A DATA-DRIVEN ROADMAP FOR COST-EFFECTIVE REDUCTIONS IN EMISSIONS, WASTE, AND RESOURCE USE IN PLASTICS: A CASE STUDY OF THE PACKAGING ECONOMY

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Abstract:

Plastic production and consumption have risen sharply, with packaging emerging as one of the most rapidly growing sectors. While plastics provide numerous societal benefits, their widespread adoption has resulted in substantial resource use, waste generation, threatening biodiversity and human health. We dynamically model the plastic packaging economy and evaluate a portfolio of cost-effective technologies to reduce emissions and waste. The analysis considers a broad range of solutions, from optical and AI-assisted sorting to multiple end-of-life pathways, including mechanical recycling (high TRL), chemical recycling (mid-TRL), and solvent-based processes (low TRL). A key novelty of this study is the explicit inclusion of macro- and microplastic pollution in the packaging sector and the evaluation of technologies to mitigate these impacts. Results highlight that no single technology is sufficient; rather, a coordinated portfolio of complementary solutions is required to enable a sustainable packaging economy. Integrating circularity with renewable feedstocks, renewable energy, and advanced mitigation technologies is shown to substantially reduce emissions and costs, offering a viable pathway toward a win–win outcome for industry and the environment. In addition, we introduce a multi-objective optimization framework built on freely available data, for modeling the packaging economy. The framework is designed to interoperate with open-source integrated assessment models (IAMs), which are large-scale models that link energy, economic, land-use, and climate systems, to make it possible to evaluate how plastics system transitions interact with broader national and global developments. This integration allows the assessment of the impacts of changing economic policies, energy pathways, and climate conditions on plastics management strategies. A global plastic packaging model to explore potential pathways for achieving net-zero greenhouse gas emissions and minimizing waste generation under different IAM scenarios is developed. By framing the analysis around the “triple planetary crisis” — climate change, human health impacts, and biodiversity loss, the study identifies system-level interventions and technology roadmaps required to transition the packaging industry toward sustainability. For human health impacts, the analysis emphasizes the consequences of open burning of plastics at the end of life, which is prevalent in regions with inadequate waste management infrastructure. For biodiversity loss, the focus is on marine ecosystems, as the majority of mismanaged plastic packaging ultimately leaks into the ocean, where it threatens marine life through entanglement, suffocation, ingestion, and the toxicity of microplastics formed from the degradation of larger debris. By integrating environmental and techno-economic perspectives, this work quantifies trade-offs between economic feasibility and environmental performance, ultimately proposing a dynamic and cost-effective technological roadmap for achieving global net-zero and zero-waste targets in the plastic packaging sector.

1. Introduction and Motivation

Plastic packaging constitutes the largest share of both production and waste generation, accounting for approximately 40% of total plastic production and nearly 50% of plastic waste[1]. Due to its predominantly single-use design and short service life, packaging is typically discarded shortly after use, leading to widespread littering and mismanaged waste, particularly in regions with insufficient waste management infrastructure. A portion of this mismanaged waste escapes formal collection and end-of-life systems, leaking into terrestrial and marine environments where it contributes to biodiversity loss and the accumulation of microplastics that infiltrate food webs and pose risks to ecosystem and human health. In addition, a large portion of plastic waste is openly burned, releasing toxic pollutants and persistent compounds that exacerbate air pollution and threaten public health[2]. We aim to address the triple planetary crisis[3] driven by the global plastic economy by developing a technological roadmap

that facilitates the transition of the packaging industry toward sustainability. Such a roadmap should integrate environmental, economic, and technological considerations to identify pathways that minimize waste generation by implementing Re-X design (incorporating recycling and closed-loop strategies), reduce greenhouse gas (GHG) emissions, and mitigate ecosystem degradation. Developing such a technological roadmap also necessitates differentiating among various types of packaging, as end-of-life processing options are highly dependent on the physical and chemical characteristics of the materials[4]. A dynamic, data-driven roadmap must couple the packaging sector with broader economic, climatic, and societal systems, recognizing that external dynamics shape technology performance and adoption over time. For example, projections of packaging demand are governed by socio-economic drivers such as population and consumption growth[1]. Life-cycle climate impacts depend on emissions trajectories and radiative forcing assumptions, which are typically explored through scenario families provided by Integrated Assessment Models (IAMs). Likewise, the electricity grid's evolution, under differing mitigation pathways, alters both the carbon intensity and cost of energy used across the packaging supply chain[5]. By linking technology portfolios to these time-varying conditions, the framework identifies cost-effective, low-emission investment pathways and the optimal timing of deployment, enabling decision-makers to sequence interventions as system conditions evolve. This work develops a global plastic packaging model to explore potential pathways for achieving net-zero GHG emissions and minimizing waste generation under different IAM scenarios[5]. By framing the analysis around the triple planetary crisis, the study identifies system-level interventions and technology roadmaps required to transition the packaging industry toward sustainability. For human health impacts, the analysis emphasizes the consequences of open burning of plastics at the end of life. For biodiversity loss, the focus is on marine ecosystems, as the majority of mismanaged plastic packaging ultimately leaks into the ocean, where it threatens marine life through entanglement, suffocation, ingestion, and the toxicity of microplastics formed from the degradation of larger debris. By integrating environmental and techno-economic perspectives, this work quantifies trade-offs between economic feasibility and environmental performance, ultimately proposing a dynamic and cost-effective technological roadmap for achieving global net-zero and zero-waste targets in the plastic packaging sector.

