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The Contributions of Biomass Supply for Bioenergy in the Post-COVID-19 Recovery

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Abstract: This research investigates how biomass supply chains (BSChs) for bioenergy within the broader bioeconomy could contribute to the post-COVID-19 recovery in three dimensions: boosting economic growth, creating jobs, and building more resilient and cleaner energy systems in four future scenarios, in the short term (by 2023) and long term (by 2030). A SWOT analysis on BSChs was used for generating a questionnaire for foresight by a two-round Delphi study. To interpret the results properly, a short survey and literature review is executed to record BSChs behavior during the pandemic. In total, 23 (55% response rate) and 28 (46% response rate) biomass experts from three continents participated in the Delphi and the short survey, respectively. The strongest impact from investment in BSChs would be on economic growth, followed by a contribution to the resilient and cleaner energy systems and job creation. The effects would be more visible in the long- than in the short-term period. Investments with the most impact on recovery are those that improve biomass material efficiency and circularity. Refurbishment of current policies to enhance the supply of biomass as a renewable resource to the future economy is a must.

Keywords: biomass supply chains; pandemic; Delphi; bioenergy; bioeconomy; recovery; investments

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1. Introduction

In late 2019 and early 2020, COVID-19 triggered a worldwide recession, in conjunction with a global health crisis and uncertainty that continues to evolve with new virus variants at the time of publication, a combination not encountered in the modern history of a global economy [1]. Governments across the world encouraged different levels of social restrictions, including public health measures, to reduce the spread of the virus and balance the economy. Restrictions have induced abrupt shifts to digital/online business models to compensate for limited mobility that not all industries could uptake swiftly (e.g., tourism, culture, and leisure industries) [2]. Economies with a high integration in global value chains experienced shortages of intermediary goods [2] and other disruptions of trade, while import-dependent economies experienced shortages of both goods and labor [3–5]. The uncertainty that the virus brought to society halted consumption among consumers and investment cycles among the industry [4–6]. In turn, limited mobility labor, goods and services have affected the mix of energy sources [7], substantially reducing the use of fossil fuels due to travel restrictions but also lowering electricity demand from the industry [8–10]. Most, if not all, national economies have suffered a recession, loss of workplaces as well as lack of workers due to safety measures and increased governmental expenditures, namely those related to healthcare, employment insurance and business support. While it was obvious that the global economy experienced a severe contraction, the behavior of individual sectors of that global economy was uncertain. Businesses related to the pandemic (e.g., pulp and paper industry for hygiene products, spirits for disinfectants, online shopping, and delivery services) were gaining momentum, but this was difficult to quantify in a short time span. Governments across the world reacted to the pandemic with different approaches and interventionist measures related to recession and health uncertainties, which gained various levels of support from their citizens [11]. The pandemic has increased the awareness of the role of the government in society with a strong interconnection between the economy and energy and health systems [8,12] where governments are preparing, announcing and implementing recovery plans to re-start and re-shape the economy [13–16].

The pandemic created demand and supply shocks in almost every area of human activity [17]. The ideal recovery investment would have a short production cycle, based on the available (local) inputs, and exhibit a high multiplier effect that would allow a fast return of the invested money into the economy. Biomass is a locally available source that could have a short production cycle (annual crops and post-harvest residues, manure, industry relying on processing primary biomass, biological part of municipal waste). The International Energy Agency (IEA) recovery plan [18] investigated the effect of clean energy investments on economic growth, jobs and cleaner and more resilient energy systems. It concluded that spending on biofuels had the highest multipliers of investments in the energy sector because of the labor intensity of harvesting and processing feedstocks [18]. Fuel supply distinguishes bioenergy from fuel-less renewable energy sources where the supply allows for more opportunities for interactions with sustainability aspects along the biomass supply chain and not only at the end-use as a renewable energy source [19]. Biomass supply, whether it is used for bioenergy or the broader bioeconomy, has the potential to help drive economic growth, jobs and resilience of an economy, particularly if the cross-sectoral framework is set to maximize the desired and discourage the unintended behavior [20,21].

The biomass supply chain (BSCh) is an integrated network of facilities and processes, each responsible for a range of activities, varying in scale and complexity [22]. Bioenergy comes to the market with three end-uses: bioheat, bioelectricity and biofuel for transport—all behaving differently in both supply and demand, and across net energy importers and net energy exporters. The use of biomass for energy production (heat, power or fuel) has numerous benefits, including economic, social as well as environmental. It is particularly of interest to create local jobs and support regional bioeconomies for communities, even in areas where biomass availability is low [23]. Simultaneously, the BSCh as part of the bioenergy sector is confronted with large volumes of biomass with low densities, low economic value, and is variable in nature, thus causing high costs in logistic operations [24–27]. These challenges can affect the continuity of supply, making supply chains susceptible to disruptions [25–27]. These disruptions can occur within the operation or technology; however, significant external factors such as a global pandemic or the pandemic's effect on energy demand are hard to predict [28]. The factors affecting the supply of biomass for bioenergy also apply to the broader bioeconomy, where other sectors to which biomass supplies renewable carbon can usually tolerate higher biomass prices and, thus, a wider radius of biomass collection or longer distances for biomass supply.

Physical and financial shocks caused by the pandemic disrupted common commercial practices and highlighted the need for securing supply chains, storage and maintained production [28,29]. Resilient supply chains need to be able to react to interference to overcome the stress placed on the system and mitigate the impact of the disruption swiftly and effectively [24]. All stages of supply chain organization and the three principle competitive priorities: cost efficiency, reliability of supply and sustainability [30], are subject to disruptions from COVID-19.

Modelling and optimization efforts in BSCh design have envisaged the effects induced by the pandemic but would need further refinement to capture observed consequences. Until May 2021, very few publications quantified the impact of the pandemic on BSChs for bioenergy. Traditional assumptions of uncertainty do not sufficiently account for events related to the current pandemic. Uncertainty is typically linked with critical parameters such as biomass demand, prices, resource capacities, availability, quality, and costs [31–33]. Zamar et al. [31] applies a quantile-based approach from stochastic optimization under uncertainty, where their approach is to analyze competing supply chains subject to stochastic demand and supply and argue that those critical parameters are usually uncertain in competing supply chains subject to stochastic demand and supply, while the conventional approach assumes that the operational characteristics and design parameters are deterministic. The uncertainty stems from lack of information (e.g., quality characteristics of available biomass feedstock), noise (e.g., lack of data) and events that have not occurred (e.g., energy demand or feedstock supply shortages) which could be applied to COVID-19 effects to some extent. Medina-Gonzalez et al. [32] focus on the potential effects of different quality streams on the overall system, which is argued to have been omitted in previous approaches. This study focuses on the challenges of multi-objective approaches (maximize economic performance while minimizing environmental impact) coupled with uncertainty strategies for a quick response against unpredictable situations (e.g., demand, price, availability, quality). The approach can serve as a framework where uncertainty events such as COVID-19 can be introduced, but it is not discussed as such. Hu et al. [33] use cyberGIS (geographic information science and systems based on advanced cyberinfrastructure and e-science) to address uncertainty in BSChs, which could be expanded for the pandemic. Yet, modelling based on uncertainty requires substantial and reliable data sources which are inherent to all mentioned examples. In the absence of quantitative data, qualitatively modelling methods, such as Delphi, can help assess the possible futures [34]. Sajid (2021) [35] studied the impacts of COVID-19 on the performance of BSChs' modelling risks using a dynamic risk assessment methodological framework, showing a drastic reduction in risk after gradual business re-opening, but the case specificity of the studied value chain vacates space for a more holistic approach, as presented here.

