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Transition to a Sustainable Bioeconomy

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Abstract: Exceeding planetary boundaries, and especially climate change, requires economies worldwide to decarbonize and to incorporate principles of sustainable development. Transforming a traditional economy into a sustainable bioeconomy by replacing fossil resources through renewable biogenic resources offers a solution to this end. However, seemingly opposing transition perspectives (i.e., technology-based vs. socio-ecological) lead to fragmented efforts, and the exact form of the transition pathway to the goal of a bioeconomy remains unclear. We examine the issue by involving an international expert sample in a Delphi survey and subsequent cross-impact analysis. Based on the experts' views, we present a list of events necessary to achieve the transformation ranked by the experts to reflect their urgency. The cross-impact analysis facilitates combining the eight most urgent events to create an integrated model of the transition to a sustainable bioeconomy. Our findings suggest that, rather than bioeconomy strategies, investment in the relevant sectors currently constitutes the main bottleneck hindering such a transition.

Keywords: bioeconomy; biobased economy; transition; transformation; sustainability; Delphi

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1. Introduction

The transgression of planetary boundaries—and most prominently climate change—endangers the well-being of human societies, which depends on the integrity of the earth system, thus, requiring humanity to identify a safe operating space for future societal development within planetary boundaries [1]. Against this background, there is a strong call from scientists, citizens, politicians, and business leaders to transform the economy into a sustainable one, where exiting the era of fossil resources and commencing the era of the bioeconomy offers a promising option [2–4]. A bioeconomy can be broadly defined as "an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources" [5]. A plethora of national and international bioeconomy strategies seeks ways to transform economies into bioeconomies [6], and academic research supports this goal [7]; not least, because a successful transition towards a bioeconomy bears the potential to contribute significantly to the achievement of many of the United Nations' Sustainable Development Goals [8,9].

However, since the field of bioeconomy research is still young and rather fragmented, there is as of yet no universal definition of the topic. Instead, the understanding of the term and its underlying visions and values is multifaceted [10,11]. Two seemingly opposing perspectives in the transition from a fossil to a biobased economy emerged [12]. That is, (1) the *technology-based transition perspective* introducing technology, innovation, and market efficiency as the key drivers of the economic transition [13,14] and (2) *the socio-ecological transition perspective* highlighting a change in consumer behavior and awareness as well as a change toward sustainable production processes as crucial enablers of a bioeconomy transition [15].

In addition, the perspective of social sciences on the targeted transition process seems to be underdeveloped but is urgently needed to take account of the various political, societal, and economic implications [16]. Furthermore, previous research indicates that adopting the lens of stakeholders seems to be advantageous when assessing and shaping the transition process [17]. And indeed, approaches to develop international [18], national [19] and also regional [20] monitoring frameworks benefitted from involving various stakeholders to create multi-dimensional and comprehensive frameworks.

Fortunately, there is initial progress on combining those two prevalent perspectives on the transition process through interdisciplinary multi-stakeholder debates and the integration of the two perspectives [21,22]. Nevertheless, academic, political, and economic efforts worldwide are mostly scattered across many different areas without channeling resources into an actionable pathway leading, step by step, to the targeted bioeconomy transition [23]. Consequently, it remains unclear how, where, and when the transformation will gain momentum and how an actionable transition pathway might look like.

Thus, this study aims to provide an integrative and navigable transition pathway toward a sustainable bioeconomy giving a clear guideline to decision makers and future research. Therefore, we conducted a Delphi study involving experienced European bioeconomy experts representing different transition perspectives, spanning various disciplines and organizations. As a result, we identify important and urgent events essential to achieving the transition toward a bioeconomy. Moreover, we illustrate how these events—presented as milestones along the transition pathway—impact each other and eventually constitute a navigable transformation pathway. The resulting model responds to the call for climate action by providing decision makers and researchers with pathways by which the vision of entering the era of bioeconomy can be turned into reality.

In the remainder of this paper, we first present the theoretical underpinnings of recent bioeconomy transformation research. Second, we explain in detail our research design and the applied methods. Afterward, we present the results of our study and finally discuss the implications of the presented transformation pathway for future bioeconomy policy and research.

2. Theoretical Background

The current bioeconomy discourse shows a variety in the understanding of the term, its underlying visions and narratives, and, consequently, the resulting implications for the transition to a bioeconomy [10,15]. For example, based on an extensive literature review, Bugge, Hansen and Klitkou [10] identified three distinct ideal-type visions of the bioeconomy. These are (1) a bio-technology vision, (2) a bio-resource vision, and (3) a bio-ecology vision of the desired future bioeconomy. Of course, these visions are not mutually exclusive and may overlap [10], but they still provide valuable orientation in the ongoing bioeconomy discourse.

While the first two visions differ mainly in their emphasis on the role of either the application of biotechnology (i.e., bio-technology vision) or, respectively, the conversion and upgrading of biomass (i.e., bio-resource vision), they both promise green economic growth and assume sustainability to be inherent in the bioeconomy per se [10]. In contrast, the bio-ecology vision focuses on sustainability and the conservation of ecosystems and questions the compatibility of the former with perpetual economic growth [10]. Consequently, the latter vision implies a strong sustainability approach, while the previous two imply only a weak sustainability approach [15].

