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Transition paths towards a bio-based economy in Germany: A model-based analysis

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ABSTRACT

The reduction of use of fossil fuels is inevitable for a transformation to a sustainable economy. Developing possible transformation pathways from the current fossil-based to a more bio-based economy and getting a better understanding of driving forces and trade-offs can help to shape the real desirable path. To get a complete picture, general social, economic and policy developments as well as specific developments related to the bio-based economy have to be covered. This article presents a model-based analysis of three different transformation paths to a bio-based economy with a special focus on Germany and a time horizon until 2050 using the general equilibrium model MAGNET.

Results show that 'framing drivers' (e.g. GDP and population developments, trade and land use policies) play an important role and can either significantly encourage or hinder the transformation towards a more bio-based economy. Regarding the biomass, increase in productivity of agriculture and reduction in post-harvest losses are the main factors on the supply side, which help to decrease possible market tensions. On the demand side, the key lever identified in our analysis is the change in consumers' behavior and preferences regarding food. Increased demand for biomass for energy and material use was not identified as a critical factor by the underlying assumptions. To take the most favorable path with less trade-offs, implies, besides the 'wise' policy decisions regarding the support of use of biomass for material and energy use, also the transformation of the whole society, which on its turn should be promoted by policy.

1. Introduction

The transition of the current fossil-based to a more bio-based economy is seen together with the concept of circular economy as an important part of the envisaged transformation of the German economy to a more sustainable economy [1]. Such a transformation embedded in the idea of sustainable bioeconomy is also seen by policymakers of the EU as an option for a better future. This is confirmed by the EU's 2018 Bioeconomy Strategy Update, which also acknowledges the important contribution the sustainable circular bioeconomy can make towards the achievement of the Sustainable Development Goals (SDGs), as well as the Paris Agreement. To maintain this role the bioeconomy requires its integration in other policy actions. With the European Green Deal, important steps of such integration in policies related to biodiversity, circularity, climate change, food systems, forest protection and restoration, and renewable energy are underway [2].

The departure from the fossil-based economy requires that both, energy and material use, of fossil fuels should be significantly reduced or even phased out. As fossil fuels are of organic matter, they could theoretically be fully substituted by biomass by application of appropriate technologies; however, the quantity of the required biomass would be enormous. Fortunately, it is neither requested nor necessary. In case of energy use, generation of bioenergy or production of biofuels are just some of many options of renewable energy generation. The phasing out of fossil fuels by material use does not leave so many options. For instance, the organic chemistry is relying on carbon, which by waiving off fossil fuels, can only be replaced through recycled carbon, carbon from biomass or carbon gained by processing of carbon dioxide. The use of carbon dioxide as a feedstock is a potential long term option; therefore, it leaves recycling and biomass as main options for the near future. Respectively, the expectation regarding the replacement of fossil fuels by biomass is higher for material use. The focus on the phasing out of fossil fuels causes the narrowing of the focus area from bioeconomy to a bio-based economy. Even though the bio-based economy relates to the conversion of biomass into products and materials, the emphasis is often put on innovative materials.

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In the current debate about bioeconomy, the traditional and still dominant use of biomass for instance for food and feed is often treated only marginally or practically excluded and considered only as a restricting factor for the material and energy use of biomass. However, such kind of "restrictions" could lead to a distorted picture and a situation in which the forest cannot be seen for the trees. First, there are no separate markets for biomass for food-feed use and energy-material use. Wheat, corn, sugar, vegetable oils and other kinds of biomass in most cases are not produced for one specific use and all purchases of biomass (irrespective the use purpose) have a market impact. This kind of interaction is discussed in different studies focusing on the biofuels policies and analyzing impacts of increased demand for agricultural biomass for energy use on relevant agricultural markets and food security issues [3–7]. Similar interactions, but with respect to land, are found in studies analysing options for afforestation and other land use changes in the context of climate policy, where the distribution of land between different types of uses, e. g. agricultural production or afforestation, negatively impacts the availability of total agricultural used area and thus, total agricultural production and consequently, food security [8–11]. Second, changes in food consumption patterns and the appearance of novel food could play a crucial role in the change of demand for biomass for food and feed purposes [12–14] and therefore, deserve more attention. If the transformation from a pre-dominantly fossil-to a more bio-based economy should proceed in a sustainable way, scientific research is needed to identify potentials of the bioeconomy as well as its limits and areas of conflict and to propose possible solutions.

Therefore, besides studies with a strong focus on a specific part of bioeconomy, other studies should take a more holistic view covering the full range of different driving forces by featuring possible paths on the way to the bioeconomy. However, considering different driving forces, each of which can take different expressions, is associated with a wide range of uncertainties. A useful approach to examine future developments under a range of uncertainties is the definition and analysis of alternative scenarios [15]. This approach is broadly acknowledged in climate science, where currently numerous studies examine a set of alternative equally likely to occur pathways of future societal development, described as shared socioeconomic pathways (SSPs), to make projections for greenhouse emissions and to analyze climate policies [16]. However, increasingly more researchers use the scenario approach (often based on pre-defined SSPs) for instance to analyze land use change dynamics [17,18], achievement of SDGs [19–21] and more recently also to analyze possible developments and contribution of bioeconomy [22,23].

The objective of this article is to quantify three alternative scenarios of the transformation to a more bio-based economy in Germany until 2050, to reveal potentials of the bioeconomy as well as associated trade-offs, and to highlight policy actions needed to achieve the envisaged goals. The quantification of the scenarios is based on the general equilibrium model MAGNET. Three scenarios were developed in a multi-stage interactive procedure using the "Story and Simulation" (SAS) approach under involvement of stakeholders, researchers and citizens, and embedded in three SSPs. This article contributes to the ongoing discussion on the future transformation paths putting bioeconomy in the spotlight. It is organized as follows: the following chapter outlines the scenarios of bio-based transition paths to be analyzed. In chapter 3, the analyzing tool – the CGE model MAGNET – is presented, followed by a description of the implementation of the scenarios in MAGNET as well as model modification carried out for the purpose of the analysis. Chapter 4 presents the main results of the model-based analysis with a focus on the production of agricultural commodities, their use for food, feed, biofuels and biochemicals, and their trade. Chapter 5 closes with a discussion and conclusions.

