Whitepaper

Pathways to sustainable plastics

Unlocking opportunities in biobased plastic

Auteur
Ellen de Ruiter, Jan Harm Urbanus,
Anna Schwarz, Milad Golkaram, Pieter Imhof

TNO innovation for life

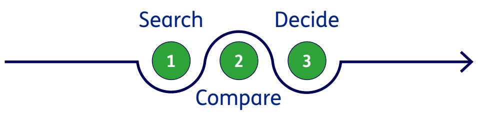
Executive Summary

Pathways to sustainable plastics: Unlocking opportunities in biobased plastic

A comparative framework to assess pathways to bio- and CO_2- based plastics in view of application

Plastics are likely to remain a globally omnipresent material due to their unique characteristics and versatility. In a circular and sustainable future, plastics are produced from renewable carbon feedstocks like recycled plastics, biomass, and CO_2/hydrogen, requiring transformation of global value chains. Producing new plastic from recycled plastic is a preferred pathway, as it is the best use of plastic waste. However, even if global recycling rates achieve their theoretical potential, only about 60-70% of plastic volumes can be produced based on recycled feedstock considering losses in production, use, collection, (bio) degradation, microplastic formation, and recycling yields. Consequently, significant production volumes of sustainable virgin plastic will still be required to replace these losses and meet growing demand. Biomass- and CO_2-based plastics are the only remaining options to achieve this in a circular manner. The share of total plastics that can be expected to be biobased in a fully non-fossil plastics system is difficult to predict. To understand the potential of biobased plastics, it is essential to examine the entire plastics system and compare biobased feedstocks with other renewable options.

The missing link in decision-making on biobased plastics is a system perspective that spans the different renewable carbon-based plastics alternatives in view of application. TNO has developed a 3-step framework to provide this perspective:



This approach lays the foundation for strategic choices regarding the best pathway to renewable carbon-based plastic per product (best in terms of sustainability and economic feasibility). To find potential options, the first step in the framework is to search options and specify the pathways per plastic material and application (the product), selecting feedstock, production steps, and technologies.

Here, we define three different pathways for virgin sustainable plastic based on renewable carbon:

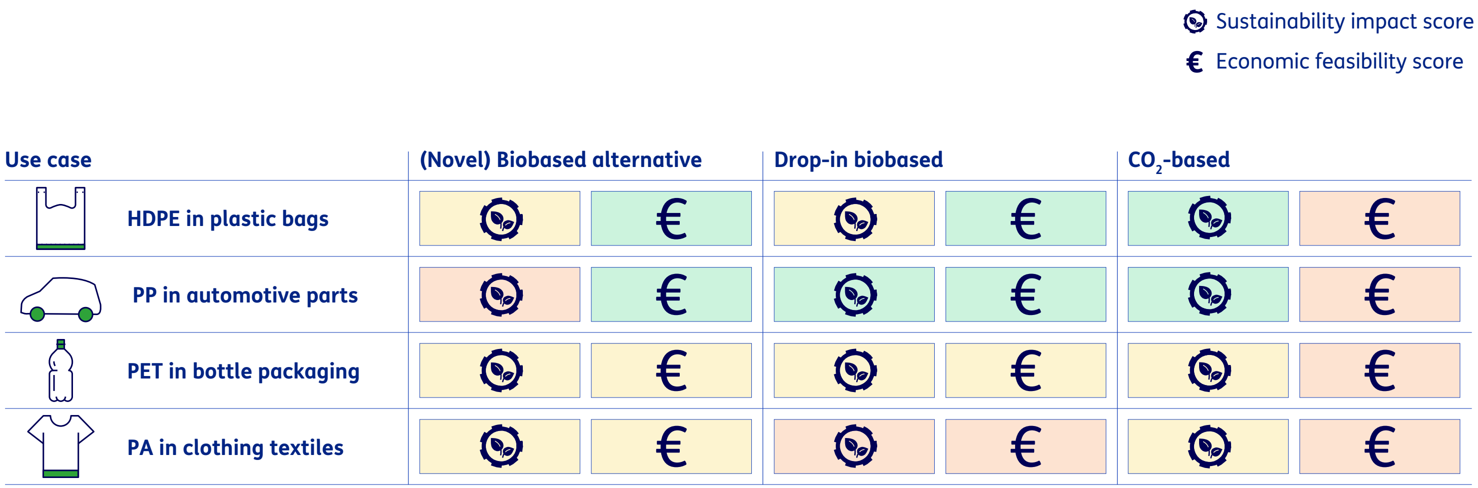
- (Novel) **Biobased alternative** polymers
- **Drop-in biobased** polymers
- **CO_2-based** polymers

The (novel) biobased alternative for a material is determined by assessing the fit of biobased polymers with the existing fossil material properties. This approach allows for screening of many (undeveloped) options and estimation of performance in an early stage. In the second step of the framework, environmental sustainability and economic feasibility are determined for each pathway-product combination. This can be done across all nine common types of plastic materials that represent 80-90% of today's global plastic volume. This comparative analysis provides a system perspective at an early stage of the design phase and allows stakeholders to understand which of the three pathways described above is most optimal for a product. The third and final step in the framework is to decide on the pathway per product in a specific situation, given the impact of constraints (e.g., local biomass availability) and assessment of scenarios (e.g., spatial and temporal boundaries).

The framework application results are illustrated in this whitepaper by presenting the results for four use cases, covering representative plastic materials and applications: 1. High-density polyethylene (HDPE) in plastic bags, 2. Polypropylene (PP) in automotive parts, 3. Polyethylene terephthalate (PET) in packaging bottles, and 4. Polyamide (PA) in clothing textiles. A summary color score on sustainability impact and economic feasibility (results of step 2 of the framework) per use case and pathway are shown in the figure on this page. Green indicates a relatively good score (lowest sustainability impact and most economically feasible) and orange indicates the least preferred option from sustainability and economic feasibility perspective.

The framework's further application potential is described, highlighting its value for policymakers and industry. It enables stakeholders to envision strengths and weaknesses of renewable carbon options from a future plastics production system perspective and/or make strategic product material choices in a specific situation, as a basis for further research and development.

Let's apply this framework together, find the best solution for your product(s) and accelerate the transition to renewable carbon in plastics!



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Chapter 1

Unlocking opportunities in biobased plastic by taking a systems perspective

As a versatile and lightweight material used in a variety of applications, thereby contributing to improved sustainability for society, plastics are likely to remain globally omnipresent even in the future [1]. However, the prevailing global plastics system is based on fossil feedstocks and remains predominantly linear: only an estimated 14% of plastic waste is collected for recycling globally [2] [3]. Greenhouse gas emissions related to fossil plastics production and use are significant, accounting for ~4% of global emissions [4] [5]. Plastics are also notorious for their end-of-life impact, polluting the environment and breaking down into microplastics causing harm to people and the planet. On top of that, projections indicate a sharp increase in global plastics demand towards 2050 driven by rising global living standards and industrialization. Estimates range from a doubling of current yearly plastic demand [6] to even tripling [7]. This presents a substantial challenge for the plastic industry, as the current way of production and use of plastics contributes to climate change, the depletion of natural resources, and the destruction and pollution of the environment. Therefore, society needs to find a way for more sustainable production, use, and end-of-life for plastics, today and in the future. To do so, all circular economy principles (the so-called ‘R-strategies’) must be applied to increase the refusal, reuse, and recycling of plastics [8] [9]. However, while we can refuse and reuse some plastic products, we cannot refuse all plastics due to the unique functions that plastics have, and that we rely on in our daily lives [1]. To achieve sustainability goals, the plastics industry must move away from fossil feedstocks and begin producing plastics from renewable carbon sources, i.e. recycled plastics, biomass, and CO_2 (and hydrogen), thereby requiring transformation of global plastics value chains [10] [11]. Whether phasing out fossil fuels completely by 2050 is possible remains to be seen, yet that year is used aspirational in this whitepaper and should be read as ‘when the plastics system had achieved sustainability’.