Along this dividing line between the ideal-type bioeconomy visions, two distinct theoretical conceptualizations of an implementation pathway emerge [12]: On the one hand, a *technology-based transition approach*, highlighting the importance of innovations in biotechnology and increased biomass production, as well as resource efficiency [12,14]. On the other hand, a *socio-ecological transition approach* promoting social innovation through the participation of civil society, reduced resource demand, and agro-ecological biomass production [12,24].

2.1. Technology-Based Bioeconomy Transition

A technology-based perspective stresses the importance of technological innovation for the bioeconomy transformation [13,14,25]. Fundamental to these innovations is academic research on underlying bio-technologies opening up avenues of industrial applications [13].

Hence, collaborations between research institutes and industry actors turn research outcomes into competitive biobased products on existing markets [26]. Bioeconomy start-ups (often spin-offs from research institutes) play a vital role in commercializing and diffusing these new technologies and substituting fossil-based industry standards [27–30]. According to the technology-based perspective, without significant technological progress and innovation, biobased products would be either unavailable due to resource constraints [31–33] or not competitive due to a lack of value-generating efficiency [13].

The narrative underlying the *technology-based transition pathway* dominates the current bioeconomy discourse [12,15]. That is, it finds its implementation in policies around the world (e.g., it is the inherent vision of the European Union's bioeconomy strategy) [10,15,34].

2.2. Socio-Ecological Bioeconomy Transition

However, especially the understanding of sustainability and the green growth paradigm inherent in the bio-resource vision increasingly have aroused criticism. For instance, criticism flares up at the EU bioeconomy policy's relatively weak sustainability ambitions that are stated to be used only as a "selling point" to promote mainly economic interests [24] and the conceptual hijacking of the term bioeconomy, as originally coined by Georgescu-Roegen [15]. In contrast to the currently dominating bioeconomy policy, Georgescu-Roegen argues that based on the laws of thermodynamics, every economic activity is entropic and results in the consumption of resources. Hence, to operate within the biosphere's boundaries, current economic growth needs to slow down to a level that aligns with the biosphere's supply capacity for renewable resources and its regeneration capacity for ecological externalities from economic activities [35,36].

In addition to the rather conceptual criticism, various empirical studies underpin the criticism concerning the questions of sustainability and growth. Indeed, the bioeconomy cannot be considered sustainable per se, but needs to set sustainability as a central target to contribute to sustainable development [37]. Furthermore, many bioeconomy scholars question whether bioeconomy is truly capable of contributing to sustainable development without incorporating a degrowth perspective [21]. Furthermore, the feasibility of the current bioeconomy policy to reconcile both the targeted economic growth on the one hand and sustainability goals on the other hand might be questionable as well [38].

2.3. Integrated Perspective on a Bioeconomy Transition

The current bioeconomy discourse is divided into two theoretically conceptualized transition pathways (*technology-based approach* vs. *socio-ecological approach*) that summarize the respective extreme positions on ten key issues critical for the success of the bioeconomy transformation, i.e., the understanding of sustainability, biomass production, perspective on nature, resource utilization, consumer behavior, innovation, spatial level, the scale of technology solutions, participation, and research funding [12]. However, across these key issues, the single positions are not necessarily incompatible with each other [12]. Indeed, there are first indications that some of these elements may be combined, e.g., an improvement of resource efficiency, which is central to the technology-based approach, and the promotion of sustainable consumption patterns, central to the socio-ecological approach [22]. However, to integrate both positions, governments may need to play a stronger role in the bioeconomy transition [38,39] to fulfill a two-fold function: on the one hand, an enabling function to level the field for biobased products and to compensate for competitive disadvantages in comparison to fossil-based products; on the other hand, a limiting function to ensure compliance with ecological and social sustainability targets [40].

For a successful transition toward a sustainable bioeconomy, mere techno-economic knowledge will not be sufficient, but needs to be complemented by systems knowledge (i.e., knowledge about how relevant systems work), normative knowledge (i.e., knowledge about the desired system states), and transformative knowledge (i.e., knowledge about how to transform systems) [41,42]. However, the current discourse is dominated by a rather technological perspective and lacks research from social sciences applying mixed methods and multidisciplinary approaches [16]. Thus, to move the discussion on integrated transition pathways forward, research needs to consider the perspective of multiple bioeconomy stakeholders [16,41].

What is needed is an actual debate across representatives from different disciplines and transition perspectives to avoid juxtaposing potential pathways and, instead, synthesizing perspectives into an integrated pathway [22]. Hence, the present study applies the Delphi technique—a method specifically designed to bridge various perspectives and gain mutual understanding—to answer the research question of how an integrated transition to a bioeconomy will gain momentum and which milestones lie down the road. The subsequent cross-impact analysis allows modeling a concrete transition pathway to a future bioeconomy. The following section describes in detail the methodological foundations of the Delphi technique as applied in this study and the subsequent cross-impact analysis.

