Research in Globalization 3 (2021) 100060

Contents lists available at ScienceDirect

Research in Globalization

journal homepage: www.sciencedirect.com/journal/research-in-globalization

Scenarios for an impact assessment of global bioeconomy strategies: Results from a co-design process

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ARTICLE INFO

Keywords:
Co-design
Scenario analysis
Bioeconomy
Modelling framework

ABSTRACT

The replacement of fossil resources with renewable biomass in a bioeconomy is seen as a major contribution to climate change mitigation. This transformation will affect all members of society, making it crucial to consider the views of different stakeholders to ensure a socially acceptable transition towards a sustainable bioeconomy. To explore potential outcomes of bioeconomy strategies assuming different future pathways, a scenario analysis is a tool to inform decision-makers about policy impacts and trade-offs. The inter- and transdisciplinary research project "BioNex – The future of the biomass nexus" is the first project to develop bioeconomy scenarios together with stakeholders from politics, industry, and civil society in an iterative co-design process. As a result, three storylines describing diverging potential global futures are developed and quantified: Towards sustainability, business as usual, and towards resource depletion. The futures are driven by different assumptions on climate policy, cropland expansion, productivity growth in agriculture, prices of fossil energy, and consumption behaviour. Additionally, in the co-design process, three bioeconomy policies are developed: policy as usual, stronger development of the bioeconomy, and no policies. Besides presenting the results of the stakeholder workshops, this paper evaluates the strengths and shortcomings of a stakeholder approach in terms of policy-oriented research. According to the experience made within this study, it provides valuable insights for researchers and funding authorities they can use to optimise the employment of stakeholder-based research approaches.

Introduction

Transdisciplinary research that simultaneously involves scientists of different disciplines, as well as practitioners, has emerged as an essential tool for research that aims at solving "grand challenges" (Reid et al., 2010) towards sustainable development (Lang et al., 2012; Mauser et al., 2013). One of these challenges is the mitigation of climate change through the reduction in greenhouse gas (GHG) emissions based on a renunciation of using fossil resources. This will require an economic and societal transformation from a fossil-based to a biomass-based economy (bioeconomy), in which fossil material is replaced with "sustainably produced, renewable natural resources" (BMBF/BMEL, 2015) in the form of biomass. To facilitate this transition, many countries have been implementing bioeconomy policies such as the introduction of biofuel mandates in the transport sector in the European Union (EU) (Scarlat et al., 2015). The main challenge for this transformation, however, will be the simultaneous achievement of sustainable use of natural resources, global food security, and economic growth (Heimann, 2019). As land for biomass production is limited, increased use of biomass will likely lead to competition amongst different uses, such as food production and ecosystem services (Delzeit et al., 2018; Zabel et al., 2019). The inter- and transdisciplinary research project "BioNex – the future of the biomass nexus" seeks to identify and quantify trade-offs between alternative uses of land and biomass to support the transition towards a sustainable bioeconomy.

For this purpose, we employ a participatory co-design approach where economists and natural scientists work together with stakeholders from politics, industry, research, and civil society to develop exploratory and policy scenarios on the development of the bioeconomy. Participatory scenario development has already been successfully used

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https://doi.org/10.1016/j.resglo.2021.100060
Received 3 January 2020; Received in revised form 7 July 2021; Accepted 24 August 2021
Available online 29 August 2021

for the derivation of scenarios in the field of agriculture, environment and biodiversity on a regional scale (e.g. Reed et al., 2013; Priess and Hauck, 2014; Oteros-Rozas et al., 2015; Siew et al., 2016; Kok et al., 2019), but rarely in the emerging field of bioeconomy research (e.g. European Commission, 2018; Hagemann, Gawel, Purkus, Pannicke, & Hauck, 2016). This is a major research gap since a transformation to a biomass-based economy will have a profound influence on the economy and society on the whole. Given that the bioeconomy involves all activities and actors that produce, process or use biomass, including the agri-food industry[1], forestry, and energy production as well chemical and biotechnological sectors (BMBF/BMEL, 2015) any strategy and research aiming to facilitate this transformation will need to consider the view and concerns of stakeholders on different aspects of the bioeconomy. Further, as some bioeconomy technologies are in their infancy and not market-ready, stakeholder knowledge is essential to inform about potential future developments. Moreover, the supply and demand for land and biomass are dependent on many uncertain trends, such as climate change, changing diets, and in particular different policies.

While in the project's funding proposal broad research questions had to be stated before the co-design process started, the first objective of this paper is to identify important trade-offs between different biomass uses caused by bioeconomy policies which are used to specify research questions. Further, since scenarios are a common method to analyse and cope with uncertainties in the future development (e.g. Peterson et al., 2003; van Vliet and Kok, 2015; Kok et al., 2019) our second objective is to define together with stakeholders scenarios that capture the most important drivers of the bioeconomy until 2030 and can be applied in an interdisciplinary modelling framework. Depending on the purpose of the scenarios, different approaches for scenario development exist (see e.g. Schoemaker, 1993; Van Notten et al., 2003; Börjeson et al., 2006; Kok et al., 2019 for an overview). We distinguish between scenarios on possible futures incorporating the main trends influencing the bioeconomy on the one hand and scenarios on EU level bioeconomy policies on the other hand. For the final analysis of the scenarios in the model framework, we use a combination of these two types of scenarios by analysing different bioeconomy policies in the context of different possible futures. Following the scenario typology of Börjeson et al. (2005), the scenarios on possible futures can be categorised as exploratory scenarios since these scenarios tend to sketch possible future trends and are defined alongside the most important drivers affecting the bioeconomy, whereas the bioeconomy policy scenarios can be categorised as predictive scenarios since they explore the question of what-if a certain bioeconomy policy is implemented. The third objective of this paper is to evaluate the strengths and shortcomings of a stakeholder approach for scenario development in terms of policy-oriented research and to present resulting bioeconomy scenarios.

Fig. 1 gives an overview of the project design, including the co-design and modelling framework. The arrow on the left indicates the involvement of researchers and stakeholders in the specific phase of the project. The first phase includes the abovementioned definition of research questions and potential scenarios for future biomass use together with stakeholders in co-design. In the second phase, researchers will use an integrated modelling framework consisting of the global economic model DART-BIO and the bio-physical plant growth model PROMET to simulate and evaluate these scenarios over a mid-term horizon of 20 years. Following the scenario analysis, researchers will identify and quantify trade-offs between alternative uses of biomass again together with stakeholders. To the best of our knowledge, we are the first modelling team to comprehensively identify both research questions and scenarios of the bioeconomy together with stakeholders in an iterative process.[2]

This paper presents the results of the first phase, in which we conducted two stakeholder workshops in the format of group discussions. During the first workshop, stakeholders helped to define significant trends, policies, trade-offs, and technologies, which globally affect the transition towards a sustainable bioeconomy. We then proposed three storylines that are characterised by different assumptions under which different bioeconomy policies are analysed. In a second workshop, stakeholders and researchers quantified these storylines and bioeconomy policies aiming to implement them as scenarios in our modelling framework in the second phase of the project.