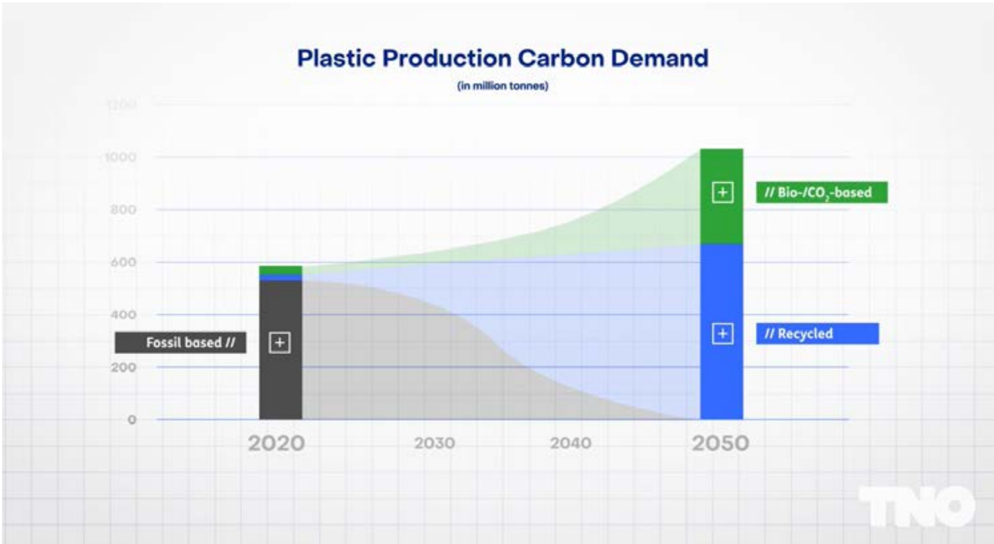
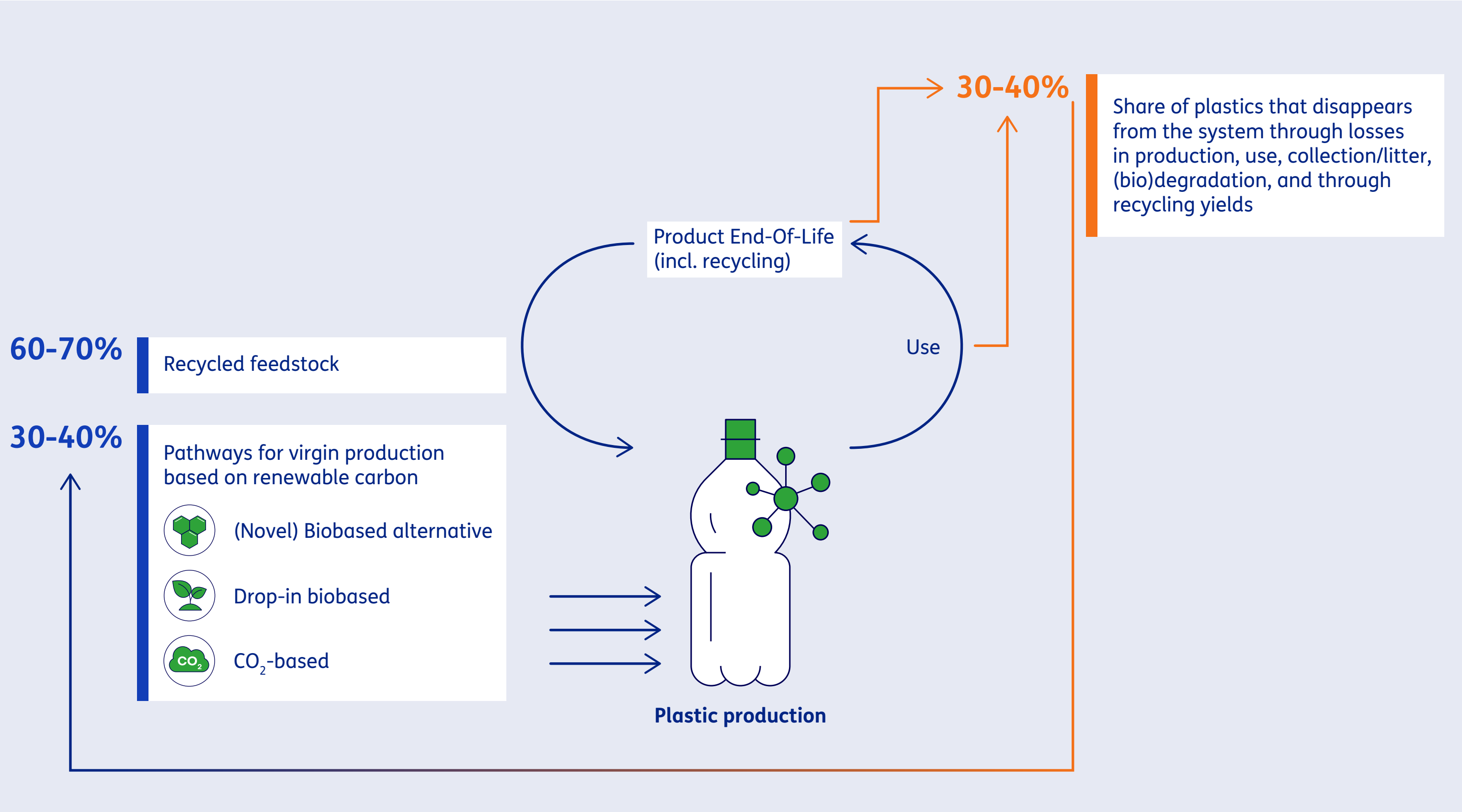


Figure 1: Plastics will need to be produced based on renewable carbon feedstocks (Adapted from Nova Institute 2023 [12])

It is likely that recycling of plastics will play a significant role in our future plastics system. Whilst constituting the most preferred option from a sustainability and cost- perspective, mechanical recycling has the drawback of reduced product quality, contamination sensitivity, and is not suitable for all plastic types. Physical and chemical recycling technologies are more versatile and yield limited quality loss, typically come at higher costs, higher energy intensity, and require further technological development [13]. In addition, chemical recycling constitutes an inherent loss of carbon due to yield losses in the process. Despite the drawbacks and some criticism described above, recycling plastic remains an important potential route in a renewable carbon-based plastics system and it presents an effective use of plastic waste feedstock (resource conservation) [14] [15]. In other words, the pathway of producing plastics based on recycled feedstock must be maximized. However, even if global recycling rates reach their theoretical maximum, it is estimated that only approximately 60-70% of the total volumes can be produced based on recycled plastic feedstock. This estimation takes into account unintended losses that

Figure 2: Sustainable production of plastics will still be required to cover losses and increasing plastics demand. Three pathways for virgin production based on renewable carbon are 1. (Novel) Biobased alternative polymers, 2. Drop-in biobased polymers, and 3. CO_2-based polymers

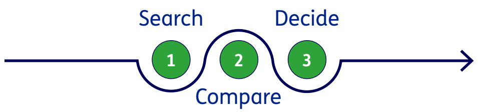


occur during production, usage, collection, (bio)degradation losses, microplastic formation, and yield losses in the recycling process [4] [16] [17]. Thus, significant sustainable plastic production will still be required to replace losses and meet growing demand. The production pathways from biomass- and CO_2- are the only remaining options for sustainable virgin production. Here, natural biopolymers such as cellulose, starch, and their derivatives will play a critical, but smaller role due to limited performance in most of the commonly used application areas. Hence, biomass and CO_2 will predominantly be used to produce known or novel man-made polymers (like PE, PET, or PLA) instead of natural biopolymers. The term biobased plastics refers to plastics made from biomass. More details are described in the sidebar 'Introduction to biobased plastics, terminology, and the regulatory environment'.

Determining the best mix of renewable carbon for sustainable plastic production is challenging. Not every renewable carbon option is automatically more sustainable [12]. The share of total plastics that can be expected to be biobased in a fully non-fossil plastics system is difficult to predict. European Bioplastics suggests around 15%, Nova Institute indicated ~25%, McKinsey forecasts bioplastics might account for 30%, and various industry reports show ranges between 10-35%. Predictions are difficult since they are dependent on total demand growth/reduction, regulation, approval and adoption, plus it involves matching the right feedstocks and conversion technologies with the right product and applications in the right geographical locations [18]. Regional considerations are important; for example, in areas of the world where suitable biomass is abundantly available, the most sustainable carbon could be derived from that type of biomass, while in regions with limited biomass but good access to renewable energy and green hydrogen, captured CO_2 could be the preferred feedstock.

The challenge of determining the best mix of renewable carbon pathways leaves policymakers and industry unable to make effective decisions and act upon it. For example, industry players are unwilling or unable to invest due to unclear long-term perspectives and complexity in decision-making for their own products. Policymakers are struggling to establish a long-term vision for which products and industries biobased and CO_2-based plastics are best suited, making it difficult to develop effective policies. The missing link in decision-making for biobased plastics is a systems perspective that spans different renewable carbon-based production pathways in view of application.

TNO suggests that we need to examine the entire plastics system and compare different renewable options for a specific material application (product) to understand the potential of biobased and other sustainable plastics. This whitepaper presents a 3-step comparative framework to provide this missing link.

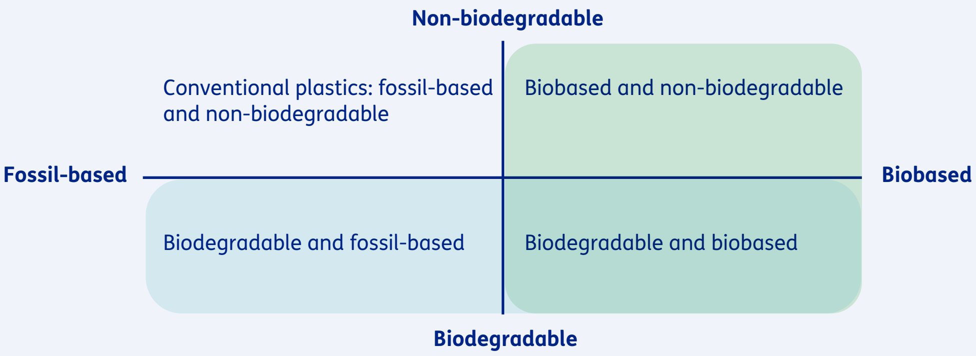


In this framework, we define three pathways for virgin plastic production based on renewable carbon: **(Novel) Biobased alternative** polymers, **Drop-in biobased** polymers, and **CO_2-based** polymers. 'Novel biobased alternative' implies that a biobased polymer with a different (alternative) chemical structure and similar, or better, properties can be used to fulfil the same function. Please note that the term 'novel' here is optional. Some biobased polymers or biopolymer uses are not recent inventions, like polylactic acid (PLA), which was discovered in 1920. 'Drop-in biobased' means that biomass is used to make the exact same chemical building blocks (and polymers) as currently being derived from fossil. 'CO_2-based' here refers to the use of captured CO_2 to make the same chemical building blocks and polymers as are currently being derived from fossil. This is thereby also a drop-in pathway. Similar to synthetic fuels (fuels made based on CO_2), polymers from CO_2 are sometimes also called 'synthetic' or 'syn'-polymers. The three pathways need to be compared to determine the optimal balance of sustainability and economic feasibility for a specific product. The goal of this whitepaper is to outline the approach of the 3-step framework, as described in Chapter 2. Furthermore, potential results of the framework application for specific products are illustrated by four global use cases in Chapter 3.

