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System Dynamics Modelling of the European Demand for Bio-based Plastics

An Analysis of Scaling and Learning Effects and Framework Conditions on Price Competitiveness and Market Growth

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Abstract

Bio-based plastics are used as raw materials in a wide range of applications and provide potential for mitigating climate change by lowering CO_2 emissions. However, because of the high production costs compared to fossil-based alternative products, they are currently not cost competitive on the market. Moreover, the decrease of oil price as main antecedent of fossil-based plastics has even been diminishing their competiveness. Thus, the future of bio-based plastics on the market depends on the changing framework conditions, in the form of policy supports and increase in oil price. The key question that arises, in this regard, is how the linkage between the reduction of production costs and the changed framework conditions influences the competitiveness of bio-based plastics on the European market in the next 15 years period. To examine these dynamics and interaction, we developed a simple System Dynamics as a part of a research project funded by the European Union. The results of our simulation runs show a positive impact of scaling and learning effects resulting from build up and running of new capacities as well as adopting new technologies on the price of bio-based plastics and thereby on their demand on the market. However, without changed framework conditions in terms of increasing oil price and new policy incentives in the form of tax exemptions and subsidies for new technologies, bio-based plastics cannot achieve cost competitiveness on the European market in the next 15 years period.

Key words: *System Dynamics, bio-based plastics, scaling and learning effects, price competition*

1. INTRODUCTION

Bio-based plastics (bio-based polymers) represent an important segment of bio-economy. The term bio-based plastic refers to the raw material used (biomass instead of fossil fuels), or to production methods (bio-technology instead of chemical synthesis) or to bio-degradability [6, 8, 11]. In this paper, we refer to biotechnology-produced plastics based on biomass.

Bio-based plastics are used in a wide range of applications (e.g. packaging, textiles, consumer goods, agriculture & horticulture, automotive & transport) and provide potential for mitigating climate change by lowering CO_2 emissions [9]. However, for most bio-based products and applications the costs are twofold or even higher compared to fossil-based alternatives [7, 14]. Despite the considerable technological progress [2, 11, 14] this gap has not been closed yet [14]. Moreover, the decrease in oil prices has even diminished their cost competiveness, because the competing fossil-based plastics thereby became cheaper on the market.

In the last 5-10 years, various policy instruments for supporting the competitiveness of bio-based plastics on the market have been discussed [1, 6, 8]. The propositions range from bans for fossil-based plastics to exemption from value-added tax, grants for commercial plants, standardization and labelling [1]. Such measures may support the uptake of bio-based plastics and lead to high cost competiveness in the long-term.

Although we know from the literature that production scale size and technological progress can reduce market price via production costs [5] and that policy incentives may reinforce this effect [8], we do know much about their interlinked effect on the competitiveness of the bio-based plastics on the market. Furthermore, we do not know in any greater detail how the changing prices of oil, as a basis for fossil-based plastics (alternative products on the market), influences the competitive situation on the market. Hence, we led the focus of this study on the research question:

How does the linkage between the reduction of production costs (resulting from scaling and learning effects) and the changed framework conditions (resulting from policy incentives and oil price dynamics) influence the competitiveness of bio-based plastics on the market?

To answer this question we constructed a System Dynamics [12] model for the value chain of bio-based plastics. Our model contains only those segments where bio-based plastics compete mostly directly as a drop-in for certain applications and can be approximated by the relative costs between the fossil-based and bio-based alternatives. Cost structures, current market figures and potential learning rates have been based on current literature [3, 4, 5, 11, 13, 14, 15].

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2. MODEL CONCEPTUALISATION

To develop a system structure which links scaling and learning effects resulting from production capacities with the effects of the price competition on demand for bio-based plastics, we built a simulation model with two subsystems. The subsystems are interacting with each other via the key variables – "Demand for bio-based plastics", "process costs" and "production costs" as well as via variable which compares prices of "bio- vs. fossil-based plastics".