2. Review of Related Work

2.1. Roadmap studies on plastics

Stegmann et al.[6] developed a multinomial logit model that generated cost-effective recycling for reducing CO_2 emissions in the global plastics sector through 2100. Meys et al.[7] developed a bottom-up optimization framework to dynamically model approximately 90% of global plastic production and waste flows. Their optimal transition roadmap integrates large-scale recycling with chemical utilization of CO_2 captured from plastic incineration. However, these studies make broad recycling assumptions that ignore differences among plastics and practical limits such as poor recyclability, contamination, and sorting challenges. They also assume abundant landfill capacity, overlooking regions where open burning or dumping dominate. Moreover, they focus only on climate impacts, neglecting biodiversity and human health effects, which risks shifting burdens across impact categories. In a more recent study, Huo et al.[3] sought to address previous gaps by developing a life-cycle optimization framework aimed at circularizing the plastic economy and reducing its life-cycle impacts across all three dimensions of the planetary crisis. However, it focuses primarily on recycling and biodegradable plastics without differentiating between packaging types or tailoring solutions to their specific material and structural characteristics. Moreover, the study does not explicitly account for the generation and fate of macro- and micro-plastics, acknowledging this omission as a limitation. Efforts to prioritize life cycle solutions based on the functional category of packaging, rather than solely on the material from which it is made, have been discussed in the Ellen MacArthur Foundation's report[4]. The report highlights that different groups of packaging products face distinct challenges in achieving circularity, emphasizing the need for function-specific strategies. It notes that only about 50% of current packaging formats are recyclable in their present form, while the remainder must either transition toward reusable systems or undergo redesign to eliminate problematic elements such as multi-material compositions and small-format plastics that hinder effective collection, sorting, and recycling. However, the report does not present a data-driven or quantitative roadmap outlining the transition toward a sustainable and circular packaging economy. Instead, it primarily focuses on articulating the scope of the problem and identifying potential solution pathways in a qualitative manner.

2.2. Plastic and environment

Regarding the impact of plastic on biodiversity, the works by Jambeck et al.[8] and Lebreton et al. [9] first contributed to quantifying macroplastic (large plastic debris pieces typically greater than 5 millimeters in size) pollution at the global scale from both rivers and direct ocean transfers. The environmental threat of macroplastic pollution is known[10–12], but its study from a life cycle perspective is at its infancy, with some proposal for a dedicated "plastic pollution" impact category[13]. Furthermore, for marine plastic pollution, a focus was put on fishing gear[14]. In general,

due to the complexity of the behavior of macroplastic applicable to packaging, enhanced by their persistence in the environment, from a life cycle perspective, fate, exposure, effect, and severity factors are required to obtain characterization factors to assess the impact on biodiversity. Current studies are limited to the superficial microplastic debris in marine environments quantifying the exposure factor, with more studies necessary to fully map and estimate the total impacts on marine ecosystems through the different mechanisms (e.g., physical, chemical, and biological) [15] while most studies focus on the physical effect only (e.g., entangling and ingestion). Beside macroplastic, the detrimental effects of microplastic on ecosystem and human health is well-known [16] and can follow the same mechanisms. Still, the focus is placed on the physical mechanisms of impact. For this, several works modeled the fate, effect, exposure, and severity factors to obtain characterization factors that fully capture the microplastic behavior in marine ecosystems and their impact on biodiversity [17–19].

