TranZero: A Tool for Guiding the Transition to Resource Efficiency and Net-Zero Emissions

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Abstract:

In alignment with the Paris Agreement, nations have committed to limiting global temperature rise to below 1.5°C by reducing greenhouse gas emissions. The private sector plays a critical role in curbing Scope 1, 2, and 3 emissions, yet many companies have struggled to achieve their targets. We sought to address some of the challenges the private sector faces by developing a tool for guiding the **Tran**sition to resource efficiency and net-**Zero** emissions (*TranZero*). This tool is a user-friendly software designed to streamline decision-making and provide actionable pathways toward sustainability. The goal is to reduce stakeholders' hesitancy to act on sustainability initiatives caused by a lack of clarity and understanding of viable pathways.

A significant barrier to carbon neutrality is the high cost of alternatives. Carbon footprint assessments often fail to consider economic implications, making it difficult for companies to balance cost and emissions reduction. Furthermore, current pathways to carbon neutrality are typically siloed, neglecting other environmental goals such

as waste reduction, circularity, and water conservation. This fragmented approach risks burden-shifting, where improvements in one area exacerbate impacts in another.

The complexity of these multi-objective challenges further complicates decision-making. Effective data visualization is essential but often inadequate. *TranZero* addresses these issues with an intuitive interface and advanced visualization capabilities, enabling decision-makers to navigate trade-offs clearly and confidently. By integrating techno-economic analysis, life cycle assessment, and multi-objective optimization, the tool identifies optimal solutions for achieving net-zero and circularity goals simultaneously.

One version of *TranZero* focuses on achieving a sustainable circular economy for multi-layer plastic barrier films. This version enables our industrial partner, Kohler, and other barrier film producers/consumers to identify the best technologies for achieving circularity and reducing emissions in a cost-effective manner. The tool evaluates and selects among reuse, recycling, and downcycling technologies to optimize end of life treatment for these films. The analysis identified the Solvent Targeted Recovery and Precipitation (STRAP) process as the most effective end of life technology in minimizing global warming potential. Notably, this process achieves its environmental benefits without significantly increasing costs. Furthermore, it demonstrates a high degree of material circularity, further enhancing its sustainability profile. By considering both environmental impacts and economic feasibility, *TranZero* helps companies to achieve circularity without compromising on emissions targets or financial goals.

Additionally, *TranZero* is being developed for a wide range of products and industries, including carbon fiber, polyesters, and the global chemicals and materials industry. Its generic and modularized design ensures adaptability for any product, company, or sector, making it a versatile tool for driving progress toward net-zero emissions in a cost-effective manner.

1. Introduction and Motivation

To mitigate the devastating consequences of climate change, achieving climate neutrality has become a central priority for stakeholders at all levels of decision-making. The private sector plays a pivotal role in our capitalist society and is accountable for a significant share of global greenhouse gas (GHG) emissions [1]. As a result, there is a growing emphasis among major corporations on addressing climate change, particularly through science-based strategies and systems thinking approaches. Net-zero commitments saw the most significant growth, rising sharply from 5% in 2019 to nearly 50% by 2024, reflecting the prioritization of long-term decarbonization strategies [2]. Despite the growing number of corporate pledges for carbon neutrality, a report by the New Climate Institute reveals that many companies fall short of genuinely committing to their climate goals. The study highlights discrepancies between public declarations and actionable strategies, with many firms relying heavily on offsetting emissions rather than implementing meaningful reductions in their own operations [1].

It is not surprising that the pursuit of decarbonization poses considerable challenges. Although numerous sustainable alternatives now exist throughout a product's life cycle, their widespread adoption frequently requires substantial capital investment and may incur higher operational costs [3]. Moreover, an exclusive focus on decarbonization can inadvertently shift the environmental burden to other impact categories, including increased water consumption, plastic pollution, and eutrophication [4]. Therefore, decision-making in this context is complicated and requires a systems thinking approach, rendering the process more complex and less straightforward.