2.1. Causal loop diagrams for two subsystems of the model

We started our modelling with the assumption that a multiplication of the production capacities reduces the process costs having thereby a lowering effect on the market price for bio-based plastics [7, 14, 15]. Dynamic scaling and learning effects resulting from production scale size and technological process improvements represent the main reasons therefore [3, 5]. A quite large amount of literature has studied potential costs reduction from scale and learning effects and assumes significant reductions, which may lead to convergence compared to fossil-based plastics in around 15-20 years [3, 4, 5, 11, 13, 14, 15]. Finally, via higher price elasticity it leads to a positive feedback loop within the subsystem which explains the positive influence of learning and scaling effects on demand for bio-based plastics.

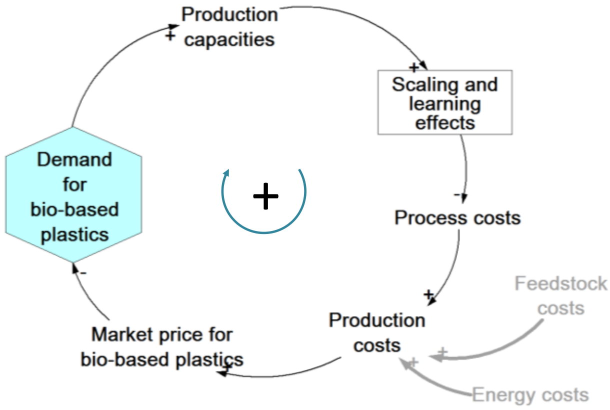

Figure 1. Causal loop diagram for the first subsystem

To simplify our System Dynamics model, we assume production costs as a sum of process costs, energy costs and feedstock costs. With the same reason, we considered only the effects of process costs on real price and demand and calculate production costs as an individual variable of the market price for the bio-based plastics, neglecting thereby e.g. R&D costs, distribution costs etc.

The market price of bio-based plastics operates in competition with the market price of fossil-based plastics as their non-bio-based alternative [1, 6, 7, 10]. The price of fossil-based plastics depends directly on the oil price on the market. Because of this interrelatedness, the price elasticity for bio-based plastics is in conjunction with the price of the fossil-based plastics. Namely, it will be higher in case the bio-based plastics are cheaper in contrast to fossil-based plastics and lower in case they are more expensive on the market – building thereby a negative feedback loop [12]. From the perspective of oil price, the higher the oil price, the higher the price for fossil-based plastic and thus the higher the demand for bio-based plastics – building thereby a positive feedback loop [1, 4, 14].

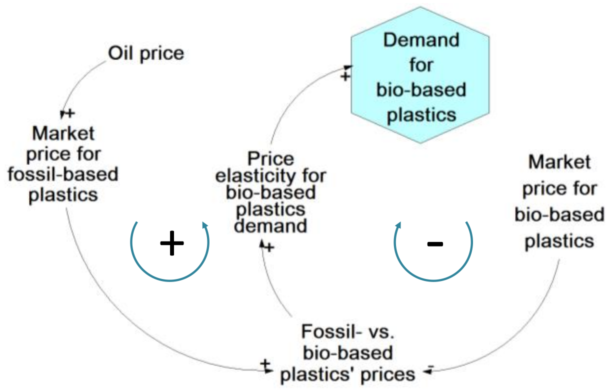

Figure 2. Causal loop diagram for the second subsystem

2.2. Stock and flow diagram of demand for bio-based plastics

Based on the conceptual models of two above presented subsystems (causal loop diagrams) we build a simulation model on the VENSIM software platform.

As the starting point for the modelling we use the initial demand for bio-based plastics and reflect it on production capacities under the assumption:

$$D_{overall}(t) = PR_{monthly}(t) \quad (1)$$

where:

$D_{overall}$ - *Monthly demand [million kg/month]*

$PR_{monthly}$ - *Monthly production capacity [million kg/month]*

For modelling process costs we use scaling and learning effects whose level is based on the monthly production capacities, as explained in the first conceptual model.