2. Transition paths to the bioeconomy and derived scenarios

In this article, we analyze three scenarios developed within the research project BEPASO[1] (BioEconomy PAthways and SOcietal transformation strategies) that feature different future developments towards bioeconomy until 2050 with a special focus on Germany [24]. These scenarios were developed using the "Story and Simulation" (SAS) approach which allows to bring qualitative and quantitative scenarios together [25]. In a multi-stage interactive procedure, qualitative scenarios or storylines developed by a Scenario Panel consisting of stakeholders and experts were combined with quantitative scenarios from storyline-modelling procedure to get a consistent set of three scenarios. In addition, citizens and further stakeholders were involved to ensure that different views on future developments are considered and that scenarios are generally considered as realistic by outsider.

BEPASO storylines provide a detailed description of social, economic and technological developments as well as of use of biomass for food and feed, energy use (generation of bioenergy) and material use (production of biomaterials with a specific focus on the chemical industry) for Germany, but only redundant for the rest of the world. However, it was acknowledged that international impacts as well as interactions of Germany with other countries are important and have to be considered. Therefore, the global computable general equilibrium (CGE) model MAGNET (see Chapter 3) for storyline-modelling procedure was applied.

For the modelling with a global CGE model, however, information about global developments is required. We used Shared Socioeconomic Pathways (SSPs) scenarios [16,26] to determine an appropriate international framework. Three national BEPASO storylines and five SSPs storylines (SSP1-SSP5) were compared based on the broad description and resulting in the choice of SSP1, SSP2 and SSP4 as counterparts for national storylines. The SSPs are applied as a background for our scenarios indicating projections for important scenario assumptions on the global level, e.g. population, GDP developments etc. Table 1 summarizes scenario elements considered in our analysis and their characteristics as they were implemented in the scenarios. More information about the quantification of these elements is presented in Chapter 3. The following short description provides a qualitative overview of the analyzed scenarios:

"Bioeconomy on the drip" (or "On the Drip", embedded in SSP2 "Middle of the road"): Social, economic and technological developments continue following historical patterns. No changes take place in international trade regulation. Land use change regulations are only partly enforced and make further deforestation possible. Yields are rising at moderate rate. Consumption patterns of food follow historical trends without a transition of the food industry. Both, biofuels of the first generation and advanced biofuels are promoted to some extent. In general, the use of biomass for the production of advanced biomaterials (especially chemicals) hardly gains further importance. Due to the lack of a political and societal strategy, the transition towards a significant bio-based economy is 'on the drip'.

"Bioeconomy islands" (or "Islands", embedded in SSP4 "Inequality—A road divided"): Unequal social and economic developments at international level with an increase in disparities between poor and rich countries are in place. Some innovative technology solutions are realised but not fully implemented. For material use of biomass for the production of chemicals, "drop-in" technologies dominate. International trade with primary agricultural products is further liberalized with highly regulated land use practises in high-income countries. However, there are no effective land use regulations in low-income countries. Productivity of agriculture raises in high-income countries stronger than in low-income countries. Food consumption patterns change in high-income

[1] https://www.thuenen.de/en/cross-institutional-projects/scenarios-of-the-bio-economy-2050-potentials-trade-offs-solution-strategies/.

Table 1
Scenarios elements and their characteristics.

	"On the drip"	"Islands"	"(R)Evolution"
POP and GDP	SSP2 projections	SSP4 projections	SSP1 projections
Trade	No changes	Liberalization of trade with primary agricultural products in 2030	Total trade liberalization in 2030
Land use change regulation	medium	strong (HIC)/medium (MIC)/weak (LIC)	strong
Productivity of agriculture	medium	rapid (HIC)/medium (MIC)/slow (LIC)	medium (HIC)/rapid (MIC)/rapid (LIC)
Food consumption and food waste (in HIC)	No changes	Shift in consumer preferences: reduced consumption of meat and dairy products	Shift in consumer preferences: reduced consumption of meat and dairy products; total reduction in consumption of food due to reduction of food waste
Food industry	No changes	No changes	Transformation of food industry: Shift to less use of animal products as input
Biofuels policy	EU-wide target (2050): 1st generation of 3,8%; for 2nd generation of 3,6% World: the same as in 2015	EU-wide target (2050): 1st generation of 3,8%; for 2nd generation of 7% World: the same as in 2015	EU-wide target (2050): 1st generation of 0%; for 2nd generation of 7% World: the same as in 2015
Use of biomass in chemical industry	No changes	Medium increase	Strong increase

Source: own presentation.

countries to some extent with the decline of per capita consumption of meat and dairy products. However, the food waste problem is not solved. Both, biofuels of the first generation and advanced biofuels are promoted with a preference towards advanced biofuels. The use of biomass for the production of advanced biomaterials (especially chemicals) gains more importance. There is no general and overall transition towards a bio-based economy, which is only partially taking place on individual areas or 'islands' within the overall economy.

"Bioeconomy (r)evolution" (or "(R)Evolution", embedded in SSP1 "Sustainability—Taking the green road"): Social and economic developments shift towards a more sustainable path with a successive prevalence of innovative technologies. In the material use of biomass for the production of chemicals, the focus lays on the use of special properties of this feedstock, for example for the production of specialty chemicals. International trade is almost completely liberalized. Land use practices are effectively regulated in all countries. Technical innovations induce a strong growth in the agricultural productivity at global level. Food consumption patterns in high-income countries are changing and breaking a historical pattern: Per capita consumption of meat and dairy products decreases as well as consumption of processed food and plant-based food. Reasons for that are the preference shift by consumers and the strong reduction of food waste. The transformation of the food industry takes place causing a decrease in use of animal products as input for processed food. The production and use of biofuels of the first generation has mostly phased out while advanced biofuels are promoted stronger. The use of biomass for the production of advanced biomaterials (especially chemicals) is steadily gaining in importance. This transformation which encompasses all areas of the national economy, has brought about a '(r)evolutionary' shift towards a bio-based economy.