To advance their net-zero initiatives, many companies rely on tools such as life cycle assessment (LCA) and GHG emission calculations to evaluate and compare various pathways and technologies for achieving carbon neutrality. However, these tools typically perform GHG emission calculations in isolation from techno-economic assessment (TEA), which is a critical limitation. TEA evaluates the economic viability of strategies and technologies, providing insights into their cost-effectiveness [3]. Without integrating LCA and TEA, it is challenging to comprehensively compare pathways to carbon neutrality, as environmental impacts and financial implications are analyzed separately. Combining these methodologies is essential to develop balanced, actionable strategies that are both sustainable and economically feasible.

While emerging tools attempt to integrate economic considerations into decarbonization strategies, developing science-based roadmaps requires more than simply comparing existing, intuitively designed decarbonization pathways. To ensure these roadmaps are truly the best possible pathways without compromising other environmental impacts,

a systems thinking approach is essential [5]. This approach considers all potential alternatives at various stages of a life cycle as viable options, conceptualized as a superstructure network of processes or technologies [6]. To identify the optimal pathway(s), supply chains must be designed to minimize both emissions and costs, requiring the optimization of these networks [5]. Given the presence of multiple objectives, such as minimizing GHG emissions and costs, static and dynamic multi-objective optimization approaches must be integrated with LCA and TEA.

Moreover, systematic roadmaps not only support decision-making in the present but also guides actions as we progress toward net-zero targets by 2050. Such a roadmap outlines pathways, and the specific decisions required at each time interval to achieve these goals. This necessitates dynamic modeling of the system, incorporating uncertainties and potential future changes in our socio-economic system. These factors significantly influence investment decisions in decarbonization technologies and pathways [3, 5]. However, this critical aspect of multi-period planning is currently absent in existing tools.

In addition, integration of such complex mathematical frameworks into a decision support tool must be done in a manner that allows non-expert decision makers that may not have the technical knowledge to be able to utilize the tool. To the best of our knowledge, no existing tool currently achieves these goals all together.

In this work, we address the limitations of current tools for industrial decarbonization by developing **TranZero**, **t**ool for developing **r**esource efficient **a**nd **n**et-**z**ero **e**mission **ro**admaps. TranZero goes beyond simple comparative scenario analysis by providing advanced tools for supply chain design and multi-period planning. It enables companies to achieve net-zero targets in a cost-effective manner while avoiding the transfer of burdens to other environmental impacts. With its all-in-one platform and innovative data visualization techniques, TranZero empowers stakeholders to integrate multiple dimensions of environmental sustainability and economic performance into their decision-making processes.

TranZero employs a multi-layer analytical engine that integrates both static and dynamic multi-objective optimization frameworks, purpose-built for systematic carbon neutral and circular supply chain design. This work primarily introduces the tool and its capabilities, with a brief overview of the underlying mathematical frameworks. The underlying mathematical framework is discussed in detail in our previous publications [5,6].

As a case study, a customized version of TranZero has been developed to achieve climate neutrality and high circularity for multi-layer plastic films with barrier properties. This specialized tool, referred to as **TranZero – Barrier Film Version**, evaluates various end of life technologies to achieve high circularity and low GHG emissions. The tool incorporates the technological solutions for enabling a circular economy for multi-layer plastic films at their end of life. The underlying experimental and sustainability assessment data is provided in our previous/other papers [12,13]. While tailored to a particular product class, this version demonstrates TranZero's versatile capabilities for achieving net-zero and circularity targets. These features are adaptable to a broad range of products and industries, with ongoing development of new versions for carbon fiber, polyesters, and the broader chemicals and materials industry. The remainder of this manuscript emphasizes the unique features and innovations of TranZero, highlighting its ability to support robust, systematic decision-making for industrial decarbonization.

2. Review of Related Work

As designing for carbon neutrality and circularity inherently involves multiple objectives, previous studies have adopted a life cycle optimization approach to identify the most effective technologies and pathways for minimizing GHG emissions while optimizing other objectives such as cost. Numerous studies have explored multi-objective optimization approaches that aim to simultaneously minimize costs and GHG emissions. These investigations span a range of sectors, including the chemical and commodity chemicals industries [7-12], paper industry [13], wine industry [14], cement industry [15], waste management [16-24], food supply chains [25], and biorefinery supply chains [26-33]. However, to our knowledge, the optimization frameworks are not generic enough for designing for carbon neutrality and circularity for different types of products and industries and the frameworks are tailored for specific case studies. In this work, we use the Sustainable Circular Economy (SCE) framework that was previously developed in our group to model the optimization problem [6]. SCE uses a generic optimization formulation for multi-objective optimization towards circularity and carbon neutrality. It tailors the computational structure of LCA in order to make it applicable for circular economy systems with circular flows [6].