For calculating monthly process costs we used the model:

$$C_{process}(t) = C_{process}(t_0) + \int_{t_0}^{t_{180}} \left(C_{process}(t) * s(t)\right) dt \quad (2)$$

where:

$C_{process}$ - *Process costs [EUR/kg]*

s - *Learning and scaling effects [Dmnl]*

For modelling the influence of production capacities on process costs, we calculate on scaling and learning effects from 2% to 0.5% in accordance with the multiplication of the production capacities compared to the start demand - from 1 time to 4 times [3, 5, 15]. In accordance with the current literature [3, 4, 5, 11, 13, 14, 15] we use higher scale effects (2%) for multiplications up to 1 times and reduce them with the increase of production capacities to 0.5% for a multiplication of 4 times. A delay of 3 months is also integrated into the model, which indicates the time for real reduction of prices after a scale and/or learning effect occurs.

Based on the causal linkages of the second conceptual model, we calculated monthly demand for bio-based plastics as:

$$D_{overall}(t) = D(t_0) + \int_{t_0}^{t_{180}} \left(D(t_0) * p_{\Delta}(t) * e_p(t)\right) dt \quad (3)$$

$$p_{\Delta}(t) = 1 - \frac{(p_{real}(t))}{(p(t_0))} \quad (4)$$

where:

$D_{overall}$ - *Monthly demand [million kg/month]*

$D(t_0)$ - *Initial demand [million kg/ t0]*

p_{Δ} - *Difference between market price and initial price*

e_p - *Price elasticity*

$p_{real}(t)$ - *(real) market price [EUR/kg]*

$p(t_0)$ - *Initial price[EUR/kg]*

As the customers do not simultaneously react to price changes, a reaction time to price change as delay of two months is integrated in the model as well.