The main aim of this paper is to highlight policy and investment options to supply renewable carbon by enhancing sustainable BSCh contributions to short- and long-term economic recovery, in parallel with a faster transition to a carbon-neutral society. This work stems from the IEA Recovery Plan [18], which outlined policies and targeted investments coupled with measures for each key energy sector (electricity, transport, industry, buildings, fuels, and emerging low-carbon technologies) that could be implemented from 2021 to 2023 to aid an economic recovery. The purpose of this paper is to:

- assess how BSChs responded to the pandemic
- identify policy and investment options to enhance sustainable BSCh contributions to short- and long-term economic recovery, and
- describe how BSChs could contribute to economic recovery in four alternative post-COVID-19 development scenarios.

To identify policy options in directing limited recovery funds to generate positive contributions from BSChs in the post-COVID-19 economy, a modified Delphi foresight exercise [36–39] is applied, built upon a SWOT analysis, literature review and scan of grey literature, and an international survey of experts was conducted to collect behavior of BSChs in a pandemic.

2. Materials and Methods

The original study design was formed in March 2020, a week after the World Health Organization (WHO) announced the global pandemic [40]. Our study includes a 2-round Delphi foresight study [36], informed by a SWOT (S—strengths, W—weaknesses, O—opportunities, T—threats) analysis [41] on BSChs. The project timeline was extended in August 2020, given the severity of the ongoing pandemic that was evolving along with the research (Figure 1). The Delphi foresight study had two main uncertainties: a dynamic starting position and unseen futures. A SWOT analysis on integrated bioeconomy supply chains [42] was taken as the initial step in framing the starting point of the foresight while the future scenarios were taken from Wade (2020) [43].

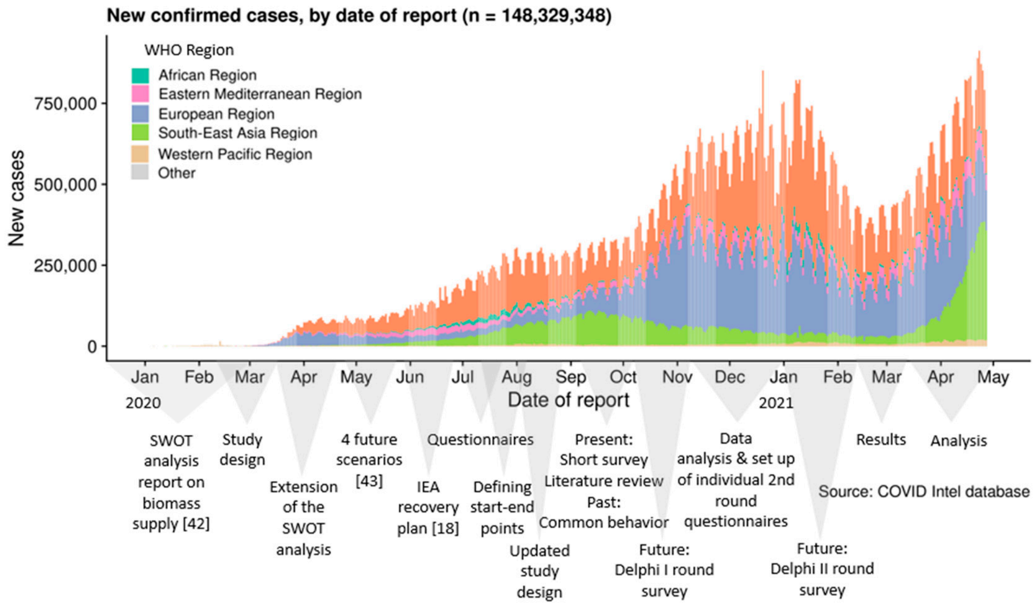

Figure 1. Timeframe of foresight research and pandemic developments (source [44], adjusted by authors).

Given the effects of the pandemic reported by the media and the absence of almost any quantitative data in the first half of 2020 to detail the overall economic slowdown as well as its structure, a SWOT analysis was completed, supported by a review of the grey and academic literatures, to contextualize the then-current environment with respect to BSCh behavior during the pandemic. The SWOT was used to assess "the present" reactions of BSChs in the pandemic; as part of this component, a short survey was sent to the bioenergy and bioeconomy experts' network (Figure 2).

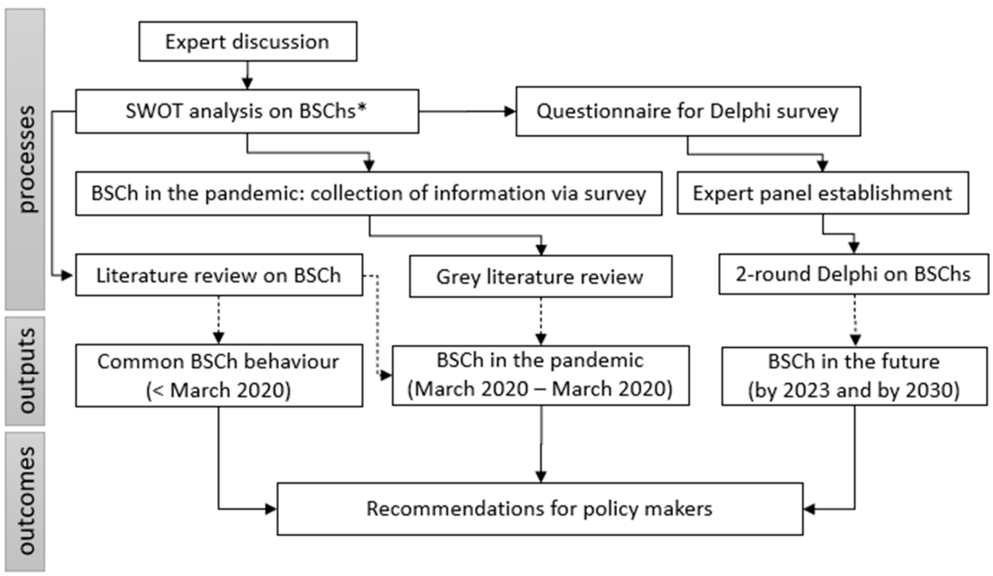

Figure 2. Foresight study design (* BSCh—biomass supply chain).

2.1. SWOT Analysis on Biomass Supply Chains

A SWOT analysis [41] on possible contributions of BSChs for bioenergy within the broader bioeconomy was conducted 22–30 March 2020 as an extension of the SWOT analysis that explored integrated bioeconomy supply chains to develop solutions for the reliable production and supply of higher-quality biomass for energy in October 2019 [42]. The core team behind the SWOT analyses is a key stakeholder group of nine international bioenergy experts—IEA Bioenergy national task leaders (NTLs) and associates of IEA Bioenergy Task 43: Biomass supply for bioenergy within bioeconomy, mapped relevant internal and external risks and their impacts, together with the main driving factors on BSCh and markets. The nine countries represented are characterized by modern bioenergy use (Australia, Canada, Croatia, Finland, Belgium, Germany, Sweden, the United States of America) and different biomass supply streams (including forestry and forest industry, agriculture and food industry, and dedicated energy crops). "Biomass produced in a sustainable way—the so-called modern biomass—excludes traditional uses of biomass as fuelwood and includes electricity generation and heat production, as well as transportation fuels, from agricultural and forest residues and solid waste. On the other hand, "traditional biomass" is produced in an unsustainable way, and it is used as a non-commercial source—usually with very low efficiencies for cooking in many countries [45].

