->(+) rPET substitution rate fraction

Positive drivers (quality, cost performance) increase the achievable substitution rate.

25. perceived rPET quality for tires -->(+) adoption driver effect

Improved quality perception increases the willingness of manufacturers to substitute rPET.

26. long term contract adoption -->(+) perceived rPET quality for tires

Long-term contracts signal stable supply and quality assurance, improving perception.

27. rPET cost performance ratio -->(-) adoption driver effect

If rPET is expensive relative to virgin material, the adoption driver effect decreases, constraining substitution (Balancing Loop B1).

28. rPET price -->(+) rPET cost performance ratio

Higher rPET price increases the cost performance ratio relative to virgin material.

29. tire sector rPET demand -->(+) rPET price adjustment from demand supply

If demand is high relative to supply, the price adjustment factor increases.

30. rPET production tire grade -->(-) rPET price adjustment from demand supply

If supply is high relative to demand, the price adjustment factor decreases.

31. rPET price adjustment from demand supply -->(+) rPET price

The price multiplier directly determines the market price of rPET.

32. rPETprice -->(+) investment attractiveness mechanical

Higher rPET price increases the profit margin for recyclers, boosting investment attractiveness (Reinforcing Loop R1).

33. rPET price -->(+) investment attractiveness chemical

Higher rPET price increases the profit margin for recyclers, boosting investment attractiveness (Reinforcing Loop R1).

34. investment attractiveness mechanical -->(+) mechanical capacity expansion

High attractiveness drives investment and capacity expansion.

35. investment attractiveness chemical -->(+) chemical capacity expansion

High attractiveness drives investment and capacity expansion.

36. mechanical recycling cost -->(-) investment attractiveness mechanical

Higher costs reduce profitability and investment attractiveness.

37. chemical recycling cost -->(-) investment attractiveness chemical

Higher costs reduce profitability and investment attractiveness.

38. Cumulative Recycled Volume -->(-) learning curve factor mechanical

Increased cumulative volume leads to technological learning and a reduction in the cost factor (Reinforcing Loop R2).

39. Cumulative Recycled Volume -->(-) learning curve factor chemical

Increased cumulative volume leads to technological learning and a reduction in the cost factor (Reinforcing Loop R2).

40. learning curve factor mechanical -->(+) mechanical recycling cost

The cost is proportional to the learning curve factor (a lower factor means lower cost).

41. learning curve factor chemical -->(+) chemical recycling cost

The cost is proportional to the learning curve factor (a lower factor means lower cost).

42. rPET price -->(+) price premium tire vs other sectors

The price premium is calculated based on the rPET market price.

43. price premium tire vs other sectors -->(+) rPET diversion fraction

If the price premium is low, more rPET is diverted to other sectors where quality requirements might be lower.

44. rPET diversion fraction -->(-) rPET production tire grade

Increased diversion to other sectors reduces the volume available for the tire grade inventory.

45. rET production mechanical -->(+) co2 emission rate

Higher production volume leads to higher total emissions.

46. rPET production chemical -->(+) co2 emission rate

Higher production volume leads to higher total emissions.

47. rPET production mechanical -->(+) energy consumption rate

Higher production volume leads to higher total energy consumption.

48. rPET production chemical -->(+) energy consumption rate

Higher production volume leads to higher total energy consumption.

49. industrial symbiosis maturity -->(-) co2 intensity mechanical

Increased industrial symbiosis leads to efficiency gains and reduced CO_2 intensity.

50. industrial symbiosis maturity -->(-) energy intensity mechanical

Increased industrial symbiosis leads to efficiency gains and reduced energy intensity.