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Abstract

This paper analyzes the future market perspectives for biodegradable bio-based plastics at the global and the European level. Relevant determinants of demand are identified, categorized and used as a basis for own projections. By implementing a system dynamics approach, the evolution of global production capacities is modelled on an annual basis for the period until 2030. To capture the inherent uncertainty in such a long-term projection, different scenarios are defined and applied to the model, reflecting different developments in GDP growth, oil and bioplastic feedstock prices. In this way, our results document the sensitivity of the bioplastics market towards changes in the macroeconomic environment. The simulations are complemented by a discussion of the relevant regulatory framework at the European level and its potential repercussions on market growth. The results indicate a significant growth potential, which however turns out to be very sensitive towards both economic and political impact factors.

JEL codes

Q57, L65, Q21

Keywords

Bioplastics, System Dynamics, European Plastic Policies, Bioeconomy

1 | Introduction

Currently, one percent of the 360 million tons of plastic produced annually can be classified as bioplastics (European Bioplastics, 2019). In analyzing this market segment, one has to be aware that "bio" can mean quite different things in this context. According to the official definition of the industry association European Bioplastics, bioplastics comprise plastic materials which are either biodegradable, bio-based or both. Specifically, materials are 'bio-based' if they are (partly) derived from biomass and 'biodegradable' if within a reasonable amount of time they can be broken down by microorganisms into the natural substances water, CO_2, and compost.

In recent years, this segment has gained attention due to its potential role in creating a fully sustainable and circular bioeconomy. As an expression of a growing environmental awareness of consumers, the demand for bioplastics is rising. Foremost, this concerns the branch that is bio-based. Due to their use of renewable instead of fossil-based resources, they exhibit ecological advantages in terms of a lower CO_2 footprint and less intense resource depletion compared to conventional plastics. To the extent that they are bio-degradable in natural habitats, they also promise a solution to the increasingly pressing issue of plastic debris on land and sea. Moreover, at least some of the materials have reached a development stage where they can offer (almost) the same technical properties as fossil-based plastics and are therefore suitable for many applications. On the downside, however, one must acknowledge the currently still very high production costs, which significantly exceed the costs of producing fossil-based plastics. Furthermore, at least with the current generation of food plant based resources used in bioplastic production, the overall environmental balance is rather mixed: there is a potential competition with food production and the emissions resulting from land use and transformation can be considerable as well.

How the demand of bioplastic will develop in the next few years depends strongly on the development of the prices of conventional plastics. Furthermore, other factors such as technological progress, economies of scale or raw material costs influence the development. In addition, policies aimed at supporting sustainable alternatives to fossil fuel-based plastics can significantly change the demand for bioplastics. In making quantitative projections, it is therefore important to use a model that takes into account as many of these factors as possible when forecasting future demand.

This report summarizes results and methodological approach of scenario-based long-term projections for the bioplastic market. In doing so, our focus is on the branch of bio-based biodegradable plastics, as this seems the most promising area from a sustainability perspective. By applying the method of system dynamics modelling and building on a previous approach by Horvat et al. (2018), the evolution of production capacities for bio-based biodegradable bioplastics is modelled on an annual basis for the time until 2030. To capture the inherent uncertainty in such a long-term projection, three different economic scenarios have been defined and applied to the model, reflecting different developments for important background factors like GDP growth, crude oil, and bioplastic feedstock prices. In this way, our approach documents the sensitivity of the bioplastics market towards changes in the macroeconomic environment. As far as possible, the model has been calibrated based on data from public databases and the relevant literature. Afterwards, the simulation results are discussed in the context of the current and potential future political framework at the European level, to shed light on the importance of providing a sound regulatory basis for the market development in this segment.

The paper is structured as follows: Section 2 gives an overview on existing projections for the bioplastic market. Section 3 discusses on a general level the different categories of impact factors on the future market evolution. Section 4 presents our modelling approach and the data sources used for calibrating the model. Section 5 presents and discusses results of our main scenarios and the subsequent sensitivity analysis. In discussing the regulatory framework, section 6 puts these results into a policy perspective. Section 7 concludes and makes suggestions for future model refinements.

2 | Existing projections for the bioplastic market

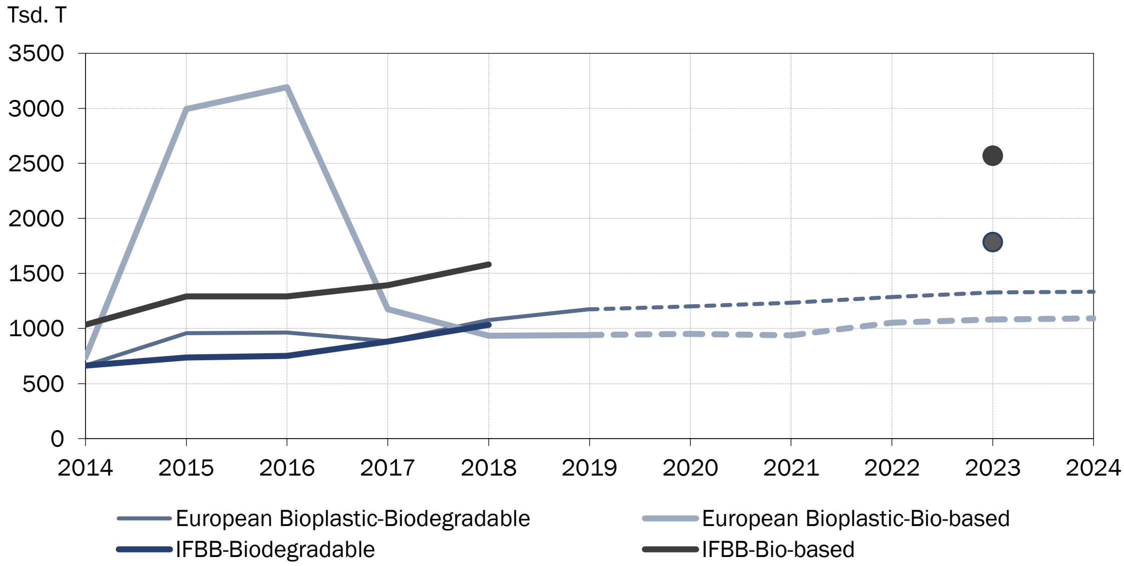
There are a few reports that provide projections for the bioplastic market. European Bioplastics and the Institute for Bioplastics and Biocomposites (IFBB) publish an annual report on the development of the bioplastics industry, which also includes forecasts on the development of global bioplastics production capacities. While the latest report of European Bioplastics shows the development of the global production capacity for the next five years (2020 – 2024), the latest report of IFBB presents only the forecast values for 2023. Both reports contain forecasts for both bio-based and biodegradable plastics.

Figure 1 below displays the development of production capacities for bio-based and biodegradable plastics for the years 2014 to 2024, with the dotted lines indicating that these are forecast values. The figure shows on the one hand the projections of the report by European Bioplastics (2019) and on the other hand those of the IFBB (2019). Please note that the IFBB only adds the four-year forecast value in their annual reports and does not update the other forecast values. Therefore, the graph only reports the forecast values for 2023.

As can be seen, both the historical values and the forecast values of the two institutions show clear differences. The two studies assume different growth rates. The IFBB (2019) forecasts significantly higher values than European Bioplastics (2019). European Bioplastics (2019) shows a percentage growth in production capacity of 23.31 % for biodegradable plastics between 2018 and 2023 and an average growth of 15.85 % for bio-based plastics. IFBB (2019) estimates the average growth in 2023 compared to 2018 at 72.80 % and 62.43 % for biodegradable and bio-based plastics, respectively. For 2023, the IFBB (2019) projects production capacities of 1.8 million tonnes for biodegradable plastics and 2.6 million tonnes for bio-based plastics. In comparison, European Bioplastics' figures are 1.3 million tonnes for biodegradable plastics and 1.1 million tonnes for bio-based plastics. European Bioplastics (2019) attributes the higher increase in production capacities for biodegradable plastics compared to bio-based plastics in particular to the significant growth rates of Polyhydroxyalkanoates (PHA).