3. Method

The Delphi technique is used to forecast the future where historical data misses and, thus, the input of experts is necessary [43]. It aims to obtain a group opinion from individually contributing experts [44] that can be geographically dispersed [43]. It is characterized by four key features: anonymity, iteration, controlled feedback, and the statistical aggregation of group response [43]. The Delphi technique has been utilized and has proven its validity in various contexts within the social sciences [45] and previous applications to bioeconomy-related research questions revealed their potential to contribute with a multi-stakeholder perspective to the ongoing bioeconomy discourse [46,47]. The combination with a cross-impact analysis (CIA) allows to create a model out of the findings from the Delphi process [48] and has also been applied in previous research, though in different context than the bioeconomy case [49,50].

Three main tasks structured the research design of this study and the remainder of this section. First, we reported the procedure to identify a qualified sample of European bioeconomy experts. Second, we conducted a Delphi survey that generates and subsequently ranks a list of events necessary to achieve a transition to a bioeconomy. Finally, we conducted a CIA combined with interpretive structural modeling (ISM) to be able to visualize a model of the proposed transition pathway. The single steps of the data collection and analysis process, i.e., the Delphi procedure and the subsequent CIA and ISM, are summarized in Table 1.

3.1. Identification of the Delphi Expert Sample

In total, we identified and eventually invited 231 leading bioeconomy experts from 18 European countries. The invited experts represent industry (from both established firms and start-ups), public administration, and academia [51]. To ensure rigor, transparency, and reproducibility, we determined and applied selection criteria for each expert category [52]. To identify representatives from industry, we consulted the member list of the Bio-Based Industries Consortium (BIC). Furthermore, we contacted bioeconomy-related entrepreneurs who engage with one of the accelerator programs of the European Institute of Innovation and Technology (EIT). To identify experts from public administration, we searched the Global Bioeconomy Summit (GBS) 2018 attendees list for participants from institutions involved in the bioeconomy strategy formulation of their respective countries. Finally, we conducted a Scopus search to identify bioeconomy scholars who were most cited and/or published most in recent years. The applied selection criteria ensured a broad scope of this study beyond mere techno-economic knowledge [41] and also allowed integrating knowledge from the social sciences. Especially, by involving experts from public institutions and inviting researchers from all relevant fields—beyond economics, natural sciences, and engineering—the sample selection equally accounts for the technology-based and the socio-ecological transition perspective.

Table 1. Subsequent steps of the data collection and analysis process.

Steps	Content of Rounds	Participants
Step 1	Open question asking for necessary events to achieve a full transformation towards the bioeconomy. Research task: qualitative content analysis resulting in an aggregated list of 14 events.	n = 50
Step 2	First ranking of the aggregated list of events regarding their urgency in realization. Research task: statistical aggregation of the responses summarized in a result report providing, in addition to individual's ranking, the mean ranking, degree of consensus and interquartile ranges (IQRs)of each event, and a selection of qualitative arguments given by experts to reason their ranking.	n = 39
Step 3	Second ranking of events regarding their urgency in realization. Research task: statistical aggregation of the responses summarized in a result report providing, in addition to individual's ranking, the mean ranking, degree of consensus and IQRs of each event, and a selection of qualitative arguments given by experts to reason their ranking.	n = 33
Step 4	Third ranking of events regarding their urgency in realization. Research task: statistical aggregation of the responses summarized in a result report providing, in addition to individual's ranking, the mean ranking, degree of consensus, and IQRs of each event.	n = 29
Step 5	Cross-impact analysis of the eight most urgent events. Research task: calculation of cross-impact matrix and derivation of interpretive structural models.	n = 41

The initial Delphi round involved 50 experts, and 29 experts were retained to share their insights in the fourth and final round of the Delphi, and 41 experts evaluated the results of the Delphi for the final CIA. Table 2 contains a summary of the number of participants from each expert category over each step of the study. Moreover, Appendix A shows an anonymized list of the eventually participating experts.

Table 2. Number and proportions of participants per expert category over all five rounds.

	Round 1		Round 2		Round 3		Round 4		Round 5	
Category	n	%	n	%	n	%	n	%	n	%
Established Firms	12	24.00	9	23.08	8	24.24	7	24.14	9	21.95
Entrepreneurs	8	16.00	7	17.95	6	18.18	3	10.34	6	14.63
Policy Makers	13	26.00	9	23.08	8	24.24	8	27.59	11	26.83
Researchers	17	34.00	14	35.90	11	33.33	11	37.93	15	36.59
$\sum$	**50**	**100**	**39**	**100**	**33**	**100**	**29**	**100**	**41**	**100**

3.2. Delphi Study

We conducted a two-phased ranking-type Delphi [53] to generate a ranked list of events. In the first phase, participants brainstormed online to determine important events necessary to achieve a full transition to bioeconomy. Based on a rigorous identification of concepts in the participant's responses and the subsequent grouping of these very specific concepts to more general categories [54,55], two of the authors coded the responses independently, using the software MAXQDA 12.3.6 from VERBI. In an inductive category formation approach, the coders gradually built categories when processing the material while at the same time checking for formative and summative reliability in accordance with the research question [56]. Finally, both coders compared the results of their individual coding, resulting in an aggregated list of 14 events, containing a short and a more detailed description for each event. Table 3 illustrates the coding process exemplarily.