The results of the extended SWOT analysis were structured in order of appearance by the experts in terms of the internal strengths and weaknesses concerning biomass logistics and supply centers [42] to assess the BSChs from a demand and supply side. The current SWOT analysis relied on hierarchical listing of factors [42] which assisted with the development of strategies for future short- and long-term planning. Based on the SWOT framework, different strategy scenarios were formulated, forecasting the aspirational contributions of BSChs for bioenergy in the broader bioeconomy. Biomass supply is very related to the context from where it occurs, subject to the sustainability constraints that vary from location to location [19]. The context of biomass origin and supply de-attached the biomass source in Delphi. To have generic strategies conforming to local peculiarities and limitations, not only in terms of biomass supply but also in terms of (final) energy demand, labor availability, land management and policy framework, single SWOT elements were clustered into SWOT features. SWOT features were used in forming Delphi statements, the combination of which will outline investment options of a universal application to be later implemented as strategies by adapting them to the local sustainability frameworks. Each of the developed strategies served as the starting point to build a questionnaire for the Delphi study to detect the optimal investment portfolio within different "futures" as well as to construct a short questionnaire to record behavior of BSChs in the times of the pandemic.

2.2. Questionnaire on BSChs's Behaviour in the Pandemic

A short questionnaire was implemented with biomass experts to collect information on the behavior of BSChs during the lockdown period (more specifically, the period from February–October 2020, "the first wave"). The geographical area included in the sample overlapped with the area planned for the Delphi survey: Oceania, North America, and the EU. The survey was spread across the bioenergy and bioeconomy network with an aim to reach as heterogeneous a mix of bioenergy respondents as possible within the geographical area. The questionnaire targeted experts in the field and was in no manner deterministic of the Delphi survey audience.

The questionnaire had three short sections: disruptions in the energy sector, economic disturbances in biomass supply chains from the supply side (e.g., raw materials, labor, logistics), and disruptions from the demand side. Economic disturbances were investigated across dairy produce, fresh produce (fruits and vegetables), food processing industry, crop production industry, forestry, pulp and paper industry and wood product manufacturing industry, acknowledging that biomass for bioenergy and other sectors of bioeconomy would very likely originate from by-products, residues, and waste as a secondary biomass.

The questionnaire also addressed dedicated biomass for bioeconomy associated with the forestry and crop production. The structure of the questionnaire is reflected in Appendix B.

2.3. Delphi Survey on Investments in BSChs That Could Contribute to the Post-COVID-19 Recovery

The framework structure of the Delphi survey was consistent with the IEA Recovery Plan goals: economic growth, job creation and having cleaner and more resilient energy systems, highlighting the need for action, and pinning down elements of strategies where external threats are minimized in hindsight of internal weaknesses, and external opportunities maximized to leverage internal strengths.

At the beginning of the questionnaire, anonymous bioenergy experts were asked if they think that the existing bioenergy policies in their countries/regions are sufficient in supporting the investments that would contribute to the economic recovery. This question represents a cross-over from "the present" to "the future". This question was posed to the handpicked bioenergy expert pool selected for the Delphi survey but not as a part of the foresight.

The Delphi method is an accepted approach to surveying expert opinions on future developments [36,37], particularly in situations where evidence is sparse or contentious [38,45–47]. This method is suitable for policy questions where little information is available, but where expedient decisions are necessary [39]. The Delphi method, or modifications of the technique, have been applied in health sciences [47–49], social policy [46], and energy policy [34,50], including management of biomass [34] and economic forecasting [36], among other fields.

A 2-stage Delphi survey [51] was organized in a questionnaire with 3 sections to collect experts' opinions (Table 1) where an optional open-ended question followed each question to collect short rationales or views of the experts. In the second round, the same experts were invited to recalibrate responses that differed from those of the group based on "controlled opinion feedback" [46,52] which iterates, in theory, until consensus is reached among experts. The definition of consensus used for Delphi-type surveys varies from 50–97% [38,53].

Table 1. Survey sections, investment statements, and verbal equivalents of the 5-point Likert-scale to collect experts' opinion, both in short- (by 2023) and long-term (by 2030).

Survey Section (IEA Recovery Plan Goals)	Questions and Statements	Likert-Scale Verbal Equivalents (1–5)
Economic Growth	- Where do you think the investments in BSChs would have the strongest impact on economic growth? (5 investment options) - Where do you think the technology and infrastructure investments in BSChs would have the strongest impact on economic growth? (6 investment options)	1—no impact 2—weak impact 3—moderate impact 4—strong impact 5—very strong impact
	Increasing specific bioenergy demand (bioheat, bioelectricity, liquid or gaseous biofuels for transport) would generate sufficient economic growth through investments.	1—strongly disagree 2—disagree 3—undecided 4—agree 5—strongly agree
Jobs	Increasing specific bioenergy demand such as bioheat, electricity, liquid or gaseous biofuels for transport would generate sufficient job growth through investments.	
	- Which investments related to the BSChs are more likely to create jobs under different scenarios? (9 investment options)	1—definitively not 2—probably not 3—possibly 4—probably 5—definitively
Cleaner, Resilient Energy Sectors	Increasing specific bioenergy demand such as bioheat, electricity, liquid or gaseous biofuels for transport would generate more resilient and cleaner energy systems through investments. - Where do you think bioenergy-related investments would contribute most to supporting and building the resilient and cleaner energy systems under different scenarios? (9 investment options)	1—strongly disagree 2—disagree 3—undecided 4—agree 5—strongly agree

The investment statements are presented together with the results in the Appendix C.

To highlight the best forward-looking policy actions and strategies by which to advance IEA recovery goals [18], the Delphi survey (see Appendices A and C) positioned the list of possible contributions identified by the SWOT analysis within the two major studies published at the time of establishing our study design (by May 2020): IEA Sustainable Recovery Plan [18]—areas of contribution and timeframe (by 2023) (Table 1) and International Institute for Management Development [43]—four future scenarios (Table 2). The scenarios were built as a combination of three factors:

- Virus longevity: The virus dissipates within a few months and isolation policies are lifted quickly (short term) vs. infections and deaths continue for at least a year and isolation policies remain in place indefinitely (long term).
- Global Mindset: How will people's views of social, economic, and political boundaries be impacted by the virus? People see the value of a global response to the virus and seek to increase coordination across the world (global acceptance) vs. people become deeply skeptical and distrustful of other countries and retreat to a more familiar and local way of living (global rejection).
- Digital Adoption: The virus initiates a wave of innovation and adoption of new digital technologies (digital acceleration) vs. digital skepticism sets in and people turn away from digital technologies (digital skepticism).

Table 2. Four possible futures investigated in the foresight Delphi (adopted by the authors according to [43]).

Scenario	Description
Global Marketplace	The world economy moves quickly past COVID-19 and recovers quickly, re-establishing global trade like that before the pandemic: short-term virus longevity; global acceptance; digital acceleration.
Digital Reset	Skepticism towards digital media because of challenges linked to failures in early, unilateral attempts to control the virus: long-term virus longevity; global acceptance; digital skepticism.
Back to Basics	The pandemic is not well controlled after the initial flattening of the curve, causing people to become suspicious of outside media and travel to be restricted: long-term virus longevity; global rejection; digital skepticism.
Walled Gardens	Borders become less permeable because of the pandemic, causing local-first distribution networks: short-term virus longevity; global rejection; digital acceleration.

The experts were asked to rate the efficacy of the range of investment instruments in BSChs (Table A6—A10, Appendix C) under four distinct future scenarios (Table 2) and two time periods, short- (2023) and long-run (2030). The term "investment" in this exercise covers a wide range of investments needed—from investments in equipment and infrastructure to investments in research and development (R&D), technology transfer and education, loans, and other types of market support to facilitate a policy. The investments as defined in the survey do not outline who will pay for the investment, but the survey introduction places the investments in a government investment context.

Broadly, experts possess knowledge, authority, and insight with respect to the issue in question [54]. The number of experts necessary is related to the homogeneity of the group; Delphi surveys with a very homogeneous group of experts can be conducted with 10–15 people, whereas surveys of hundreds of diverse experts have also been documented [36]. In a review of 57 studies from 2015 to 2018, 45.6% of Delphi-type surveys used 11 to 40 experts [51]. The selection of experts was partially anonymous, where each IEA Bioenergy Task 43 NTL identified a minimum of three experts from the US, Canada, Oceania and Europe, areas with modern biomass use, in total identifying 49 experts. While the experts' identity was known to the NTL, only survey answers and the aggregate geographical distribution of respondents were known to the data analyst.