The paper is structured as followed. The next section explains the principles of co-design as well as the specific co-design process applied in this study. Section 3 examines and discusses the resulting storylines and bioeconomy scenarios as well as the respective assumptions, while section 4 concludes.

Co-design of bioeconomy scenarios

Principles of co-design in transdisciplinary research projects

Before explaining our specific co-design process in detail, it is important to examine the principles of co-design that are guiding the transdisciplinary stakeholder involvement in this study. Transdisciplinary research projects can be divided into three stages according to Vilsmaier and Lang (2014):

1. Preparation stage: problem identification and structuring
2. Project phase: joint generation of solution-orientated knowledge
3. Follow-up work: re-integration and application of the generated knowledge

This corresponds to the steps "co-design, co-production, and co-dissemination" defined by Mauser et al. (2013). The co-design, in which research questions result from cooperation and interaction with stakeholders, is particularly important since the typical scientific research questions do not sufficiently meet societal needs (ibid.).

Ideally, the co-design integrates knowledge of scientists from natural, social, and human sciences and engineering with knowledge of stakeholders (ibid.). The objective of knowledge integration is the distinction and linkage of specialist-disciplinary knowledge with daily-life knowledge and personal opinions (Scholz and Tietje, 2001; Bergmann et al., 2012). In the process of knowledge generation, the source of knowledge (e.g. model output by scientists or information provided by stakeholders) needs to be traceable. The traceability allows then to rate the validity of data, information, and knowledge (ibid.).

The prerequisite for knowledge integration is the collaboration between researchers and stakeholders (Bergmann et al., 2012). Here, a major problem can arise through "unbalanced problem ownership", which refers to cases in which either researchers or stakeholders within a transdisciplinary research project do not have the same interest in the research topic (Lang et al., 2012). This can be caused by the fact that one

[1] The agri-food industry includes agriculture, fisheries, aquaculture and all kinds of food processing.

[2] Hagemann et al. (2016) identified key drivers of a wood-based bioeconomy together with stakeholders, but scenarios were developed separately. Similarly, researchers in the "Beyond the Horizon: foresight in support of future EU research and innovation policy (BOHEMIA)" study of the European Union first developed bioeconomy scenarios and subsequently asked stakeholder with a Delphi survey about their assessment of the likelihood of future trends (European Commission, 2018).

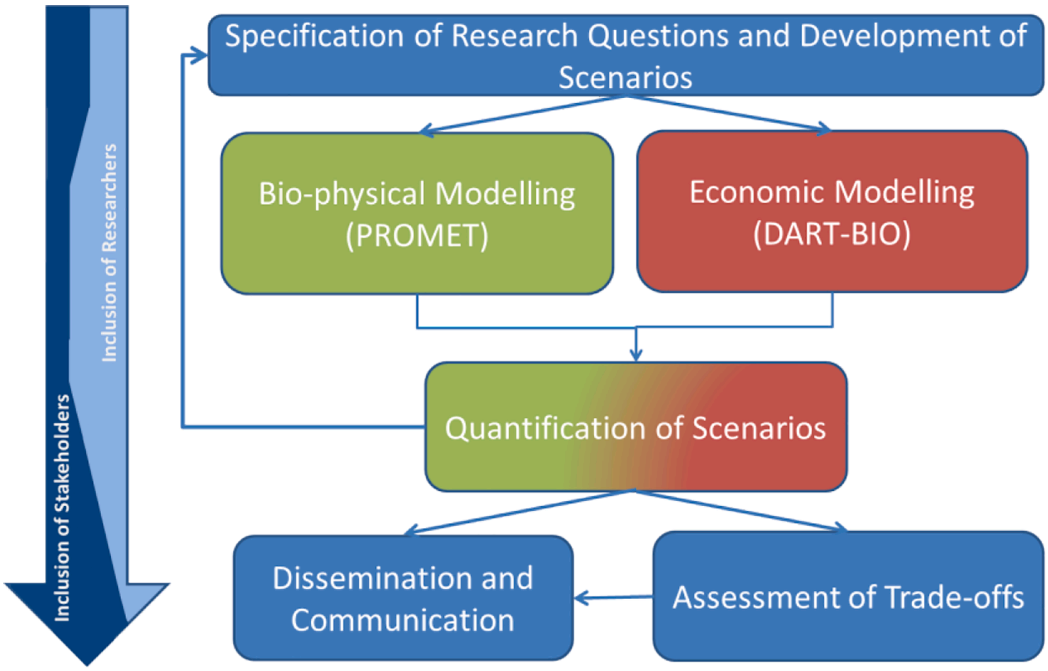

Fig. 1. Design of the BioNex project.

party initiated the project without the other party being interested in problem solutions (ibid.). Acceptance and participation willingness of stakeholders are usually very low when conflicts of interest emerge, e.g. when (financial) interests could be negatively affected by the participation process or project results (Lang et al., 2012). Additionally, Pohl and Hirsch Hadorn (2006) emphasise that transdisciplinary projects carry the danger of being overloaded with expectations and aspirations. To avoid this, Pohl and Hirsch Hadorn (2006) suggest the following principles for the research process and the co-design phase:

1. To reduce the complexity of a problem, research questions are formulated and participants are chosen.
2. Projects should be embedded in real life, and results should be translated into specific target groups.
3. All perspectives and knowledge should be deemed equally important.
4. Learning by recursively iterating steps within the project (reflexivity via recursivity)

In the spirit of these principles, this study's co-design process began with the definition of stakeholders and the integration of stakeholder knowledge in the formulation of research questions.

Co-design of research questions and bioeconomy scenarios

Depending on their purpose, scenarios can be qualitative, when describing possible futures in the form of words, or quantitative, when consisting of numerical estimates (Alcamo, 2008). In line with other international scenario exercises (e.g. the World Water Vision scenarios of the World Water Commission (Cosgrove and Rijsberman, 2000); the SRES greenhouse gas emission scenarios of the Intergovernmental Panel on Climate Change (Nakicenovic et al., 2000), the global scenarios of ecosystem services from the Millennium Ecosystem Assessment (MA, 2005; Carpenter et al., 2006), and the global environmental scenarios of Global Environmental Outlook (UNEP, 2007)), we use a combination of qualitative and quantitative scenarios. For this purpose, together with stakeholders, we first develop qualitative descriptions of different futures and then define numerical assumptions for the main drivers and trends characterising these futures. For this purpose, we roughly follow the first four steps of the story and simulation (SAS) approach suggested by Alcamo (2008) based on a review of the above-mentioned scenario exercises. These steps include: 1. The establishment of a scenario team; 2. The proposal of goals and outline of the scenarios by the scenario team; 3. The revision of the scenario goal and outline by the scenario panel and the construction of the storylines; 4. The quantification of the driving forces of the scenarios based on the draft storylines by the scenario team.