3. Modelling with MAGNET

3.1. The MAGNET model

This analysis is based on a multi-region recursive dynamic computable general equilibrium (CGE) model known as MAGNET[2] (**M**odular **A**pplied **G**e**N**eral **E**quilibrium **T**ool). With its modular set-up, MAGNET, which is built upon the **G**lobal **T**rade **A**nalysis **P**roject[3] (GTAP) model and database, allows users to start with a standard GTAP model and then add further extensions or modules adjusting the model structure to the research questions at hand [27]. The GTAP database currently used for MAGNET for this analysis (version 9) contains detailed information on production, bilateral trade flows, transport flows and trade protection data for 140 regions and 57 sectors for the reference year 2011 in US$ [28]. As a CGE model, the GTAP depicts the world's economic activity with an underlying equation system that includes two different kinds of equations. One part of the equation system consists of behavioral equations which are based upon microeconomic theory and specify the behavior of optimizing agents in the economy such as firms (minimizing production costs) and households (maximizing utility). The other part covers the accounting relationships which ensure, e.g. that income and expenditures of every agent in the economy are balanced, all markets are "cleared" (total supply equal total demand) and global investments are equal global savings [29–31]. Using the GTAP database and model as a core, MAGNET comprises a series of different adaptions and extensions. For our study, the MAGNET model covers the following extensions beyond the standard GTAP model: A fully flexible, sector-specific production structure, a land market with endogenous land supply and a restrictive, regulated allocation of land over sectors, an adjustment of income elasticities as GDP per capita changes over time as well as the introduction of new activities/products (e.g. related to bioeconomy) [27].

3.2. Implementation of scenarios in MAGNET

This section describes how specific scenario elements presented in Table 1 were implemented by modelling with MAGNET. MAGNET was run as a recursive dynamic model at five-year intervals starting from 2015.2030 was used as an intermediate time point to capture some important changes related to trade policy, biofuel policy and consumption preferences. We run the model using regional and sectoral aggregations as presented in supplementary material.

3.2.1. Population and GDP developments

Projections of population and GDP developments were borrowed from the respective SSPs scenarios [32,33]. Population is an exogenous variable and directly used by MAGNET. GDP development is used to calibrate an economy-wide productivity variable in the model. This calibrated economy-wide productivity variable is then used in scenarios as exogenous driver [27].

3.2.2. International trade

To reflect different conditions for international trade defined in scenarios (Table 1), assumptions on import taxes are made. In scenario "Islands", import taxes on primary agricultural products are assumed to

[2] www.magnet-model.org.
[3] www.gtap.agecon.purdue.edu.

be removed in 2030. In scenario "(R)Evolution", in 2030, a total trade liberalization is assumed and all trade tariffs are removed. In scenario "On the drip", trade tariffs and subsidies are assumed to stay at current level.

3.2.3. Land use change regulations

Land use change regulations and their enforcement have an impact on land availability for agriculture. In MAGNET, the total land used for agricultural production is estimated endogenously via a land supply function; the information about the amount of potentially available agricultural land is an important exogenous variable of this function [27]. The amount of potential agricultural land in each scenario was taken from estimations made by the global land-system model LandSHIFT [34]. For the calculation, different sustainability criteria in line with scenario descriptions and the AICHI Targets/Nature Conservation Action Program were defined. In addition to the sustainability criteria, the Corruption Perceptions Index (CPI) from Transparency International [35] was utilized to depict the enforcing of protection rules [24]. The summary of assumptions used to calculate the potential agricultural land with LandSHIFT is provided in supplementary material.

3.2.4. Productivity of agriculture

Changes of agricultural productivity are taken from projections made for SSPs scenarios using interactions between MAGNET and IMAGE models [17]. Therefore, for the "On the drip" scenario (embedded in SSP2), the overall regional crop yield changes are calibrated to the FAO Agricultural Outlook [36]. It is assumed that 50% of the improvement takes place autonomously and another 50% is price driven and that the autonomous improvement is correlated to GDP. As a result, advances in crop yields are high in the "(R)Evolution" scenario (embedded in SSP1) and unevenly distributed across regions in the "Islands" scenario (embedded in SSP4).

Changes in the productivity of livestock in the "On the drip" scenario (embedded in SSP2) are also derived from the FAO Agricultural Outlook [36]. In the "(R)Evolution" scenario (embedded in SSP1), livestock productivity increases faster and in the "Islands" scenario (embedded in SSP4), it increases in high and middle-income regions and stagnates in low-income regions [17].

3.2.5. Food consumption and food industry

Biomass from agricultural area is mainly used for food and feed production. Feedstuff is used for animal husbandry and the output of the last is mainly used for food production. So, consumers' behavior and preferences regarding food play a very important role in bioeconomy. Already relatively small changes in quantity of per capita consumed food, e.g. due to waste reduction or the change of consumer preferences, e.g. reduction of meat consumption, will allow much more biomass be used for material or energy purposes or simply reduce the pressure on the land use.

To model changes in consumer preferences in MAGNET, a taste shifter could be applied to change the private households' consumption for some products while respecting the budget constraint [27]. This taste shifter is used to model the decrease in consumption of animal products such as meat and dairy in the scenarios "Islands" and "(R)Evolution" to achieve reductions described in the scenario storylines.

However, such approach falls somewhat short: Animal-based products that are first used as intermediate inputs for production of processed food and only then consumed by end-users will not be targeted. Considering the significance of processed food in consumer's food basket, this shortcoming shouldn't be neglected. To overcome it, we proceed as follows. The default production function of the sector that covers processed food is modified to allow the substitution between animal-based and plant-based intermediate inputs (supplementary material). By manipulating the substitution elasticity between animal-based and plant-based intermediate inputs as well as the efficiency in substituting animal-based for plant-based inputs, we force the transformation in the processed food sector to a less animal-based diet in line with changing preferences of consumers in the scenario "(R)Evolution".