Introduction to biobased plastics, terminology, and the regulatory environment

The term biobased plastics refers to plastics that are made fully or partially from biological resources such as sustainably grown biomass and bio-waste [19]. A common misconception is that biobased plastics are always biodegradable or compostable, while in fact non-biodegradable durable biobased plastics also exist. The illustration in Figure 3 explains the terminology. The preferred quadrant to be in depends on the product application. For example, a chemical coating for housing might be biobased but should not be biodegradable. In contrast, a food packaging material that is likely to end up in bio-waste (e.g., tea bags, coffee cups) would benefit from being biodegradable. For many applications, recycling is the most circular option and thus (biobased) products should be designed for recycling. In summary, it is important to think about the product function and likely end-of-life options in determining the type of (biobased) plastic to use.

Figure 3: Bioplastic terminology



The sustainability, and therefore widespread support, of biobased plastics has been a topic of debate among experts. Utilizing biomass as a feedstock for plastics holds immense promise in mitigating greenhouse gas emissions, and under specific conditions, biobased plastics could even act as a carbon sink when integrated into durable products [20] [1]. Considerations around biomass use for plastics production and potential trade-offs in environmental impact are presented in the sidebar 'Availability of biomass and captured CO_2, and considerations around their use in (bio)plastic production'. Furthermore, it is important to examine the full life cycle of biobased plastics to ensure they are beneficial to the environment beyond reducing fossil resource use. Multiple efforts are ongoing to achieve more clarity on sustainability of bioplastics. For example, in Europe, the Circular Economy Action Plan identifies the need to address emerging sustainability challenges related to the sourcing, labeling, and use of biobased plastics. This involves assessing where the use of biobased feedstock results in genuine environmental benefits, beyond just reducing fossil resource use.

Even with these considerations, phasing out fossil fuels as a feedstock will position biobased plastics to play a crucial role in a global circular, sustainable future. There currently is little specific regulation on bioplastics. In the Netherlands, the upcoming recycled and biobased polymer obligation (Nationale Circulaire Plastic Norm) in 2027 will provide some incentives for biobased plastics [21]. Guided by sustainability ambitions, the European Commission's communication on 'Sustainable Carbon Cycles' delineates an aspirational objective for chemical and plastic products: 'by 2030, at least 20% of the carbon utilized should stem from sustainable non-fossil resources'. In addition, biomass used must adhere to stringent EU sustainability criteria for bioenergy [22]. The United States aspires to generate 30% of its chemical demand through sustainable biomanufacturing within two decades [23]. China has mandated the use of biodegradable plastics in certain packaging applications and has set production targets for specific biopolymers, accentuating a global push towards sustainable bioplastics.

Chapter 2

TNO's 3-step framework to provide a system perspective across the renewable carbon-based plastic production pathways

Plastics perform various functions in society in different applications, ranging from long-lasting construction materials to single-use packaging and mixed waste.

Currently, these functions and applications are fulfilled by 9 common (fossil) polymer materials, covering 80-90% of today's global plastic volume as shown in Table 1.

Figure 4: Plastic applications sorted by product longevity

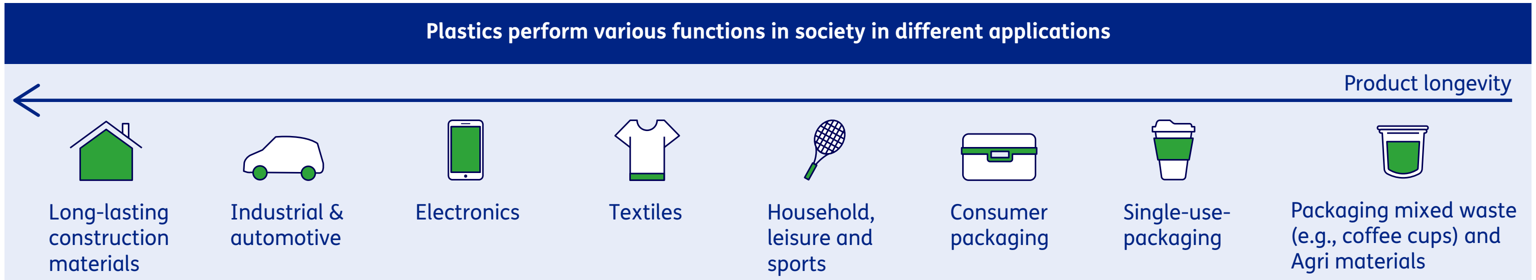


Table 1: Common polymer materials in use today [24]

Polymer material	Polymer material	Example uses	Market share (2022)
LDPE	Low-density polyethylene	Squeeze bottles, toys, flexible pipes, can rings	14%
HDPE	High-density polyethylene	Bottles, pipes, plastic bags, cables	12%
PP	Polypropylene	Auto parts, food containers, industrial fibers	19%
PS	Polystyrene	Plastic cutlery, CD case, petri dish	5%
PVC	Polyvinyl chloride	Pipes, fencing, outdoor chairs, non-food bottles	13%
PET	Polyethylene terephthalate	Bottles, packaging trays, textiles such as fleece	6%
PUR	Polyurethane	Building insulation, furniture and bedding, footwear	5%
PA	Polyamide	Textiles and fibers, automotive, sportswear	2-3%
ABS	Acrylonitrile Butadiene Styrene	Toys (Lego), electronics, 3D printing	2-3%
Other	Other plastics	Engineering plastics, other	10-20%

TNO has developed a 3-step framework to provide the currently lacking system perspective that spans the different renewable carbon-based plastic alternatives in view of application. The framework is summarized in Figure 5. This approach lays the foundation for strategic choices regarding the best pathway to renewable carbon-based plastic per product (best in terms of sustainability and economic feasibility) and is able to estimate performance of pathways or technologies in a very early stage of analysis based on initial data.