3. Technology Approach

3.1. System boundary and superstructure network

We defined the system boundary to include six predominant polymers commonly used in plastic packaging applications, which are high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS) and Polyvinyl chloride (PVC). Packaging categories were organized across three key dimensions, namely physical form, size class, and material composition [2,4,20,21](Figure 1). To develop a technological roadmap, it is first necessary to identify the processes and technologies with the potential to reduce emissions and waste. To support this effort, we constructed a superstructure network representing the cradle-to-grave supply chain for plastic packaging, incorporating alternative technologies at each stage of the life cycle. This superstructure network is illustrated in Figure 2. A wide range of processes is available for producing chemicals and monomers, managing end-of-life treatments, addressing microplastic pollution, supplying grid electricity, and implementing carbon capture and sequestration (CCS). Production of chemicals can either rely on conventional fossil-based routes, such as generating monomers through steam cracking[1], or bio-based routes, in which monomers are derived from biomass resources that undergo fermentation to produce intermediates, which can then be further processed into a variety of monomers[22–24]. At the end of life, littering behavior by consumers is modeled following the Pew Commons report[2], and no decision variable is assigned to this component. For the portion of waste that is not littered and is instead placed in either a trash bin or a recycling bin, we assume a single-stream recyclate and a general trash stream, known as dual system[25]. The proportion of waste entering each stream depends on the sorting facility and technologies[25]. After sorting, the waste is transferred to a reclaiming facility, where plastic bales are opened, washed, and processed to produce flakes[26]. These flakes can then be directed to various end-of-life processing pathways for Re-X supply chain design, depending on the packaging type and the purity of the recovered material stream[25]. The waste directed to the trash bin, along with residual waste generated during end-of-life processing, is sent to an ultimate disposal stage, where it is either landfilled, incinerated, or openly burned[2]. We apply global average distributions for these disposal pathways and do not assign any decision variable to this component. This constraint reflects our aim to evaluate whether a technological roadmap alone can achieve meaningful reductions in emissions and waste without relying heavily on large-scale infrastructural changes. Additional technological alternatives include the treatment of wastewater generated during the reclaiming process to remove microplastics formed during size reduction[27]. Electricity supply is also represented through multiple options, including clean electricity from renewable and non-renewable sources[28]. Carbon capture options target emissions from the steam cracking process, the incineration of plastic waste, and fermentation-based production pathways. For steam cracking and incineration, we assume the use of an amine-based absorption system for CO_2 capture and purification[29]. For fermentation, only CO_2 liquefaction is considered, given the inherently high purity of biogenic CO_2 streams[30]. All captured CO_2 is assumed to be sequestered. For the fraction of plastic waste that leaves the system boundary of the packaging economy and leaks into the environment, we estimate the portion that ultimately reaches the marine environment, as a substantial share of mismanaged plastic waste is known to enter the oceans over time[2,31]. All technological alternatives, together with the full superstructure network, are represented within an integrated optimization model. For the cost objective, we focus exclusively on total variable costs and do not yet account for capital expenditures or research and development costs associated with technology deployment. Although these components will be incorporated in future work, the current variable-cost formulation still offers meaningful insights into the long-term potential of emerging technological alternatives that is subsequently

evaluated using a multi-objective optimization framework for life cycle optimization.

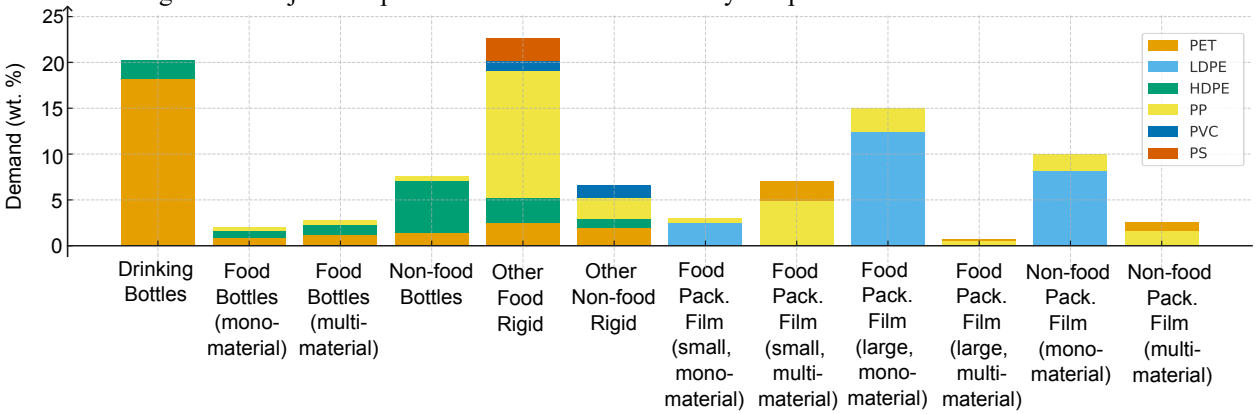

Figure 1-Demand distribution across major packaging types and their associated polymer compositions[21]. Demand in 2025 is estimated at 172 million metric tonnes (MMT). 10% of all packaging falls into the small-format category[4], of which multi-material flexible packaging accounts for 7%[20]. Overall, multi-material plastics constitute 13% of total packaging demand, with flexible packaging representing 10 percent of this share[4].