Although, a reduction of food waste is an important element of the scenario "(R)Evolution", we implement it in our model very simplistically. We assume that the whole reduction of food waste could be attributed to the reduction in food consumption by private households. According to FAO data, about one-third of all food produced worldwide is discarded [37]. We use this information to adjust the shifter that reduces the consumption of food. It is important to note that such an implementation causes an excessive reduction in household food consumption as the reduction of losses does not take place along the entire value chain, but at the end of it. However, it still allows at least roughly to simulate the effect of reduction in demand for biomass used for food production attributed to reduction of food waste.

3.2.6. Material and energy use of biomass

The modelling of the transition of our present fossil-based economy to a bio-based economy is a challenging task. On the one hand, it requires a model adaption to depict new bioeconomy related activities that can be already observed. On the other hand, some future developments barely observed now, but expected to evolve in the near future also have to be introduced. To cope with these challenges, the MAGNET model has been constantly revised and extended for a better capture of particularities of a bio-based economy [3,4,22,38,39].

The production of 1st generation biofuels – biodiesel and bioethanol from primary agricultural crops – is modelled in MAGNET already for a while [3,4]. Recently [38,39], the use of biomass for 2nd generation biofuel technologies and the production of some specific bio-based chemicals was introduced (supplementary material).

Despite this considerable progress in the modelling of bioeconomy in MAGNET, the model has still shortcomings, especially by simulation of long-term scenarios. The point is that it is not possible to determine at present, which technology will assert it and which bio-based products will be of particular importance in the future. Without this knowledge, it is quite impossible to describe the transition to the bioeconomy only by means of specific new bio-based sectors. Therefore, we use additionally a more general approach with a modified production function of fossil-based chemicals allowing for a long-term replacement of fossil-based feedstock by biomass. This allows us to simulate the transformation of the fossil-based chemical sector to a more bio-based chemical sector without prior specification of a technology that underlines this transformation (S4, supplementary materials). Similar as in case with a processed food sector, we manipulate the substitution elasticity between fossil-based and bio-based feedstocks to force the transformation of the chemical industry in line with descriptions in the scenarios.

For biofuels, we assume that the production is policy driven. The EU targets are implemented as shown in Table 1 from 2020 onwards.

4. Results

The presentation of results is focused on the most relevant for bioeconomy developments: The use of biomass for production of food (reflected in per capita food consumption), biofuels and biochemicals, the production of crop-based biomass and the trade with selected agricultural products. While most results will be presented for Germany, the international trade of agricultural and food products will also be shown.

It is important to mention that the three scenarios we analyze describe three alternative paths. None of them should be seen as a baseline. Therefore, presented results should be compared with each other. Most of the results show changes that occur in each scenario between 2015 and 2050.

4.1. Use of biomass for food production

Most of the biomass produced from agriculture is used for food and feed purposes. Therefore, changes in consumer behavior (reduced food waste) or preferences (lower consumption of meat and dairy products) are, along with GDP and population developments, important drivers for the demand of biomass for food production.

In case of changing consumer preferences, it is important to cover the composition of processed food, which uses both, plant-based and animal-based products as inputs. Fig. 1 shows how private households allocated their expenditure for food between different categories in Germany in 2015. The left-side part of Fig. 1 shows that 25% of total expenditure for food were used to buy animal-based products (meat, dairy etc.), 11% to buy plant-based products (cereals, oils, sugar, fresh fruit and vegetables) and 64% for purchasing of processed food (pizza, ready meals with different components, beverages etc.). Therefore, in terms of expenditure, processed food produced from plant-based and animal-based inputs is by far the most important category. We are interested in how expenditure for food is allocated between plant-based and animal-based components over total food category? We calculate such derived allocation expenditure (right-side part of Fig. 1) using information about a ratio between plant-based and animal-based inputs (in value terms) in processed food (middle part of Fig. 1). According to this calculation, 55% of total households' expenditure for food could be attributed to the plant-based food and 45% to the animal-based food (right-side part of Fig. 1).

Fig. 2 presents changes in per capita expenditure of private households for food between 2015 and 2050 in Germany and the entire world. Calculating these changes in expenditure, we keep prices for products constant. Therefore, numbers in Fig. 2 can also be read as changes in per capita consumption. In scenario "On the drip", German per capita consumption of plant-based products is projected to decline until 2050, whereas the consumption of processed food and, especially, animal-based food continues to increase. At global level, per capita consumption increases by 19–25% across different food categories. In scenario "Islands", per capita consumption of animal-based products decreases in Germany as well as in other high-income countries by −30% and of plant-based products by −7%, whereas the consumption of processed food slightly increases (+3%). Per capita food consumption in Germany faces a strong decrease under scenario "(R)Evolution" between −42% and −61%. This is the result of significant reduction of food waste and the change in consumer preferences towards diets with less animal-based products. Similar developments also take place in other high-income countries resulting in a decrease of the per capita consumption of animal-based products by −5% at global level. As already mentioned in chapter 3, an excessive reduction in household food consumption in scenario "(R)Evolution" is partly explained by a technique used to simulate the reduction of food losses in the model.

Though Fig. 2 clearly illustrates changes in per capita expenditure of private households for different food categories in different scenarios, it does not show whether the shift in composition of expenditure (plant-based versus animal-based) in 2050 by total food consumption occurs.

To address this question, the derived allocation of expenditure for food in 2050 using data on the shares of expenditure for each food category (plant-based food, animal-based food and processed food) and the ratio between plant-based and animal-based inputs (in value terms) in the processed food sector was calculated. Fig. 3 presents results of this calculation for Germany for the scenarios "Islands" (a) and "(R)Evolution" (b).

While the left-hand parts of Fig. 3 show a similar composition of expenditure on different food categories (plant-/animal-based food, processed food) in both scenarios, "Islands" and "(R)Evolution", the derived allocation of expenditures between plant-based and animal-based components in the total food expenditure (right hand parts of Fig. 3) differs significantly. The reason for such a difference lies in different ratios between plant-based and animal-based inputs (in value terms) in processed food (middle part of Fig. 3) in both scenarios.