Designing for carbon neutrality and supporting decision-making also demands user-friendly tools that integrate LCA, techno-economic analysis, multi-objective optimization, and stochastic optimization [5,6]. This should be coupled with effective data visualizations to showcase the optimization and multi-period planning results to non-expert stakeholders. A strong solo focus has been on LCA with tools such as GaBi [34], SimaPro [35], OpenLCA [36], and Brightway2 [37] being the leading tools in LCA. New tools, such as the industrial decarbonization platform developed by Sesame Sustainability [38], address this gap by integrating a generic TEA model into GHG emission calculations. Our tool offers not only the integration of LCA and TEA but it also leverages our multi-objective optimization and roadmapping mathematical frameworks [5,6] for proposing both static and dynamic results helping decision making process for decarbonization and circularity planning.

3. Technology Approach

2.1. Software Development:

TranZero is implemented as a web-based software with robust back-end and front-end platforms. The back-end operates within a Docker environment, serving as the backbone of the tool by integrating the data and mathematical frameworks necessary for LCA, TEA, optimization, and other analyses. The front-end, developed using the ReactJS framework, facilitates user interactions with the system. When a user submits a query, the front-end communicates with the back-end to request calculations. The back-end processes these requests, performs the necessary computations, and returns numerical results to the front-end. These results are then visualized as figures within the software, providing users with clear and actionable insights. This seamless interaction between the front-end and back-end ensures a user-friendly experience while maintaining computational robustness.

2.2. Features of TranZero:

TranZero provides a versatile suite of options tailored to support various aspects of decision-making for decarbonization. These include:

- **Scenario Analysis**: A tool for performing straightforward comparative analyses between desired decarbonization strategies. This option enables users to construct scenarios and evaluate them based on key metrics.
- **Design**: A sophisticated tool for designing supply chains aimed at minimizing both costs and emissions. Instead of constructing a scenario, this feature provides stakeholders with optimized supply chain networks to meet net-zero and economic objectives.
- **Roadmap**: A comprehensive module for developing multi-period plans and systematic roadmaps to achieve net-zero targets. This option incorporates dynamic modeling and accounts for future uncertainties, guiding long-term decision-making.

Each of these features involves specific user inputs and targeted outcomes, offering distinct ways to assist stakeholders in making informed decisions. These functionalities will be explored in more detail in their respective sections.

This version of the tool is tailored for the analysis and design of sustainable and circular supply chains for multi-layer plastic films, specifically polyethylene-polyamide multilayer films. A cradle-to-grave system boundary for these films is presented in Figure 1.

Scenario Analysis:

Scenario Analysis enables users to construct and evaluate various scenarios, assessing both their life cycle impacts and economic performance. The primary objective is to provide stakeholders with a straightforward tool for conducting comparative analyses between scenarios of interest. This feature helps decision-makers compare and assess different decarbonization pathways in a static manner, offering a snapshot of the impacts associated with each scenario. Although Scenario Analysis does not identify the optimal pathway or generate a roadmap, it serves as a valuable tool for comparing existing and proposed scenarios provided by the user. These scenarios may be derived from science-based or intuitive roadmaps, offering flexibility in the decision-making process.