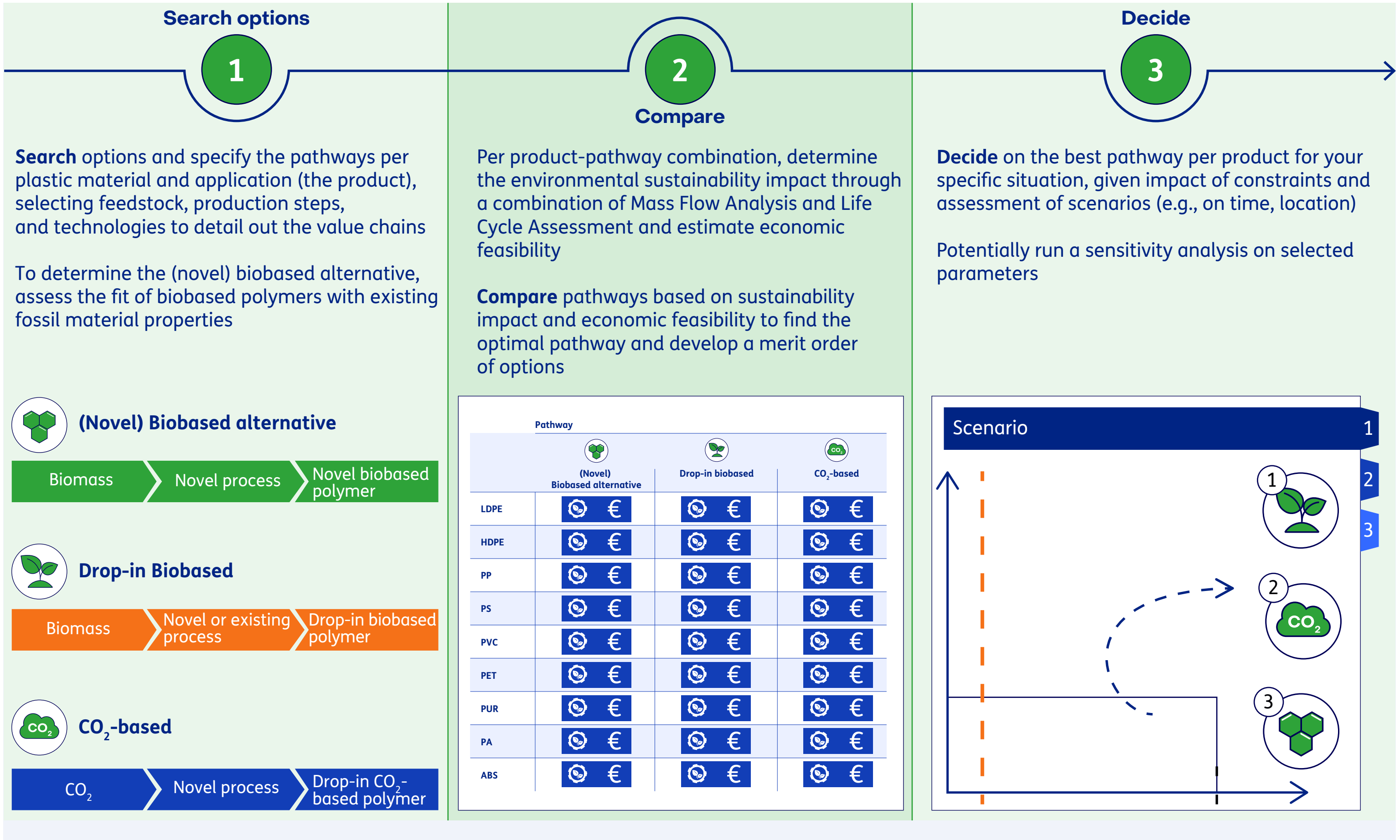


Figure 5: TNO's 3-step framework

2.1 Step 1: Search options, determine novel biobased alternatives and specify the pathways

The first step of the framework is to search polymer and technology options and specify the pathways per material and application. It encompasses detailing-out the production value chains, from biomass to final product, and selecting the technologies used in the different process steps. There are many different options for each pathway-product combination. For example, a drop-in biobased HDPE can be produced based on corn feedstock that is processed via ethanol to ethylene, or it can be based on forest residues that are processed via pyrolysis into olefins including ethylene. Therefore, it is important to specify the pathways by selecting the most relevant value chains, given the situation.

To specify novel biobased alternative pathway, the question that requires an answer is: ‘which novel biobased alternative polymer can be applied here?’. TNO developed a method to compare polymer properties of (novel) biobased polymers to the properties of existing polymer products in many different applications. The prediction of properties is based on previous work by Maastricht University and TNO that involved assessment of plastic recyclate quality [25] and substitutability of recycled plastics [26]. The method considers processing-, material-, and product properties of a plastic material. For the purpose of this whitepaper, the method assesses five key properties for plastics: modules, tensile strength, elongation at break, oxygen transmission rate (OTR), and impact strength. In addition, a weighting factor was included to put emphasis (i.e., weight) on those properties more important for specific applications or markets. For example, in food packaging the OTR and food contact regulation properties are important, whilst material properties such as impact strength and modulus may be more important in plastics used for automotive parts. The barrier properties in packaging also play a role in preventing food waste, so concessions to these properties are usually not beneficial from an overall sustainability perspective. The method determines a ‘quality’ value by comparing properties of the biobased polymer with the property requirements belonging to a certain application (product). In case this quality value is similar to the quality value of the currently used (fossil) polymer (with a 90% threshold), that novel biobased alternative is concluded to be a close substitute for that function. A list of >1000 potential novel biobased polymers and their properties (as reported in scientific literature) was loaded into the database of the method. The results of our initial analysis (see Figure 6) show that novel biobased polymer alternatives can be identified to potentially fulfil most existing applications, given a >90% match in properties.

It is important to note that for some products, the current polymer material in use has properties that perform better than needed for the product function (i.e., some products are ‘over engineered’), hence for such applications the 90% match threshold might be too strict.

⚗ At least one novel biobased alternative identified (>90% property match)

○ Material/application combination doesn't exist

● Area for further research into design of novel biobased alternatives

Product longevity	Long-lasting construction materials	Industrial & automotive	Electronics	Textiles	Household, leisure and sports	Consumer packaging	Single-use-packaging	Packaging mixed waste (e.g., coffee cups) & Agri materials
LDPE	⚗	●	●	○	●	⚗	⚗	⚗
HDPE	●	●	●	○	⚗	⚗	PLA	●
PP	●	PBF	⚗	⚗	●	⚗	⚗	●
PS	⚗	⚗	⚗	⚗	○	⚗	●	○
PVC	●	●	●	○	●	●	●	○
PET	○	⚗	●	⚗	⚗	PEF	⚗	○
PUR	●	●	●	○	●	●	●	○
PA	●	●	●	PPF	●	●	●	○
ABS	●	⚗	⚗	○	⚗	○	○	○

Figure 6: Initial analysis found at least one novel biobased polymer alternative with a 90% property match for most applications. For the four use cases presented in Chapter 3, the (novel) biobased alternative polymer that was identified is already listed here.

It is important to take recyclability, biodegradability and complexity of the plastics system into account when selecting novel biobased alternatives. The next step could be to limit the number of unique monomers (i.e., selecting specific platform chemicals), to facilitate future recycling potential and reduce complexity. Furthermore, the analysis as depicted in Figure 6 also highlights areas for future research into those applications where no novel biobased alterative is identified yet (or the quality is not good enough). Biobased polymer design by machine learning could be applied here, as it shows potential to design, identify, and/or improve novel biobased alternatives [27] [28].

For the 'drop-in biobased' and 'CO_2-based' pathways the final products are known (since they are the same as the current polymers). Therefore, all three production pathways can now be specified per product through searching and selecting the technologies and production steps to specify the value chains for comparison.

2.2 Step 2: Compare pathways on sustainability impact & economic feasibility

With the pathways for comparison specified, the next step is to assess environmental sustainability impact and economic feasibility per product and pathway (product-pathway combination). A decision matrix was designed for easy comparison of results (see Figure 7).

To compare pathways on environmental sustainability, a sustainability impact assessment tool was developed that combines Material Flow Analysis (MFA) and Life cycle assessment (LCA) inventories. This is a method that is used to assess sustainability and circularity from a system perspective [29]. At the moment, LCA is the most reliable method to identify environmental issues within a process and verify claims of sustainability advantages [12]. However, standard LCA studies usually consider a single product, process or value chain, which is compared to the status quo. By combining LCA with MFA, the assessment allows for a value chain approach, with system optimization on different impacts and constraints.

Figure 7: Decision matrix to be filled to compare pathway-product combinations on sustainability impact and economic feasibility

Environmental sustainability impact as defined in this analysis includes multiple sustainability indicators such as global warming potential, cumulative energy demand, land use, water depletion, and feedstock input required. It is important to include indicators beyond global warming potential, as biomass production as feedstock for plastics often has a relatively large impact on water use and biodiversity [30].

The framework does include indicators beyond only global warming potential in CO_2 equivalents. This is done to prevent a limited view of sustainability impact, often described as a carbon tunnel vision. The analysis of environmental sustainability impact determines the number results on each of these indicators. To deduce a single summary color score for sustainability impact (to be used in the results comparison matrix), a double weighting was given to the following indicators: cumulative energy demand and feedstock input required.

Although very relevant as key indicators for biodiversity, a single weighting was attributed to both water depletion and land use. This is because water use can vary strongly depend on crop type and spatial scale, where variations in this value can result in high uncertainties. Land use is not weighed double to allow for a more fair comparison between primary and secondary biomass sources; as primary biomass has a higher land use impact compared to secondary biomass, as such impacting the score and comparisons significantly. In the summary color score, the best options (lowest sustainability impact) are indicated as green, and the worst options are indicated orange.

The MFA includes the carbon flows, process yields, and efficiencies for each step in the value chain. The LCA module is scaled to modular life cycle inventories, all containing 1 tonne of defined output. Many (bio)chemical processes result in multiple useful products and co-products, for example, multiple chemicals and energy products. Therefore, assumptions on product allocation are needed in the analysis. Here, a consequential system expansion approach was used where all value chains are included and potential co-products that are not chemicals are assumed to be avoided products. Avoided products include feed, fertilizers and waste-to-energy processes. Mass allocation is applied to chemicals which are created as co-products. Life cycle inventories were collected from various process databases, including ecoinvent, and scientific LCA studies.

To compare pathways on economic feasibility, a simple method for cost estimation of the product-pathway combinations was developed that considers the major cost components of plastics production: feedstock, utilities, and investment. The total cost estimate per pathway (€/tonne product produced) is based on the cost of feedstock input used e.g., biomass type or captured CO_2, plus the cost of main utilities used e.g., electricity, heat, and (green) hydrogen, plus an estimation of capex per tonne product. To deduce a single summary color score for economic feasibility (to be used in the results comparison matrix), cost ranges for the total estimated cost per tonne determine the color. In the summary score, the best options (best economic feasibility) are indicated as green, and the worst options are indicated orange.

Figure 8: Environmental sustainability impact as defined in the framework

Sustainability impact				
Global Warming Potential	Energy demand	Land use	Water depletion	Feedstock input

Figure 9: Economic feasibility as defined in this framework

The input requirement of feedstock and utilities (and thus their cost) is linked to the production steps in the mass flow analysis of the sustainability impact assessment tool. In this way, economic feasibility estimates are linked to the process yields, which include valorisation of byproducts via mass allocation.
The estimate of investment used here is based on the general number of processing steps required in the value chain. It follows the principle that a more complex and longer production process would require more investment. First, an average capex per production step, a 'capex unit', was approximated to be 125€/tonne product, based on industry estimates of capex for fossil production of plastics [24]. An estimate of investment was determined by multiplying the cost per capex unit with the number of general production steps in the value chains for the renewable carbon-based production pathway. Generally, production of a (novel) biobased polymer requires additional steps compared to fossil production for feedstock preparation and processing. Production of CO_2-based polymers requires new types of production facilities such as for methanol to olefins. This estimate of investment required per tonne product is a rough approximation. In practice, this would be highly dependent on many factors including scale of production, cost variations for equipment and land, process- and/or technology complexity, potential innovations or chain synergies, and (regional) market developments or policy factors. To this effect, a scenario assessment was performed on the investment cost included in the results of the four use cases presented in Chapter 3. This was done by halving and doubling the capex costs in the results. In both cases, the order of performance of pathways did not change (as the investment-component varied between roughly 5-25% of the total costs for the calculated pathways).