In scenario "Islands", the ratio between plant-based/animal-based inputs in processed food changes from 2015 to 2050 in favor of animal-based inputs (from 68/32 to 59/41) (middle part of Figs. 1 and 3a, respectively). As a result, the derived allocation of expenditure between plant-based and animal-based food in 2050 in scenario "Islands" in Germany remains almost unchanged (%-shares of expenditure for plant-/animal-based food: 55/45 in 2015 to 53/47 in 2050) (right part of Figs. 1 and 3a, respectively). In scenario "(R)Evolution", however, driven by the strong transformation of the processed food industry (the ratio between plant-based/animal-based inputs changes in favor of plant-based inputs from 68/32 in 2015 to 89/11 in 2050) (middle part of Figs. 1 and 3b, respectively) considerable change takes place: The share of expenditure for animal-based food declines from 45% in 2015 to 26% in 2050 allowing the share of expenditure for plant-based food to grow from 55% in 2015 to 74% in 2050 (right part of Figs. 1 and 3b, respectively).

As we use figures on values making our calculations, we cannot say how a ratio between plant-/animal-based components in food changes in terms of volume or calories. However, it was shown that by using a sectoral approach to analyze changes in consumer preferences for food, more attention has to be paid to the processed food sector.

4.2. Use of biomass for biofuels production

Beside the traditional use of biomass for heat generation, it is also used in power plants for power generation, production of biomethane and biofuels. In our simulations, we focus on production and use of biofuels and distinguish between the first generation of biofuels (biodiesel and bioethanol) produced from primary agricultural products and the second generation or advanced biofuels (bioethanol and Fischer-Tropsch fuels or biodiesel) produced mainly from residues. Due to

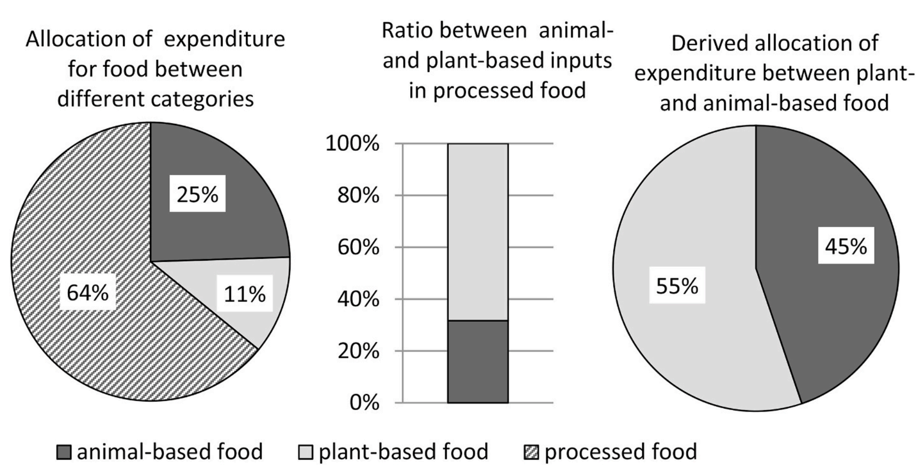

Fig. 1. Allocation of the expenditure on food in Germany in 2015.

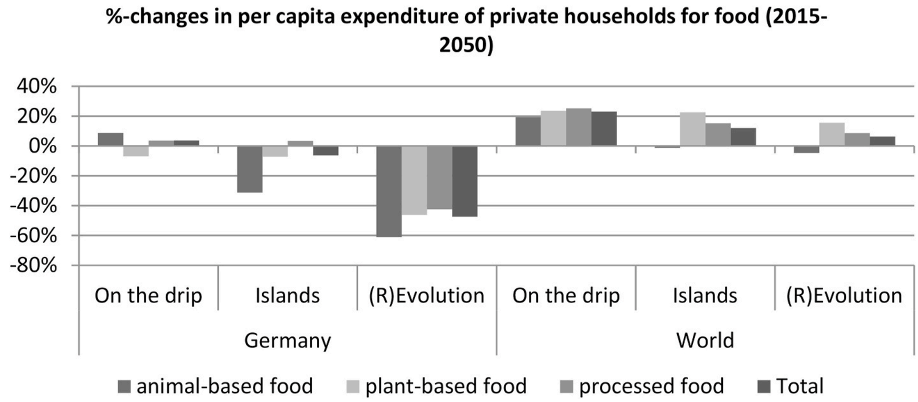

Fig. 2. %-Changes in per capita expenditure of private households on food (2015–2050).