As technologies mature through sustained R&D efforts and economies of scale, their capital requirements are expected to decline and converge toward those of conventional systems, making a variable-cost comparison a useful indicator of their prospective competitiveness[7]. We considered three scenarios associated with different levels of collection and sorting infrastructure. In the first scenario, we assume that no recyclate collection or sorting system is available, resulting in all waste being directed immediately to the ultimate end-of-life pathways. All other technological alternatives remain accessible in this scenario. This configuration is intended to evaluate the extent to which non-circular technological pathways alone can contribute to achieving net-zero outcomes. We refer to this scenario as the "Non-circular Path". The second scenario assumes large-scale adoption of a conventional collection and sorting system that targets PET and HDPE bottles, assuming a recyclate collection rate of 90% for these items, and a sorting efficiency reported by Roosen et al. [25]. All other packaging materials are treated as non-recyclable in this scenario. The purpose of this case is to assess whether scaling up existing material recovery facility operations, which rely primarily on mechanical and manual sorting[32], along with conventional optical sorters for rigid PET and HDPE packaging[33], combined with the other technological alternatives in the superstructure, is sufficient to meet environmental and cost objectives. We refer to this scenario as the "Moderate Circular Path." The third scenario assumes that all packaging types are collected, with a recyclate collection rate of 90%, and sorted with efficiencies derived from Roosen et al.[25]. The sorting stage is performed by a high-technology facility capable of separating not only PET and HDPE bottles but also a broad range of additional packaging formats. Technologies required in such facilities include vacuum-based systems for sorting flexible packaging[33], cyclone systems for separating small-format plastics[33], and advanced optical sorters capable of distinguishing both mono-material plastics[33] and multi-material structures[34]. The aim of this scenario is to evaluate the potential benefits and implications of scaling up circularity through expanded sorting capabilities and advanced end-of-life processing technologies. We refer to this scenario as the "Highly Circular Path."

We first conduct a static optimization to assess the potential of the technological alternatives in achieving net-zero emissions and waste across all three scenarios. We then extend the analysis to a dynamic framework to examine how emissions and waste trajectories evolve over time along the optimal pathway. This dynamic assessment incorporates projected growth in packaging demand as well as temporal changes in the electricity grid mix. Packaging demand growth is modeled using an integrated assessment model for plastics[1]. Changes in the electricity grid are derived from the IMAGE 3.0 model, from which we extract time-dependent electricity-mix data under different Shared Socioeconomic Pathways (SSPs). In this study, we focus on two baseline scenarios: SSP1-baseline, which reflects a sustainability-oriented world with lower resource intensity and relatively rapid adoption of clean electricity, and SSP2-baseline, which represents a "middle-of-the-road" trajectory with moderate socio-economic development and a delayed and uneven transition to clean electricity[5]. Future work will incorporate additional dynamic components, including temporal changes in biomass availability and composition, technological learning and cost evolution, and potential shifts in waste-management practices over time.

3.2. Assessing the impact of macro and microplastic on marine biodiversity

The macroplastic waste that eventually reaches seawater is subjected to different processes (e.g., mechanical, physical, chemical, and biological) that can determine its behavior. In turn, the macroplastic waste can itself exert

impact on marine biodiversity via physical (e.g., entanglement and ingestion), chemical (e.g., release of substances such as additives or absorption/adsorption to the macroplastics themselves), or biological (e.g., being a vector of potential biological pathogens) pathways.