Establishment of a scenario team

The scenario team consists of the team of the research project and a scenario panel, which consists of the participating stakeholders. Aiming to avoid "unbalanced problem ownership", already in the course of writing the project proposal in 2015/2016, three potential stakeholders from existing networks were contacted and asked whether they were interested in contributing as stakeholders. There was no funding available to conduct a proper selection and engagement of stakeholders at that time, which is a common constraint of transdisciplinary research projects (Vilsmaier and Lang, 2014). However, when the project and its funding started in April 2017, the interdisciplinary research team selected stakeholders intending to have representatives from all groups involved in the bioeconomy. The first list of potential stakeholders was compiled including representatives from different industries, ministries, international organisations, and non-governmental organisations (NGOs). Also, we listed the fields of knowledge and expected contributions to the workshop. To capture knowledge about new technological developments in the field of bioeconomy activities, we performed a systematic search on private companies involved in bioeconomy technologies. The final list consisted of 38 stakeholders, of which 10 participated in the workshops (see Table 1). The expertise of the participating stakeholders covered amongst other expertise biomass and bioenergy markets, global agricultural production and trade, bio(energy)technology, policymaking, and economic modelling. The relatively low share of the final number of participants compared to those initially invited was likely because several transdisciplinary bioeconomy research projects started simultaneously under the funding from the German Ministry for Education and Research. Stakeholders were invited to participate in several similar workshops. Two NGOs expressed interest in the project but cancelled last minute. They were informed via

Table 1
List of invited, confirmed, and participating stakeholders.

Institutional Setting	Invited Stakeholders	Confirmed Stakeholders	Participating Stakeholders	
			Workshop 1	Workshop 2
Politics	6	4	3	2
NGO	3	1	0	0
Research	14	4	1	3
Private Business	13	2	2	1
International Organisations	2	1	1	1

minutes and asked for comments after the two workshops.

First proposal of goals and outlines of scenarios

The project's goals were very broadly defined in the funding proposal before the co-design process started. Yet there was sufficient room to specify the research questions during the course of the project. In order prepare the first joint proposal of goals and outlines of scenarios, the research team invited stakeholders for the first workshop and provided information about the project's broad objectives, their potential contributions, and the first potential research questions. Those stakeholders who confirmed their participation (n = 12) were asked to fill out a short questionnaire with questions on i) technologies ii) policies and iii) trends that are relevant for the bioeconomy until 2030 to define priorities. The outcomes were summarised and presented to the stakeholders at a first workshop to provide a starting point for a group discussion. In addition, the results were used to define three topics for a "world café": "trends and policies", "trade-offs" and "technologies". The method "world café" allowed the stakeholders to get to know each other in smaller groups during the first workshop and to incorporate diverse perspectives and contributions from the stakeholders in order to specify research questions and to outline scenarios. Subsequently, results from the three tables (topics) were summarised and discussed with the whole group.

Following Bohnsack (2013), all workshops were organised as group discussions. They started with explaining the formal procedure, a round of introduction of all participants, followed by a discussion incentive (Bohnsack, 2013). As a discussion incentive, three stakeholders were asked for input talks on the current state of bioeconomy technologies and the global agricultural sector to provide a basic level of information for all participants. We considered these input talks as crucial information for the following discussion and therefore accepted that three stakeholders take a double role in providing information as well as being stakeholders with equal participation rights in the discussion. Researchers lead the group discussions and wrote summarising minutes.

Revision of outline and construction of the storylines and quantification of driving forces

Based on the trends and policies suggested and debated during the first workshop, in preparation for the second workshop, five drivers combined to generate three different futures were selected by the researchers. To reflect the suggested technologies, bioeconomy policies were incorporated to analyse the implications of bioeconomy activities under different future developments. The researchers' proposal, including a detailed description of the futures until 2030 in the form of storylines[3] was provided to the stakeholders before the second workshop. During this workshop, researchers and stakeholders decided on a final set of storylines and scenario assumptions, i.e. the quantification of the storylines. In this workshop, the researchers presented the draft of storylines and related assumptions in short PowerPoint presentations separately for each trend. Subsequently, stakeholders were asked for feedback, which was collected, discussed, and synthesised. This resulted for each topic in a quantification of assumptions all participants agreed upon.

Conflict of interest was not observed during the co-design process. Stakeholders voiced significant interest in the project and project results, e.g. politicians were interested in improving bioeconomy related policy-making whereas the private business representatives emphasised their need for information on investment opportunities and developments on the world market.

The next section presents the storylines and quantification of the scenario assumptions.

Resulting storylines and scenarios

First list of trends, policies, trade-offs and bioeconomy activities

The first workshop resulted in a set of eight trends for which stakeholders stated priorities (see report in supplement). Four trends (consumption of animal-sourced products, fossil fuel prices, climate change, and productivity growth rates in agriculture) were considered most relevant by stakeholders. Stakeholders and researchers agreed that climate change is not an important driver of results for a mid-term perspective, but should nevertheless be included in all scenarios. In addition to the trends, stakeholders named six policy measures but did not state which they deemed most relevant (see report in supplement). For the topic "trade-offs" stakeholders emphasised trade-offs in land-use that cause social and environmental conflicts between industrial and developing countries. Another trade-off was seen between increasing agricultural yields and implementing the Paris Climate Agreement if yield increases are achieved with more capital (i.e. tractors using fossil fuels) or fertiliser input. While the project proposal defined broad goals (e.g. identify trade-offs between alternative uses of biomass), at the first workshop this was specified (e.g. identify trade-offs between high yields vs climate protection).

For the third topic "technologies", the stakeholders' answers to the questionnaire underlined the importance of biofuels and biopolymers as technology options and of oil crops, maize, sugarcane, and waste and crop residues for the provision of biomass. Note that biofuels and biopolymers are not technologies per se, but bio-based products for which different processing technologies can be used, e.g. fermentation for conventional and thermochemical conversion for advanced biofuels. Also, stakeholders named precision farming and new breeding methods as important bioeconomy technologies. A major result of the first workshop was the view that biofuels will remain the dominant bio-based product with conventional and advanced conversion technologies under the current policy setting. Stakeholders argued that the development of non-energy bioeconomy sectors is highly uncertain. A major reason why bio-based inputs are not (yet) used for replacing fossil inputs in existing value chains are price differences between fossil and bio-based inputs and high uncertainties in fossil fuel prices, hence the need for policy support for further growth of the bioeconomy sector was highlighted. It was agreed that the researchers propose a set of storylines and scenarios at a follow-up workshop.