Table 3. Exemplary category formation in the coding process (table based on Brady [54]).

Example Response	Concepts	Category	Category Description
"Acceptance of and interest in buying biobased products from customers." "Reduction of personal/public/societal demands/requirements." "People should eat much less animal-based protein and more plant/fungi-based protein." "Encouragement of gardening in urban areas." "Sustainable decentralized vertical farming becoming mainstream."	Consumer awareness Sufficiency Urban food production	Consumer awareness	Consumers who are aware of the consequences of their consumption behavior on the environment and change their consumption behavior accordingly

In the second phase, we asked participants to assess the aggregated list of events in terms of urgency in a three-rounded iterative ranking process. Additionally, participants were asked to provide a reason for their ranking qualitatively. Furthermore, they were asked to verify whether they perceived the aggregated list of events as complete or whether it was missing anything essential they mentioned in the first round [53]. Including this step contributed to achieving validity and, consequently, to enhancing rigor [57]. Four event descriptions were changed slightly to reflect the feedback from the participants. After each iteration, we provided to every participant an intermediate result report containing quantitative statistics of the ranking process as well as qualitative arguments mentioned by the participating experts. A combined feedback of statistics and reasoning was more likely to increase the performance of a Delphi expert sample in terms of its accuracy, change in judgment, and the degree of consensus [43]. This way, we facilitated an exchange of opinion, yielding eventually stable ranking results (measured by the Wilcoxon matched-pairs signed-rank test [58]) and a slightly increased degree of consensus among the participants (measured by Kendall's coefficient of concordance W [53]). We computed both the Wilcoxon test as well as Kendall's W using IBM's SPSS.

3.3. Cross-Impact Analysis and Interpretive Structural Modeling

CIA complements the Delphi method by allowing the introduction of greater complexity to its results [48]. It assesses the type of events, which may or may not occur in the time interval under investigation and for which no statistically significant data are available to infer its probability of occurrence from history [59]. Basically, it is the estimation of the relationships among n events considering two at a time and is, therefore, only an approximation of the real world where, in fact, relationships among more than two events are thinkable and possible [48].

Core of the CIA is the cross-impact matrix in which each cell represents the cross-impact factor C_{ij} of the event in the j-th row on the event in the i-th column [59]. C_{ij} is specified as:

$$C_{ij} = \frac{1}{1 - P_j} \left[\ln(R_{ij}/(1 - R_{ij}) - \ln(P_i/(1 - P_i) \right] \quad (1)$$

where P_i represents the experts' aggregated estimations of the probability of occurrence of the i-th event and R_{ij} experts' aggregated estimations of the probability of occurrence of the i-th event under the condition that the j-th event will certainly occur in the investigated time interval [59].

This means surveying the data for the CIA was undertaken in two steps [59]: In the first step, participants were asked to estimate the probability of occurrence P_i for the i-th event in the time interval from now to the year 2030. The second step perturbed the participants' view of the world by assuming certainty that one of the considered events will definitely occur in the investigated time interval. Subsequently, the participants were asked to estimate the probability of occurrence R_{ij} of the i-th event under the condition that the *j*-th event will certainly occur in the investigated time interval. We decided to undertake the CIA with only the eight most urgent ranked events, which required each participant to make 64 estimations, that is, $n = 8$ estimations of P_i and $n * (n - 1) = 56$ estimations of R_{ij}. An event set of 14 events would have been too comprehensive to assess all potentially existing cross-impacts in a survey-based CIA, since it would have required each participant to make 196 estimations. Our procedural choice was also justified by a leap in the means of the urgency ranking between the eighth and the ninth event.

Subsequent ISM [51] permitted the visualization and a graphical mapping of the detected cross-impact relationships among the investigated eight most urgent-ranked events in a multilevel diagraph [48]. Input for the ISM algorithm was a binary version of the cross-impact matrix, where all C_{ij}- values greater or equal to 1.55 (percentile 70 of the C_{ij}-values distribution) were transformed to a "1", values below that threshold to a "0".

To visualize the binary ISM input matrix in a multilevel diagraph, the events were illustrated as vertices, while the considered cross-impact relationships, that is, the value "1"s in the ISM input matrix, were illustrated as edges with arrows in the direction of the detected cross-impact relationship [48]. Furthermore, the vertices (i.e., the events) had to be divided into two sets: antecedents and consequences. These two sets had to then be compared for intersections. If the intersection set was equal to the consequences set, the vertices (events) of the intersection set formed the highest level of the diagraph. This procedure was then repeated for the following lower levels of the diagraph, though the vertices (events) of the already identified higher levels of the diagraph were not further considered [48,60]. The algorithm used and the profound mathematical foundations of ISM were described in detail in [60]. For the purpose of this study, the binary ISM input matrices were processed by means of the ISM package of the statistic software R [61].

The following section describes in detail the generated and ranked list of events, the cross-impact matrix, and, finally, the transition pathway resulting from the application of Delphi, CIA, and ISM.