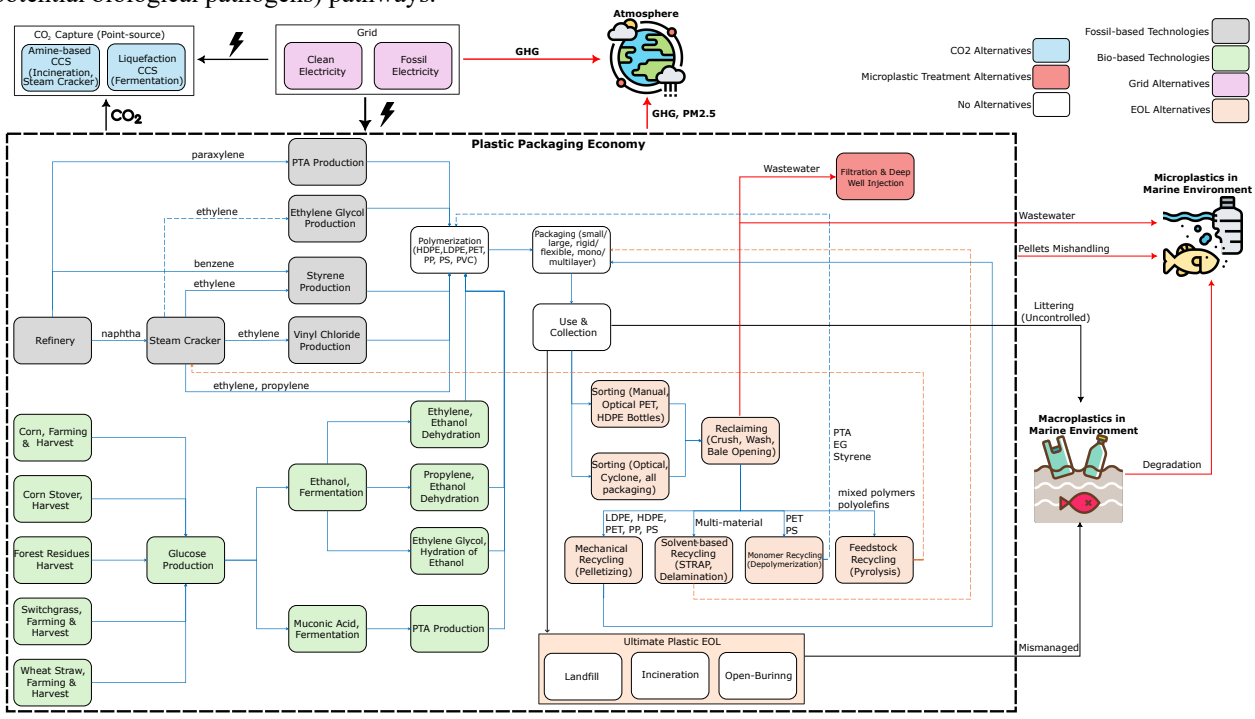

Figure 2 – Cradle-to-grave system boundary and superstructure network of technologies

Due to the lack of data, this work focuses on the physical effects only. In particular, the only available model to assess the impact of macroplastic on marine biodiversity focuses on the buoyant fraction. Therefore, modeling transport means modeling the buoyancy dynamics of macroplastics. The buoyancy rates were derived from Fazey and Ryan[35] and converted into days/year. Specific rates were available for HDPE and LDPE while for the multilayer packaging the rate was calculated as the average of these rates. Finally, for the polymers with missing data a rate 1 day/year was assumed as rate due to the higher chance of sinking linked to the polymer density being higher than water. The effect factor for the buoyant macroplastic is derived from the loglogistic Species Sensitivity Distribution (SSD) curve's parameters reported by Høiberg et al. [17]. The global average macroplastic surface density derived from Eriksen et al. [36], and the ocean surface commonly utilized ($3.61*10^8$ km^2). The incremental slope (in terms of additional % of PAF) per kg of macroplastic added with respect to the baseline, i.e., the quantity of macroplastic already present on the ocean surface, is obtained in this way. As the curve is based on the HC50, the severity factor to move from PAF to PDF, i.e., from midpoint to endpoint, is assumed to be 0.5 as in other studies [18]. Contrary to macroplastics, CF for microplastic impact and damage to marine biodiversity are readily available from Saadi et al. [37]. These are polymer specific.

The particles are assumed to be spherical and of 5 mm dimensions for expanded PS and film-shaped for all other polymers. They are provided in terms of species*yr, and are compatible with ReCiPe damage category[38]. For other polymers and for multi-material packaging waste the average of the available ones was utilized. Microplastic enter the seawater through different streams. The major stream is the gradual degradation of macroplastic over time. This degradation follows a first order decay process. The related degradation factors were retrieved from Schwartz et al.[39]. As they are specific only for PP, LDPE, and PET, for HDPE the LDPE one was utilized, while for the remaining polymers (and multi-materials) an average was assumed. Other sources are plastic pellet manufacturing, plastic shredding during downcycling operations, and wastewaters, either treated or untreated. We excluded microplastics from landfill leachate and incineration ash due to lack of data, and considered their amounts to be negligible compared to other sources of microplastics. The rate of microplastic generation from pellet production is taken from Eunomia[40]. The microplastic is assumed to be transferred in wastewater during washing operations in the facilities. The rates are not polymer-specific. A similar pathway is assumed for the microplastic generated within plastic packaging recycling facilities during shredding operations. The generation rates in this case are taken from Suzuki et al.[41] and they are

specific for PP, PP/PE, LDPE, HDPE, PET, PS (general purpose and high impact), PVC (soft and rigid). The current global wastewater treatment plants' efficiency in filtering out microplastic was estimated about 6% using the data from Uddin et al.[42]

3.3. Tracing plastic accumulation and long-term fate

Microplastic in seawater undergo a mineralization process during which from a polymer they get degraded into simple hydrocarbons such as methane and ethylene, thus changing their essence. The fragmentation rates are available from Schwartz et al.[39] for PP, LDPE, and PET. For HDPE the LDPE one was utilized, while for the remaining polymers (and multi-materials) an average was assumed. As macroplastic fragmentation into microplastic takes time, a dynamic assessment must account for the inflow of macroplastic into seawater. Part of this flow will become a stock of macroplastic which will start fragmenting into microplastic, generating a microplastic inflow (corresponding to a macroplastic outflow). Part of this microplastic inflow will become a stock of microplastic, which will undergo mineralization, generating an ultimate microplastic outflow. To account for all these dynamics and capture both stocks and flows at every year, the following equations were used:

$$MAP_{n+1} = MAP_n\, e^{-k} + A_{n+1}$$

Where MAP indicates the stock of macroplastic, n indicates the time (year), k is the fragmentation rate [y^{-1}], A is the inflow of macroplastic at time n (year). The fragmentation follows a first order decay dynamic.

$$F_n = MAP_n\,(1 - e^{-k})$$

Where F is the flow of microplastics that is generated at time n, inflow to the microplastics stock.

$$G_n = MiP_n\,(1 - e^{-l})$$

Where G is the flow of microplastics mineralized at time n, outflow from the microplastics stock, and l indicates the mineralization rate [y^{-1}].

$$MiP_{n+1} = MiP_n\, e^{-l} + F_n$$

where MiP indicates the stock of microplastics at time n. The mineralization follows a first order decay dynamic.