Unfortunately, neither report contains information on the methodology used. It remains unclear which model was used to calculate the forecasts and which data and impact factors were considered. It is therefore incomprehensible how the differences in the values came about. The sources or the calculation methods of the historical capacity values are also not presented transparently and even these differ greatly between the two reports.

Figure 1: Global production capacities for bioplastics



Source: European Bioplastics (2019); IFBB (2019)

In addition to the technical reports, there are also scientific papers dealing with the projection of future developments of the demand for bioplastics. For example, a study by Horvat et al. (2018) uses a system dynamics model to simulate three different growth paths of global demand for bio-based plastics up to 2030. The system dynamics model is used to capture the interplay of different impact factors on the bioplastic production, e.g. learning effects, oil prices, prices for fossil-based plastic, feedstock and production costs and price elasticities. The three simulation scenarios differ in the development of oil prices and the policy measures taken. The study considers a baseline scenario, a high oil price scenario and a de-risking scenario (including policy measures). In all three scenarios the demand for bio-based plastics increases, whereby the de-risking scenario assumes a significantly higher growth. In the baseline scenario, demand doubles between 2015 and 2030 and in the high oil price scenario, demand increases by 150 %. The de-risking price scenario forecasts an increase in demand for bio-based plastics to over 6 million tonnes in 2030, which is more than six times higher than the demand in 2015. However, in view of current developments in the oil markets, the assumed growth rates of the oil price are relatively high in all three scenarios, and even in the low oil price scenario the assumed oil price is significantly higher than the average oil price in 2019 and 2020.

3 | Impact factors on bioplastic demand

The difficulty in projecting the future development of the demand for bioplastics lies on the one hand in the multitude of factors influencing the demand and on the other hand in the quantification of these impact factors. Furthermore, the development of the impact factors is also subject to uncertainty.

The main impact factors can be divided into the following four impact categories:

1. **Macroeconomic factors**:

    - **Crude oil prices:** The development of crude oil prices significantly influences the development of bioplastics demand. As conventional plastics are largely produced from crude oil, the price depends strongly on the development of the oil price. With a high oil price and the associated high prices for fossil plastics, bioplastics become more attractive as a substitute. Therefore, an increase in oil price will lead to an increase in bioplastic demand.

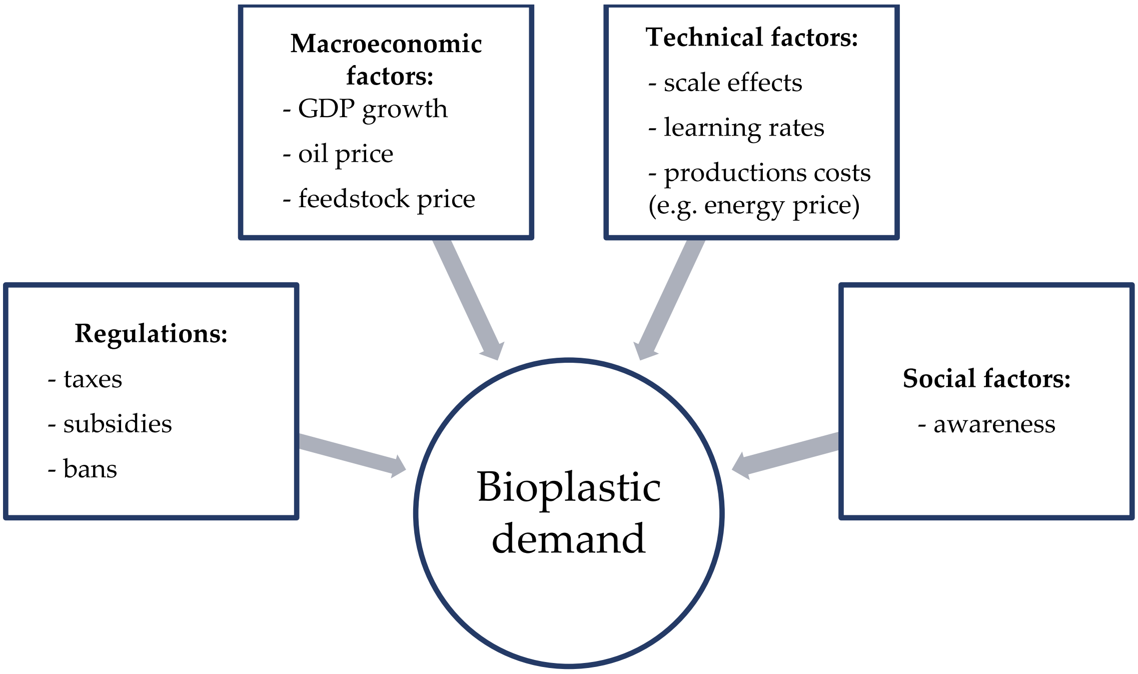
- **GDP growth:** A rise in GDP could lead to an increase in the demand for plastics in general and thus also to an increase in the demand for bioplastics. Assuming that market participants with higher incomes spend higher prices on environmentally friendly alternatives, this effect could boost the demand for bioplastics even more.
- **Feedstock costs:** The production costs of bioplastics are highly dependent on the development of feedstock prices. Currently, bioplastics are mainly produced from corn starch or sugar cane. If the prices for corn or sugar rise, the production costs and thus the prices for bioplastic also increase. The higher prices would in turn lead to a decline in demand for bioplastics. The prices for corn and sugar are formed on the world market and can show high volatility.

2. **Regulatory factors:** Policy measures to support environmentally friendly alternatives such as:
    - **Taxes:** Taxes on products made from fossil fuels could lead to an increase in the price of conventional plastics. As a result, the prices for bioplastics would be lower in relative comparison, and thus the demand for bioplastics would increase.
    - **Subsidies:** Through government subsidies, the producers of bioplastics could offer their products at lower prices, which would increase demand.
    - **Bans:** State bans on fossil plastic products would have a strengthening influence on the demand for bioplastics products. However, if the bans apply to any type of plastic, bioplastics products could also be banned, and demand would fall.
3. **Technological factors**: All factors that reduce the production costs of bioplastics production:
    - **Technical progress and learning effects:** Over time, more efficient production methods could be developed, and the learning effects can lead to decreasing costs.
    - **Economies of scale:** By expanding the production volume of bioplastics, companies can exploit cost advantages and generate more output at lower average (unit) costs. Currently, the production volume for bioplastics is relatively low, which results in high production costs.

4. **Social factors**:

- **Awareness:** As awareness of sustainability and environmental protection increases, so does consumers' willingness to pay for sustainable products. This would have a positive effect on the demand for bioplastics.

Figure 2: Factors affecting demand for bioplastics



Source: own representation

As mentioned above, it is difficult to quantify the various influencing factors in order to incorporate them into a model for projecting bioplastics demand. Time series of historical data for crude oil prices, feedstock prices and GDP can be used to derive information about the dependence on bioplastics demand. Since the future development of these variables is also characterised by high uncertainty, in literature and in this paper different scenarios are used to project a range of future developments. Quantifying policy measures that could be imposed in the future is also a challenge, as there is a wide range of policy measures that could all have different impacts. Furthermore, it is also problematic that policies can be introduced at both national and supranational levels, which in turn could lead to different effects. The operationalisation of the awareness effect would be even more difficult.