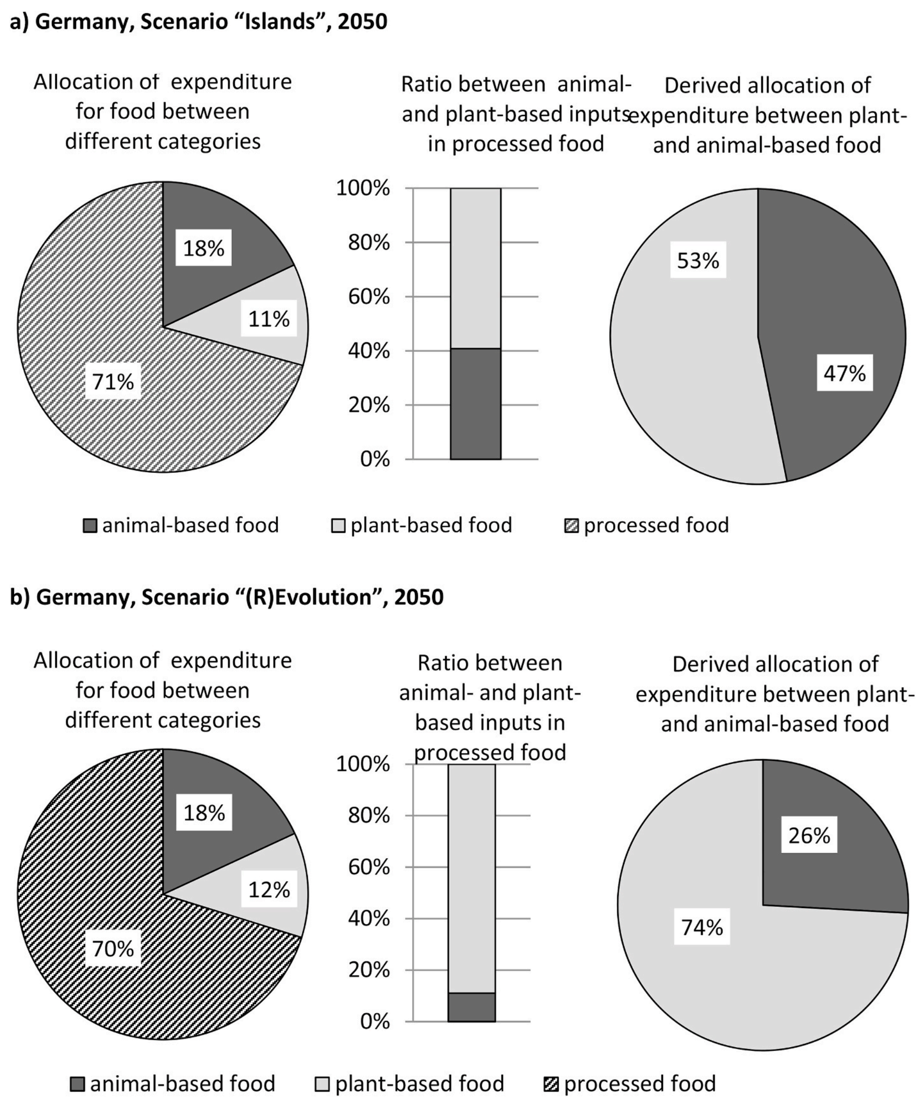

Fig. 3. Projected allocation of expenditure on food in Germany in 2050.

high production costs, policy incentives such as mandatory blending requirements are the main driver for the production and use of biofuels in the transport sector. In all scenarios in 2020, the EU-blending mandate of 7% is almost entirely achieved with first generation biofuels. Even beyond 2020, political measures are required to achieve higher rates of utilization of biofuels (Table 1).

Fig. 4 shows the real supply volumes of biofuels in the transport sector in Germany in 2015 and their projections in different scenarios for 2050. In scenario "On the drip", supply volumes of biofuels doubles until 2050 due to an increase of supply volumes of advanced biofuels, whereas supply volumes of first generation biofuels are approximately the same as in 2015. Also in scenario "Islands", supply volumes of first

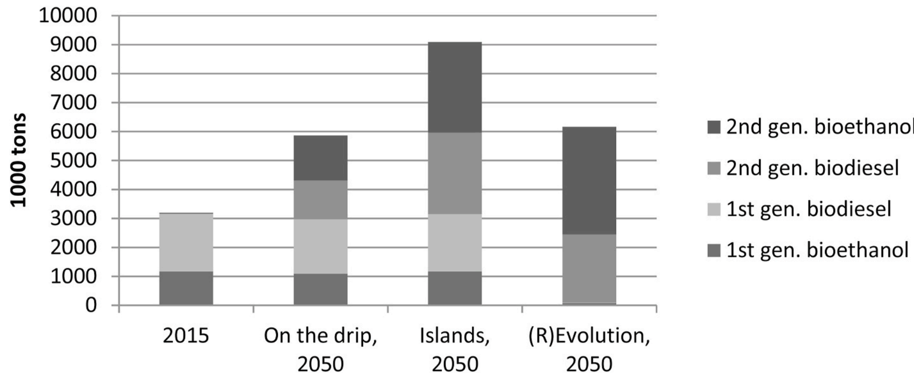

Fig. 4. Supply of biofuels in Germany (in 1000 tons).

generation biofuels in 2050 remain almost constant compared with 2015 vol, but the total supply of biofuels strongly increases due to a larger share of advanced biofuels in total biofuel supply. The development is even stronger in scenario "(R)Evolution", where supply of first generation biofuels are phased out until 2050. The total supply volume of biofuels increases, but solely due to the increase in supply volumes of advanced biofuels.

4.3. *Use of biomass in the chemical industry*

Organic chemistry is based on the use of carbon. If fossil sources of carbon such as crude oil, natural gas and coal are on a phasing out path, other sources of carbon are phasing in and become more important for this sector. For this analysis, we distinguish three sources of renewable carbon which are carbon from recycling (of already existing carbon-containing products), carbon gained from biomass and carbon from direct carbon dioxide utilization (from fossil point sources, permanent biogenous sources or direct air capture) [40,41]. However, the technology of carbon dioxide utilization as a carbon source for the chemical industry is very energy intensive and could become sustainable only when the required power also comes from renewable energy. In our scenarios, this technology is assumed to play some role in "(R)Evolution" scenario and to an even less extent in "Islands" scenario. Already now, carbon from recycling plays an important role and is assumed to gain more importance until 2050 in all scenarios. For this analysis, carbon from biomass stands in the focus.

In 2015, German chemical industry used more than 20 million t organic raw materials as feedstock, thereof 17.5 million t were fossil-based raw materials and 2.5 million t were biogenic resources, mainly agricultural and forest biomass [42]. Fig. 5 shows how the use of this feedstock in chemical industry develops until 2050. In all three scenarios, the total quantity of feedstock decreases significantly, almost exclusively due to the decrease in use of fossil-based raw materials as a feedstock. It reflects the decreasing competitiveness of German chemical industry by production of (bulk) fossil-based chemicals. However, the use of biomass from agriculture and forestry differs significantly across scenarios. In "On the drip", the ratio of fossil-based materials and biomass used as a feedstock remains almost constant and results in a decline of the total level of biomass use. In "Islands", the demand for biomass from agriculture and forestry increases mainly due to the widespread use of drop-in technologies: Production of bio-based chemicals that are identical to their fossil-based peers (e.g. bio-based/fossil-based ethylene, propylene etc.) and, therefore, can be easily further processed in existing chemical facilities. In s "(R)Evolution", the use of biomass from agriculture and forestry as feedstock is the highest across the three different scenarios. This increase is driven by innovative technologies and extensive use of special properties of biomass for the production of new dedicated chemicals, which do not have identical fossil-based counterparts (lactic acid, PLA, PEF, PHA, bio-based lubricants and surfactants, cellulose fibres etc.). The production of such chemicals, however, takes place via dedicated pathways and requires the construction of new chemical facilities.