The 1st round of the survey consisted of 248 investment-related statements in two timeframes and four different futures (Appendix C). In the 2nd round, each expert was asked only about statements which did not reach a consensus. Experts were given an option to change their opinion towards the majority or to keep their initial answer. In addition, an opportunity was given to the experts to explain their choices. The limited information presented in the 2nd round of the survey was intentional as information presented in subsequent surveys can cause opinion change [38,52].

Consensus among the experts was defined as 60% agreement within a range of connected ratings rather than as a single rating. The decision to include a range of scores in the definition of consensus is consistent with the other research that utilized a range of Likert scales to define consensus [53]. For each question, consensus was reached when a sum of a range of three response values, starting with a mode, and followed by the second and the third most frequent answers reached >60%. In cases where the third most frequent answer was beyond the range of three values, the second most frequent answer gave a direction to the range as an indication of a general direction of the experts' opinion. In the case of multiple modes or different combinations of ranges and directions to reach >60% consensus, the statement was revisited in the 2nd round (check for an example in the Appendix C, Table A5). In reporting results, the nature of each consensus is characterized by the mode if the response mode approximately equals one of the defined options. If the mode fell between two defined points on the scale, the consensus was defined as between the closest two points on the scale. For instance, a consensus where the modal score fell between strong and very strong was described as "Strong—Very Strong".

For the 2nd round, individual questionnaires were prepared and sent over to the NTLs to be forwarded to the experts to capture only the questions that the individual expert missed answering in the 1st round or where a consensus was not achieved, but only if the opinion was not equal to the mode.

3. Results

3.1. SWOT Analysis on BSChs

The SWOT analysis, focusing on both biomass demand and the supply side (Appendix A), identified BSChs as generating strong local impacts because they are based on local supply and typically develop an added value for local farmers, forest managers and industries by valorizing the residues, by-products, and waste of their core business. In addition to the local impact, the expanded view of the local region and the ability of biomass to integrate and service multiple markets were seen as offering a sustainable local impact. The SWOT outcomes also identified clear links to expand local opportunities, acting as a catalyst for jobs related to improved land management made possible by the value added to resulting biomass while offering a sustainable locally reliable energy to support local economic development. Finally, the deployment of readily available commercial solutions using known and reliable technology is a strength that strongly positioned new biomass utilization to fit emerging carbon-constrained, bio-based, and circular economies.

The SWOT identified seasonality of supply, costs, and competitiveness as key threats/ weaknesses of the sector (Tables A1–A4). These issues affecting BSCh apply to the different futures, yet the reasons to intervene with investments to secure renewable carbon supply to the economy vary. Other weaknesses identified in the SWOT was an imbalance in supply and demand for bioenergy, storage costs, dependence on co-productive sectors, and price inelasticity.

The SWOT results concerning BSChs (Tables A1–A4) were clustered (Figures A1 and A2) to formulate short- and long-run strategy features of aspirational biomass supply contributions to the post-COVID-19 economy (Table 3), which were further elaborated to generic investment strategies in Delphi survey.

3.2. Behavior of BSChs in the Pandemic

The short survey was sent to 61 biomass experts and achieved a 46% response rate (see Appendix B for comprehensive results of the survey). No shortages in energy supply were reported in any sector. Narrowing the question down to bioenergy supply, 93% of the experts reported no shortages, while one expert identified a shortage of solid fuel supply (pellets, briquettes, chips) and gaseous biofuels (e.g., biomethane).

Table 3. Clustered BSCh features that could contribute to the post-COVID-19 recovery.

Short Run: Immediate Reaction	Long Run: Requires Policy Adaptation
S-R:1. Increase in pellet production due to improved forest management. S-R:2. Bioelectricity use to balance the grid if the share is sufficient. S-R:3. Promoting pellet use and stove industry and services. S-R:4. Labor intensive, highly distributed: job generation tool. S-R:5. Develop skills and training on how to mobilize and process biomass. S-R:6. Any measure reducing tax/fiscal burden on biomass. S-R:7. Co-firing or replacement of coal-fired CHP units ** with biomass if biomass is readily available. S-R:8. Inventory of CO_2 demand and renewable CO_2 supply and present options to the industry. S-R:9. Biomass from co-productive systems increases productivity and has a short production cycle that can yield income faster than the others. S-R:10. Mature technology.	L-R:1. BECCSU * could replace all forms of fossil CO_2. L-R:2. Bioelectricity can be used to balance the grid if the share is sufficient. L-R:3. Biomass supply for bioenergy will be used as a tool to absorb atmospheric CO_2 and keep the fossil CO_2 unused. L-R:4. A higher share of biofuels in transport fuel demand (air industry) L-R:5. Diversify energy supply to ensure energy security L-R:6. Defossilization/SDGs of Agenda 2030 /Paris Agreement and Nationally Determined Contributions [19] L-R:7. Bioeconomy where bioenergy plants convert to biorefineries L-R:8. Invest in R&D in renewable CO_2 supply (BECCSU) and with the options to the industry. L-R:9. Invest in R&D for valorization of by-products of bioenergy.

* BECCSU—bioenergy combined with carbon capture, storage and use ** CHP—combined heat and power.

About a third of the experts (37%) reported not knowing if any disruptions occurred in the bio-based industry due to the disruptions in markets during the COVID-19 outbreak. At an aggregated level (Figure A1), 40% of the experts reported no change in production; most negative disturbances were recorded in the wood product manufacturing industry and fresh produce (both 56% and 53%, respectively). Gains were reported by 47% and 29% of experts in the food processing industry and the pulp and paper industry, respectively. Overall, biomass supply was viewed by experts as resilient to the pandemic: 40% of experts reported no change in production due to the pandemic and 19% of experts reported a productivity gain.

When asked to assess the reasons for the negative disturbances, about half of the experts reported not knowing the reason (47%). From the estimations provided by the experts, both lack of workers to harvest biomass and prohibited mobility (lockdown measures) were mentioned equally (24%), whereas the lack of biomass from imports was the least common reason (Figure A2). On the demand side, 44% of experts reported no changes observed. From the reasons for negative disturbances from the demand side, the same reasons for the disturbances from the supply side were reported: lack of workers to harvest biomass (24%) and prohibited mobility (lockdown measures) (18%). In addition, 21% of the experts estimated the loss of export markets as a negative disturbance, with the highest effect in the wood product manufacturing industry (20%). Reduced or stopped supply of biomass from imports was not identified by experts as causing any demand-side economic disturbances. Instead, 28% of experts reported that the market demand increased due to the pandemic, at the aggregated level, with the most being reported in the food processing industry (32%) (Figure A3).

3.3. The Delphi Study: Investments in BSChs That Could Contribute to the Post-COVID-19 Recovery

The Delphi survey (Table 4) captured different waves of the pandemic: the first round of opinions was collected under the impressions of the first reactions, subsiding the pandemic in Europe and various intervention measures across and within the countries, whereas the second round captured the peaks for the number of COVID-19 cases in the regions of the Americas, Europe and Western Pacific (Figure 1).

Given the broad definition of consensus, the experts' opinion gave a general direction on the possible contributions of various investments to BSChs in 84% of the statements after the first round and 95% after the second round (Table 5).

Table 4. Structure of the Delphi survey respondents.

Delphi Round	Invited Experts	Responded			Response Rate
1st round (September–October 2020)	42	23	Oceania Europe North America	3 14 6	55%
2nd round (February–March 2021)	23	13	Oceania Europe North America	1 8 4	57%

Table 5. Survey results and consensus reached by Delphi round and survey section.