4 | Method and data

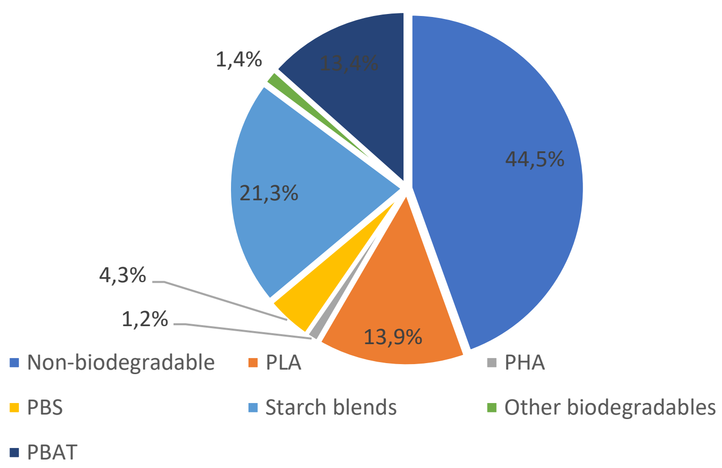
4.1 | Modelling approach

To capture the interplay of some of the most important (and quantifiable) influencing factors on the bioplastic market, we apply a system dynamics approach. System dynamics modelling is a technique that attempts to simulate the behaviour of complex systems over time. In these systems, variables interact with each other in a potentially non-linear manner, which implies that changes in the system as a whole are more than just the sum of changes in its single determinants (Dangerfield, 2020). The types of interactions that can be modelled are diverse, including feedback loops with self-reinforcing or mitigating patterns. As time is an explicit component of these models, functional relationships between variables can also take the form of a delayed influence, which further increases the complexity of dynamic patterns. Nevertheless, in order to ensure some degree of transparency, it has become a usual practice in the system dynamics literature to display a model not just formally (i.e. as a system of equations), but also in the form of easily accessible process graphs.

In case of the still emerging bioplastic production, complex dynamics can e.g. result from the exploitation of learning effects over time and their interaction with market prices and demand. Moreover, the interplay with the price level of fossil-based plastics as the main competitor of bio-based plastics should be taken into consideration. At the same time, data scarcity in this segment prevents a meaningful application of economic General Equilibrium Models. System dynamics modelling thus seems a good choice to project the fate of bioplastics in the near- to mid-term future.

We build our model on the approach by Horvat et al. (2018), which is adapted to explicitly capture the role of macroeconomic impact factors for the bioplastic market. As no immediate data on total demand is available, production capacities represent the main target variable, which are assumed to respond to changes in demand over time. Precisely, we consider capacities for bio-degradable bio-based plastics, as they are of special interest concerning their technological development potential and the political long-term goal of avoiding microplastic emissions (Chinthapalli et al., 2019). Concerning the definition of this segment, we follow European Bioplastics (2019), which classify materials as 'bio-based' if they are (partly) derived from biomass and 'biodegradable' based on the possibility to be broken down by microorganisms into the natural substances water, CO_2 and compost. Within the family of bioplastic polymers, there are some that fit only one of these categories and some which fit both. Figure 3 illustrates the share of different polymers/polymer categories in global bioplastic production capacities in the year 2019. While 55.5 % of the substances are classified as biodegradable, not all within this group are (partly) bio-based. As examples for materials which fit both definitions, Polylactic acid (PLA) and PHA can be mentioned. Concerning Polybutylene succinate (PBS) and Polybutylene adipate terephthalate (PBAT), the categorization is more difficult, as they can be both produced based on fossil or renewable feedstocks, without significant changes in processing technologies (Aeschelmann & Carus, 2015). While there are hopes that the share of bio-based feedstocks used in the production of these polymers will continue to increase in the future, there is no current quantitative breakdown available, so we disregard these polymers in our further analysis. Starch blends are made up of starch added to biodegradable polymers, so the requirement of an at least partly bio-based origin is fulfilled in this case.

Figure 3: Global production capacities 2019 by polymer category



Source: European Bioplastics (2019)

The competition of the so-defined group with conventional fossil-based plastics is modelled by capturing the role of relative prices in plastic demand. Prices are assumed to be determined by unit costs, which for both types of plastics are split into feedstock and process unit costs. Feedstock unit costs reflect the costs of acquiring the central feedstock for the respective plastic type. In case of fossil-based plastics, main feedstocks are crude oil and natural gas. To have a clear point of reference (and given the price correlation between the two resources), we choose the crude oil price as feedstock price variable in our model. In case of bioplastics, production technologies allow for the use of several types of bio-polymers as feedstocks. Unfortunately, no aggregate statistics regarding the share of different feedstocks in current production of bio-based biodegradable plastics are available. However, qualitative information stresses that first-generation feedstocks still represent the dominant source for large-scale production (Ögmundarson et al., 2020). These are carbohydrates originating from agricultural plant production. Starch obtained from corn grain and sucrose obtained from sugar cane are reported as agricultural sources for current mass production (European Bioplastics, 2019). We define the representative bioplastic feedstock as a weighted average of the two. To incorporate potential market repercussions along the value chain, we allow for a feedback effect from bioplastic demand to feedstock unit costs, following Horvat et al. (2018). This reflects a potential demand-induced price change in the biomaterial dedicated for use in bioplastic resin production.

For our purpose, we define process unit costs simply as the cost residual. Hence, they include all the production and transportation costs accruing in the transformation of the extracted bio-polymers into bioplastic resins[1], related to the use of additional material, energy, labour, machinery, and equipment. Since we analyse the market for bioplastic polymers, not for compounds and final applications produced from these polymers, costs incurring further down the value chains are not considered here. As production technology will continue to evolve over the upcoming years, these process unit costs can in case of bioplastics not be expected to remain constant over time. Instead, productivity increases through economies and of scale and the occurrence of learning effects can be expected. In our model, this factor is captured by means of a learning parameter that measures the annual percentage decline in process unit costs.

Finally, we consider the impact of the macroeconomic environment by letting the demand-function for bioplastic not only depend on the relative price of the two plastic types, but also on the Real GDP. Together with the prices for crude oil and agricultural goods, this variable reflects the general economic conditions for the bioplastic market. The three measures make up the foundation of our scenario-based analysis. By varying growth rates for these measures between scenarios, we obtain a spectrum of bioplastic demand projections dependent on the economic outlook (see Section 4.3).

Given the existing data limitations, simulations are undertaken at a global level. Cautious inferences from these global results for bioplastic production in Europe are drawn subsequently. It needs to be stressed that our model is targeted at identifying long-run relationships between the variables of interest. Year-to-year fluctuations in bioplastic demand, as they are caused by short-term variations in prices and income, are thus explicitly not captured. At the same time, predicting future market disruptions, which might

[1] In case of PLA production, for instance, this involves the extraction of starch molecules through wet milling, the decomposition into glucose through hydrolysis, the generation of lactic acid through fermentation and finally the polymerization of molecules to Polylactic acid.

result from changes to the regulation regime or technological breakthroughs, is outside the scope of such an aggregate projection model. Rather, the results of our simulations should be interpreted as plausible long-term paths for bioplastic production under the current market environment and for specific macroeconomic scenarios. Precise model equations are reported in Appendix 9.1. A graphical summary of the relationships embedded is depicted in Appendix 9.2.