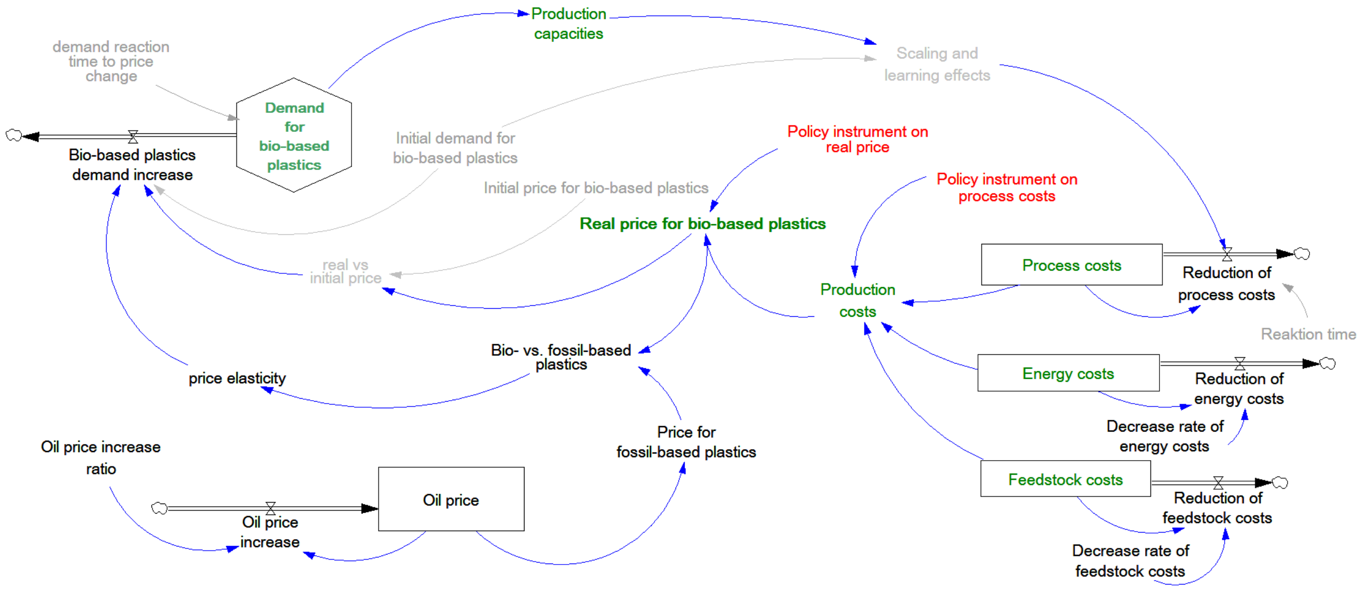

Figure 3. The simplified Stock and Flow diagram for modelling dynamics of demand for bio-based plastics

3. FIRST RESULTS OF THE BIO-BASED PLASTICS DEMAND DYNAMICS

After validation tests of our System Dynamics model, in which we verified the structure of the model and validated it through extreme conditions experiments and sensitivity tests, the model was ready for the first system behaviour analysis for policy making. For a dynamic analysis and a deeper understanding of the system's behaviour, we conducted various simulation runs and tests. Some exemplary runs are shown in the following and interpreted to generate the first dynamic hypotheses.

In order to gain a deeper insight into the price competitiveness and the dynamic demand for the bio-based plastics, we ran various model simulations based on different assumptions for the future oil price and policy incentives (see table 1). For oil prices, we used low and high scenarios. For policy incentives, we calculated tax exemptions as price lowering effects and direct subsidies for new technologies in production as process costs lowering effects. For analysing the effects of price competition we calculated lower price elasticity in the situation that bio-based plastics are more expensive than fossil-based plastics, and higher elasticity in the opposite situation. Based on the current literature, we calculated 80 million kg monthly for initial demand of bio-based plastics [13, 14].

Figure 4 depicts three scenarios of dynamics of the demand for bio-based plastics resulting from the effects of scaling and learning effects on market price as well as on competitive market situation of bio-based with fossil-based plastics.

Scenarios	Oil price	Policy incentives		Price elasticity	
		Policy instrument on real price	Policy instrument on process costs	Bio-based > Fosill-based	Bio-based < Fosill-based
Baseline scenario	low	no	no	0.3	0.6
High oil price scenario	high	no	no	0.3	0.6
De-risking scenario	low	yes	yes	0.4	0.7

Table 1. Assumptions for scenarios

The **baseline scenario** presented with the blue line in the figure 4 depicts the development of demand for bio-based plastics at a low oil price and thereby lower prices of fossil-based plastics on the market. In this scenario, no policy incentives are calculated. In such a case, the slow reduction of process costs of production is based only on incremental advances in technology leading to a lower increase in process efficiency and thereby to limited learning and scaling effects. Hence, the price for the bio-based plastics does not achieve the competitiveness in the considered time period (see Figure 5).

The second scenario represents the **high oil price scenario** that assumes a steady rise of the oil price to 127 US$/bbl in 2030 [6, 8, 14]. To analyze only the effects of higher oil price on demand of bio-based plastics, we took the same assumptions of the base run and increased the oil price ratio only. As the red line in the figure 4 shows, the higher price for fossil-based plastics has only a modest effect on market demand. Hence, it still takes some years till the cost competeviness to fossil-based products is achieved. The results show also that only when the tipping point of price competeviness is reached, the demand for bio-based plastics will significantly take up.