4. Results

The four rounds of anonymous discussions among experts from industry, public administration, and academia yielded stable results on a list of the most important events that might drive the transition to bioeconomy, ranked according to their urgency in realization. Table 4 summarizes the 14 generated events, including a short definition of each and the final rank, and the mean rank of the last iteration. Additionally, it contains the value of Kendall's W (W = 0.334) after the final iteration of the ranking, which indicated only a weak degree of consensus but still a clear increase in comparison to the first (W = 0.078) and the second iteration (W = 0.267) of the ranking. Table 5 shows the results of the Wilcoxon matched-pairs signed-rank test, proving stable results after the third iteration of the ranking. The results reflect the multidisciplinary and multi-sectoral background of the experts who agreed on the diverse events whose occurrence will be driven by the public and private sector and by society as a whole.

The two events ranked the most urgent to facilitate a transition to bioeconomy were *strategies and action plans* and *legislation and standards*, which are clearly policy-driven. They were followed by industry-driven aspects such as the *competitiveness of biobased products* and also *investments* in research and bioeconomic products and processes. The events considered markedly less urgent included innovation-driven events such as the *biomass supply* and *technological progress* and societally driven events such as the *development of a common understanding* and *consumer awareness*.

Table 4. Final ranking of the list of events. Columns one and two contain the event title and a more detailed short description of each event. Column three contains the final rank of the respective event based on the mean rank reached in the final round of the ranking (column four).

Event	Short Description	Final Rank	Final Mean Rank
Strategies and action plans	Development and establishment of national and international bioeconomy strategies, including action plans with concrete targets.	1	2.79
Legislation and standards	Bioeconomy-friendly legislation and the establishment of standards for the biobased sector considering a long-term perspective and principles of sustainable development.	2	3.93
Competitiveness of biobased products	Biobased products that are available and competitive in comparison to fossil-based products. Better competitiveness can be delivered by corporate strategies dedicated to bringing biobased products to market as well as taxation of fossil solutions and an end to subsidies for fossil solutions.	3	4.90
Investments	Investments in research but also in products and processes within the biobased sector.	4	4.97
Biomass supply	Sufficient and sustainably produced biomass supply which requires the integration of farmers, forestry owners, and fishermen into biobased value chains.	5	6.41
Technological progress	Further development and application of key technologies for the biobased sector, e.g., cascade biomass utilization in biorefineries, biobased construction materials or carbon capture.	6	7.07
Common understanding	Development of a common understanding of the bioeconomy concept, especially considering questions of sustainability, circularity, growth, and the impact of the bioeconomy on the environment and biodiversity.	7	7.28
Consumer awareness	Consumers that are aware of the consequences of their consumption behavior for the environment and change and/or reduce their consumption behavior accordingly.	8	7.69
Informing society	A society that is informed about the concept of bioeconomy, aware of the necessity of a transformation towards bioeconomy and is included in the debate about the design of the transformation.	9	8.86
Consumer policy	Consumer policy aiming to increase consumer awareness but also to set standards regarding sustainability of products, e.g., by bans of pesticides or single-use plastics.	10	9.10
Bioeconomy ecosystems	Bioeconomy ecosystems that facilitate innovation, (interdisciplinary) research and networking among involved actors of the bioeconomy.	11	9.17
Education and empowerment	Members of society who are educated and empowered to actively engage in the transformation towards bioeconomy.	12	9.31
Industry collaboration	An industry that collaborates with each other, also across industry sectors and value chains.	13	9.52
Public procurement	Public procurement that prioritizes biobased products to increase the demand from the biobased sector.	14	9.69 *
Kendall's W			0.334

* Due to its comparably low mean rank, we took public procurement out of the ranking task after round 2, to increase the clarity of results of the subsequent rankings [42].

Table 5. Results of the Wilcoxon matched-pairs signed-rank test after rounds 3 and 4.

		Strategies and Action Plans	Legislation and Standards	Competitiveness of Bio-Based Products	Investments	Consumer Awareness	Biomass Supply	Technological Progress	Common Understanding	Informing Society	Consumer Policy	Bio-Economy Ecosystems	Education and Empowerment	Industry Collaboration
Between round 2 and 3	Z	−3.150 [b]	−3.491 [b]	−2.800 [b]	−3.377 [b]	-0.523 [c]	−1.630 [b]	-0.631 [b]	-0.834 [b]	−1.242 [c]	−1.339 [c]	−1.886 [c]	-0.782 [c]	−1.070 [c]
	Asymptotic significance (2-sided) [a]	0.002	0.000	0.005	0.001	0.601	0.103	0.528	0.404	0.214	0.181	0.059	0.434	0.285
Between round 3 and 4	Z	−1.000 [c]	−1.000 [b]	0.000 [d]	0.000 [d]	0.000 [d]	−1.000 [b]	0.000 [d]	0.000 [d]	0.000 [d]	0.000 [d]	0.000 [d]	−1.000 [c]	−1.732 [b]
	Asymptotic significance (2-sided) [a]	0.317	0.317	1.000	1.000	1.000	0.317	1.000	1.000	1.000	1.000	1.000	0.317	0.083

[a] $p = 0.05$; [b] based on negative ranks; [c] based on positive ranks; [d] the sum of the negative ranks is equal to the sum of the positive ranks.

Table 6. Cross-impact matrix of the eight most urgent events.