Proposed storylines

In line with step three of the SAS approach by Alcamo (2008), researchers developed three different global futures consisting of five drivers each based on the most important trends, policies, and technologies compiled in the first workshop. Following the axes-scenario technique used for exploratory scenarios (van't Klooster & van Asselt, 2006) researches used the axes of "environmental protection" and "resource consumption" as a backbone to position the storylines. The development of the storylines along these axes aims at analysing the full

[3] Storylines are defined as "narrative description[s] of a scenario (or a family of scenarios), highlighting the main scenario characteristics, the relationships between key driving forces and the dynamics of their evolution" (IPCC, 2007).

spectrum of possible futures and the impact of key drivers defining the corridor or upper and lower bounds for the development of the bioeconomy. Therefore, in addition to a business as usual future which continues current trends, current environmental protection and resource consumption two futures were positioned at the extremes of the axes (high environmental protection and lower resource consumption in contrast to low environmental protection and high resource consumption). The five drivers consist of four policies and trends suggested by stakeholders (climate policies, consumption of animal-sourced products, fossil fuel prices, and productivity growth rates in agriculture), and expansion of agricultural land – which the researchers added to include potential trade-offs with biodiversity. The time horizon for the storylines is 2030 because the EU's bioeconomy policies are only defined until then. The proposed storylines, which are the basis for the exploratory scenarios, (Fig. 2) are explained in the following:

A: Towards sustainability

In this storyline, the future is characterised by sustainable consumption patterns, i.e. a decline in consumption of animal protein in industrialised countries, and a decline in the use of fossil energies along with a strong implementation of climate policies to reach the 2 °C target in all countries that signed the Paris Agreement. In addition, in this world productivity growth rates in the agricultural sector and energy prices are high due to better management practices. The production is sustainable, which implies that there is no cropland expansion into uncultivated areas, and forests are managed sustainably across the world.

B: Business as usual

In this storyline, future development continues to follow current trends. The consumption of animal protein will globally increase with rising incomes. Climate policies such as the European Union's Emission Trading System (EU-ETS) are in place. In the agricultural sector, current growth rates in productivity and energy prices are lower compared to the storyline towards sustainability. Across the globe, cropland expands into uncultivated areas if it is legal.

C: Towards resource depletion

In the world of this storyline, consumers do not care about the environment and climate change, shown through the high consumption growth of animal proteins. Further, the international community does not implement the Paris Agreement and environmental protection areas are not considered, such that protected areas can be used for crop production. Due to a lack of international cooperation, agricultural productivity is lower compared to the Business as usual situation. Although fossil energy consumption is high, energy prices are lower compared to the Business as usual world until 2030 since exploitation is increased and there are no climate policies.

In a matrix structure, different potential developments of the bioeconomy (predictive scenarios) are analysed for all three futures (explorative scenarios). This allows the evaluation of potential outcomes of different bioeconomy strategies within different futures. This would add a third dimension to Fig. 2. Since stakeholders highlighted the need for policy support for the development of new bioeconomy technologies, two policy support schemes were proposed to the stakeholders in the second workshop. The proposed support schemes specify two out of three developments of the bioeconomy analysed in predictive scenarios.

1. Bioeconomy policies as usual: In this world, current bioeconomy policies across the world are not changed. This implies a world with policy support only for biofuels.

2. Strong support of bioeconomy policies: In this world support policies for biofuels are further developed such that the production of biofuels increases. This relates not only to industrialised countries but also to emerging and developing economies. Besides, there are policy measures in place which trigger a higher use of bio-based inputs in the material industry.

The third potential development of the bioeconomy consists of no support scheme of the bioeconomy. Since this potential development serves as a counterfactual to the two support schemes it was not explicitly discussed with the stakeholders.

The storylines together with the potential quantification of the five drivers in each storyline and the different support schemes for the bioeconomy resulted from the second workshop as described in section 2.2.3.

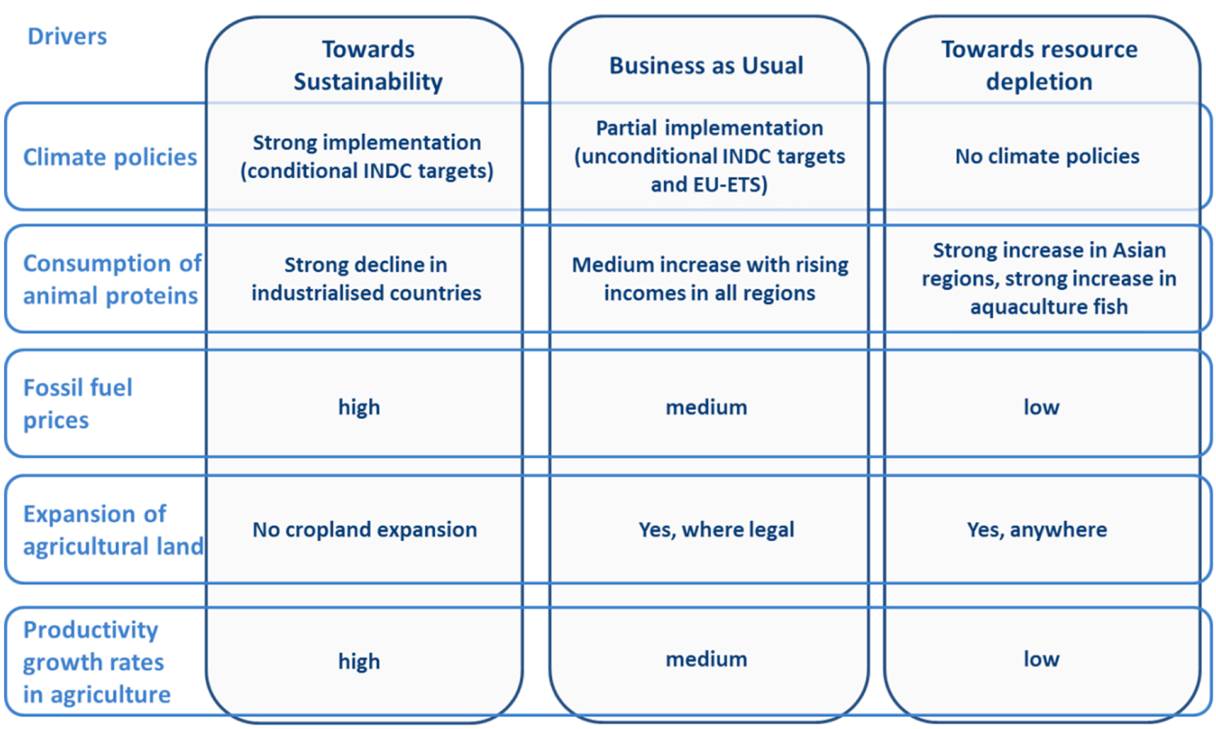

Fig. 2. Proposed BioNex storylines.