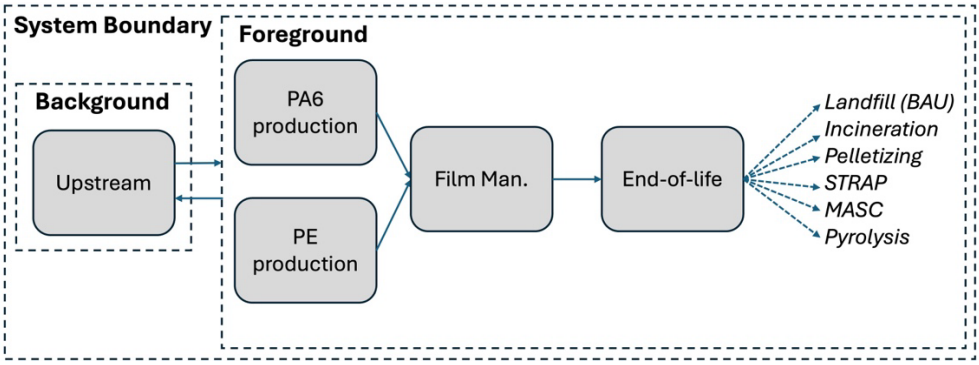

Figure 1 - *Cradle-to-grave* system boundary for multilayer plastic film life cycle. For end of life recovery, there exists multiple options including the business as usual (BAU) (landfill), energy recovery (incineration), downcycling (pelletizing), solvent-based recycling (STRAP), solvent-based reuse (MASC), and chemical recycling (pyrolysis). (STRAP: solvent targeted recovery and precipitation, MASC: mechanical and solvent cleaning, PA6: polyamide 6, PE: polyethylene, Man.: Manufacturer)

The user interface of the Scenario Analysis is structured into three key components: main assumptions, decision variables, and results, and is presented in Figure 2. In the main assumptions section, users can modify or select their preferred assumptions for the LCA and TEA. Options include the choice of life cycle impact assessment method (either TRACI [39] or ReCiPe [40]) and the background life cycle inventory database (Ecoinvent v3.8 [41] or USLCI [42]). Foreground data is provided by our industrial partner, Kohler. This version of the tool is specifically tailored to a case study for Kohler and does not currently support user-uploaded industry data. Instead, the database is embedded within the software. In future versions of TranZero, we plan to address this limitation by allowing users to input their own data and configure custom supply chains. Users can also define economic and circularity metrics: the total supply chain cost is used for the economic metric, while Ellen MacArthur Foundation's Material Circularity Indicator (MCI) [42] is used to assess circularity. Additional options include the choice of allocation method (substitution vs. cut-off approach for handling end of life environmental credits) and functional unit, which in this case is metric ton of multilayer plastic film waste generated. Further details on the sources of economic data can be found in our previous publication [43]. To ensure a fair comparison, users can limit their scenarios to technologies within a specific range of technological readiness levels (TRLs). For example, users may choose to build scenarios exclusively with commercial technologies for current applicability or include all TRLs for a broader, forward-looking study. This flexibility allows for both practical and futuristic analyses while maintaining consistency in the comparative framework.

In the decision variable section, users construct their scenarios by selecting various decision factors across different stages of the life cycle. These factors may include the choice of technology for manufacturing and end of life processes, the selection of production materials (e.g., bio-based versus fossil-based), or the type of energy source utilized within the supply chain. This flexibility allows users to explore diverse pathways and tailor scenarios to align with specific objectives and technological options.

In the results section, the software presents a variety of visualizations to effectively communicate the outcomes of the analysis. These include comprehensive results for LCA, TEA, and circularity, along with hotspot analyses identifying key contributors to environmental and economic impacts. Sankey diagrams illustrate material and energy flows throughout the supply chain as well as technologies and processes selected at each life cycle stage.

Design:

In the Design section, the software shifts from scenario construction and comparative analysis to the optimization of supply chain design. Instead of relying on user intuition to create a scenario, the software explores all possible pathways to achieve net-zero emissions. By considering the constraints and objectives defined in the model, it identifies the optimal pathway, providing a data-driven and comprehensive solution for sustainable supply chain planning. The underlying mathematical framework of SCE is extensively discussed in previous publications [6].

SCE leverages the computational framework of LCA to model both objectives and constraints as functions of the scale at which each end of life technology (in Figure 1) is deployed (treated as degrees of freedom within the network). In this framework, a technological matrix (A) represents the interdependencies and flows between different nodes within the economic system. These flows, along with their interactions with the environment (such as resource inputs and emissions) are captured through the environmental intervention matrix (B). The resulting environmental exchanges are then translated into impact categories using the characterization matrix (C), which quantifies the environmental burdens associated with each flow. Nodes are scaled up using the following equation:

$$As = f \tag{1}$$

where s is the scaling factors of each process, and f is the final demand vector. The environmental flows corresponding to a final demand f can be calculated using the following equation:

$$g = Bs \tag{2}$$

where g is the environmental flow vector. The impacts corresponding to all environmental flows (ϕ) is calculated using the following equation:

$$\phi = C^T g \tag{3}$$

To formulate the multi-objective optimization, all objectives (e.g., circularity, cost) as well as constraints must be a function of the decision variables (s). This for instance, requires harmonizing the circularity and cost with the computational structure of the LCA, done by defining these objectives as a function of the scaling factors of each node [6]. Therefore, our three-objective optimization framework is defined as follows:

$$\text{min. } \phi_{\text{GWP}} = C_{GWP}^T g \tag{4}$$

$$min.\ Cost := Y(s) \tag{5}$$

$$max.\ Circularity := Z(s) \tag{6}$$

$$Subject\ to:$$

$$As = f\ (demand\ and\ balance\ constraints) \tag{7}$$

$$s \geq 0 \tag{8}$$

Equation 4 shows the objective for minimizing global warming potential (GWP), which is the impact indicator for GHG emissions. ϕ_{GWP} is the GWP impacts of the entire system, with C^T_{GWP} as the characterization factors for GWP. Equation 5 and 6 show the other two objectives, i.e., cost and circularity, as a function of scaling factors. Main constraints in the system are the demand constraint as well as the mass and energy balance constraints (Equation 7), and Equation 8 shows that scaling factors must be positive in order to ensure positive physical flows within the system.

The user interface of the Design section consists of three components: main assumptions, objective functions, and results, and is presented in Figure 3. The main assumptions align with those in the Scenario Analysis section, allowing users to define parameters such as the functional unit, impact assessment method, and more. In the objective functions' module, users select their objectives of interest. Currently, the software supports three key objectives: environmental, economic, and circularity. These objectives guide the optimization process to align with the user's priorities. The results section provides a comprehensive visualization of the outcomes. On the right-hand side, a Pareto frontier is displayed, showcasing all possible optimized solutions. Since the objectives may conflict, the Pareto frontier highlights the trade-offs between them, enabling stakeholders to select solutions based on their preferences. On the left-hand side, the software displays detailed results corresponding to the selected solution on the Pareto frontier. These include total LCA, TEA, cost breakdown, and a Sankey diagram (A Sankey diagram illustrates material, and energy flows and highlights the selected technologies, represented as nodes within the diagram). These features are not fully depicted in Figure 3 but can be explored in detail through the software link provided [44]. This novel visualization framework offers an intuitive view of the optimized supply chain as well as its performance metrics.