Survey Section	Expert Consensus (% Agreement)			
	Round 1		Round 2	
	By 2023	By 2030	By 2023	By 2030
Economic Growth—BSCh Investments	15/20 (75%)	13/20 (65%)	20/20 (100%)	19/20 (95%)
Economic Growth—Investments in Technology and Infrastructure	18/24 (75%)	21/24 (88%)	24/24 (100%)	24/24 (100%)
Jobs—Investments in BSChs	32/36 (86%)	27/36 (75%)	36/36 (100%)	34/36 (94%)
Cleaner, Resilient Energy Sectors	33/36 (92%)	34/36 (94%)	36/36 (100%)	36/36 (100%)
Investments in specific bioenergy demand	11/12 (92%)	12/12 (100%)	11/12 (92%)	4/4 (100%)
Overall consensus:	**216/256 (84%)**		**244/258 (95%)**	

The bridging-over question to verify is whether the existing bioenergy policies in specific countries with modern bioenergy use are sufficient in supporting investments that would contribute to economic recovery (Figure 3). The experts, without defining what those investments would be, agreed that the existing bioenergy policy is in a range of a scale of "sufficiency" in both time frames for the Global Marketplace scenario, which reflects the times before the pandemic. In all other scenarios, in both time frames, experts agreed that the existing bioenergy policies are insufficient to slightly insufficient to support investments that would contribute to economic recovery.

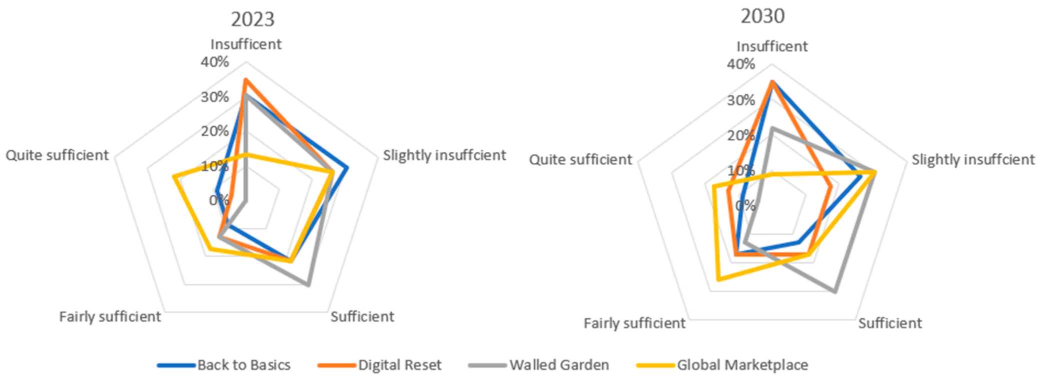

Figure 3. Experts' opinion if the existing bioenergy policies in their countries are sufficient in supporting investments that would contribute to economic recovery.

With respect to the impact of future investments, Delphi survey experts assessed investments in BSChs within the Global Marketplace scenario as having the most impact on economic growth, both in the short and long run. In the long run, the impact of investments in BSChs on economic growth was assessed as "moderate to strong" in all future scenarios (see Appendix C for a detailed breakdown of expert consensus on the various investments to BSChs and their possible contributions to economic growth, job creation and building a more resilient and cleaner energy systems). This section highlights investments in BSChs that a consensus of experts endorsed as having "moderate to very strong" contributions to the post-COVID-19 recovery. The experts reflected in the open-ended questions that "by 2023" is too short a period to see any effects of any investments, regardless of the field, which was true to some extent, as the group assigned more positive effects in the long term than in the short run, in general. One of the experts found the future scenarios as "limiting" since the pandemic has affected the entire fabric of society.

Table 6 represents a summary ranking of the impact of the investments in different BSChs on the economic growth, reflecting experts' consensus. A detailed overview of experts' consensus on each scenario for each of the five BSChs across both time perspectives, however, can be found in Appendix C Table A6. Overall, experts assign the most impact from investments in BSChs to the economic growth within the Global Marketplace scenario, both in the short and long run. Yet, in the long run, the impact of investments in BSChs on economic growth was assessed as "moderate to strong" in all future scenarios.

Table 6. Aggregated experts' consensus on the impacts of the investments in different BSChs to the economic growth, across different scenarios.

Statement	By 2023	By 2030
3 Investments in improving forest BSChs	moderate to strong	strong to very strong
4 Investments in improving agricultural BSChs	moderate to strong	strong
1 Investments towards unlocking new BSChs from waste and by-streams.	moderate to weak	moderate to strong
2 Investments in growing terrestrial biomass (dedicated biomass such as short rotation coppice, energy crops) to supply biomass for the market	weak to no impact	moderate

The numbers next to the investments relate to Table A6.

Impacts of technology and infrastructure investments were identified by experts as primarily experienced in the long term (Table 7, Table A7). In the short run, positive effects from such investments on economic growth occur in scenarios that assume short virus longevity and digital acceleration (Global Marketplace and Walled Gardens), assuming IT solutions would aid in securing biomass supply to the industry. In comparison, the long-term effects of investments in BSCh-related technology and infrastructure on economic growth range from "weak to moderate" to "moderate to strong" in the Digital Reset scenario. Overall, experts identified investments in small-scale, decentralized bioenergy facilities, coupled with the substitution of fossil fuel use, fit for a local supply chain as having positive effects on economic growth across the scenarios (Table 7).

Table 7. Aggregated experts' consensus on the impacts of the investments in infrastructure and technology to enhance BSChs to the economic growth, across different scenarios.

Statement	By 2023	By 2030
5 Investments in small-scale, decentralized bioenergy facilities, coupled with substitution of fossil fuel use, fit for a local supply chain	moderate	strong
1 Investment programs for preferred bioenergy technologies coupled with targeted BSChs	moderate to strong	moderate to strong
3 Investment in biomass logistic-distribution centers (bio-hubs)	moderate	moderate to strong
2 Programs supporting all technologies and BSChs	moderate	moderate
4 Investments in upgrading the existing agricultural collection and processing centers into bio-hubs	moderate	moderate
6 Investments in large scale, centralized bioenergy facilities, coupled with substitution of fossil fuel power plants (coal, gas) or a biorefinery.	weak	moderate

The numbers next to the investments relate to Table A7.

Interestingly, investments in tailored programs for preferred bioenergy technology (e.g., the one that would have the desired multiplier effect across the economy) coupled with targeted BSCh (e.g., the one that represents a low-hanging fruit, such as corncobs, or possess environmental risks, such as olive oil cake, or pruning or supporting wood pellets for household heating given a strong domestic industry in pellet stoves) (statement 1) were ranked higher than the investments that let the investors recognize the technology and supply chain (statement 2).

In open-ended feedback, experts suggested additional investments that could have strong impacts on economic growth: local investments that address climate mitigation issues, and investments to further optimize existing well-working BSChs with innovations and better business planning. If biomass is used locally in small-scale facilities, investments in the sector which address problems (air pollution from small combustors, efficient supply chains for residues, improvement in quality, etc.) will lead to the greatest impacts for BSChs. Economies of scale were recognized by experts participating in the Delphi survey, but the ability of supply to meet large biomass demand was controversial among experts. Specifically, large-scale biomass operations were thought to have mixed effects on economic growth depending on whether biomass is imported or locally supplied, and whether the supply is sustainable, or if there is a need for subsidies to operate a large-scale bioenergy facility.

When looking at a specific intervention (Table 8, increasing biomass demand for bioenergy (or any other sector in bioeconomy) would "probably" create jobs across the scenarios in the long run. Experts agreed that investments related to growing biomass for bioenergy within the bioeconomy (statements 6–8) would "possibly" have a positive impact on job creation in the long run. BSCh investments were viewed by experts as having only slight effects on job creation (Table A8). Instead, only in the long-term would these investments "probably not to possibly" (Digital Reset) and "possibly" (Back to Basics and Walled Gardens) or "possibly to probably yes" (Global Marketplace) contribute to job creation.