Deciding on storylines and quantification of scenario assumptions

The final set of storylines and the quantification of the scenario assumptions resulted from the second workshop and subsequent decisions by researchers after evaluation of the workshop outputs. This co-design and decision process, as well as the resulting storylines for the three futures and scenario assumptions (see Table 2 for an overview), are elaborated in the following sections.

After exchanging the views on the role of extreme scenarios along the two axes, stakeholders generally approved the storylines suggested by the researchers. The major focal point in the second workshop with the stakeholder was then put on the quantification of the drivers of the storylines.

In order to conduct step four and five of the SAS approach for the quantification of the scenario assumptions, the researchers first presented their ideas to quantify the single drivers with short PowerPoint presentations and then subsequently asked for feedback and discussed the scenario quantifications after each presentation in the form a group discussion. To present this process in a structured manner, the next sections will review each driver by first providing a short background as given to the stakeholders in small presentations followed by the group discussions and the results of the co-design process in terms of quantification of each scenario in each storyline.

Driver 1: Climate policy in the three futures

In the course of the COP21 in Paris, each participating state identified national climate goals, the Intended Nationally Determined Contributions (INDC) (UNFCC, 2018). The INDCs are the basis of the post-2020 global emissions reduction commitments included in the climate agreement and state the conditional and unconditional national targets for emission reductions. Conditional targets are subject to nation-specific conditions for implementation, such as financial support, which have been agreed upon with the international community. The unconditional targets need to be fulfilled independent of the actions of the international community. Regional emissions trading schemes already implemented such as the EU-ETS are included in unconditional targets (UNFCC, 2018).

While stakeholders agreed on assuming strong climate policies in a sustainable future and a partial implementation in a business as usual world, a debate evolved regarding the interactions of climate policies and other drivers, such as high fossil fuel prices. It was debated whether climate policy should be formulated as a driver of its own or simply be integrated into the three storylines due to its strong interlinkages with other policies. Ultimately, the participants decided to have climate policy as a separate driver within the storylines such that it can be combined with the bioeconomy policy shocks.

For the implementation of the driver climate policy in the economic DART-BIO model, it is assumed that all governments fulfill the conditional targets under Towards sustainability since in this world industrialised countries provide financial resources to developing countries to materialise higher reductions in GHG emissions. Under Business as usual, it is assumed that only the unconditional targets are fulfilled. Although the latest emissions gap report by the UN environmental program states that the majority of the G20 countries are not yet on a path to meet their NDCs in 2030 (UNEP, 2018), the researchers decided to keep the scenario as agreed upon with the stakeholders. In both scenarios, the emission reduction targets are taken from the CAIT Paris Contributions Data compiled by the World Resource Institute (2018). In the world Towards resource depletion, no climate policy is in place.

Driver 2: Fossil fuel prices in the three futures

Prices of fossil fuels are determined by the interplay of demand and supply that is influenced by several factors. The supply side output of fossil fuels is determined by resource constraints, production costs, geopolitical considerations, and distortions such as OPEC production targets, trade embargos, or wars in oil-producing countries (EIA, 2018).

Table 2
Overview on drivers and scenario assumptions. * Global Trade Analysis Project.

Scenarios	Drivers				
	Climate Policies	Consumption of animal products	Fossil fuel prices	Expansion of agricultural land	Productivity growth rate in agriculture
Towards resource depletion	No climate policies or climate change mitigation measures are included in the model.	Stronger increase in animal protein consumption than in the BaU scenario. No restrictions on captured fish or aquaculture production.	Growth rate of the oil price is 1.5% lower than in the BaU scenario.	10% increase in agricultural land compared to BaU. No legal constraints for expansion.	The annual growth rate is reduced by 0.2 percentage points compared to BaU.
Business as usual	Implementation of the national unconditional targets of the INDC including existing climate policies such as EU-ETS.	Animal protein consumption grows as implied by preferences in original GTAP* database. Strong increase until 2030 driven by income and population growth in Asia. Aquaculture fish production increases by 3% p.a.. Captured fish increases by 1%. until 2025 and is constant afterwards.	Supply elasticities for fossil fuels chosen to match the 2030 carbon emission projections of the IEA.	Global expansion of 7% until 2030 is assumed. Expansion into protected areas is restricted to IUCN category III-VI.	Region-specific trends derived by OECD/FAO describe a global average annual growth rate of 1.2%.
Towards sustainability	Implementation of ambitious and binding climate policies: National conditional targets of the INDC.	Animal protein consumption decreases by 50% in industrial countries in 2030 compared to current levels. Captured fish catch is reduced by 5% per year until 2022 and then constant. Aquaculture production increases max. 3% p.a..	Fossil fuel prices in the electricity sector through climate policies. Growth rate of the oil price is 1.5% higher than in the BaU scenario.	No expansion of managed land. Land-use change according to a constant elasticity of transformation (CET) function.	Annual growth rate of 2.8% on global average, regional specific growth rates derived from linking DART-BIO and PROMET.

The higher the prices, the more lucrative it becomes to explore more expensive production methods such as fracking (Frondel et al. 2018). Fossil fuel demand determinants include the political and economic state of the global economy, e.g. economic growth or financial crises, developments in energy efficiency as well as various energy policy instruments such as subsidies or taxes (OECD, 2018; EIA, 2018). The development of competitive renewable energy sources can further decrease the demand for fossil fuels (IEA, 2018).

The implementation of climate policies in the three storylines will already affect the prices of fossil fuels in the model. The introduction of a GHG emission cap, for example, will increase the price of commodities using fossil fuel inputs. This should result in different fossil fuel price scales in the three different worlds: high prices in the world Towards sustainability, low prices in the world Towards resource depletion, and medium prices in the Business as usual case. The participants agreed that it would be useful to have starker effects on fossil fuel prices. Therefore, besides different developments in fossil fuel prices due to climate policies, both extreme scenarios include additional policy measures lifting and lowering the oil price.

To meet a medium level of fossil fuel prices under the Business as usual scenario, the supply elasticities of fossil fuels are chosen in such a way that the GHG emissions in 2030 resulting from the model in Business as usual meet the newest projections of the International Energy Agency (IEA) for world regions. In the case of Towards Sustainability, in line with the scenario on climate policies, ambitious climate policies lead to high energy prices. Also, growth rates of global energy prices increase by 1.5 percentage points in 2030 compared to the BAU scenario. In the Towards resource depletion scenario producers do not face additional price mark-ups from climate policies and therefore prices for fossil fuels are lower. At the same time, higher demand for fossil fuels is likely to drive up fossil fuel prices. To keep growth rates of global energy prices 1.5 percentage points lower in 2030 compared to the BAU scenario, the supply of fossil fuels is simultaneously increased reflecting that OPEC and other oil-producing countries are boosting their supply to benefit from high demand. We are aware that these effects might be contracting but need to allow for the stakeholders' wish for extreme scenarios with diverging fossil fuel prices. The actual scenario implementation will show whether this manipulation of supply is at all feasible or whether we need to adjust the scenario.