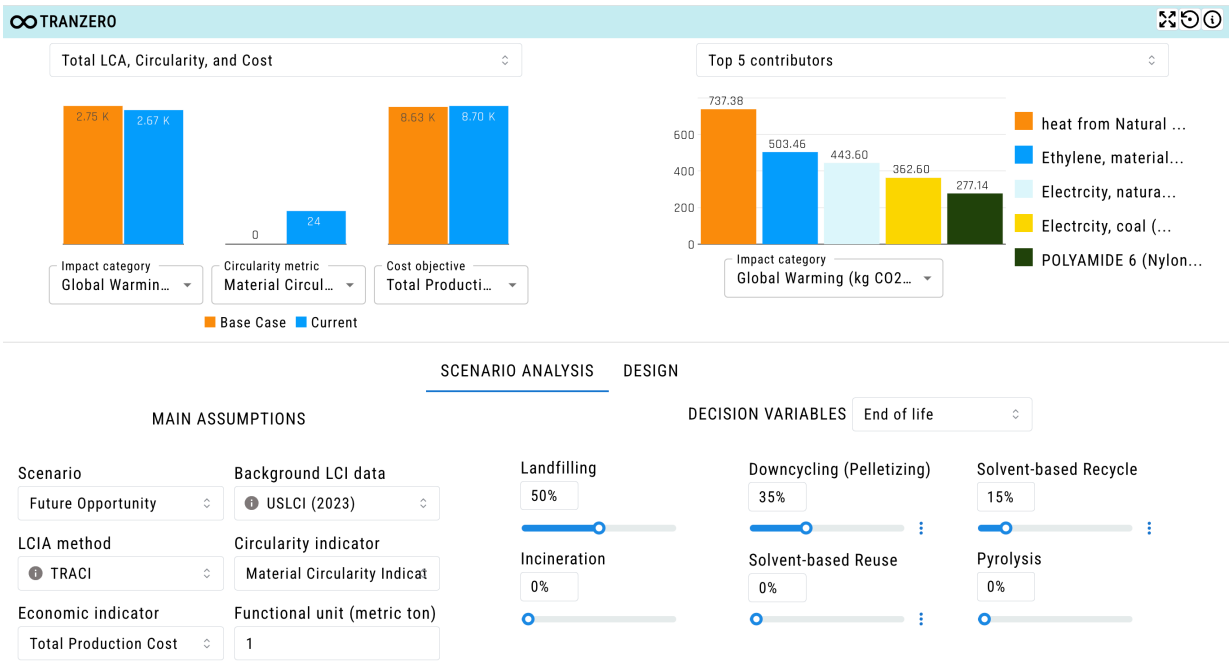

Figure 3 - A screenshot of the Scenario Analysis Section of TranZero. Scenario Analysis includes two user-input sections, i.e., Main Assumptions (bottom left), Decision variables (bottom right), and results (top half). The percentage numbers in the decision variables indicate the ratio of each end of life technology selected for constructing that scenario. Further guidelines on this section are provided in our user-tutorial available with the software [44]

Roadmap:

TranZero generates comprehensive, science-based roadmaps designed to guide organizations through the transition to net-zero emissions. These roadmaps consider evolving industrial dynamics, regulatory developments, and market uncertainties. By incorporating multi-period planning, TranZero ensures that users have a phased, actionable plan for achieving sustainability goals over time, while maintaining the flexibility to adapt to emerging challenges and opportunities. The mathematical framework has been extensively detailed in previous publications [5]. While this feature is still under development and has not yet been implemented in the software, a mock-up of the roadmap interface is provided in Figure 4. The roadmap section will consist of two components: the assumptions (depicted at the bottom of Figure 4) and the results (shown at the top). The assumptions section will include standard LCA/TEA parameters as well as inputs specific to the dynamic model, such as the objective function, socio-economic scenarios (e.g., changes in grid composition over time), and the technology evolution model. The latter is critical for calculating investments in each technology and determining whether a technology is ready for large-scale adoption at each time interval. The figures are based on illustrative, dummy data and do not represent an actual roadmap for achieving net-zero in the multi-layer plastic film economy. These placeholders serve to demonstrate the potential layout and functionality of the roadmap feature.

4. Discussion

In the Scenario Analysis section of the multi-layer barrier film case-study (The tailored version of TranZero, shown in Figure 2), users can perform comparative analysis between different end of life technologies (or a combination of end of life technologies for each scenario) for treating this type of waste. These technologies include incineration, solvent-based recycling (or solvent targeted recovery and precipitation (STRAP)), solvent-based reuse (mechanical and solvent cleaning (MASC)), downcycling (pelletizing) and chemical recycling (pyrolysis). Detailed descriptions of these end of life technologies (shown in Figure 1) are provided in our other publications [43]. This section can help stakeholders compare their multi-layer film circularity scenarios of their interest effectively, in terms of GHG emission, circularity, and cost.