4.4. *Crops production*

In 2015, the total production of wheat, other grains, oilseeds and sugar beet/cane tip the scales at 76 million tons in Germany [43] accounting for approximately 1.5% of the global production (ca. 5 billion tons [44]) (Fig. 6). In Germany, the total production quantity raises until 2050 to 87 million tons in scenarios "On the drip" and "Islands" and declines to 72 million tons in "(R)Evolution". Worldwide total crop production increases to approx. 7.2 billion tons in "On the drip" or

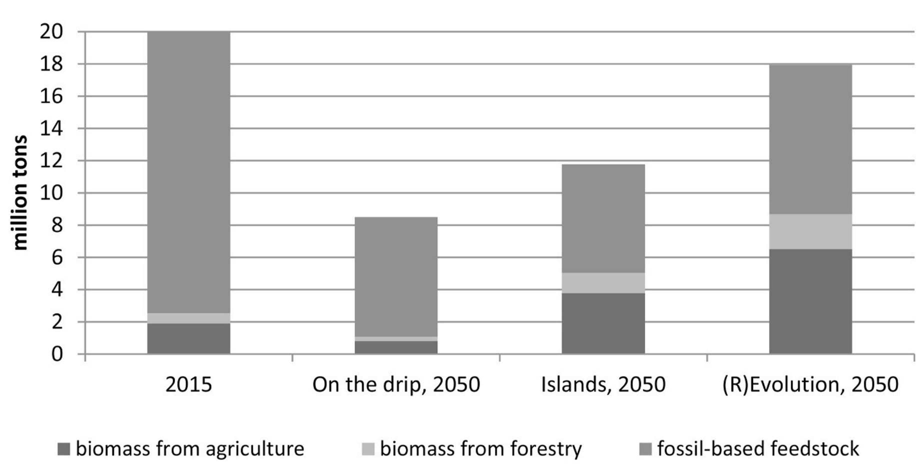

Fig. 5. Use of fossil fuels and biomass as sources of carbon in chemical industry in Germany.

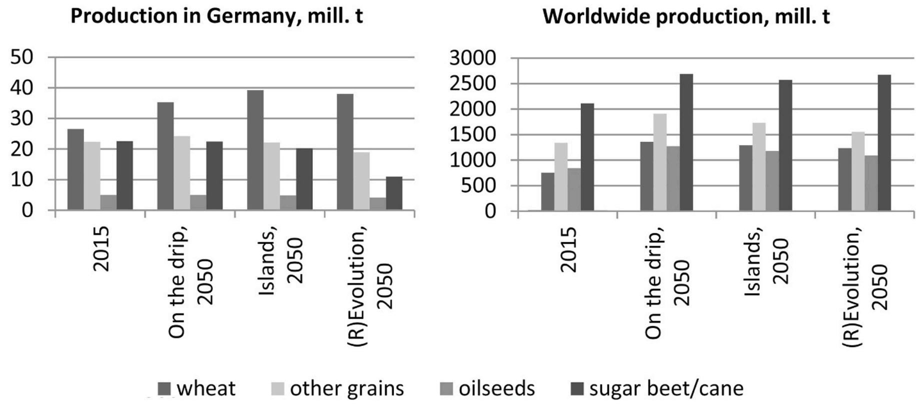

Fig. 6. Production quantities of main crops in Germany and worldwide.

almost 6.5 billion tons in "Islands" and "(R)Evolution".

Wheat is the most important crop in Germany and its production increases strongly over all scenarios (from +30% to 48%) until 2050. The production of other grains, oilseeds and sugar beet declines in Germany in scenario "(R)Evolution" (by −15%, −18% and −50% respectively) and stagnates in scenarios "On the drip" and "Islands" with the exception of a production growth of other grains by 8% in "On the drip" and a drop in sugar beet production by 10% in "Islands".

The global wheat production increases at the highest rate (+80% in "On the drip", +72% in "Islands" and +64% in "(R)Evolution") until 2050. By the end of the projection period, the global wheat production exceeds the global oilseed production. The global production of other grains increases by 43% in "On the drip", by 30% in "Islands" and with 16% considerably smaller in "(R)Evolution". The global production of sugar beet/cane increases at a similar rate across all scenarios (+27% in "On the drip", +22% in "Islands" and +27% in "(R)Evolution").

4.5. Trade with agricultural products

The biomass needed for the production of food, feed, biofuels and biomaterials can be produced nationally or imported from abroad. At the same time, the surplus of nationally produced biomass can be exported. Fig. 7 shows German trade with selected agricultural products in 2015 [43,45] and in different scenarios in 2050.

In terms of quantities cereals, oilseeds and –cakes are the most important agricultural trade commodities in Germany. Germany is a net exporter of wheat and exported around 10.5 million tons with an import volume of 4.3 million tons in 2015. In case of other grains, Germany had a slightly negative trade balance of approximately 1 million tons in 2015, which is mainly due to large imports of corn for animal feeding of approx. 2.4 million tons. Germany is a clear net-importer of oil seeds of more than 9 million tons net-imports in 2015. As Fig. 7 shows, the biggest change in term of quantity until 2050 occurs in wheat trade: Germany doubles (scenario "On the drip") or even triples (scenario "(R) Evolution") its export and, therefore, strengthens its export position in all scenarios. By other grains, exports slightly rise in all scenarios and by stagnating (scenario "On the drip") or decreasing (scenarios "Islands" and "(R)Evolution") imports result in an improvement in the trade balance in all scenarios, making Germany partly even to net-exporter. By oilseeds, no changes in export take place over all scenarios, whereas imports increase slightly in scenario "On the drip" and decrease in scenario "Islands" and more significant in scenario "(R)Evolution". In case of vegetable oils and oilcakes similar movements as by oilseeds can be recognized resulting in improvement of the trade balance.