Driver 3: Consumption of animal proteins in the three futures

Rapid income increases in emerging and developing countries lead to a nutrition transition that implies a convergence of food demand patterns to Western diets with a high share of animal proteins and processed food types (Pingali, 2006; Popkin et al., 2012). Simulations show that this dietary change will have substantial impacts on global land-use in the mid-term as a lot of the animal feed used in Asian countries is produced elsewhere, for example in Brazil (Delzeit et al., 2018; Schuenemann and Delzeit, 2020). Researchers, therefore, suggested assuming in all storylines that the protein share in diets will increase with rising income levels, in particular in Asian countries.

The stakeholders noted that Asian diets contain more fish and poultry than red meat and that aquaculture production will continue to grow significantly. Therefore, it was concluded to add an explicit fish sector to the economic model. In the Business as usual world, protein consumption will follow current trends. For the Resource depletion scenario, it was agreed to implement an additional increase of global animal protein consumption in Asian regions and no restrictions in fishing and aquaculture. Further, it was agreed not to consider alternative protein sources like lab-grown meat and insects, since they will not play a significant role until 2030.

In the world Towards sustainability, animal protein consumption in industrial countries will be reduced by 50% compared to current levels. If this is implemented by a tax, the participants suggested taxing both meat and fish to avoid undesirable substitution effects.

Additionally, researchers will specifically analyse fish production from aquaculture and its linkages to global land-use. Today 3.2 billion people cover 20% of their protein diet with fish, and the FAO estimates that until 2030 fish production in Asia will increase by 18.8% (FAO, 2018). Since expected increase rates of capture fisheries production are very low, aquaculture fish production is expected to fill the demand gap. In the last decade, aquaculture production grew by 5.7% p.a. and is estimated to grow further by on average 2.1% p.a. from 2017 to 2030. It is important to note that the reason for the reduced growth rate is not a slower growth of demand, but production constraints (FAO, 2018). For capture fish, the projections by FAO (2018) are employed in the BAU scenario, which means an increase in production by 1% between 2017 and 2030.

For the Towards sustainability scenario, we assume the moderate adjustment path drawn by the World Bank (World Bank, 2017). According to this path, capture fish landings must be reduced by 5% p.a. until 2022, and then converge to the ideal level until 2040 to rebuild sustainable fish stocks for future fishing activities. Since the economic model runs until 2030, we keep the fish landings constant after 2022.

Driver 4: Expansion of agricultural land

Agricultural expansion may have several negative implications, such as the displacement of natural ecosystems and biodiversity (Delzeit et al., 2017), but has been used in the past to increase agricultural production. From 1961/63 to 2005/07, arable land globally expanded by 16 % and contributed to an increase in crop production by 14 % (FAOSTAT, 2018). While this trend stagnated during the 2000s, the global agricultural area again increased in the last years (FAOSTAT, 2018). The FAO expects a further expansion until 2030 by 53 million ha (3.3%) compared to 2005/2007 and by 70 million hectares (ha) until 2050 (4.3%).

There was general agreement between stakeholders and researchers that the expansion of agriculture needs to consider physical land restrictions as well as political regulations, such as the designation of protected areas. It was suggested by stakeholders to review the possibility of carrying forward FAO trends for expansion. However, after examination, the assumption of a linear continuation turned out to be unrealistic and physically not possible in many regions, since the approach does not consider physical land restrictions.

The world database on protected areas collects global information on protected areas. Globally an area of 11.4 million km^2 is reported to be under protection without counting coastal and marine areas (UNEP-WCMC, 2015). While 39% are strictly protected (category Ia, Ib, II), 61% are less strictly protected (category III-VI), which means that agriculture is allowed under certain restrictions. Stakeholders agreed that agricultural expansion should not be allowed in the Sustainability scenario, while it should be restricted in the world with Business as usual. In Towards resource depletion, there are no restrictions on where cropland expansion can take place.

The scenarios differentiate between cropland expansion into already managed and unmanaged land. Expansion of cropland into other cultivated areas (pasture and managed forest) is possible in all scenarios. The Towards sustainability scenario does not allow for expansion of managed land, while land-use change within managed land is possible. In contrast, agricultural land is assumed to expand globally by 7% into unmanaged land until 2030 in the Business as usual scenario, but the expansion is restricted according to different categories of protection. While strictly protected areas (IUCN category I-II) are not allowed for expansion in Business as usual, less strictly protected areas (IUCN category III-VI) may be used for expansion if they are profitable. As the Towards resource depletion scenario allows expansion anywhere the area for expansion is 10 percentage points higher until 2030 than in the Business as usual scenario.

Driver 5: Productivity growth rates in the three futures

Intensification of agriculture has contributed the most to growth in world agricultural output during the 1960–1990 period (Fuglie et al., 2012). However, during the last two decades, its contribution has substantially decreased (Delzeit et al., 2018).

Under Business as usual, it was agreed to carry forward current trends, while reduced international cooperation that inhibits knowledge-transfer, technological progress, and variety breeding results in weaker global agricultural growth. Further, it was concluded to have high productivity growth rates under Towards sustainability, though a potential trade-off with climate mitigation was debated. Researchers explained that in a world Towards sustainability, high investments in technology (e.g. precision agriculture) and knowledge transfer are assumed to drive global productivity growth rates – not higher inputs of fertilisers and pesticides. To consider a stronger increase in crop production in developing countries than in developed countries, researchers suggested a) to increase productivity growth rates by a certain rate, or b) to close yield gaps by a percentage. As a result of b), regions that show large yield gaps will experience a larger production increase in comparison to regions that are already close to their potential yields. Stakeholders agreed that this is a more realistic and consistent approach. Further, the stakeholders suggested a delay in closing the yield gaps over time to allow for time for forward-planning when introducing new technologies.

For quantification of the storylines, in the Towards sustainability scenario, stakeholders suggested to double annual growth rates in productivity compared to Business as usual, but with regional differences according to the region-specific yield gap. Numbers are generated by applying a modelling framework linking DART-BIO and PROMET based on Mauser et al. (2015). For the Business as usual scenario the DART-BIO model is calibrated to match region and crop-specific average annual growth rates of the Agricultural Outlook 2018 (OECD/FAO, 2018). The growth rates result in a global average growth rate of 1.4%. It was agreed to assume the annual growth rate to be 0.2 percentage points lower in Towards resource depletion than in the Business as usual scenario in order to capture reduced international cooperation.