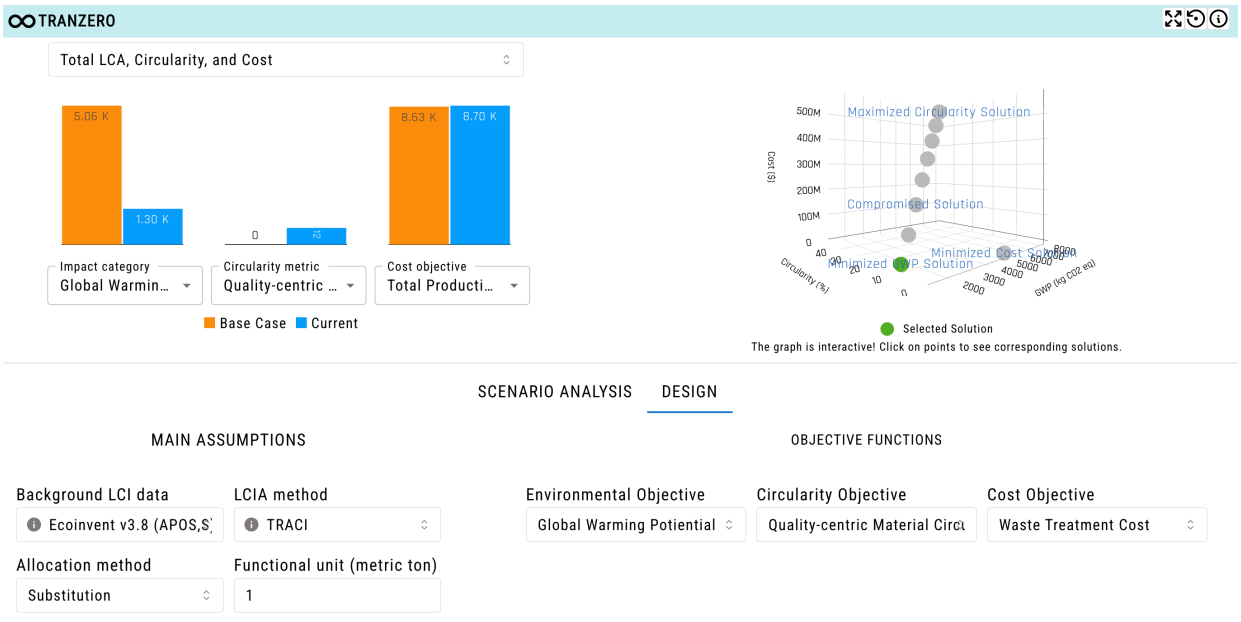

Figure 3 - A screenshot of the Design Section of TranZero. Design Analysis includes two user-input sections, i.e., Main Assumptions (bottom left), Objective Functions (bottom right), and results (top half). The top-right figure presents the Pareto frontier, and the top-right figure shows the performance metrics corresponding to the selected scenario on the Pareto. Further guidelines on this section are provided in our user-tutorial available with the software [44].

Figure 4 - Mock-up of the Roadmap Section of TranZero. The bottom half are the user inputs, and the top half are the roadmapping results. The right-hand side figure shows the optimal combination of technologies and when the technologies should be replaced with the new or emerging ones for optimal cost-effective decarbonization. The left-side figure shows the GHG emission profile from the time of roadmap initiation until the target year (2050). The

results in these figures are generated with arbitrary numbers and are only for illustrative purposes and for showing the capabilities of the Roadmap section of the software.

In the Design section of the barrier film case study, the software optimizes the end of life and finds trade-offs between different solutions. In this case, the STRAP process shows promising in terms of minimizing GHG emissions (40% reduction in GWP compared to BAU), while it is only slightly more expensive compared to the business-as-usual (BAU) , or landfilling (1.1% increase in total supply chain cost). However, landfilling still is selected as the cheapest option as we have not accounted for landfilling tipping fee or carbon tax. The most circular scenario is solvent based reuse (MASC) due to its ability to preserve as much product as possible through the inner reuse cycle. However, this scenario is extremely cost-intensive due to its lack of commercial development at the current stage.

5. Conclusions and Recommendations

TranZero is a user-friendly tool that aims to perform a rigorous analysis for comparing and finding decarbonization pathways. It's a versatile tool that equips stakeholders with strong rigorous mathematical framework while it benefits from novel data visualization techniques that make the interpretation easier. A tailored version of TranZero is developed for multi-layer barrier films, which offers solutions towards net-zero. It suggests that a Solvent Targeted Recovery and Precipitation (STRAP) recycling process can minimize GHG emissions (by 40% from compared to BAU) with slightly higher cost of capital and operation (1.1% increase of total supply chain cost compared to BAU). TranZero showed trade-offs between maximizing circularity, minimizing GHG emissions, and minimizing cost, and uses a novel visualization framework to effectively show the trade-offs and make them easier to interpret. TranZero is under development for other product systems and industries, and due to its generic structure, can be implemented for any class of product or industry. The software can be accessed through the link provided [14], allowing users to explore its features in detail. A comprehensive user tutorial is included within the platform to assist users in navigating its functionalities effectively.

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