3.4. Assessing the impact of open burning on human health

Open combustion of plastic packaging generates particulate matter (PM) that is harmful for human health. The emission factors for PM from plastic combustion were retrieved from Wang et al.[43]. Since ReCiPe accounts for $PM_{2.5}$, the emission factor for $PM_{2.5}$ only was calculated assuming that 47% of the total PM is $PM_{2.5}$[43]. The emission factors are polymer-specific for LDPE, HDPE, PVC, PS, PET, and PP.

3.5. Multi-objective optimization

We employ a life cycle optimization framework to identify optimal technologies across the product life cycle. The model includes an economic objective and an environmental objective, where the latter may represent GWP, marine biodiversity loss, or human health impacts. The economic objective minimizes the total variable operating cost of the foreground system (Figure 2). The optimization is formulated as a cost minimization problem subject to environmental and system constraints. An epsilon-constraint formulation is used to limit total environmental impact to a specified threshold. Mass and energy balances are enforced through the technosphere matrix A, ensuring that process scaling factors satisfy the final demand vector f, while all scaling variables are constrained to be non-negative.

$$Min \sum_{j}^{J} \sum_{i}^{I} |a_{i,j}|.|s_j|.p_i \qquad Eq.1$$

$$s.t. \quad C_v B\, s \leq \varepsilon \qquad Eq.2$$

$$As = f \qquad Eq.3$$

$$s_k \geq 0 \qquad Eq.4$$

In this formulation, $a_{i,j}$ are the elements of the technosphere matrix, s_j are process scaling factors, p_i is the price of flows entering processes j, B is the environmental intervention matrix, and C_v is the characterization factors vector for impact v. Equation (1) defines the cost objective, Equation (2) the environmental constraint, Equation (3) the balance equations, and Equation (4) the non-negativity conditions. The data populating the technosphere matrix and intervention matrix are primarily sourced from the 2025 USLCI database[44], supplemented with values from the literature when processes or flows are not available in the database. The final demand vector is derived from global plastics production data[45], while process prices are compiled from published literature sources.

4. Discussion

The results of the static optimization are summarized in Figure 3. The right-hand panel presents a Pareto front representing the trade-off between two objectives: global warming potential (GWP), expressed in kilograms of CO_2-equivalent, and total variable operating cost. The Base Case (baseline) serves as the reference point, corresponding to a linear, fossil-based economy without recycling or emission-reduction technologies. The shaded "win–win" region identifies solutions that simultaneously achieve lower costs and lower GWP relative to the Base Case, demonstrating that environmental and economic gains can be realized simultaneously. In the Non-circular Path, clean electricity offers both emission and cost reductions, reducing GWP by 21% and cost by 7%. This is because clean electricity has become cheaper than fossil-electricity. However, in this study we haven't considered the intermittency and availability of clean electricity for the packaging economy, leaving those for future work. Nevertheless, switching to clean electricity offers win-win solution for the packaging industry to reduce their cost and emissions. The Moderate Circular Path yields a larger set of solutions within the win–win region, indicating that meaningful reductions in both cost and emissions can be achieved when conventional circularity measures are scaled. In these solutions, mechanical recycling, low-technology sorting, and clean electricity emerge as cost-effective strategies. Their selection reflects the reduced reliance on virgin materials and the associated decrease in upstream environmental burdens. This pathway is primarily driven by the collection, sorting, and mechanical recycling of PET and HDPE bottles, which together form the most mature and economically favorable recycling stream. Under this configuration, the system achieves a 36% reduction in GWP and a 22% reduction in total variable operating cost relative to the Base Case. In the Highly Circular Path scenario, all Pareto-optimal solutions fall entirely within the win–win region, underscoring the transformative potential of emerging technologies and advanced circular technologies in simultaneously lowering emissions and reducing long-term operating costs. In this scenario, all packaging types are collected, sorted via high-tech sorting, and directed to appropriate end-of-life processing pathways. Mechanical recycling is predominantly selected for rigid, mono-material plastic packaging, reflecting its maturity and cost-effectiveness for high-quality, homogeneous waste streams. Solvent-based recycling, specifically Solvent-Targeted Recovery and Precipitation (STRAP), is selected for multi-material plastics, enabling the recovery of near-virgin-quality polymer pellets. Pyrolysis is chosen for the remaining fraction of plastics that are unsuitable for mechanical or solvent-based recycling due to contamination or poor material quality since it can accommodate higher impurity levels. In our framework, the pyrolysis gas is utilized on-site to supply process heat for the reactor, while the resulting pyrolysis oil is returned to the steam cracker as a naphtha-quality hydrocarbon feedstock. Additional technologies selected within the Highly Circular Path include bio-based chemical production routes, which offer notable reductions in GWP due to the biogenic carbon uptake that occurs during biomass growth. Clean electricity also emerges as a preferred option, reflecting its role in lowering upstream emissions across the system. Furthermore, CCS is selected for CO_2 emissions from both waste incineration and fermentation processes, providing an additional layer of mitigation by preventing these point-source emissions from entering the atmosphere. In this scenario, GWP is reduced by 63% and total variable operating cost by 14%. In addition, impacts on marine biodiversity decline by 29%, and human health impacts decrease by 75%. These improvements are largely driven by the substantial reduction in mismanaged waste resulting from the widespread adoption of circular end-of-life pathways. By recovering materials through advanced sorting and recycling technologies, as well as microplastic filtration at recycling facility, the system prevents plastics from leaking into the environment or being openly burned, thereby closing the loop and mitigating the primary sources of marine biodiversity loss and pollution-related human health burdens. We refer to this solution as the Best Case.