5. Discussion and conclusions

There are many possible pathways to describe the transition of our current fossil-based to a more bio-based economy in Germany. In this article, we present three possible pathways which differ from each other regarding specific bioeconomy related as well as overall societal, political and economic developments. Taking into account such a variety of driving forces enables to draw a manifold picture. In our case, for example, using different population and GDP developments in line with different SSPs allows to depict different frames for the transition towards a bio-based economy. However, these 'framing drivers' have such an important impact, that the impact of other drivers such as policy measures or changing behavior are sometimes overwhelmed. This is also the reason why aggregated results, e.g. the total aggregated use of biomass, hardly provide helpful indicators to evaluate the impact of specific

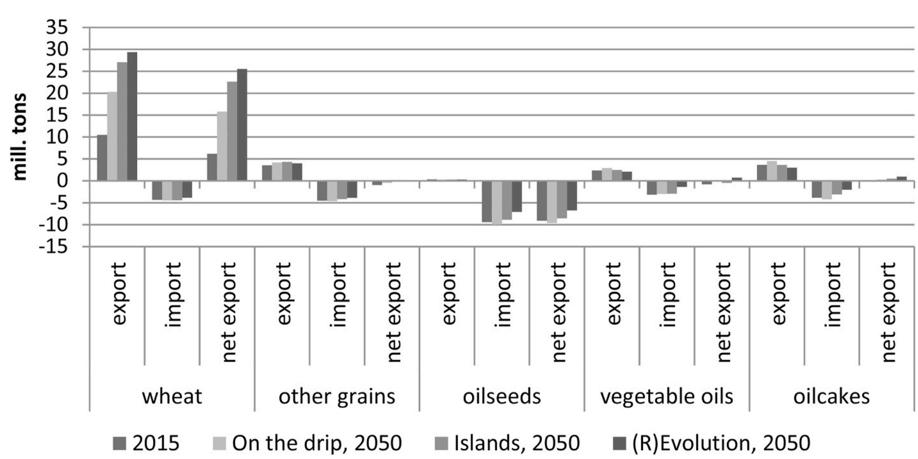

Fig. 7. German trade with selected agricultural products.

bioeconomy related technological developments or policies. To avoid this problem, we look closer at detailed results and, if possible, separate and identify the impact of other scenario specific drivers from the general 'framing' drivers. The advantage of analyzing three scenarios is given by the importance of different scenario elements, e.g. population and GDP developments, technology developments, policies etc.

General social, economic and policy developments (modeled by taking into account different GDP and population developments, international trade and land use change policies) play an important role and can either significantly encourage or hinder the transformation towards a more bio-based economy. Strong growth in GDP will foster investments in new bio-based production technologies and help to reach market maturity. At the same time, this development increases purchasing power of consumers encouraging them to buy more or even switch easily to partly more expensive bio-based products. A growing population is associated with a growing demand for agricultural products in the first place for food, but also for material and energy use. Therefore, a higher global population growth rate is more likely to rise trade-offs between different types of biomass use. Furthermore, the growing demand for agricultural products enhances the pressure on the land used for agriculture and implies the risk of further deforestation and other associated land use changes.

An active policy in the form of stronger land use change regulation plays an important role to solve this problem. It is important to have a strong land use change regulation worldwide, as if it is enforced only in high- and medium-income countries, it results in leakage effects (relocation of production). Trade liberalization on its own also implies the risk of leakage effects, although it is associated with many advantages and is favorable for a reliable access to raw materials required also by bio-based industries.

Besides the 'framing' drivers described above, a series of specific bioeconomy related drivers will determine how strongly certain trade-offs will appear. Simulation results show that the global crop demand strongly increases over all scenarios. A corresponding increase in production is predominantly achieved by an increase in yields and not by a further expansion of agricultural areas [24]. Especially the increase in land productivity by higher yields and a reduction of post-harvest losses in low- and medium-income countries turn to be very important. Therefore, a rising productivity of agricultural land is the main driver on the supply side that mitigates trade-offs associated with the production and use of biomass. On the demand side the key lever identified in our analysis is the change in consumers' behavior and preferences regarding food. Already the decrease in per capita consumption of meat and dairy products in high-income countries such as Germany helps to mitigate the pressure on agricultural land. If also the transformation of the food industry through using less animal-based input for production of processed food takes place, and the total per capita consumption of food due the waste prevention decrease, the effect is much sounder. An increased demand for biomass for energy and material use is an additional factor, which could intensify the pressure on the land use. In our scenarios, however, these types of biomass use do not appear to be critical. Of course, the underlying assumptions play an important role. In none of the scenarios we assume an enhanced political promotion of the first-generation biofuels. In Germany (and in the EU), the quantities of biofuels of the first generation used in the transport sector in 2050 don't exceed the level of 2015 and the increase of the total quantity of biofuels is reached only due to the increase in use of advanced biofuels. The material use of biomass, especially in the chemical industry, increases notable in two of three scenarios. However, the demand for biomass for material use is still relatively low, and if it is accompanied by other developments that reduce the pressure on land, it is quite bearable. Such developments enable Germany also for example to raise its importance as exporter in case of wheat and hold stable or even decrease levels of imports of oilseeds and other coarse grains.

The phasing out of the massive use of fossil fuels is inevitable for a transformation to a more sustainable economy. The use of biomass from agriculture not only for food and feed but also for energy and material use plays an important role in this process. However, other sustainable options also have to be exploited. Paracelsus said: "The dose makes the poison". The same applies to the ambitions regarding the role of the bio-based economy: If potential conflicts are to be minimized and the entire transformation towards a more bio-based economy should also become a transition to a more sustainable economy, the bio-based part of our economy should be constantly monitored and both, achieved and pursued targets, should be regularly questioned regarding their sustainability. As shown above, taking the favorable path with less trade-offs implies besides a 'wise' policy decisions regarding the support of use of biomass for material and energy use also the transformation of the whole society which on its turn should be promoted by policy. It is important to raise the awareness of each individual regarding the negative impact of a fossil-based economy and to encourage active participation in the transformation process. One of the most promising developments that can be promoted through such a raise in awareness, possibly accompanied by other policies, is the transition of consumer behaviors and preferences regarding food consumption.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2021.106002.

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