4.2 | Data

External data was used on the one hand to define the starting values of the variables in our dynamic system and on the other hand to choose appropriate values for the time-invariant parameters. As starting period, we defined the year 2018, which is the most recent year for which complete information for all variables in the model was available. Data for GDP was taken from the IMF. The crude oil price was calculatedas the annual average of the daily rates of the three most important brands on international oil markets: Brent, WTI and DEM Oman Physical in 2018. The price of the agricultural good used for bio-plasticproduction was defined as an average of the commodity market prices for corn starch (DCE, Future) and sugar (ICE, Future), each again calculated as the annual average of the reported daily prices. The future evolutions of these three economic measures were varied based on different scenarios (see Section 4.3). Regarding the market price of bio-plasticpolymers, availability of public data is very limited. Time series data of prices could only be obtained for PLA (Plasticsinsight, 2020) and merely for 2017. For the other polymer categories (PHA, Starch blends), only experience-based single values could be obtained from van den Oever et al. (2017). As their magnitude matches more general descriptions (Chinthapalli et al., 2019), we adopted these figures. Accordingly, the starting price for bioplastics in our model was computed as a weighted average of these prices, with reported polymer shares in 2018 as weights. Regarding the price of conventional plastics, more recent time series data is available from Macrobond (Macrobond, 2020). The price used in the model was computed as a weighted average of DCE future prices for Polyethylene (PE), Polypropylene (PP) and Polyvinyl chloride (PVC) in 2018.

Estimates for feedstock costs in the starting period were obtained by multiplying prices with the inverse of conversion efficiencies stemming from Gervet (2007) for the case of conventional plastics and IFBB (2019) for bioplastics. Process costs are then deduced as the residual cost components. The time-invariant parameters in the model are specified according to the list below. The technical conversion efficiencies for bio-plastic and conventional plastic production were calculated based on weighted averages of the efficiencies reported for the single polymers considered, as they were published by Gervet (2007) and IFBB (2019), respectively. For the sensitivity of bio-plastic demand towards income changes, no empirical estimates were available. As a conservative default assumption, we consider an income elasticity of 1, implying a proportional adjustment of demand to incomechanges. Given that there is some evidence that income increases come along with a higher preference for environmentally friendly consumption patterns (Levinson & O'Brien, 2019), income elasticities larger than one could be considered plausible as well. This is something we investigate further in the sensitivity analysis. Concerning the price sensitivity, we adopt a result from Dornburg et al. (2006). Given the lack of other estimates, this is also a parameter value whose implications shall be investigated in the sensitivity analysis. The learning rate is adopted from general estimates for bio-refinery processes from Daugaard et al. (2015). For our main scenarios, we implement their most conservative estimate of 5 %, which is increased as part of the sensitivity analysis. In line with Horvat et al. (2018), we assume the learning potential in conventional plastics production to be already exploited. Finally, we account for a potential repercussion of changes in bio-plasticproduction on demand on upstream feedstock markets. However, given that bioplastics will continue to represent a fairly small segment in total demand, this demand sensitivity is practically of a very limited nature. In this regard, we follow Horvat et al. (2018) in setting it to 0.1.

Table 1: Values of time-invariant parameters of the system dynamics model

Parameter	Value	Unit	Source
Conversion efficiency bio-plastic production	0.58	Dimensionless	IFBB (2019); own considerations
Conversion efficiency conventional plastic production	0.75	Dimensionless	Gervet (2007)
Income elasticity bioplastic demand	1	Dimensionless	Own considerations
Price elasticity bioplastic demand	0.5	Dimensionless	Dornburg et al (2006)
Learning rate bioplastic production	0.05	Dimensionless	Daugard et al. (2014)
Learning rate conventional plastic production	0	Dimensionless	Horvat et al. (2018)
Demand elasticity feedstock price	0.1	Dimensionless	Horvat et al. (2018)

Source: own representation

4.3 | Scenarios

As explained above, the focus of our quantitative analysis is on the role of influencing factors from the economic sphere. For the three macroeconomic variables in the model, different growth paths were selected based on external projections and own considerations of likelihood. Concerning World GDP, the current long-term projections by the OECD were consulted. Over the past years, the global GDP grew annually in a range from 3 to 4 %. The OECD long-term projections indicate for the period 2020-2030 a long-term growth potential of about 3.4 % on average per year (OECD, 2018). Alternative long-term projections are available from The Economist, which predict an annual growth potential of merely 2,5 % until 2030 (The Economist, 2015), and PWC, which predict a growth rate of 2.7 % (PWC, 2017). However, these are all projections made before the Corona crisis. Therefore, in order to account for a potential medium-term level effect of the current economic downturn, we complemented these long-term projections with current short-term projections of the IMF for World GDP growth in 2020 and 2021. As a result, when expressed in average growth rates from 2019 to 2030, this gives us a range of growth rates from 2.35 % to 3.03 % as a basis for our different scenarios.

Regarding the development of crude oil prices, we draw upon long-term forecast scenarios from the International Energy Agency (IEA, 2019). They are distinguishing between a reference scenario, a high-price and a low-price scenario. The reference price scenario is for the period 2018-2030 associated with an average annual real price increase of about 1 %. The high-price scenario suggests a much more substantial real price growth of about 10 % per year. By contrast, the low-price scenario implies a decline in real prices compared to the 2018 level by about 4 % per annum. Incorporating the recent price downturn into the forecast leaves us with a potential parameter span from – 0.53 % to + 4.63 %, whose median is used as the baseline case.

Regarding the price development of the relevant agricultural bioplastic feedstocks, two sources were consulted. First, the OECD-FAO agricultural outlook reports long-term projections for a range of agricultural goods for the period 2019-2028, including maize and raw sugar (OECD-FAO, 2019). We extended these projections until 2030 and calculated the weighted average of growth rates based on the assumed feedstock projection. This resulted in an average annual real price decline of -0,45 % for bioplastic feedstock prices. Second, the United States Department of Agriculture has published long-term projections for the development of corn prices until 2029 (USDA, 2019). As a result of several counterbalancing factors, real prices of corn are assumed to stay almost constant until 2029. We converted this information into a parameter span from -0.45 % to 0 %.

Past data indicates that the bivariate correlations between the three measures are only of a modest nature. Hence, statistics alone do not enable us to rule out any specific combination of scenario values as completely unlikely. In order to make the range of resulting projections transparent, we chose the following approach. First, we constructed and simulated a baseline scenario, which is based on the mean values of the reported ranges. Then, we complemented this baseline with one optimistic and one pessimistic scenario, which reflected the (from the perspective of the bioplastic market) most and least favourable conditions within our parameter ranges, respectively. Table 2 summarizes the three simulation scenarios.

Table 2: Overview on simulation scenarios

Variable	*Baseline Scenario*	*Optimistic Scenario*	*Pessimistic Scenario*
World GDP	+2.69 %	+3.03 %	+2.35 %
Crude oil prices	+2.05 %	+4.63%	-0.53 %
Agricultural prices	-0.23 %	-0.45 %	0.00 %