In the dynamic analysis, we examine the temporal evolution of both the Base Case and the Best Case pathways to assess whether the packaging sector can achieve a net-zero-carbon and zero-waste-to-ocean future before the end of the century. By projecting emissions and waste flows through 2100 under changing demand and electricity-mix conditions, this analysis evaluates the long-term feasibility of the industry's transition. The results for CO_2 emissions over time are presented in Figure 4. Panel A illustrates the trajectories under SSP1, which reflects a rapid transition toward clean electricity. Under this scenario, the Best Case pathway achieves net-zero carbon emissions before 2100, whereas the Base Case pathway does not, highlighting the critical role of advanced technological adoption in conjunction with a decarbonized grid. Panel B shows the outcomes under SSP2, a scenario characterized by a slower and uneven transition to clean electricity. In this case, neither the Base Case nor the Best Case pathway reaches net-zero emissions; in fact, emissions continue to rise over time even for the Best Case. This occurs because many of the low-emission technologies deployed in the Best Case are electricity-intensive, and their environmental performance depends heavily on the carbon intensity of the grid. Overall, these results indicate that a transition to clean electricity is essential but not sufficient for achieving net-zero emissions in the packaging sector. Only when grid

decarbonization is paired with the deployment of low-emission and circular technologies can a net-zero packaging economy become achievable within this century.

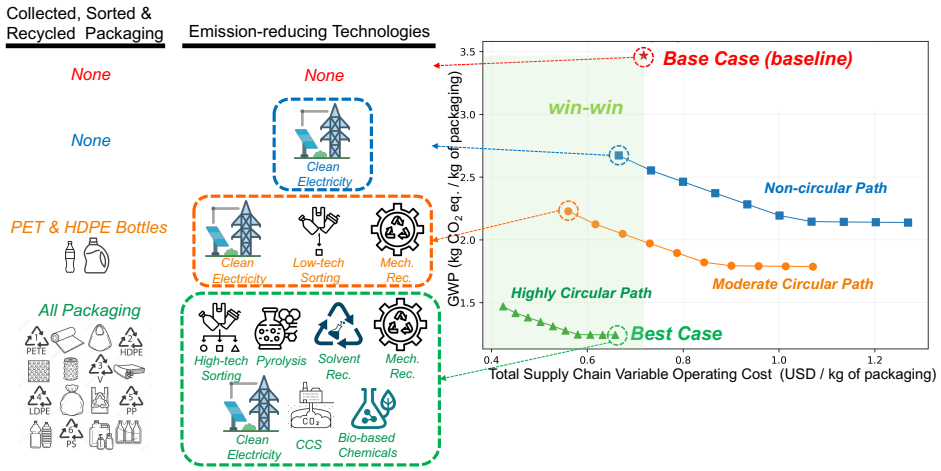

Figure 3 - Static multi-objective optimization, with pareto front on the right-hand-side panel.