The combined results for sustainability impact and economic feasibility per product-pathway combination allow stakeholders to conclude which renewable plastic pathway is the theoretical 'best' for a product. This provides essential information to develop a perspective on the transition towards renewable carbon-based plastics.

Availability of biomass and captured CO_2, and considerations around their use in (bio) plastic production

An obvious potential constraint for bioplastic production is the availability of (sustainable) biomass feedstock. Biomass serves as a renewable source of carbon due to its relatively rapid regeneration [31]. Typically, biomass is divided into first, second, and third generation feedstocks. First generation biomass refers to readily fermentable sugars from edible polysaccharide sources (e.g., corn, sugarcane) and edible (vegetable) oils. The application of first-generation biomass continues to be subject to debate, primarily due to ethical issues related to competition for food resources and alterations in land use. Although there are also studies that suggest sustainable co-production of biomass for food and materials should be possible [32] [33] [34]. Second-generation biomass refers to non-edible biowastes such as agricultural and food waste (e.g., non-edible oils, forest residues, agricultural residues, organic waste). Second-generation biomass offers a less debated, cheaper, and widely available feedstock for bioplastics, although there are the downsides of complexity and additional pre-treatments required. Third-generation biomass refers to novel biomass feedstocks that are being explored for use, such as manure or algae. For the pathway specification in this whitepaper, no biomass types are being excluded for now, whilst the importance of focusing on the use of second- and third-generation feedstocks for bioplastics production is emphasized.

A major consideration around biomass utilization for bioplastic is the definition of sustainable biomass. Although the division into different generations says something about sustainability of the feedstock variety, it is as important that the feedstock is sourced sustainably (i.e., avoids deforestation and loss of biodiversity, sustainable agriculture practices, pesticide use, and carbon footprint of farming practices) and does not compete with food security. Land and water use need to be balanced to avoid negative impacts on food security and ecosystems. Production of sustainable biomass can be advanced by better agricultural methods, the restoration of marginal and degraded lands, and proper adaptation to climate change with respect to maintaining and increasing vegetation [32]. Another key consideration is competition for use. In a sustainable future, biomass feedstock will also be used to produce biofuels (e.g., for sustainable aviation fuels) and/or bioenergy. Although production of chemicals constitutes the intrinsically highest value use of biomass feedstock [35] followed by biofuels and finally energy and heating, the current regulatory environment and practical considerations do not always promote that same order of use [21]. Finally, other considerations around biomass use are the global differences in supply and demand, whether and how a ‘fair share’ principle should be applied, the concept of biomass re-use, and developments in sustainable agriculture to achieve higher yields whilst reducing environmental impacts.

Global sustainable biomass availability estimates range widely, from 1 to 30 billion tonnes by 2050 depending on assumptions around collection and preconditions for sustainability [36] [37] [38]. The current worldwide biomass demand according to a study by Nova Institute is 13.4 billion tonnes, of which only about 3.8 million tonnes (<0.1%) is used for biobased polymers [12]. It is important to note here that demand for biomass does not only come from materials, but also from food (15% in 2022) and feed (56% in 2022) and this demand is likely to grow with a growing population. The increasing demand for these uses from population growth might be balanced by an increasing uptake of a (more) plant-based diet. Since >7 bn tonnes of biomass are currently used for feed, if global meat consumption were to halve towards 2050, an additional 3.5 bn tonnes of biomass would become available for potential use in biobased products.

For the current bioplastic production levels, biomass availability seems not to be an issue. However, it is possible that a supply-demand gap will emerge when vast volumes of plastics will shift towards biobased and there is no significant plastics recycling capacity build-up. For example, studies have estimated that a complete replacement of global packaging plastics (170 million tonnes) by bioplastics would require 54% of the current corn production and a large share of freshwater withdrawal [30]. At the same time, as other biomass feedstocks such as second and third-generation and other renewable sources such as recycled plastic feedstock and CO_2 will also take a share, and use of fossil feedstock use will not cease immediately, this scenario is not likely. There will be a transition, where gradually more biomass will be required for bioplastics. Eventually, assuming a global plastics demand of 1,000 Mt by 2050, assuming a biobased share of 20% (200 Mt bioplastics) and assuming 3-5 tonnes of biomass are required to make 1 tonne of bioplastic (with allocation to by-products), 600-1000 Mt of sustainable biomass would be required globally by 2050. Considering the ranges of availability estimates, it would be reasonable to say that sufficient biomass will be available for biobased polymers if biomass is prioritized for this use.

The other renewable carbon feedstock considered here is CO_2. There are two possibilities to obtain this feedstock: from air via Direct Air Capture (DAC) and from point sources via Carbon Capture and Utilization (CCU) from for example power generation and hard-to-abate industries (e.g., cement production). The estimated global availability of captured CO_2 by 2050 is around 5,500 Mt [39], of which the vast majority is expected to be from point sources. Although the transport and logistics of the captured CO_2 is a critical factor for practical application and there is some debate regarding whether (EU) regulation will continue to allow use of captured fossil CO_2, it was assumed in this whitepaper that CO_2 as a feedstock for plastics production is sufficiently available. The limiting factor in this value chain is, however, not the availability of CO_2, but rather the green hydrogen available and the renewable energy required to produce this. Again, assuming a global plastics demand of 1,000 Mt by 2050 of which 20% is CO_2-based, will result in a demand for 200 Mt synthetic plastics produced per year. Assuming 40% conversion efficiency in the Methanol to Olefins process, 500 Mt of green methanol would be required, translating to about 100 Mt of green hydrogen required [40]. This would require over 4,000 TWh of green energy to be produced (assuming 44 kWh required to produce 1 kg of hydrogen as is the case for Alkaline and PEM electrolysers), constituting about a third of the current total global renewable electricity production and about 8% of the 50,000 TWh renewable energy McKinsey estimates to be generated by 2050 in the continued momentum scenario [41]. It is challenging to conclude whether enough green hydrogen is expected to be available to meet the demand for plastics production, as availability will be highly dependent on the speed of the energy transition, magnitude and cost of renewable energy generation, and the hydrogen production capacity build-up.

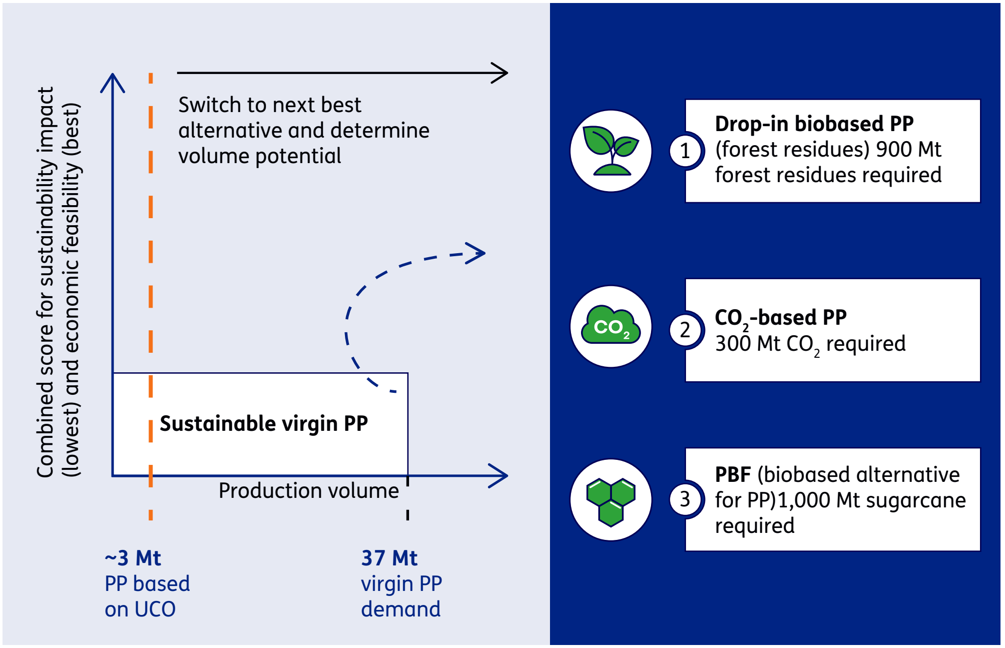
2.3 Step 3: Decide on the pathway for the situation, given constraints and scenarios

The third step in the framework is to decide on the pathway per product for a specific situation, given the impact of constraints and the assessment of scenarios considering time, location, and situation. The results of step 2 can be ranked to create a merit order, indicating which solutions should be given priority for implementation since they score best in terms of sustainability impact (lowest) and economic feasibility (best). The practical implementation of the solutions in a specific situation is dependent on constraints such as the availability of biomass, captured CO_2, (renewable) energy, green hydrogen, and on other globally or locally relevant parameters.