Table 8. Aggregated experts' consensus on the impact of the investments in BSChs on job creation, across different scenarios.

Statement	By 2023	By 2030
9 Increased demand for bioenergy would increase jobs in BSChs.	possibly to probably yes	probably yes
2 Market incentive programs for replacing fossil fuel heating and cooling with biomass in agriculture (e.g., stables, greenhouses ...), post-harvest (e.g., drying, cooling) and primary processing (e.g., dairy, juices, spirits).	possibly	possibly to probably yes
3 Investments in replacing fossil fuels in public institutions with a biofuel with the highest multiplier effect in jobs	possibly	possibly to probably yes
5 Investments in establishment of biomass logistic-distribution centers to stabilize the biomass supply market: secure supply, quality, price and sustainability.	probably not	possibly
7 Investments in planting biomass for bioenergy within a bioeconomy at non utilized agricultural land.	probably not	possibly
6 Investments in planting biomass for bioenergy within a bioeconomy, in general.	probably not	possibly
8 Investments in planting additional biomass as a part sustainable intensification of agriculture (intercropping, agro-forestry).	probably not	possibly

The numbers next to the investments relate to Table A8.

The experts found investments in BSChs to have a smaller impact on building more resilient and cleaner energy systems ("probably not to possibly" and "possibly" in the short and long run, respectively) compared to investment impacts on overall economic growth (Table A9). Investments in small-scale, decentralized bioenergy facilities, coupled with the substitution of fossil fuel use, fit for a local supply chain (Statement 8, Table 9), surfaced again, with the consensus of experts, as contributing to economic growth (Table 7).

Experts agreed that increasing bioenergy demand that is tailored to the specific end-use of bioenergy and linked with the specific, locally available BSCh would have "moderate to strong" and "strong" impacts on post-COVID-19 recovery in the long run (Table A10 details, Table 10 aggregated). Increased demand for bioenergy was ranked by experts as having the greatest contribution to job creation (Table 8).

Table 9. Aggregated experts' consensus on the impact of the investments in BSChs on building cleaner and more resilient energy systems, across different scenarios.

Statement	By 2023	By 2030
8 Investments in small scale, decentralized bioenergy facilities, coupled with substitution of fossil fuel use, fit for a local supply chain.	possibly	possibly to probaby yes
6 Investment programs for preferred bioenergy technologies coupled with targeted BSChs	possibly	possibly to probaby yes
9 Investment in R&D to increase efficiency in the bioenergy system relying on local biomass supply.	possibly to probably not	possibly to probaby yes
3 Investment in diversification of conversion technologies to accommodate local biomass supply.	possibly	possibly
7 Investments in upgrading the existing agricultural collection and processing centers (e.g., flour mills, oil mills, vineries, dry fruits and nuts . . .) into bio-hubs to mobilize waste- and side-streams.	possibly	possibly
2 Investment in establishment of locally available BSChs to facilitate a targeted fossil fuel replacement or power grid flexibility.	possibly	possibly
1 Investment in biomass logistic-distribution centers (bio-hubs) to stabilize the biomass supply market: secure supply, quality, price and sustainability.	possibly to probably not	possibly

The numbers next to the investments relate to Table A9.

Table 10. Aggregated experts' consensus on the impacts of increasing bioenergy demand to the post-COVID19 recovery, across different scenarios.

Goals	By 2023	By 2030
Job creation	weak to moderate	moderate to strong
Economic growth	weak	moderate to strong
Cleaner and more resilient energy systems	weak	moderate

4. Discussion

Global supply chains survived and thrived through historical disruptive events and have generally shown a high level of resilience. BSCh are characterized by a variety of feedstocks and variable processing technologies for energy, each of them having trade-offs [22]. In the past, this variability in supply and technology was considered rather influential as resource markets were competing with biomass for bioenergy and putting a constraint on the market [28]. Due to a shift in the use of resources and energy caused by the ongoing global COVID-19 pandemic, the BSChs have the potential to overcome these constraints and break out into new strategies leading the future energy markets.

While it was evident that the pandemic caused disruptions in supply chains in general and globally [30,55], BSChs were re-established faster, especially considering the short supply chains, within a country or administrative border. For the difference in co-productive (food, forestry) BSChs, biofuel industry that relies on dedicated crops would require more than a year to recover [35]. The SWOT analysis indicated that the biomass for bioenergy within the bioeconomy will very likely come from co-productive systems, in a shape of a by-product, waste or residue from primary production. Hence, the literature review was expanded to the food and wood supply chains in the time of pandemic. A short communication in July 2021 discussed how the resiliency of BSChs in six areas (supply availability, digitalization and automation, collaboration within the supply chain, community-focused energy production, social challenges and opportunities, and policy) can be improved in the post-pandemic scenario. While some areas were challenging in general (supply availability, digitalization and automation), limited mobility of the workforce due to the pandemics resulted in the shortage of labor in BSChs across the supply chain [25]. The main issue was the inability to perform agri-technical measures [3], which was also detected as a threat element in performed SWOT analysis (Table A2). Agriculture, like any other labor-dependent sector, has shown poor resilience from the start of the pandemic [56], but the learning curve from different levels of lockdown and response measures to reduce contact allowed field workers and logistics to operate under certain restrictions. The pandemic has increased uncertainty in biomass supply, which would force most biomass users to obtain their biomass from various sources without tracing their origin or quality. Such uncertainty consequently reduced the collaboration within the supply chain [25,55]. Simultaneously, the pandemic also exposed biomass versatility and flexibility [20,22,25] when supplied for bioenergy.

The pandemic exposed limitations (short run) and opportunities (long run) in dealing with energy supply, in general, and the role of biomass, in particular. The food supply chain review identified small farmers as a group particularly affected by the pandemic, and study experts emphasized a need to avoid food protection policies to prevent an increase in food prices, consistent with other publications [57,58]. Others highlighted the vulnerability of SMEs in general [3]. Yet, wood pellet producers in the southeastern United States fared better in terms of employment than the United States economy overall just because previously implemented systems designed to promote safe operations were fit to reduce the impact of the pandemic [58].

Dewick et al. [59] argue that in agri-food system production, the pandemic has led to concerns about fluctuations in international commodity prices, changes in patterns of consumption and disruptions to global distribution networks. Limiting access to inputs and markets disrupts the traditional supply chain interactions between rural and urban areas, especially in the developing countries. In this situation farmers will be forced into self-sufficient production, such as the Back to Basic scenario (Table 2).

On the other hand, manufacturing experiences a unique set of risks, which include high uncertainty in increasing propagation and long-term disruption to supply chain actors [60]. Often, disruptions in the manufacturing processes and systems and shifts in supply and demand are caused by exogenous supply chain disruptions. The types of disruptions faced by manufacturing seem to be qualitatively different from the usual (historically observed with known and documented consequences) disruptions in BSChs, thus unlikely to be captured by models using uncertainty as discussed above.

Experts reported different resilience of BSChs to the economic disturbances due to the pandemic during the first six months (by September 2020), which is supported by research (e.g., [57–59]) published after the survey had been implemented. For instance, health and food safety measures resulted in increased interest in automation and robotics in the food and beverage industry as compensation for the limited availability of workers [4,60]. More automated food processing industries showed more resilience than those that were relying on manual work. Stocking up on food and stay-at-home measures increased home cooking and demand for ready-made products with increased layers of packaging [4,61,62] and hygiene items. Industries supporting such changes in behavior thrived, and many of those rely on BSChs. Consequently, biomass supplied for bioenergy as secondary biomass sourced from primary product growth and processing followed the behavior of the primary product industry. Yet, most of the disruptions in biomass supply and demand were related to logistic, distribution and delivery limitations [4,25,56]. While the pandemic exposed limitations to the BSChs in the short run, it also helped identify long-run opportunities for BSChs in responding to energy supply and co-productive systems. For instance, in the past, this variability in supply and technology challenged BSChs as resource markets competed with biomass for bioenergy and constrained the market [28]. Now, due to a shift in the use of resources and energy caused by the ongoing COVID-19 pandemic, BSChs have the potential to overcome these constraints with strategies built around investments that experts tagged with positive contributions to the overall economic recovery.