	Strategies and Action Plans	Legislation and Standards	Competitiveness of Biobased Products	Investments	Biomass Supply	Technological Progress	Common Understanding	Consumer Awareness
Strategies and action plans	-*	2.78	1.86	0.98	1.88	1.31	1.77	1.77
Legislation and standards	1.58	-*	1.98	1.12	1.37	1.39	1.45	1.32
Competitiveness of biobased products	0.16	1.48	-*	0.62	1.40	1.24	0.94	1.24
Investments	1.09	1.98	2.66	-*	2.34	2.72	1.20	1.46
Biomass supply	0.65	1.21	1.11	0.34	-*	0.93	0.39	0.68
Technological progress	0.52	1.84	2.77	1.36	1.37	-*	0.21	1.17
Common understanding	1.13	1.82	1.02	0.41	0.93	0.44	-*	1.83
Consumer awareness	0.41	1.74	1.61	0.65	0.83	0.73	1.55	-*

* for the diagonal of the matrix (i.e., the intersections of each event with itself) cross-impact values cannot be calculated.

As Table 4 shows, the mean ranks sharply dropped after the eighth event *consumer awareness*. This justified a cut-off after the eight most urgent ranked events to receive a manageable number of events for the CIA, as reasoned in the previous section. Notably, also the lower ranked events could have been assigned to one of the previously identified drivers of the transition: While *consumer policy* and *public procurement* are clearly policy driven, *bioeconomy ecosystems* and *industry collaboration* can be considered as industry-driven. *Informing society* and *education and empowerment* are rather societally driven but showing an overlap to the category of policy-driven. Additionally, without a doubt, each of the dropped events represents an important step of the transition to bioeconomy and can possibly serve itself as a reference point for future research on the bioeconomy transition.

Having obtained the ranking and dropped the six least urgent events, we conducted a CIA to investigate potential cross-impacts among the eight most urgent identified events.

We aggregated the experts' estimations on these potential cross-impacts and computed them into cross-impact factors that were summarized in a cross-impact matrix (Table 6). To reduce complexity and to simplify the interpretation of the CIA's results, we visualized them in a multilevel diagraph by applying ISM (Figure 1). The diagraph considers the strongest 30% of the measured cross-impacts, representing 48% of the sum of the measured cross-impacts. In Figure 1, each box represents a unique event.

The multilevel diagraph suggested four hierarchical levels indicating the ratio between antecedents and consequences of the single events within the respective level. The higher the level, the fewer the number of consequences and the greater the number of antecedents. Accordingly, the event *investments* at the bottom level of the diagraph showed no antecedents but several consequences, while in contrast, the events *biomass supply* and *competitiveness of biobased products* had several antecedents but no consequences. Hence, the event *investments* is part of the very foundation of the combined transition pathway, while *biomass supply* and *competitiveness of biobased products* can be seen as the final outcome of the desired transformation.

The remaining events occupy both central levels of the diagraph. Level three contains only *technological progress*, which plays an enabling role in the transformation pathway and is strongly affected by *investments*. Level two stands out by including two mini-scenarios, each composed of two events, and which lie at the heart of the revealed transition pathway. Mini-scenarios consist of events with exactly the same set of antecedents and consequences. Remarkably, the events *common understanding* and *consumer awareness*, both representing the strong role of society in the transformation process, take such a prominent position, despite being ranked less urgent in the Delphi phase of this research. More expectedly, *strategies and action plans* and *legislation and standards* together illustrate the need for dedicated bioeconomy policy to facilitate the transformation pathway and tie together the single events required to succeed.

What the multilevel diagraph in Figure 1 does not reveal is the relative strength of the depicted cross-impact relations. To increase interpretability, the ISM process reduces complexity, thereby neglecting information obtained in the CIA process; however, that information was preserved in the cross-impact matrix (Table 6). The cross-impact matrix illustrates that among the several cross-impact relations rooted in investments, the strongest lead to *competitiveness of biobased products* and *technological progress*. Additionally, the impact of *technological progress* on *competitiveness of biobased products* was the second strongest measured cross-impact relation within the whole analysis. Hence, the cross-impact relations among these three predominant industry-driven events build a strong case emphasizing the important role of the private sector in the transition process to a bioeconomy.