The merit order needs to be combined with the plastic volume to be produced, resulting in a 'marginal implementation curve'. The system can then be optimized given the selected constraints or scenarios. An example of how such a marginal implementation curve can be used is shown in Figure 10 for the sustainable production of PP. By 2030 the estimated global market volume of PP is ~105 Mt [42], translating to roughly 37 Mt virgin production demand (35% virgin production required given 60-70% recycling). As determined in the analysis of the use cases presented in Chapter 3, a winning pathway toward PP is the utilization of the feedstock Used Cooking Oil (UCO). The global estimated availability of UCO by 2030 is ~30 Mt [43], which through utilizing the propane byproduct from renewable fuel production translates to ~ 3Mt PP production volume potential (in total 9.8 tonnes of UCO are required to produce 1 tonne of PP). This 3 Mt PP from UCO (the volume left from the orange availability line) is only 8% of the global production volume required (37 Mt). For the volume falling to the right of the red availability line (~34 Mt), an alternative production pathway needs to be selected. In this case through switching to the other options in order of preference: using forest residues to produce drop-in PP, or switch to CO_2-based PP production, or switch to the biobased alternative PBF. When not considering allocation efficiency to by-products (which is the relevant view here, since the total volume that can be produced based on the total availability is determined), this would require 950 Mt of forest residues (29 t/t PP) or 20% of the potentially available 5,000 Mt [36], 300 Mt of CO_2 (8.5 t/t PP) or 5% of potentially available 5,500 Mt, or 1,000 Mt of sugarcane (30 t/t PP) or 50% of potentially available 2,000 Mt.

Finally, the impact of scenarios can be assessed in step 3 by changing one or more parameters in a similar way. It also allows for running a sensitivity analysis.

Figure 10: Example constraint assessment for PP production by 2030, given expected global availability of Used Cooking Oil



Chapter 3

Applying the framework to selected use case examples

The framework presented in this whitepaper can be used to develop insights across the entire global plastics system by working out the results for all major polymer types and applications, thereby providing direction on where and which type of biobased plastics can be best applied and thus substantiating the share of biobased vs. CO_2-based renewable carbon in plastics. To illustrate the framework application, four use cases have been selected and results were determined using the TNO framework: 1. HDPE in plastic bags, 2. PP in automotive parts, 3. PET in packaging bottles, and 4. PA in clothing textiles. These use cases cover common applications of the selected polymers and collectively cover a significant share of the plastics used today.

3.1 Step 1: Search options, determine novel biobased alternatives and specify the pathways

Following the steps in the framework, we first specify the three pathways for each of our four use cases and determine which novel biobased polymers could fulfil the same functionalities in these existing applications. The prediction model shows that in terms of quality of properties, the biobased polymer PLA should be able to replace HDPE in plastic bags [44] [45], a novel polymer of butanediol and FDCA (for convenience abbreviated here as PBF) could replace PP in automotive parts, the biobased polymer PEF could replace PET in plastic packaging bottles [46], and a novel polymer of 1,3-propanediol and FDCA (abbreviated as PPF) could replace PA in clothing textiles [47][1].

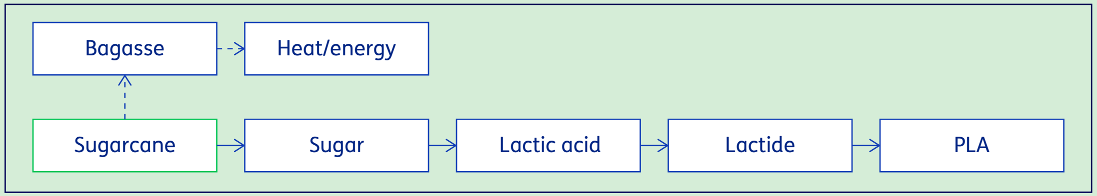
The pathways for the use cases were specified and the underlying value chains were detailed out. An overview is shown in Figure 11.

1 Please note that this is a theoretical exercise based on 5 selected polymer properties and does not consider practical limitations such as market introduction and production scale of novel polymers, nor does it suggest all global volumes should presently be replaced. Further research with more technical criteria and practical testing would be required.

Figure 11: Overview of the four use cases and specified renewable carbon production pathways. The value chain for each specified pathway was detailed out (example shown here for PLA)

Use case	(Novel) Biobased alternative	Drop-in biobased	CO_2-based
HDPE in plastic bags	PLA	Bio-HDPE	Synthetic HDPE
PP in automotive parts	PBF - A novel copolymer of butanediol and FDCA	Bio-PP	Synthetic PP
PET in bottle packaging	PEF	Bio-PET	Synthetic PET
PA in clothing textiles	PPF - A novel copolymer of 1,3-propanediol and FDCA	Bio-PA6	Synthetic PA6

The underlying production value chains were detailed out for each pathway-product combination, example shown here for PLA

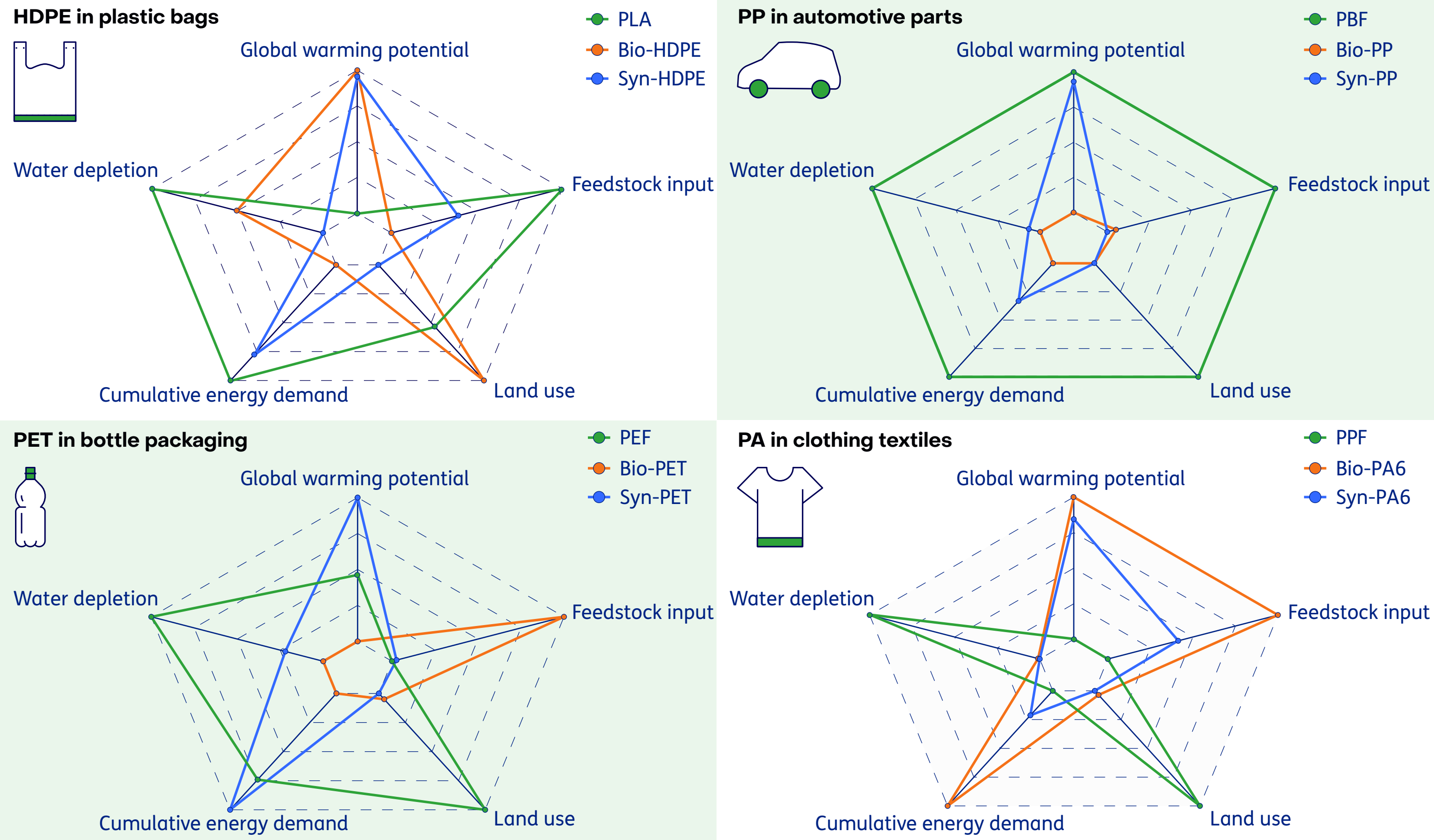


3.2 Step 2: Compare pathways on sustainability impact & economic feasibility

In step 2 of the framework, sustainability impact in terms of global warming potential, cumulative energy demand, land use, water depletion, and feedstock input required of these pathways was assessed in TNO's sustainability impact assessment tool. The results are shown in Figure 12.