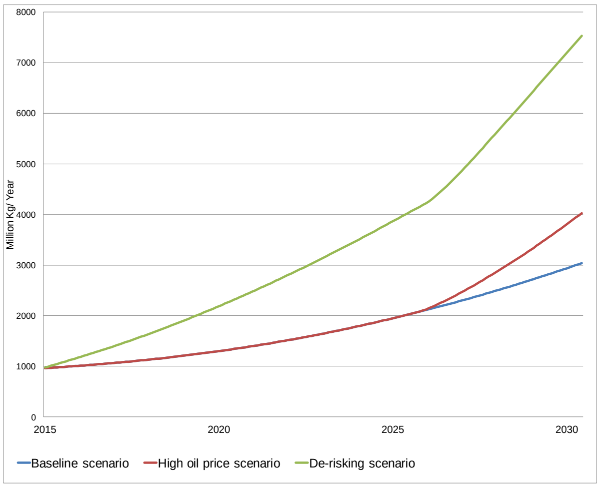

Figure 4. Demand for bio-based plastics by low and high oil prices as well as by the influence of policy measures

In the third **"de-risking" scenario** we assumed low oil price, but we integrated policy support for commercial activities into the simulation analysis. Moreover, we used higher market response of consumers operationalised with higher price elasticity in contrast to the previous scenarios for calculating demand for bio-based plastics in competition with the fossil-based plastics. The results (see the green line in the figure 4) show a much stronger growth of demand for bio-based plastic in comparison to the other scenarios despite the low oil price on the market. This result shows that stronger policy incentives in the form of tax exemptions with price lowering effects as well as subsidies for new technologies with process costs' lowering effect [6, 8, 10] can reinforce the effects that production scale size and technological process improvements have on the competitiveness of bio-based in comparison to fossil-based plastics (see figure 5).

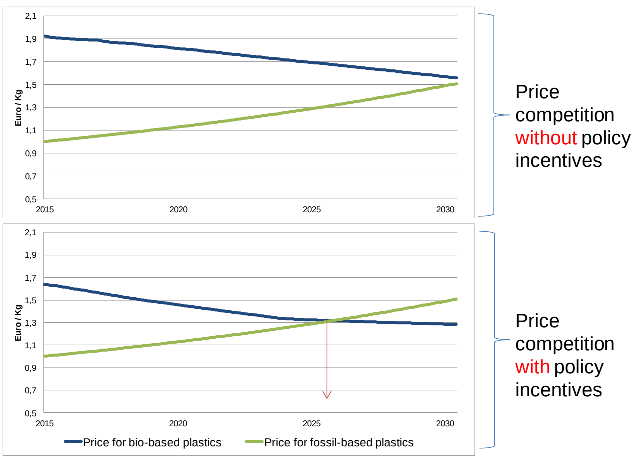

Figure 5. Price competition between the bio-based and fossil-based plastics with and without policy incentives

4. CONCLUSIONS

This paper takes the first step towards analyzing how the linkage between the reduction of production costs (resulting from scaling and learning effects) and the changed framework conditions (resulting from policy incentives and oil price dynamics) influences the competitiveness of bio-based plastics on the market. Therefore a first System Dynamics model was developed, which reproduces the system structure in a very simplified way, but is able to provide first insights into the system's behaviour.

Based on our analysis it was possible to develop the first hypothesis about the dynamics of the demand for bio-based plastics. By means of our simulations we can show that the *scaling and learning effects influence positively the reduction of process costs and the bio-based plastics price on market, thereby influencing the demand positively.* However, these effects alone are *not sufficient for achieving cost competitiveness of the bio-based plastics on the European market.* Thus, the *framework conditions* in the form of increasing price of oil as main antecedents of the fossil-based plastics, and policy incentives in form of tax exemptions and subsidies for new technologies *will play a crucial role for further dynamics of the demand for bio-based plastics.*

However, this dynamic analysis is just the first step based on simplified systemic structures and is still ongoing research. The production costs, for example, include a couple of other factors that have not been considered so far. Moreover, feedback on feedstock may arise in the case of the production of large quantitative as residues and straw might get scarce and land use changes and/or feedstock price increases may happen again. Summing up, there are still a few loops, restrictions, resource limitations and political decisions that are not included in this first model so far. Nevertheless, these effects may take place in a more detailed System Dynamics model in the future.

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