Resulting bioeconomy technologies and policies

Following the procedure of small presentations and a subsequent group discussion as for the exploratory scenarios, stakeholders were asked about their views on the most promising bioeconomy technologies as well as under which kind of bioeconomy supporting policy environment these technologies can prosper. Their development will be simulated with the help of the different bioeconomy policy scenarios under the three storylines. Table 3 summarises the results of the co-design process concerning three policy scenarios and different bioeconomy technologies.

Deciding on bioeconomy technologies

The identification of the relevant bioeconomy technologies together with the stakeholders is an important prerequisite for the development of scenarios on bioeconomy scenarios since it narrows possible policy options in case polices address specific bioeconomy technologies (like the Renewable Energy, Directive European Union, 2009). In addition, from the identification follows the necessary technologies and production pathways the model framework needs to incorporate in order to quantify the scenarios. Stakeholders emphasised the continued importance of biofuels as the main bioeconomy product using conventional and advanced conversion technology in the near future. Similarly, studies on trends of the bioeconomy (e.g. Dammer et al., 2017; Dieckhoff et al., 2015; meó Consulting Team, 2014) do not identify any other technology that dominates future developments of the bioeconomy under the current policy setting. To avoid conflicts with food security, many countries aim at promoting advanced biofuels e.g. based on municipal or so-called green waste. Other bioeconomy technologies such as the conversion of biomass into material used in existing industries are not supported by policies and the future market developments are highly uncertain (meó Consulting Team, 2014).

Based on these trends, researchers proposed a set of different bioeconomy technologies consisting of biofuels and bio-based material processing value chains to be implemented in the modelling framework. For the case of conventional biofuels, researchers proposed to have biodiesel produced from rapeseed, palm fruit, and soybean oil and bioethanol from sugarcane, sugar beet, maize, wheat, and other grains with conventional conversion technologies in the modelling framework. As advanced biofuels, researchers proposed to introduce "used cooking oil" (UCO) for biodiesel production and green waste from unused agricultural and forest residues which can be used as lignocellulosic biomass for bioethanol production using thermochemical conversion technologies. Stakeholders agreed on the proposed selection of biofuel options.

For bioeconomy technologies in the material industry, it was agreed to focus on the most promising non-energy biotechnology sectors identified during the first workshop, i.e. chemicals (including plastics, rubber materials, and lubricants) and construction, which is supported by the literature on bio-based material value chains (Aeschelmann et al., 2017; Dammer et al., 2017; meó Consulting Team, 2014). Both chemicals and construction are represented in the DART-BIO model through the GTAP (Global Trade Analysis Project) data sector definition that constitutes the database used by the model (Aguiar et al., 2016). Researchers proposed to maintain the sectoral aggregation of the GTAP sectors and not to model specific bioeconomy technologies except for the biofuel sector. The analysis will thus focus on existing technologies where fossil inputs can be (partly) substituted by renewable inputs without changing the overall production process. Researchers argued that market shares of potential new emerging bio-based products are expected to be too small within the period covered by the model to be separately represented in a global model. This proposal was supported by stakeholders since they agreed that currently, the most promising bioeconomy technologies consist of replacing fossil inputs with renewable inputs without changing the overall technological approach. Stakeholders argued that in this case, the analysis of policy support is even more important since price differences between fossil and bio-based inputs need to be overcome to increase the share of bio-based inputs within these sectors.

Deciding on the bioeconomy policy scenarios

During the second workshop, researchers proposed two bioeconomy policy scenarios to the stakeholders under which the development of

Table 3
Proposed bioeconomy activities and scenarios.

Bioeconomy activity	Scenario 1: Policies as usual	Scenario 2: Stronger development of the bioeconomy	Scenario 3: No support policies
Biofuels	• Current global biofuel mandates are met • EU-RED II implemented in a sub-scenario (minimum targets for advanced biofuels and further cap on conventional biofuels)	• Subsidy for all biofuel options: 10% higher than implicit subsidy in the Policies as Usual Scenario. scenario 1 • No cap on conventional biofuels	• No biofuel mandates
Bio-based value chains in other industries	• No support	• Same level of subsidy as for the biofuel sector is granted for the use of bio-based inputs in the chemical and building sector.	• No support

bioeconomy technologies is implemented: 1) extrapolation of current trends and 2) stronger development of the bioeconomy. After the workshops, a third scenario was added because researchers found the comparison to a situation without policy support of bioeconomy activities important to evaluate the sensitivity of model results against the assumptions on bioeconomy policies. The scenario with no support schemes serves as a hypothetical counterfactual scenario to the two bioeconomy policy scenarios. Therefore, it was not explicitly discussed with the stakeholders, but the decision to add a scenario is made transparent and therefore in line with the co-design process according to Bergmann et al. (2012).

Policies as usual. Regarding the policy scenario Extrapolating current trends, researchers suggested implementing the existing global biofuel policies until 2030 which are included in shares of biofuels in total transport fuels in the OECD/FAO agricultural outlook (OECD/FAO, 2018). Concerning advanced biofuels researchers proposed to extrapolate current market shares of UCO until 2030. Stakeholders disagreed on this assumption arguing that the proposal for a revision of the "Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources" (EU-RED II) includes a gradual reduction of biofuels from cultivated biomass from 7.0 % to 0% in 2030 (European Union, 2016), hence the market share of UCO might increase. Stakeholders suggested a scenario that assumes the proposal (or final directive) of the EU-RED II to be fulfilled. Therefore, researchers decided to analyse a scenario with the currently implemented biofuel mandates of the EU-RED I (European Union, 2009) and an additional sub-scenario with the EU-RED II in place. Under an extrapolation of current policies, there are no support measures for bio-based value chains in other industries. After the workshop, researchers decided to re-name this scenario to Policies as usual to be more precise.

Stronger development of the bioeconomy. For the scenario with a stronger development of the bioeconomy, researchers suggested introducing quotas in their modelling framework to reach a certain level of advanced biofuels as well as of material use of biomass. To determine the appropriate levels for these quotas on advanced biofuels, the debate between researchers and stakeholders first focused on which future trends in the biofuel sector stakeholders are feasible. To inform the discussion on potential growth rates of waste-based ethanol in this scenario, researchers presented results of different studies on the potential of agricultural waste for ethanol production, showing that a high quota on waste-based ethanol would be feasible in terms of feedstock availability in this scenario. However, for both advanced biofuels, stakeholders recommended not to overestimate the production potential given the period of the modelling exercise. Stakeholders emphasised that higher demand for waste-based feedstocks should not trigger any additional waste production for the biofuel sector. To determine the boundaries of a feasible scenario, stakeholders suggested collecting data on potential waste collection rates until 2030 in order to approximate the maximum development in feedstock availability.