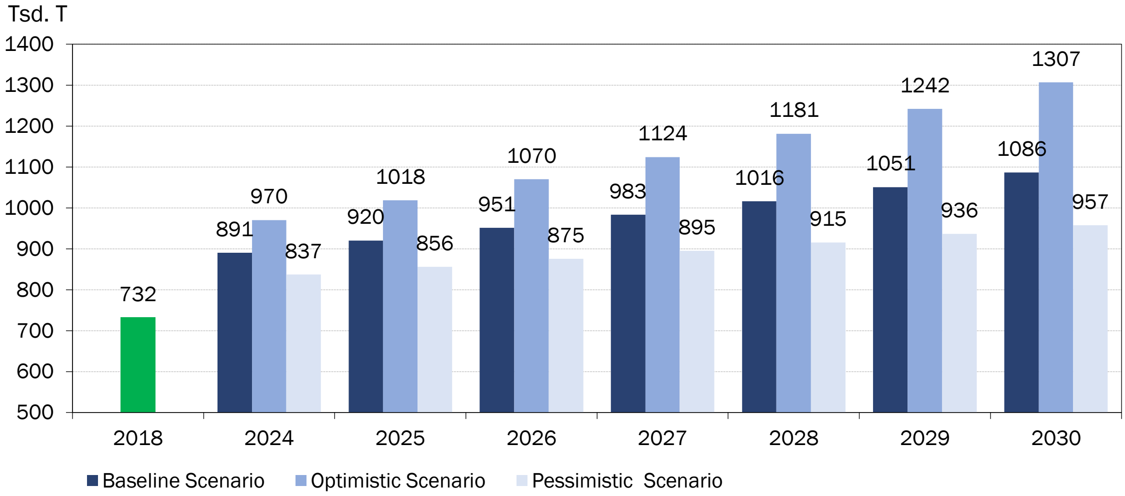
Source: own representation

5 | Results

5.1 | Main scenarios

This section presents the projection results regarding the evolution of production capacities for the market segment of bio-based biodegradable plastics until the year 2030. Given the long-term nature of the scenario values, the current model cannot be expected to produce meaningful results for the most recent future, especially not for the highly distorted years 2020 and 2021 due to the corona crisis. Therefore, the attention has been restricted to the projection results for the time span 2024 to 2030, for which short-term distortions are assumed to have tapered off. Figure 4 depicts the simulation results of our three main scenarios for global production capacities of bio-based biodegradable plastics for this time span.

Figure 4: Simulation results global production capacities biodegradable bio-based plastics

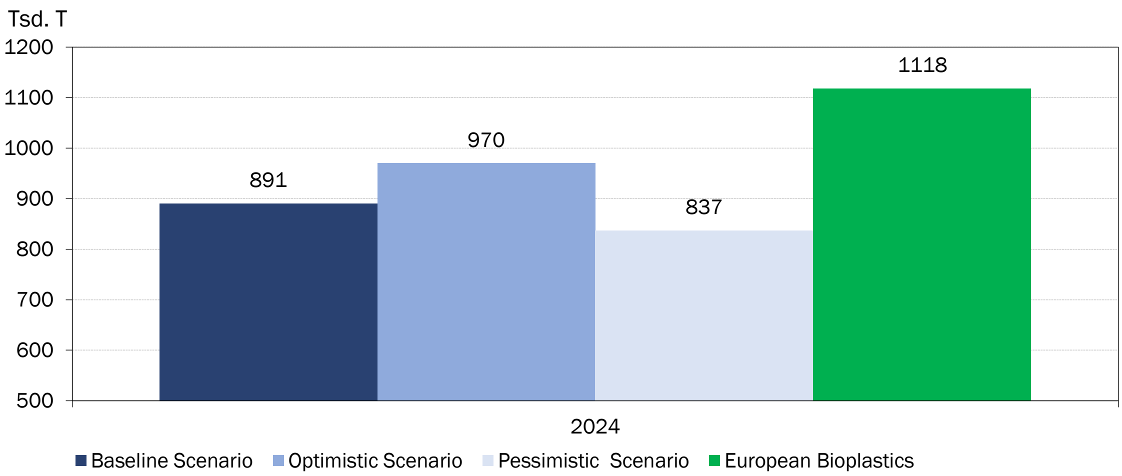


Source: own representation

All three scenarios are characterized by persistent growth for this segment. As expected, the optimistic scenario yields the strongest growth path, the pessimistic scenario the weakest. In the baseline scenario, global production capacities are simulated to grow by 3.35 % on annual average over the projection horizon. In 2030, capacities are projected to reach a level of about 1.09 million tonnes. In the model, this growth results from the combined influence of several factors: general economic growth, an increase in oil prices making conventional plastic production more expensive, a slight decline in prices of agricultural feedstocks as well as the presence of cost-reducing learning effects. In the optimistic scenario, projected capacities exceed to about 1.31 million tonnes in 2030, i.e. almost a doubling of capacities reported for 2018. This corresponds to an average annual growth rate of 4.98 %. A stronger increase in oil prices, a more significant decline in bioplastic feedstock costs as well as more solid GDP growth are responsible for this quite substantial gap to the baseline scenario. Due to the presence of learning effects, the positive demand impulse caused by a relative price decrease of bioplastic materials contributes indirectly to a faster decline in production costs, which in turn stimulates future demand. Thereby, the initial demand impulse initiates through its interplay with the supply-side a reinforcing feedback loop, which further widens the projection range over time. In the pessimistic scenario, shrinking oil prices and the absence of a decline in agricultural prices limit the occurrence of such a positive demand impulse, as the relative increase of feedstock costs counterweighs the impact of learning effects on process costs. As a consequence, capacities merely grow by 2.27 % on annual average, leading to a mass of 0.96 million tonnes in 2030.

In all, the results demonstrate the relevance of the considered macroeconomic impact factors. For a wider view, it is important to put the results into the context of existing projections. Unfortunately, as explained above, the two institutions regularly publishing forecasts for biodegradable bioplastics (European Bioplastics and IFBB) significantly differ both in the reported quantities and the timing of their forecasts. Only from European Bioplastics projections for the year 2024 are already available. Figure 5 compares their reported value for global production capacities in bio-based biodegradable bioplastics with our scenario-dependent simulation results for the same year. While the order of magnitude does not differ dramatically, none of the scenarios under experimentation within this work reaches the expectations of European Bioplastics, not even the optimistic scenario. Reasons for this could be manifold. For instance, the fact that the European Bioplastics analysis stems from a time before the COVID-19 outbreak implies that the current economic downturn and its implications for average economic growth over the upcoming years could not have been considered. Related to this, a more optimistic view on the evolution of oil prices would imply a more favourable outlook on bioplastics' future price competitiveness. It could also be the case that the reference projections attached more importance to the future innovation potential within the bioplastic segment. This could take the form of a more ambitious learning curve, leading to stronger cost declines in upcoming years. It could also reflect specific hopes regarding a future breakthrough of certain polymers. In the biodegradable segment, this mainly concerns PHAs, which are projected by European Bioplastics to experience a substantial increase in market shares.

Figure 5: Global production capacities biodegradable bio-based plastics: comparison results



Source: own representation

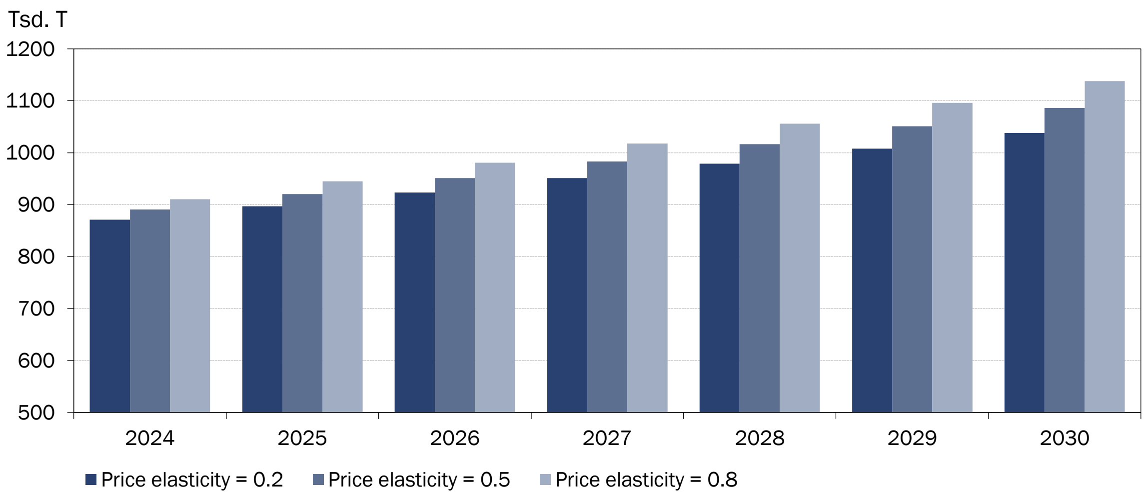
A breakdown of global production capacities published at the continental level is the only official regional information published by European Bioplastics and IFBB. European Bioplastics (2019) reports for 2019 a market share of 25 % for Europe, the second largest behind Asia (45 %). They characterize Europe as a centre of research and development in this field, and at the same time as the largest market in the world. By contrast, IFBB (2019) report in their most recent numbers (for 2018) a European share in global production capacities of only 11.8 %. In their figures, Asia is dominating considerably more, being responsible for more than two thirds of global capacities (69.4 %). Regarding the future evolution, both sources predict a substantial increase for European capacities, both in absolute and relative terms. European Bioplastics (2019) projects the European share to increase from 25 % to 30 % in 2024. IFBB (2019) even projects almost a doubling of this share from 2018 (11.8 %) to 2023 (20.2 %). As an explanation, Chintaphall et al. (2019) refers to a particular growth of certain polymers where Europe exhibits a competitive advantage. Regarding the segment of bio-based biodegradable polymers, PHA is listed as such a polymer category. Against this background, there is reason to believe that also in this segment the share of Europe in global production capacities is about to rise.