For HDPE in plastic bags, the three renewable carbon-based pathways have different impact patterns. Biobased HDPE scores best (lowest) on cumulative energy demand and feedstock input required, but worst in terms of land use. PLA shows a lower efficiency in feedstock use, energy demand, and water depletion but shows a relatively good overall global warming potential due to energy recovery in the process. CO_2-based HDPE scores best in terms of water depletion and land use and average on feedstock input, but has a relatively high global warming potential given the cumulative energy demand. For PP in automotive parts, biobased PP scores best on all indicators due to use of second-generation feedstock without land use

Figure 12: Sustainability impact results for the four use cases



(UCO), an energy efficient production process, and high yields. The novel biobased alternative PBF scores worst in most indicators driven by high feedstock input required and corresponding land use and water depletion combined with a relatively high cumulative energy demand for production. For PET in plastic bottles, biobased PET has a high feedstock input required, but aside from that seems to be environmentally favorable compared to PEF and the synthetic route because of the lower cumulative energy demand. The high sustainability impact, mostly driven by the cumulative energy demand, for CO_2-based PET can be explained by the inefficiency of the methanol to BTX process, as well as the general process complexity of this pathway. When comparing biobased PET and PEF, PEF scores significantly better in terms of feedstock efficiency while biobased PET scores better on other indicators. For PA in clothing textiles, it can be observed that PPF scores best on feedstock input required, cumulative energy demand, and global warming potential. Both PA6 pathways score better on land use and slightly better on water depletion but generally do not score well due to high energy demand and feedstock required in the complex processes.

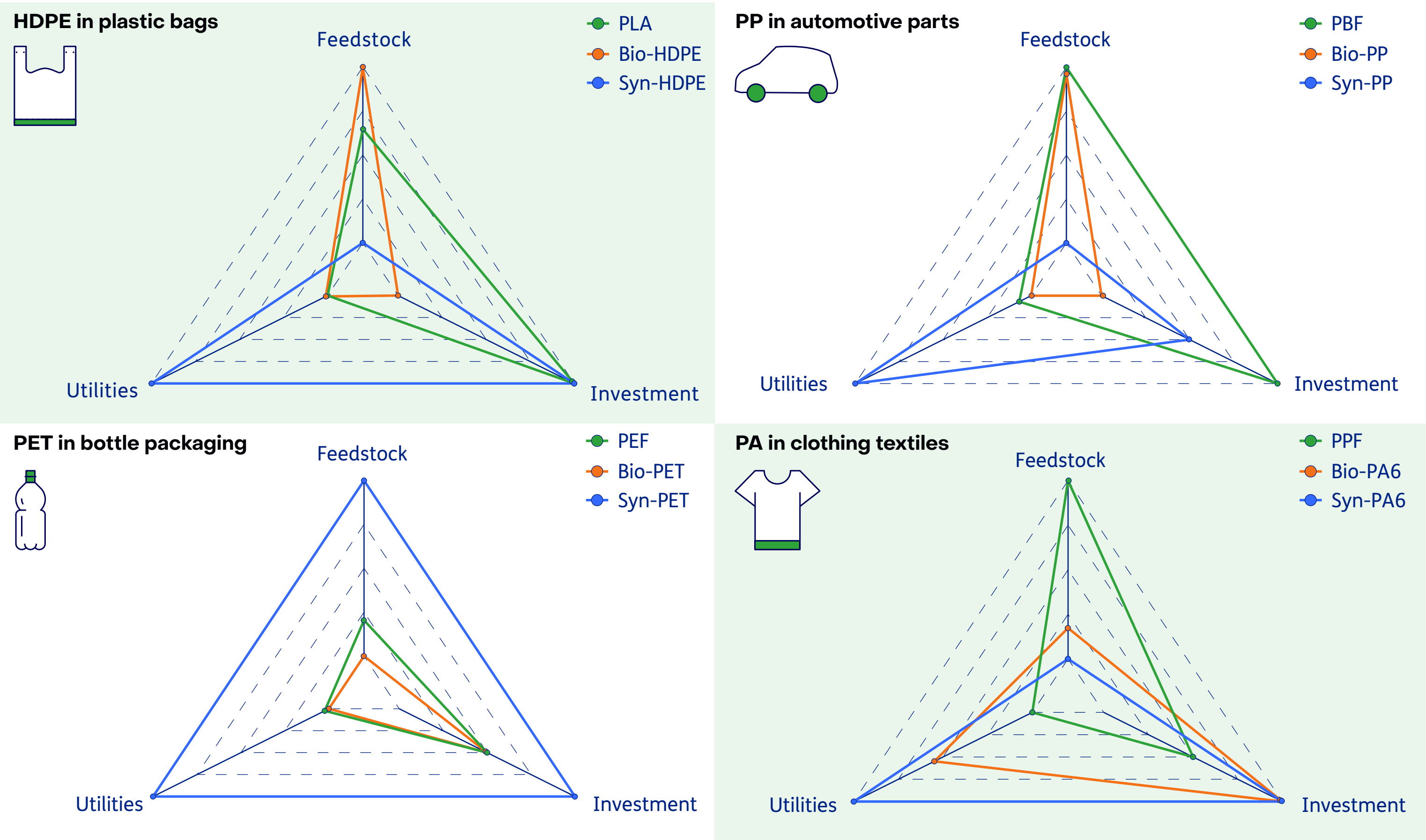
The environmental sustainability impact results seem to be quite dependent on both process yield and type of biomass used, which is resembled in the amount of feedstock input required, land use and water depletion that are all related to biomass growth. For first-generation feedstock (e.g., sugarcane, corn) these impacts are highest, whereas production routes using second-generation feedstocks (e.g., used cooking oil, forest residues) show lower (better) scores on these indicators. Switching to second-generation feedstocks for production of novel biobased plastics (in this example PLA, PEF, PPF, and PBF) could thus improve the sustainability performance of those bioplastics, particularly when renewable energy is applied for the potentially additional energy demand of the additional feedstock processing steps required. As mentioned in Chapter 2, a single focus on global warming potential in CO_2 equivalents (as is not the case here) would result in a limited view of sustainability impact, which is often described as a carbon tunnel vision. Especially given the strong influence of the assumptions on energy mix (i.e., the global warming potential is a result of the cumulative energy demand multiplied by the CO_2 footprint of the energy mix used) and potentially integrated heat sources. In this analysis, the current energy mix (mostly grey) was used in determining global warming potential. The energy mix is expected to change significantly over the next few decades, decreasing the CO_2 footprint and thereby the absolute global warming potential in sustainability impact determination. The relative order of results will however not change, as this is driven mostly by the cumulative energy demand. Therefore, the cumulative energy demand may prove to be a more comparable indicator to consider and the global warming potential was excluded in determining the summary color scoring for the use cases.

Furthermore, the results based on the current assumptions suggest that drop-in versions of carbon backbone polymers like HDPE and PP can generally be produced efficiently with lower feedstock input required compared to the novel biobased alternatives for these polymers. This can partly be explained by the years of efficiency and engineering improvements in the petrochemical industry, whilst the production of novel biobased alternatives has not been established long enough for such process and scale improvements to fully materialize. The novel biobased options subsequently show a relatively high environmental impact in these results.

For condensation polymers, the opposite pattern is observed. Here the novel biobased alternatives already generally perform better compared to drop-in polymers on feedstock input required and sustainability impact. This is in line with the principle of 'oxygen efficiency'; conversion of biomass into hydrocarbon drop-in building blocks requires the full removal of oxygen in biomass (presenting yield losses since CO_2 or CO are being formed in this process) while some novel biobased alternatives can be produced with improved atom efficiency from biomass to monomer (maintaining the oxygen).

Subsequently, economic feasibility was estimated for all pathways for the four use cases as per the method described in Chapter 2.2. Results are shown in Figure 13.

Figure 13: Economic feasibility results for the four use cases



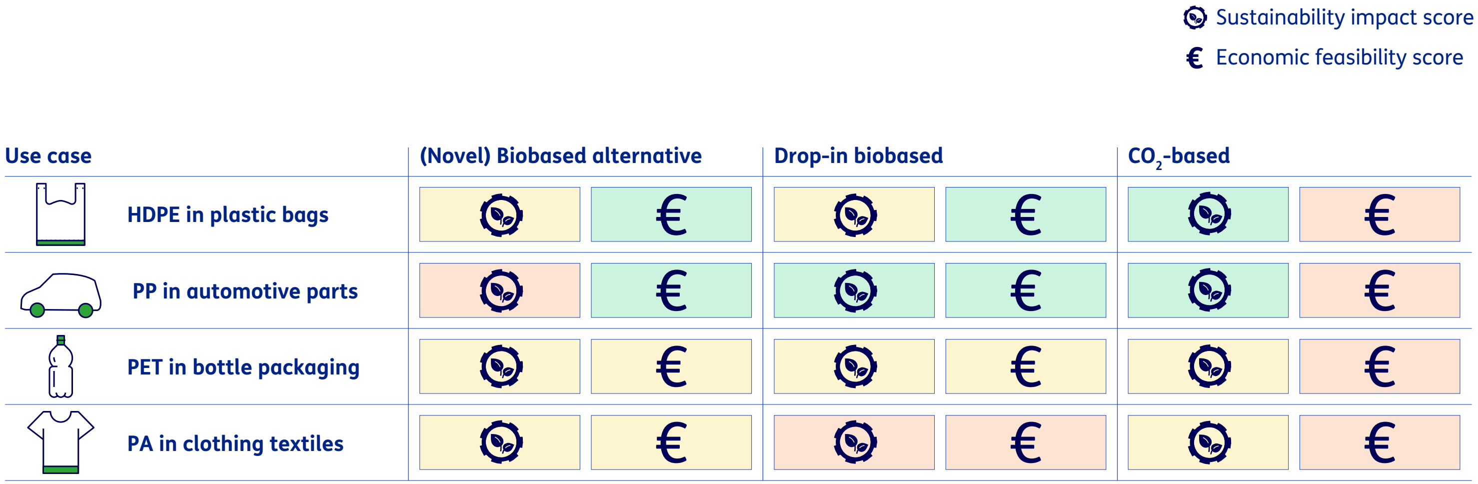
The underlying total estimate of economic feasibility for the four use cases shows that for relatively less complex production processes (HDPE and PP), the absolute cost per tonne product is estimated to be lower than for more complex production processes (PET and PA). Novel biobased alternatives usually have a more complex production process and thereby a relatively higher costs for utilities and capex. Although it can also be observed that the existing biobased alternatives (PLA and PEF) already score better in terms of economic feasibility than 'novel' biobased that are still on lower TRL level. All synthetic (CO_2-based) routes have high utilities costs due to the high costs of green hydrogen which is required in the process.