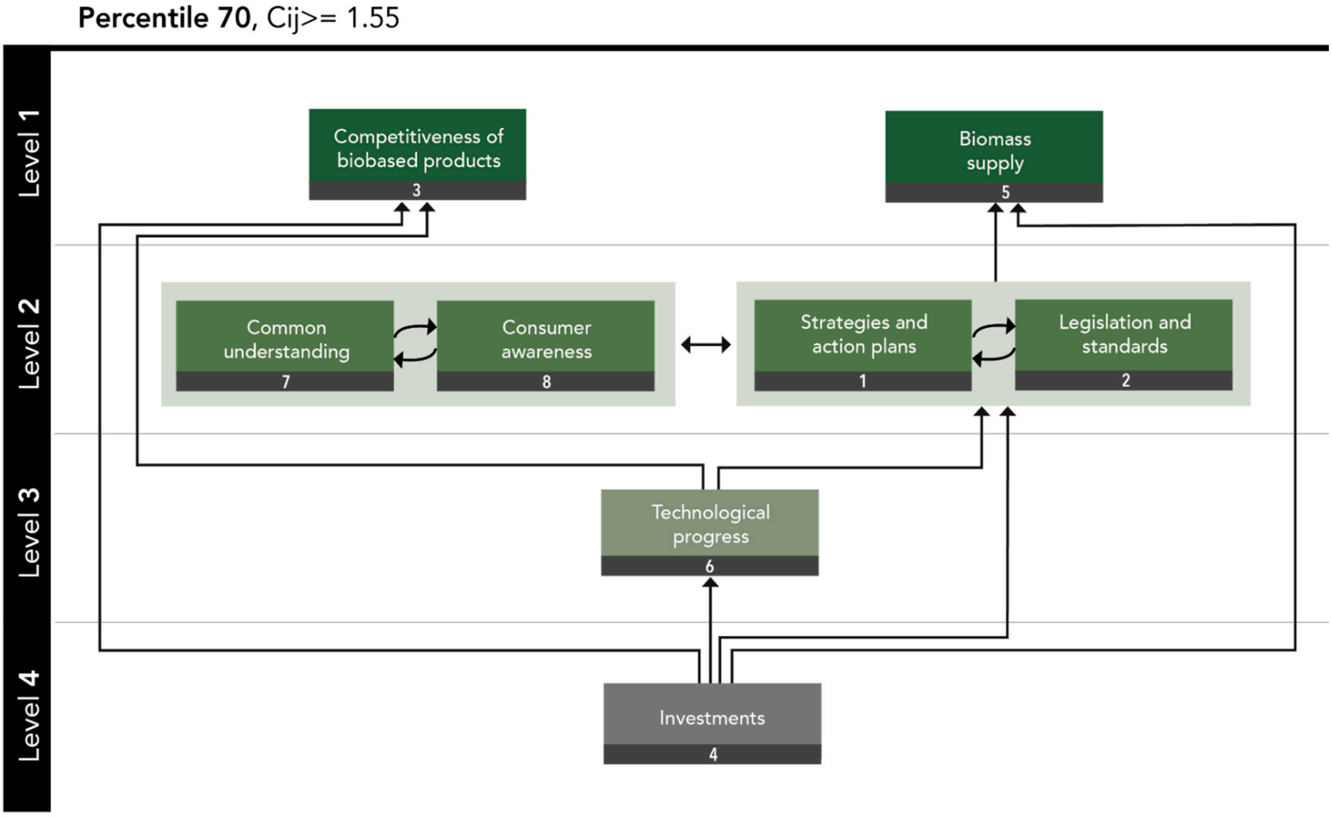

Figure 1. Multilevel diagraph of the bioeconomy transition pathway. Each box represents an event, while the numbers at the bottom indicate the urgency ranking of the respective event. An arrow represents the cross-impact relation between the two connected events in the direction of the arrow.

5. Discussion

The results of this analysis provide valuable information for policymakers aiming to initiate or adjust initiatives and can illustrate to researchers where they might focus their efforts. The list of most urgent events suggested by the Delphi experts is, however, only the first step, and any recommendation based on urgency alone must be considered somewhat insubstantial. Of course, each of the identified and urgently needed events themselves provide a reference point for future activities and research in the field. Greater potential, however, resulted from the novel combination of a Delphi procedure with a subsequent CIA and ISM approach. It allowed placing events into a logical, interdependent sequence to eventually form a transition pathway that provided explicit guidance.

This study aimed at combining seemingly opposing bioeconomy transition perspectives (i.e., *technology-based approach* vs. *socio-ecological approach*) through a Delphi study with leading bioeconomy experts into an integrated pathway to a sustainable bioeconomy. We thereby contributed to the convergence of so far divergent perspectives and visions of the bioeconomy transition, potentially affecting the success of the bioeconomy project [62]. Our results indicate how these different perspectives could be integrated into a common transition pathway. This is illustrated by the central role of consumers and policies in harmonizing technological progress toward a sustainable bioeconomy [63].

More specifically, *common understanding* and *consumer awareness* in combination with *strategies and action plans* as well as *legislation and standards* mediate technological progress toward a sustainable *supply of biomass*. They show the crucial importance of finding compromises between technological progress and socio-ecological demands through mechanisms of national strategy developments and legislation. That is, to involve consumers, i.e., citizens, in these discussions to raise, on the one hand, awareness, but to also increase, on the other hand, the acceptance for the resulting policy measures. Previous research has shown that not only scholars, but also citizens are critical for the sustainability of the bioeconomy [64] and that broad societal participation is necessary to ensure a good governance of the transition to a sustainable bioeconomy [65].

The study's results indicating that strategies to implement a transition to a bioeconomy along with legislation and standards are situated on level two of the transformation pathway model (and accordingly rather represent an outcome than a starting point) might initially be astonishing; however, although any policymaker would consider such strategies the initial step of any transition process, the results indicate that with the overall adoption of such strategies worldwide [6,66], the first important step has already been taken. Now, based on the emerging technological progress, bioeconomy policymakers must adjust existing strategies and translate them into action plans backed by legislation and regulation that meet the requirements of the biobased sector.