Concerning a comparison with the other two segments of the bioplastic family (fossil-based/biodegradable, bio-based/non-biodegradable), similar restrictions apply. No aggregate projections are made for fossil-based biodegradables, which is likely due to the uncertainty of the spread of bio-based feedstock alternatives in the production of the two most important polymers in this segment, PBS and PBAT. For PBS in total, European Bioplastics (2019) projects a slight decline in market shares until 2024 (from 4.3 % to 3.8 %). For PBAT, a decline is reported as well (from 13.4 % to 11.6 %). At the same time, Nova-institute (2016) stresses that the share of renewable feedstocks used in these two polymers is going to increase. Hence, the existing information points towards a less dynamic development for fossil-based biodegradables than what we projected for bio-based biodegradables. Finally, regarding bio-based non-biodegradables, the existing projections also indicate a substantial growth potential. For instance, PEF is in the current market report discussed as a potential game changer, whose market entry is expected for 2023 (European Bioplastics, 2019).

5.2 | Sensitivity analysis

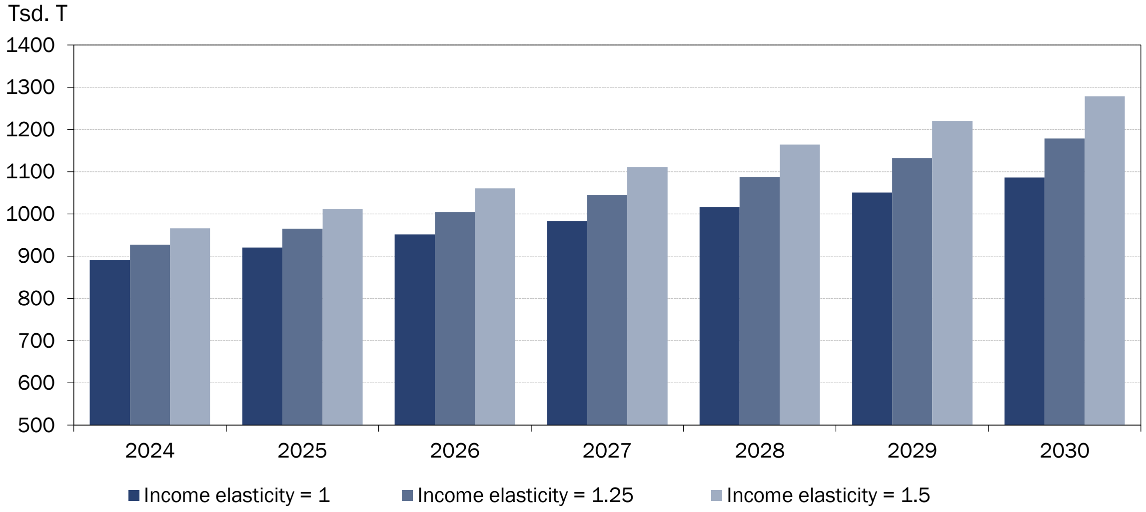
To address the sensitivity of this projection results towards certain model parameters, simulation exercises has been done with varying parameter values. The results are depicted in the graphs below. First, the impact of a changing price sensitivity of the demand for bioplastic polymers has been considered. This sensitivity influences on what degree improvements in the relative price competitiveness of bioplastics stimulate capacity growth in the future. As expected, the sensitivity tests indicate that a higher price sensitivity is associated with a more optimistic outlook for market growth. The relevance of the sensitivity increases with increasing time horizon, as its impact positively interacts with learning effects: a stronger initial demand reaction creates more opportunities for learning in the future. At the same time, a stronger income sensitivity likewise spurs market growth. This aspect is related to the awareness issue. If increasing standards of living really raise consumer preference for sustainable products, which would manifest itself in an income elasticity of bioplastic demand larger than one, this is an additional channel that could favour the evolution of the bioplastic market in the long run, even though current income growth is subdued. Finally, the intensity of learning could be different than expected. In Daugaard et al. (2015), learning rates for bio-refinery processes are estimated in a range from 5 % to 20 % and thus partly higher than the 5 % applied in our main analysis. The sensitivity tests demonstrate that varying learning rates within this range does not make much of a difference, projection results stay within a comparatively small range.

Figure 6: Global production capacities - impact of price sensitivity of bioplastic demand



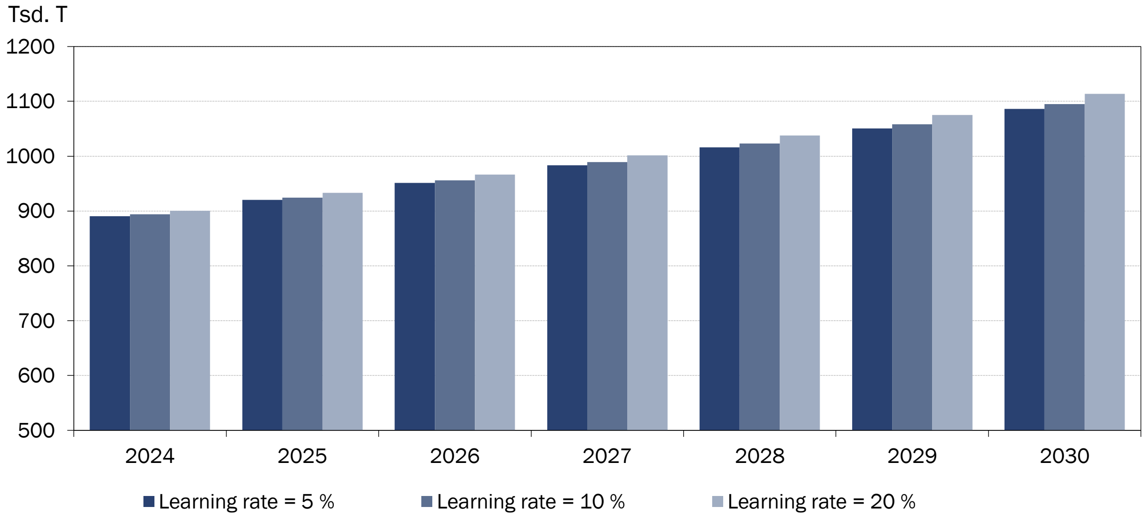
Source: own representation

Figure 7: Global production capacities - impact of income sensitivity of bioplastic demand



Source: own representation

Figure 8: Global production capacities - impact of learning rates



Source: own representation

6 | Linkages with European policies

Not only since the signing of the *European Green Deal*, which aims to achieve climate neutrality by 2050, Europe has been committed to the transition from a linear to a sustainable circular economy. It is expected that the bioeconomy will make an important contribution to the circular economy, as it provides alternatives to fossil-based products and supports the transition to an economy based on renewable resources. Bioplastics as an important part of the bioeconomy can hereby offer advantages in terms of renewability, biodegradability or compostability (Viaggi, 2016). The European Commission has published strategies and directives to mobilize the member countries and to foster the transition to a greener and more sustainable economy.