Generally speaking, the economic feasibility of all pathways is lower compared to their fossil counterparts. For renewable carbon-based plastics, the cost per tonne product can be reduced over time as production capacity and market penetration of biobased or synthetic plastics go up, especially for the novel biobased alternatives. The economic feasibility results also show that the choice for pathway often presents a trade-off between types of cost: using a lower cost feedstock such as forest residues or CO_2 often results in higher utilities cost due to higher energy demand for processing.

Furthermore, utilities and feedstock costs were now assumed based on global averages, whilst in reality these prices are likely highly dependent on location.

Combining results for sustainability impact and economic feasibility allows stakeholders to draw conclusions on the theoretical 'best' pathway for virgin production for each of the four use cases. The deduction method for a single summary color score for sustainability impact (based on absolute results ranges per indicator and subsequent weighting of indicators) and economic feasibility (based on total cost estimate ranges) was described in Chapter 2.2. The best options (lowest sustainability impact and best economic feasibility) are indicated as green, and the worst options are indicated orange. The results comparison matrix for the use cases is shown Figure 14.

Figure 14: Results comparison matrix for the four use cases



3.3 Step 3: Decide on the pathway for the situation, given constraints and scenarios

The use cases do not consider a specific situation and the input assumptions for this analysis were based on literature-backed global averages. Hence, a decision based on situation-specific constraints is not yet possible. To assess the potential variability with situation-specific case studies, several scenario assessments were performed on these results to test the methods' robustness and sensitivity towards data inputs. In the first scenario assessment, it was assumed that all process yields could be increased to 95% of the theoretical maximum. A yield improvement would be reasonable to assume once the novel biobased routes achieve similar efficiency as is now possible in the petrochemical industry. This would lead to a higher feedstock efficiency for the novel biobased alternative and CO_2-based routes, thereby decreasing costs for feedstock and utilities. The effect is most significant for PPF (novel biobased alternative for PA), PBF (novel biobased alternative for PP), and PEF (novel biobased alternative for PET), however not significant enough to change the relative order of performance of the pathways. A second assessment was performed, where a reduction in costs for utilities was assumed. In a future with significantly more renewable energy generation, it would be reasonable to assume that the costs for electricity, heat and steam, and green hydrogen would decrease significantly [48] [49]. A reduction of 50% in utilities costs greatly improves the economic feasibility of pathways with high energy demand, with the greatest effect visible for the CO_2-based pathways. Nevertheless, the CO_2-based pathways remain the most expensive option and the relative scoring of pathways per use case again stays the same. The third scenario assessment was performed on the required investment by halving and doubling the capex costs. In both cases, the absolute effect was greatest for those routes with highest capex (PET, PA and alternatives), but again the relative performance of pathways did not change (as the investment-component varied between roughly 5-25% of the total costs for the calculated pathways). At last, competition for biomass feedstock may put pressure on the cost price. A scenario where all biomass feedstock costs increase by 50% has most effect on routes where the most expensive feedstock is used (first generation feedstocks or used cooking oil), such as the novel biobased alternatives PPF and PBF, and bio-PP. The conclusion is however, again, that the order of economic feasibility across the different pathways is not impacted. The four scenario assessments show that, even though based on relatively high-level assumptions, the use case results are robust. As such, these assessments highlight the robustness of the methodology and where the sensitivities are within the boundaries set. Finally, the assessment results show that application of location-specific restraints would likely yield significantly differentiated outcomes between pathways. For example, a location with renewable energy abundantly available, but lacking sustainably sourced biomass might favor CO_2-based pathways over biobased pathways.

In conclusion, the framework application to the four use cases based on the assumptions used in this study has shown that a good option for virgin production based on renewable carbon for HDPE in plastic bags would be to replace fossil HDPE by either biobased HDPE or PLA. A good alternative for fossil PP in automotive parts is biobased PP, although synthetic (or CO_2-based) PP could be a good alternative when costs for renewable electricity and green hydrogen come down. For PET in bottle packaging, either biobased PET or PEF score as suitable pathways. Finally, for PA in clothing textiles the best option based on this analysis would be to use the novel copolymer PPF.

Chapter 4
Framework application potential

The framework presented in this whitepaper provides an approach that can be used in many different scopes, highlighting its further application potential. In applying the framework for all major plastic products in our global plastics system, optimized pathways towards a sustainable circular plastics system can be determined. This approach enables stakeholders to select the most suitable renewable carbon-based production pathway for each specific plastic type and application. Consequently, it provides clear guidance on the decisions and actions necessary to achieve this transition. Compiling the results also allows stakeholders to draw conclusions on the overall share of biobased versus CO_2-based plastics and in which products application of bioplastic makes most sense, thereby unlocking market opportunities.

Furthermore, the framework is adaptable to regional contexts, accommodating local constraints such as access to feedstock and utility costs. For instance, in Northern Europe, forest residues may be a more viable feedstock compared to sugarcane given the region's specific resource availability and economic factors. Additionally, regional differences in the energy mix—both in cost and the share of renewable energy—can significantly impact decision-making. By tailoring the input parameters and option space to a specific location, region, or country, policymakers and industry leaders can gain valuable insights to optimize their strategies.

Moreover, this framework has potential for practical application in specific scenarios for industry players, enabling the determination of the best pathway for renewable carbon-based production of their products, as demonstrated in the use cases. Similarly, it could allow companies to assess the impact of potential changes in their production pathways, for example assessing the impact of switching from first generation to second generation feedstock for the same biobased plastic material. By setting precise input parameters for the company and defining the constraints (such as practical availability of biomass or setting boundary conditions for the solution space given supplier offering of materials or other strategic considerations), stakeholders such as brand owners, polymer producers, and/or plastic compounders can make informed choices about the plastic materials to use in their products or packaging.

Table 2: Summary of framework application potential for various stakeholders

Stakeholder	Example insight	Scope
Global (sustainability or branch) organizations	Pathways to a sustainable plastics system for all major plastic products, a systems perspective on volumes per renewable carbon feedstock type, and insight in where biobased (alternative) plastics are best applied	Common plastic materials and application domains globally
(Regional) Policymakers	Regional pathways to a sustainable plastics system for all major plastic products, a systems perspective on volumes per renewable carbon feedstock type, and insight in where biobased (alternative) plastics are best applied	Common plastic materials and application domains for the respective region given regional specifics (e.g., on biomass availability and prices, energy mix and costs, environmental impacts of biomass production or import in that location)
Brand owners (and/or compounders)	The optimal renewable carbon-based production pathway for their product(s)	Brand owner's product material specifications and specifics on the situation (e.g., local production input assumptions, supplier options)
(Biobased) Plastic producers	Impact assessment of potential changes in production pathways and/or materials produced and identification of the most optimal product application for existing materials	Producer's current and potential production pathways, materials produced, and specifics of the situation (e.g., feedstock types used and obtainable incl. their sustainability profile and price)

In addition, the framework could provide a robust tool for strategic assessment of the impact of technical advancements on the plastics production system. As new production pathways for biobased polymers or synthetic polymers emerge or are further refined—such as the development of a fermentation route to CO_2-based plastics that can bypass the platform chemical methanol [50] — the framework allows for immediate screening and comparison with existing alternatives. It also highlights pathways that are currently non-viable or less sustainable, providing critical insights into areas where innovation is necessary. Similarly, the framework can evaluate the impact of technological developments or novel innovations within specific steps of a production pathway. It can analyze the effects of different technological scenarios, such as learning curves, yield improvements, and time-sensitive input factors (e.g., future energy mix assumptions).

Finally, the results generated by the framework are dynamic and can be continually refined as more specific or optimized input data becomes available, driven by ongoing advancements in sustainability analysis, biobased polymer design, and process engineering.

In conclusion, TNO's 3-step framework presented in this whitepaper can support industry players such as brand owners, chemical producers, and compounders, as well as policymakers in the transition towards renewable carbon-based plastics by finding the most sustainable and economically feasible solution for your product or scope. Let's apply this framework together, find the best solution for your product(s) and accelerate the transition to renewable carbon in plastics!

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Auteurs
Ellen de Ruiter, Jan Harm Urbanus,
Anna Schwarz, Milad Golkaram,
Pieter Imhof

Contact
Pieter Imhof

Business developer
Circular Plastics

Pieter.Imhof@tno.nl
+31 6 5152 1179
https://www.linkedin.com/in/pieterimhof

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