Investments that experts identified as having the highest impact on recovery are investments that improve biomass material efficiency and circularity from forestry and agriculture biomass short-supply chains, including dedicated crops in the long term. In general, experts favored investments with short supply chains, specialized approaches, small-scale operations and decentralized facilities, instead of general measures supporting investments in BSChs and bioenergy. Small-scale bioenergy facilities will more likely face the challenge of competitiveness for which, again, tailored programs supported by R&D can aid in increasing the energy and material efficiency, improving the business models to source income not only from bioenergy but also from renewable CO_2 and other residues such as digestate, ash, biochar, etc., depending on the conversion technology or cascading use of biomass. In that context, not only BSChs, but also the general challenges that agri-food chains are facing, such as collaborative trust and community-focused energy production [55], can be addressed. Small-scale, decentralized bioenergy facilities, coupled with substitution of fossil fuel use, fit for a local supply chain, combined with market incentive programs for replacing fossil energy for heating and cooling in agriculture and agri-food chain represent a solid option to invest on post-COVID-19 recovery. The absolute size of "small-scale" and "local" will be determined by the context where the investment in BSCh occurs, and will significantly differ between small countries (e.g., Croatia) and large countries (e.g., Canada). In addition, BSChs will face different ecological boundaries that also have to be placed in the broader context when considering such investments [19].

Additionally, infrastructure investments to stabilize biomass supply from forestry, agriculture and waste streams in terms of quantity, quality and sustainability were seen to have a similar "moderate to strong" impact across all tested scenarios (Table 7: Statements 3 and 4). Such measures contribute not only to economic growth, but also job creation and to build cleaner and more resilient energy systems.

Technologies to replace fossil fuels with the highest multiplier effect on jobs can play an important role when job creation is the primary goal in post-COVID-19 recovery. Countering the focus on job creation, automatization and robotization to replace the manual work in mobilizing biomass would reduce supply costs and the vulnerability of labor supply from migrant workers in the pandemics where it has been reported as the reason for BSChs disruptions. In some countries, such labor shortages persist in sectors where work is demanding and provides low wages, in part because of emergency unemployment programs, thereby hampering possible recovery via investments in BSChs.

Experts give most value of the investments in BCSh to provide impact on economic growth and the least in job creation in the post-pandemic period, in the short term, but likely more visible over a longer time horizon.

There are several important lessons from the pandemic with respect to BSChs. The COVID-19 pandemic resulted in significant shifts in demand. Enhancement of supply chain resilience is seen as the key driver of the reduction in vulnerabilities in disruptive events. Consequently, supply chains might tend to be shorter, focusing on relocation and back-shoring [63,64]. Resilient BSChs need to be able to react to interference to overcome the stress placed on the economic system and mitigate the impact of the disruption as swiftly and as much as possible. When BSCh disturbances occur, adaptation of incentives need to be in place faster than recorded, which assumes reducing risks of uncertainty with scenario planning for future pandemics or similar scenarios.

Experts identified several investments as contributing to economic growth outcomes in all scenarios and timeframes with different intensity. The investment portfolios in BSChs to create future opportunities underline the strategy development process in the short and long term. The ability to take local action in the support and development of BSCh towards a strong local impact that has the scope to extend globally, stands out for biomass supply and strong economic lever in recovering economies. Relatively mature technologies in BSChs are positioned to excel in emerging carbon-constrained, biobased and circular economies, further strengthening the ability to sustain and grow their impact into the future.

Disparities between biomass supply and demand was identified by the SWOT analysis as a challenge for BSChs, particularly considering multiple, competing energy sources, that can be either fossil-based or renewable. To some degree, all challenges identified by the future scenarios accurately reflect current challenges, not only with BSChs, but with the management of the pandemic itself. Long-run repercussions of the pandemic include disruptions to joint research efforts, fragmentation and the potential for internalizing efforts toward national rather than global goals [65]. Furthermore, the emergence of nationalist approaches that pre-dates the COVID-19 pandemic and their potential impact on international cooperation is characteristic of the Back to Basics and Walled Gardens scenarios. Rowan and Galanakis [66] suggest the path of COVID-19 could take us to catastrophic global upheaval, with the potential to alter geopolitical and socio-economic norms. However, they also argue that the future looks bright for the creation of new sustainability multi-actor innovation hubs that will support, connect, and enable businesses to recover and pivot beyond the COVID-19 pandemic. The Back-to-Basics scenario is characterized by virus longevity over a year, digital skepticism, and global rejection. While the social and economic boundaries have shifted unevenly during the pandemic, both transportation and labor disruptions are in evidence. The concomitant contraction of the global mindset will persist until rolling pandemic waves and corresponding restrictions cease or ease. In terms of digital skepticism versus acceptance, an "infodemic" (or an over-abundance of information, both true and misleading) has emerged as a major challenge in managing the pandemic [67]. While the current reality may not be as bleak as a complete "Back-to-Basics" scenario [43], to some degree, all the challenges identified by the future scenarios accurately reflect ongoing challenges, not only with BSChs, but with the management of the pandemic itself. Further, while digital skepticism has increased and global supply chains have been constrained by labor mobility restrictions as well as health measures, in general, supply chains have shown resilience and adapted to new challenges posed by the pandemic effectively.

The question on how the COVID-19 pandemic will end is still open ended at the moment this paper is published. According to the WHO Coronavirus (COVID-19) Dashboard [68] "Globally, as of 6:47 pm CEST, 13 August 2021, there have been 205,338,159 confirmed cases of COVID-19, including 4,333,094 deaths, reported to WHO. The first vaccines against COVID-19 were approved in early 2021; as of 12 August 2021, a total of 4,428,168,759 vaccine doses had been administered. WHO highlights that the vaccines will not stop the pandemic but rather vaccinations that are fairly and equitably shared across countries, regardless of income status." As COVID-19 vaccines are rolled out across the world, there are growing concerns about the roles that trust, belief in conspiracy theories, and spread of misinformation through social media play on vaccine hesitancy [67].

As of September 1, 2021, the fourth wave of COVID-19 had begun in the countries surveyed for our research. On August 24, 2021, the WHO reported that Europe and the Americas had the highest weekly case and deaths incidence rates per 100,000 population [69]. Therefore, the Global Marketplace and Walled Gardens scenarios posed in this Delphi survey were too optimistic, in that these two scenarios assumed a virus longevity of one year or less. This brings some cause for concern; a consensus of experts from modern biomass sectors rated current national investments in the biomass supply chain as slightly insufficient to insufficient. However, the world economy is on track for strong growth in 2021, despite the recovery being uneven between countries, and sectors closely tied to bioenergy (agriculture and wood product manufacturing) coping better than most other sectors [58].