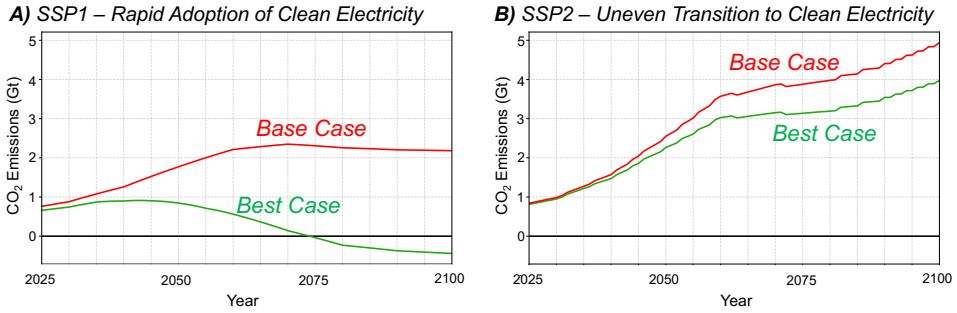

Figure 4 - Dynamic analysis for CO_2 emissions over time across SSP1 and SSP2.

The results for plastic pollution over time are presented in Figure 5, where Panel A depicts the accumulation of macroplastic in the ocean and Panel B shows the corresponding accumulation of microplastic. In both cases, even under the Best Case scenario, which includes comprehensive material circularity and microplastic filtration, substantial quantities of plastic continue to enter the marine environment. This outcome is primarily driven by consumer littering, which remains outside the direct control of businesses and is not mitigated by technological advances alone. In essence, once plastics are produced and introduced into the economy, a certain level of environmental leakage becomes inevitable, even under highly advanced circularity systems.
For macroplastics, the Best Case scenario achieves a 29% reduction relative to the Base Case by 2100. However, macroplastic stocks still increase by approximately 900% compared to present-day levels, largely due to escalating demand for packaging and persistent littering behavior. Microplastic stocks grows exponentially over time because of the degradation of macroplastics in the marine environment. Although the Best Case scenario moderates this growth, the overall trend remains the same. These findings highlight a critical insight: technological solutions can reduce but cannot eliminate plastic pollution without complementary societal, behavioral, policy, or product design interventions. Such interventions, including using biodegradable plastics, material substitution strategies (for example, replacing plastics with paper where feasible), and expanded reuse systems for bottles and other packaging, will be examined in future work.

5. Conclusions and Recommendations

To conclude, this study presents a cost-effective, data-driven technological roadmap for transforming the global plastic packaging sector in support of mitigating the triple planetary crisis, namely climate change, marine biodiversity loss from macro- and microplastic pollution, and human health impacts arising from open burning at

end of life. Under the highly advanced technological pathway, GHG emissions are reduced by 63%, and total variable operating costs decline by 14%. Impacts on marine biodiversity decrease by 29%, and human health impact

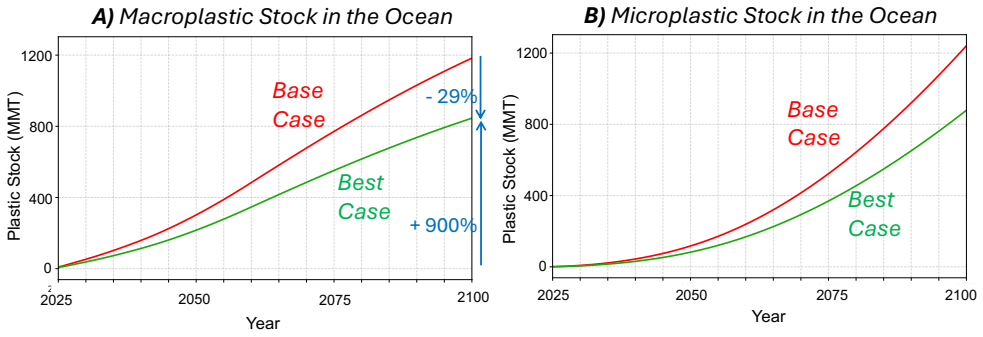

Figure 5 - Dynamic analysis of plastic pollution and its stock in the ocean in the form of macro and microplastic

drops by 75%. These gains are achieved through the combined deployment of clean electricity, carbon capture and sequestration, bio-based chemical production routes, and advanced sorting and recycling systems capable of achieving high recovery rates across all packaging types.

By integrating integrated assessment models with the plastic packaging superstructure, we developed a dynamic modeling framework that captures how the system evolves over time. This approach enables us to evaluate the effects of projected growth in packaging demand and long-term changes in the electricity grid under different future scenarios. A net-zero carbon packaging economy is attainable by approximately 2075 under favorable grid decarbonization conditions. However, even under the best pathway, plastic stocks in the ocean continue to rise. While macroplastic levels decline by 29% relative to the 2100 base case, they still increase by roughly 900% compared to present-day levels due to growing demand and persistent littering. This divergence reveals a critical mismatch: the pathway to net-zero carbon does not inherently align with a pathway to zero plastic leakage. Addressing this gap will require complementing technological solutions with alternative material and system strategies. Future work will therefore explore interventions such as biodegradable plastics, expanded Re-X strategies and reuse systems (e.g., bottle return programs), and material substitution with glass, aluminum, or paper where appropriate, with the aim of developing a unified roadmap capable of achieving both net-zero carbon and zero-waste-to-ocean goals.

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