For conventional biofuels, researchers proposed to reduce the amount of conventional biofuels proportionate to the growth of advanced biofuels. Stakeholders suggested not limiting the share of conventional biofuels in this scenario. Therefore, researchers decided after the workshop to move away from the assumption of fixed quotas for this scenario. Instead, researchers decided to calculate the implicit subsidy for each biofuel option within the policies as usual scenario and to increase it by 10% in the stronger development of the bioeconomy scenario.

Similarly, stakeholders were asked for their opinion on the potential evolution of bio-based material value-chains based on the following estimates: Aeschelmann et al. (2017) find a compound annual growth rate of 8% between 2016 and 2021 for the building block sector but a stagnating market share of 2% for bio-based polymers. The main reasons for the latter are low oil prices, low political support, and a slower than expected growth of the capacity utilisation rate. World market shares are expected to remain relatively stable with a slight increase in Asia (Aeschelmann et al., 2017). The meó Consulting Team (2014) concludes that chemicals, plastics, and lubricants together exhibit a maximum annual growth rate of 9% bio-based inputs between 2011 and 2020 and an annual increase rate of 4% bio-based material inputs for the construction sector. Therefore, stakeholders considered an increase of bio-based inputs at an annual growth rate of 9% in the chemical sector and of 5% in the building sector an ambitious but feasible assumption. As for the biofuel sector, researchers decided to move away from fixed quotas but to apply a subsidy for the use of bio-based inputs in the same amount as for the biofuel sectors. In this way, researchers avoid anticipating model results with a fixed quota but create a level playing field for the use of biomass in the energy and material sectors.

No support policies. In the No support policies scenario, no quotas or subsidies for any bioeconomy activity are in place. As a consequence, only the level of biomass input that is competitive compared to fossil inputs in the energy and material sector will enter the market. Table 3 provides an overview of the bioeconomy scenarios.

Summary and conclusions

One of today's major societal challenges is the mitigation of climate change by reducing the use of fossil resources and replacing them with renewable biomass. This transformation to a so-called bioeconomy will affect all members of society, making it crucial to consider the views of different stakeholders to ensure a socially acceptable transition towards a sustainable bioeconomy. The inter- and transdisciplinary research project "BioNex – The future of the biomass nexus" is the first project to develop bioeconomy scenarios together with stakeholders from politics, industry, and civil society in an iterative co-design process to support this transition.

Due to present funding structures in Germany (and to our knowledge also other countries), the co-design process could only be started after the project funding started. Therefore, the core structure of the research e.g. the overall approach of the project, and the selection of models could not be influence by stakeholders. This is a deviation from the listed principles of co-design (see chapter 2.1). Therefore, unless funding principles are changed, the "real" co-design of transdisciplinary projects is not possible. However, we tried to circumvent this restriction by only defining broad research questions in the proposal mentioning that they will be specified in the course of the project, which allowed to specifying the objectives of the project during project's co-design process.

The resulting scenarios show that the field of bioeconomy is highly uncertain concerning potential future developments such as climate change or socio-economic trends. Moreover, technological innovations and their ability to enter markets are unknown. The workshops underpinned the need for scenario analysis to explore the option space of new technologies and future biophysical and socio-economic developments.

The results also illustrate that knowledge integration and exchange led to new insights particularly in the group discussion about new technologies. While scientists and policymaker strongly emphasise the relevance of the material-based use of biomass, e.g. as bio-polymer or bio-lubricants, stakeholders from the private sector dampen the expectations for large-scale applications in these sectors on a global level until 2030. They assumed that in the given time horizon of the project, we will only see developments in niche markets. This skepticism considering the trends in the development of the bioeconomy has been surprising for the researcher.

Also, the need to capture the link between food-land–ocean via aquaculture is a valuable result generated at the workshops. In addition, stakeholders gained new knowledge because the methods used by the researchers, the models' scope, usability, and limitations were discussed in great detail.

Conclusions to be drawn from the co-design process itself are that better coordination between different sustainability-related research projects is needed because we acknowledge the danger of "stakeholder burn-out". This is caused by the circumstance that several transdisciplinary research projects under the same funding scheme performed workshops in the same period. In this study conflict of interest was not observed. NGOs as an important interest group did neither attend the first nor the second workshop such that the research group communicated with them bilaterally. Further, we conclude that problems of interest and "unbalanced problem ownership" (Lang et al., 2012) were avoided by actively and iteratively including stakeholders in the formulation of research questions and scenarios. With a high share of German stakeholders, our stakeholders' perspective is framed by German and European backgrounds. At the same time, a representative from the OECD provided international viewpoints. While this limits the range of a global scenario setting, rich, industrialised economies have a major impact on other economies and their environment, which was an important issue raised during discussions.

According to the experience made in the course of the co-design process, the study provides valuable insights for researchers and funding authorities they can use to optimise the employment of stakeholder-based research approaches. First, in case of funding authorities encourage transdisciplinary research based on a co-design process, applicants need to be given the opportunity to formulate open proposals that allow for a better implementation of the outcomes from the stakeholder process. Second, funding authorities and research groups need to communicate and coordinate their research process, to avoid concurrent demand for the same stakeholders or approach the same stakeholders with the same agenda. Researchers should be motivated to put more effort into these activities to avoid stakeholder fatigue that may harm the involvement of stakeholders in future projects aiming to have a long-term interaction between the different interest groups is required. The third and last point is that funding authorities and researchers need to acknowledge that projects based on stakeholder involvement require more time than projects without such an approach. While the time for planning and conducting the workshops can be estimated relatively precisely, processing and evaluating the information provided by the stakeholders adds uncertainty. In the best case of a co-design approach, stakeholders bring new perspectives and impulses. However, the evaluation and inclusion of those ideas can consume a significant amount of time which is difficult to account for by the researchers in advance.

In summary, the iterative and transparent co-design process performed for this study can be seen as a prerequisite for transdisciplinary research projects that can guide a transformation to a sustainable future. The scenarios can be used to assess trade-offs and synergies between the UN sustainable development goals "Zero Hunger", "Affordable and clean energy", "Climate Action", and "Life on Land".

CRediT authorship contribution statement

Ruth Delzeit: Funding acquisition, Writing - original draft, Conceptualization, Writing - review & editing. **Tobias Heimann:** Writing - original draft, Conceptualization, Writing - review & editing. **Franziska Schuenemann:** Writing - original draft, Conceptualization, Writing - review & editing. **Mareike Söder:** Writing - original draft, Conceptualization, Writing - review & editing. **Florian Zabel:** Funding acquisition, Writing - original draft. **Mona Hosseini:** Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project was supported by the German Federal Ministry of Education and Research (grant 031B0230A: BioNex – The Future of the Biomass Nexus).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resglo.2021.100060.

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