Table 3: Overview of European policies to promote bioplastics

European strategies supporting bioplastics:
1. Circular Economy Action Plan (first version published in 2015, latest version in 2020) 2. Updated Bioeconomy Strategy: A sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment (first version published in 2012, latest version in 2020) 3. Plastics Strategy: A European Strategy for Plastics in a Circular Economy (2018)
European legal acts supporting bioplastics:
1. DIRECTIVE (EU) 2015/720 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2015 amending Directive 94/62/EC as regards reducing the consumption of lightweight plastic carrier bags 2. DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2008/98/EC on waste 3. DIRECTIVE (EU) 2019/904 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on the reduction of the impact of certain plastic products on the environment

Source: own representation

At the beginning of the year 2020, the European Commission updated the *Circular Economy Action Plan* already adopted in 2015, which comprises a series of initiatives to promote the transition of the European Union from a linear to a circular economy. The two main objectives of the action plan are firstly to ensure that the value of products, materials and resources is maintained as long as possible in the European economy and secondly to minimise waste generation (European Commission, 2020).

In the course of the action plan, the *EU Directive 2015/720* focuses on reducing the consumption of lightweight plastic carrier bags. Packaging material, e.g. single-used plastic carrier bags were identified in the Circular Economy Action Plan as a major source of waste and therefore a major environmental burden. In order to mitigate the negative impact of packaging and packaging waste on the environment, the directive requires European member states to reduce their use of lightweight plastic carrier bags. To achieve these targets, member states are free to choose appropriate measures on their own. These measures can range from national reduction targets, financial measures as taxes to bans. Bio-based or biodegradable plastic bags are not exempted by this directive (European Parliament and Council, 2015).

The *EU Directive 2018/851* on packaging and packaging waste requires the EU member states to take measures to prevent the generation of packaging waste and to minimise the environmental impact of packaging. Thereby, the EU countries are encouraged to promote an increase in the share of reusable packaging. Moreover, the directive indicates that the fostering of a sustainable bioeconomy can help to reduce Europe's dependence on imports of raw materials. It is therefore important to support research and innovation in the field of bio-based, recyclable, and biodegradable materials, as these offer the EU the opportunity to increasingly replace fossil resources with renewable resources (European Parliament and Council, 2018).

In 2018 the European Commission updated the in 2012 adopted *Bioeconomy Strategy,* that fosters the production of renewable biological resources and their transformation into essential products and bio-based energy. The main features of the renewed strategy are the strengthening and expansion of the bio-based sectors, the rapid introduction of local bio-economies across Europe and the broadening of the understanding of the ecological boundaries of the bioeconomy. Furthermore, the Commission identifies that bioeconomy contributes to the solving of the problem of plastic litter in seas and oceans and intends to foster the research and development of alternatives to fossil-based materials that are bio-based, recyclable and marine biodegradable (European Commission, 2018b).

In the circular economy action plan, the European Commission identifies plastics and their challenges as a key priority. Against this background, the *EU Strategy for Plastics* was adopted in 2018. The strategy proposes measures to make the European plastics system more resource-efficient with the aim that all plastic packaging on the EU market will be reusable or recyclable by 2030. Hence, the strategy proposes various measures, including the ban of disposable plastics and the intentional use of micro-plastics. Moreover, the strategy will provide guidelines to minimise plastic waste at source and strengthen the support of national awareness campaigns. The strategy also emphasises the importance of improving the efficiency and quality of plastics recycling, and waste management. Regarding the bio-based or biodegradable plastics, the Commission stresses the need to ensure that consumers receive clear and correct information about the use and the disposal of biodegradable plastics (European Commission, 2018a).

The *EU Directive 2019/904* entered into force in July 2019 and formulates measures to reach the goal defined in the plastic strategy, which states that by 2030 all plastic packaging has to be either reusable or recyclable. In particular, the directive stipulates a ban on disposable plastic products for which alternatives made from non-plastic materials are already available. In 2021 single-used products as cotton swabs, plastic cutlery and plates, drinking straws, stirrers and balloon holders, as well as cups and food containers for immediate consumption made of polystyrene and products made of oxo-degradable plastics will be banned. In addition to the bans, the directive aims to extend the responsibility of producers. Producers must inform their customers about the negative effects of plastic waste and contribute to the costs of cleaning, transport and disposal of various plastic products (European Parliament and Council, 2019).

The European Commission does not formulate concrete policy measures to support the bioplastics industry. Overall, the strategy of the European Commission focuses on recyclable plastics rather than biodegradable plastics. For example, the Commission pursues the ambitious goal that 100% of plastic packaging should be reusable or recyclable by 2030. No quantitative targets are set for the proportion of bio-based or biodegradable plastic. The EU strategies and directives introduced above clearly point out both the opportunities and the risks of bioplastics. On the one hand, bioplastics products are seen as a promising alternative to fossil-based plastics and hence as an important step towards a circular economy. On the other hand, the Commission fears that consumers might be misled by the terms "bio-based" and "biodegradable" and that they might not dispose these products properly after use. As a result, bioplastic products would even exacerbate the problem of litter. The European Commission therefore recommends that bioplastics products should be labelled to inform consumers about their use and disposal (European Commission, 2018a). In addition, the Commission draws attention to the challenges of disposing of biodegradable plastics, as they are not necessarily suitable for home composting and could also lead to recycling problems if mixed with conventional plastics. Therefore, according to the Commission, a well-functioning system for the separate collection of biodegradable plastics is essential. Policy measures that aim to restrict the consumption of plastic do not distinguish between fossil-based and bio-based plastic products. For example, biodegradability and bio-based plastics are not excluded from the ban on disposable products. Therefore, these measures may have more of a negative than a positive impact on bioplastics. Nevertheless, the Commission sees the potential that biodegradable plastics can offer in certain applications and fosters research and innovation in this area. The Commission is particularly interested in innovations in materials that are fully biodegradable in marine and freshwater and harmless to the environment and ecosystems. Therefore, the Commission intends to increase its investment in research and development in the field of bioplastics.

It is difficult to predict how those EU policies will affect the future demand for bioplastics. The impact depends on the type of measure and its geographical scope. Obviously, a plastics tax will have a different impact on the demand than a ban on plastics. The magnitude of the impact will also depend on the number of countries (EU or worldwide) implementing these measures and, more importantly, whether EU measures distinguish between bioplastics and conventional plastics. Due to regulatory uncertainties, it is not possible to derive the quantitative effects of these policy measures on our model results. In any case, it can be assumed that an increase in EU investment in research and development could lead to innovations that reduce production costs and make bioplastic more attractive compared to conventional plastics. It can also be expected that EU policies will raise consumer awareness of the problem of plastic pollution in the future, which in turn could lead to an increase in demand for bioplastics.