Such action plans will differ from those considered valid for decades to foster a fossil-based economy. Rather than strategies, investments are the bottleneck hindering the transformation. Once resolved, the resulting technological progress will heighten the competitiveness of biobased products (see also in [67]) and propel those responsible for bioeconomy policy to organize the transformation in line with the needs of society. To transform the various required events into a navigable pathway will require dedicated bioeconomy policies and, at the same time, policymakers must involve all relevant stakeholders in the transition process. To this end, special focus needs to be placed on societal actors and their acceptance of the proposed measures [21]. Moreover, social sciences need to further increase their contribution to inform the transition process appropriately [16].

As a corollary, rather than relying on general programs that fund innovation, dedicated investment programs will be necessary if the transition to a bioeconomy is not to stall. Previous research has already suggested that there might be a "green finance gap" [68], and it is mainly this measure the Delphi experts consider the next logical transformation step. As policy plays a more important role in investments in green technology than technological progress in the field alone [69] and can also facilitate the development of lead markets for environmental innovation [70], the model clearly indicates that action from politics is needed. Moreover, policies and standards for sustainable investments serve as an enabler for sustainable venture capital [71], which contributes to the success of sustainable start-ups [72], which in turn contribute crucially to the bioeconomy transformation process [30].

6. Conclusions

The transition toward a sustainable bioeconomy requires an integrated and actionable transition pathway that combines and reconciles elements from the *technology-based approach* as well as from the *socio-ecological approach*. Our study considered various perspectives of bioeconomy experts from different professions and backgrounds to model such an integrated transition pathway. Our results suggest that it is time to move from strategy to action, and that it is investments into the biobased sector that have the most considerable leverage to get the transition rolling.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Participants were informed about their rights, the scope and purpose of the survey.

Data Availability Statement: All data generated and analyzed during this study are available upon request.

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Appendix A

Table A1. Affiliation and positions of participating experts who agreed to disclosure. The participants represent themselves and not necessarily the opinion of their organizations or institutions.

Category	Organization	Position	Country
Corporates	BioEconomy Cluster Management GmbH	Anonymous	Germany
	Bio-mi Ltd.	CEO	Croatia
	CLIC Innovation ltd.	CEO	Finland
	Cluster Food+i	Cluster Manager	Spain
	Corporación Tecnológica de Andalucía (CTA)	Biotechnology Technical Officer	Spain
	MetGen Oy	CEO	Finland
	Novamont SpA	Anonymous	Italy
	Orineo	CEO	Belgium
	Process Design Center	CEO	The Netherlands
	5 further anonymous experts		
Entrepreneurs	Chrysalix Technologies	CEO and Founder	United Kingdom
	Essento Food AG	CEO and Founder	Switzerland
	FineCell Sweden AB	CEO and Founder	Sweden
	Green Code SrL	CEO	Italy
	Ingelia	CEO	Spain
	9 further anonymous experts		
Policy Makers	Department of Agriculture, Food and the Marine	Agricultural Inspector	Ireland
	Energy Institute Hrvoje Pozar	Post-doctoral researcher	Croatia
	Italian Council for Agricultural Research and Economics	Head of Research	Italy
	Ministry of Agriculture, Regions and Tourism	Ministerial Council	Austria
	Ministry of Economic Affairs	Anonymous	The Netherlands
	Ministry of Science, Innovation and Higher Education	Head of Division	Denmark
	Norwegian Institute of Bioeconomy Research (NIBIO)	Special Adviser	Norway
	Teagasc	Principal Research Officer	Ireland
	VTT Technical Research Centre	Technology Manager	Finland
	7 further anonymous experts		
Researchers	Helmholtz Centre for Environmental Research	Head of Department Bioenergy and Professor of Bioenergy Systems	Germany
	Institute of Bioorganic Chemistry Polish Academy of Science	Head of Department of RNA Technology	Poland
	Karlsruhe Institute of Technology	Head of Bioelectrics Group	Germany

Table A1. *Cont.*

Category	Organization	Position	Country
	Lappeenranta University of Technology	Professor of Strategy Research and Sustainable Value Creation	Finland
	Nordic Institute for Studies in Innovation, Research and Education (NIFU)	Research Professor	Norway
	The Institute of Technology and Businesses in České Budějovice	Senior Researcher	Czech Republic
	Universidade Europeia Lisboa	Post-doctoral researcher	Portugal
	University of Bonn	Anonymous	Germany
	University of Bonn	Professor of Technology and Innovation Management in Agribusiness	Germany
	University of Freiburg	Research Associate at the Forest and Environmental Policy Group	Germany
	University of Graz	Professor at the Institute of Systems Sciences, Innovation and Sustainability Research	Austria
	University of Helsinki	Post-doctoral Researcher at the Department of Forest Science	Finland
	University of Hohenheim	Professor of Biobased Products and Energy Crops	Germany
	University of Hohenheim	Post-doctoral researcher at the Department of Crop Science	Germany
	University of Natural Resources and Life Sciences, Vienna	Professor at the Institute of Marketing and Innovation	Austria
	University of York	Post-doctoral researcher	United Kingdom
	5 further anonymous experts		

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