7 | Conclusion

The presented modelling approach was focused on economic impact factors. Those factors of influence which are hard to quantify and/or of a too high degree of uncertainty were disregarded in the analysis. On the one hand, this concerns the social dimension of bioplastic use. Recently, increasing awareness of the microplastic debris as well as of the long-term consequences of greenhouse gas emissions has spread due to intensified media coverage. However, it will have to be observed to what extent this will really induce a change in consumer behaviour towards biodegradable products. In this regard, future economic growth might make a difference, if it allows people in more parts of the world to depart from emission-intensive products. The sensitivity analysis results indicate that a more than proportionate income response could considerably boost the market. On the other hand, political legislation can play an important role in the upcoming years. At the European level, the European plastics and bioeconomy strategies are currently in focus. However, there is still a high degree of uncertainty how these strategies will affect the market penetration of bioplastics in general and biodegradables in particular. Within the existing plastic-related directives, no specific rules or exemptions are set for products in these categories. To quantify the policy influence on the development of bioplastics vis-à-vis conventional plastics, this would be a requirement.

Regarding opportunities for refinement, one interesting road would be to integrate demand patterns further down the value chain into the model. This would allow us to differentiate between the use of bio-based biodegradable plastics for different applications and also to address the specific role for application-related policies (e.g. packaging) for the development of different market segments. Finally, a consideration of steps even further down the supply chain, the question of end-of-life-treatment options for different materials would be of interest. This requires knowledge to what extent specific biodegradable plastics will rather be composted, recycled or incinerated in the future, another interesting area of research that will be followed in the BioPlasticsEurope project.

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9 | Appendix

9.1 | Model equations

(1) $D_t^{bio} = (\frac{p_t^{fossil}}{p_t^{bio}})^{\varepsilon_p^{demand}} \times GDP_t^{\varepsilon_Y^{demand}} \times \Psi$

(2) $PC_t^{bio} = D_t^{bio}$

(3) $c_{process;t}^{bio} - c_{process;t-1}^{bio} = \max(\frac{PC_t^{bio} - PC_{t-1}^{bio}}{PC_{t-1}^{bio}} \times \tau^{bio}; 0)$

(4) $p_t^{bio} = c_{feedstock;t}^{bio} + c_{process;t}^{bio}$

(5) $p_t^{fossil} = c_{feedstock;t}^{fossil} + c_{process;t}^{fossil}$

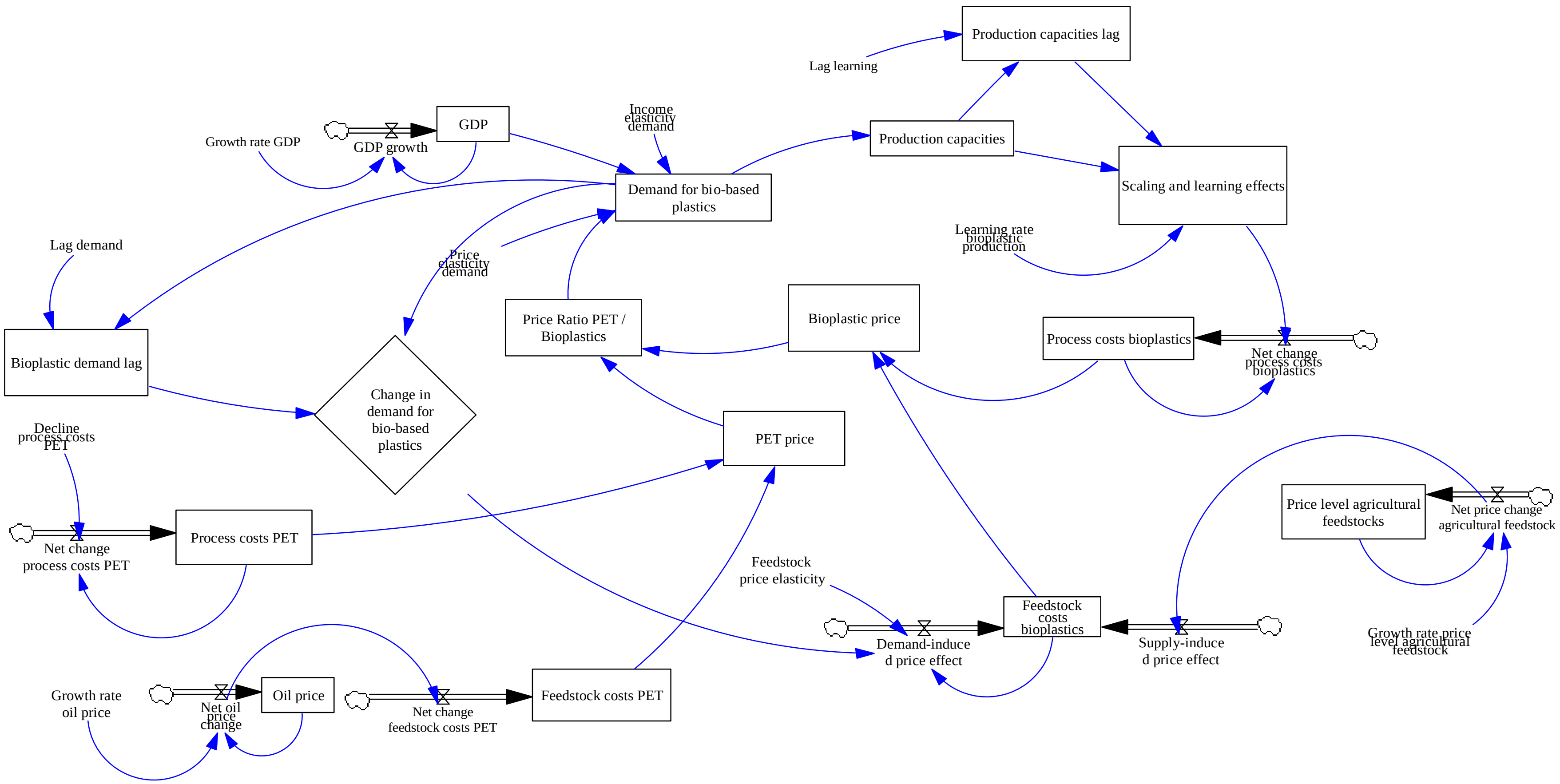
(6) $c_{feedstock;t}^{fossil} - c_{feedstock;t-1}^{fossil} = (p_{feedstock;t}^{fossil} - p_{feedstock;t-1}^{fossil}) \times \vartheta^{fossil}$

(7) $c_{feedstock;t}^{bio} - c_{feedstock;t-1}^{bio} \approx \left(p_{feedstock;t}^{bio} - p_{feedstock;t-1}^{bio}\right) \times \vartheta^{bio} +$
$(\frac{D_t^{bio} - D_{t-1}^{bio}}{D_t^{bio}}) \times \varepsilon_{feedstock}^{demand}$

where:

D_t^{bio} - Global annual demand for biodegradable plastics [tsd tonnes/year]
p_t^{fossil} - Market price for fossil-based plastics [$/kg]
p_t^{bio} - Market price for biodegradable plastics [$/kg]
ε_p^{demand} - Price elasticity of demand for biodegradable plastics
ε_Y^{demand} - Income elasticity of demand for biodegradable plastics
GDP_t - Global annual gross domestic product [$]
Ψ - Shift parameter
PC_t^{bio} - Global annual production capacities of biodegradable plastics [tsd tonnes/year]
$c_{process;t}^{bio}$ - Process costs for biodegradable plastics [$/kg]
τ^{bio} - Learning rate biodegradable plastics production
$c_{feedstock;t}^{bio}$ - Feedstock costs for biodegradable plastics [$/kg]
$c_{process;t}^{fossil}$ - Process costs for fossil-based plastics [$/kg]
$c_{feedstock;t}^{fossil}$ - Feedstock costs for fossil-based plastics [$/kg]
ϑ^{fossil} - Conversion factor for fossil-based plastics
ϑ^{bio} - Conversion factor for biodegradable plastics
$\varepsilon_{feedstock}^{demand}$ - Inverse feedstock price elasticity of demand for biodegradable plastics

9.2 | Stock and flow diagram



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