5. Conclusions

The results of this foresight exercise indicate where specific investments in biomass supply chain will likely stimulate economic growth and create cleaner and more resilient energy systems even under a more drawn-out pandemic. Resilient BSChs need to be able to react to interference to overcome the stress placed on the system and mitigate the impact of disruptions as swiftly and as much as possible. Resilience in the BSChs, which emerged as a finding of the SWOT analysis and literature review, is also predicted by experts, particularly in BSChs that could accelerate transition to a sustainable and carbon-neutral society, hopefully without the challenges of the pandemic. Some of them, such as investments to improve biomass supply from forestry and agriculture, as well as those investments that support short supply chains with a more specialized approach instead of general measures in supporting all biomass investments, regardless on the supply chain and end-use, indicate positive economic growth outcomes in all scenarios and timeframes with different intensity. Evidence-based definition of an investment in a BSCh from the source till its end-use aids blending the biomass use in its context, stimulating either desired socio-economic effects or a multiplier effect across the economy, or both. Experts agree that stimulating bioenergy demand will increase biomass supply, but such general intervention leaves the firms' behavior open to the market forces, not necessarily achieving desired impact on growth, jobs and resilience. Investing in ways to include secondary biomass from primary production in the economy could offset the loss of income in rural areas, given the adaptation measures needed due to climate change. The role of the bioenergy industry in economic recovery is to be expanded by combining the biomass supply chain with the product chain, industrial chain and capital chain to achieve more accurate effects on economic growth, energy system resilience and job creation.

It is clear is that the existing policy refurbishment towards supplying biomass to the economy is vital, not only for post-COVID-19 recovery but also to accelerate sustainable renewable carbon supply to the economy in the era of evident climate change [70]. The information collected in this study can act as a blueprint to inform investments in different possible economic and social futures.

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Appendix A

Appendix A presents the detailed results from the extended SWOT analysis on possible contributions of BSChs to bioenergy within bioeconomy, which was used to formulate the short- and long-term strategies for the foresight exercise and finalize the study design.

Example of interpretation of Figure A1: the short-run SWOT element "S-R:1. Increase in pellet production due to improved forest management" (Table 3) was generated as an action to a cluster of SWOT elements: Ss-1–7; Ws-2–6 (Table A1), Os-1–5; Ts-1; 4; 6; 8; 9 (Table A2), Sd-1 – 11; Wd-1; 9; 10 (Table A3) and Od-1; 2; 5; 6; 10; Td-1; 3; 4; 5; 8 (Table A4). To reach a generic strategy (Delphi) that includes local biofuel production with short supply chains (resilience) and fossil fuel substitution (clean energy) but not limiting to pellets or assuming specific biomass source, S-R:1 was bundled with S-R:3; S-R:4; S-R:7; S-R:9;S-R:10

under the Strategy "Investments in small scale, decentralized bioenergy facilities, coupled with substitution of fossil fuel use, fit for a local supply chain".

Table A1. Strengths and Weaknesses (SWOT) of biomass supply chains in respect to mobilizing and placing biomass to the market.

Strengths	Weaknesses
Ss-1 Inferior good at the heat market Ss-2 Locally available source of renewable energy Ss-3 Market for low value material to enhance forest management goals Ss-4 Farmer and forest owners are increasing productivity per unit of land/livestock unit by valorizing side-streams of the primary production. Ss-5 Industry associated with biomass, remained non disrupted (AUS) Ss-6 Lockdown did not force any energy provider to stop operating (DE, SE) Ss-7 Short supply chain Ss-8 Supplying biomass from the forests and field is not a COVID-19 risk activity. Ss-9 Heterogeneity of biomass	Ss-10 Imbalance between demand and supply of biomass Ss-11 Storage costs Ss-12 Storage and handling losses Ss-13 Heterogeneity of biomass Ss-14 Unstable properties of a single biomass supply chain Ss-15 The quality of biomass is not valorized Ss-16 Price inelastic Ss-17 Dependence on the co-productive sectors (livestock, crop, wood-based industry) Ss-18 Not market competitive Ss-19 Overlapping legislation, not necessarily concerted in a policy Ss-20 Local particle emissions Ss-21 Decreasing forest management reduces volumes for biomass supply Ss-22 Failure of 1G biofuels to achieve the expected GHG emission savings contributions is reducing the overall attractiveness of bioenergy Ss-23 Strict lockdown prevented mobility to mobilize and supply biomass which resulted in placing on marketpoor quality biomass that was not a long-term option.

Table A2. Opportunities and Threats (SWOT) of biomass supply chains with respect to mobilizing and placing biomass to the market.

Opportunities	Threats
Ss-24 If categorized and labelled, market value of biomass supplied can be increased Ss-25 Untapped potential Ss-26 Interest in native private forests that are unmanaged, to sell residues as bioenergy product Ss-27 Removal of harvest residues Ss-28 Forest fire management tool Ss-29 A USD 7.66 B global CO_2 market, with 3.4% growth by 2027, mostly from enhanced oil recovery¸ source of renewable CO_2 Ss-30 Integration to bioeconomy with new value chains Ss-31 A good opportunity to abandon fossil fuel subsidies Ss-32 Disrupted coal supply opens space for alternative fuels Ss-33 Grid balancing service Ss-34 Valorization of bioenergy by-products (existing bioenergy plants evolving towards biorefineries) Ss-35 Bioenergy Carbon Capture, Storage and Use (BECCSU) Ss-36 Raising industry awareness on new value chains and synergies	Ss-37 Reduced demand on biofuels Ss-38 CO_2 taxation or related CO_2 limiting policy Ss-39 Losing carbon neutrality position Ss-40 Low fossil prices Ss-41 Attached controversies about bioenergy Ss-42 Lack of concerted policy to ensure environmental and social aspects of sustainability Ss-43 BECCSU too low at TRL scale Ss-44 Electricity is preferred to other decarbonization pathways Ss-45 Lack of demand for bioenergy

Table A3. Strengths and Weaknesses (SWOT) of biomass supply chains with respect to market demand for biomass.

Strengths	Weaknesses
Ss-46 Renewable base bioenergy Ss-47 Inferior good at the heat market Ss-48 Locally available renewable energy Ss-49 Mature technology for bioheat and bioelectricity Ss-50 Pellet market can increase to substitute for firewood (local particle emissions reduction) Ss-51 Market for low value material to enhance forest management goals Ss-52 Security of supply Ss-53 Increasing productivity per unit of land/livestock unit Ss-54 Untapped potential Ss-55 Industry associated with biomass, remained non disrupted (AUS) Ss-56 Lockdown did not force any energy provider to stop operating (DE, SE)	Ss-57 Price inelastic Ss-58 In CHP, bioelectricity is valorized while heat rarely Ss-59 CHP by-products not valorized (digestate, ash, CO_2, sulfur) Ss-60 Reduced demand on biofuels Ss-61 Dependence on the co-productive sectors (livestock, crop, wood-based industry) Wd-1 The willingness to pay higher price for bioelectricity is lower than for the fuel-less technologies Wd-2 Not market competitive Wd-3 Complex Wd-4 Local particle emissions Wd-5 Decreasing in forest management reduces volumes for biomass supply Wd-6 Failure of 1G biofuels to achieve the expected GHG emission savings contributions

Table A4. Opportunities and Threats (SWOT) of biomass supply chains in respect to market demand for biomass.

Opportunities	Threats
Ss-62 Interest in native private forests that are unmanaged, to sell residues as bioenergy product Ss-63 Forest fire management tool Ss-64 A USD 7.66 B global CO_2 market, with 3.4% growth by 2027, mostly from enhanced oil recovery source of renewable CO_2 Ss-65 Integration to bioeconomy with new value chains Ss-66 A good opportunity to abandon fossil fuel subsidies Ss-67 Disrupted coal supply opens space for alternative fuels Ss-68 Grid balancing service Ss-69 Valorization of bioenergy by-products (plants evolving towards biorefineries) Ss-70 BECCSU Ss-71 Raising industry awareness on new value chains and synergies	Ss-72 CO_2 taxation or related CO_2 limiting policy Ss-73 Losing carbon neutrality position Ss-74 Low fossil prices Ss-75 Attached controversies about bioenergy Ss-76 Lack of concerted policy to ensure environmental and social aspects of sustainability Ss-77 BECCSU too low at TRL scale Ss-78 Electricity is preferred to other decarbonization pathways Ss-79 Lack of demand for bioenergy

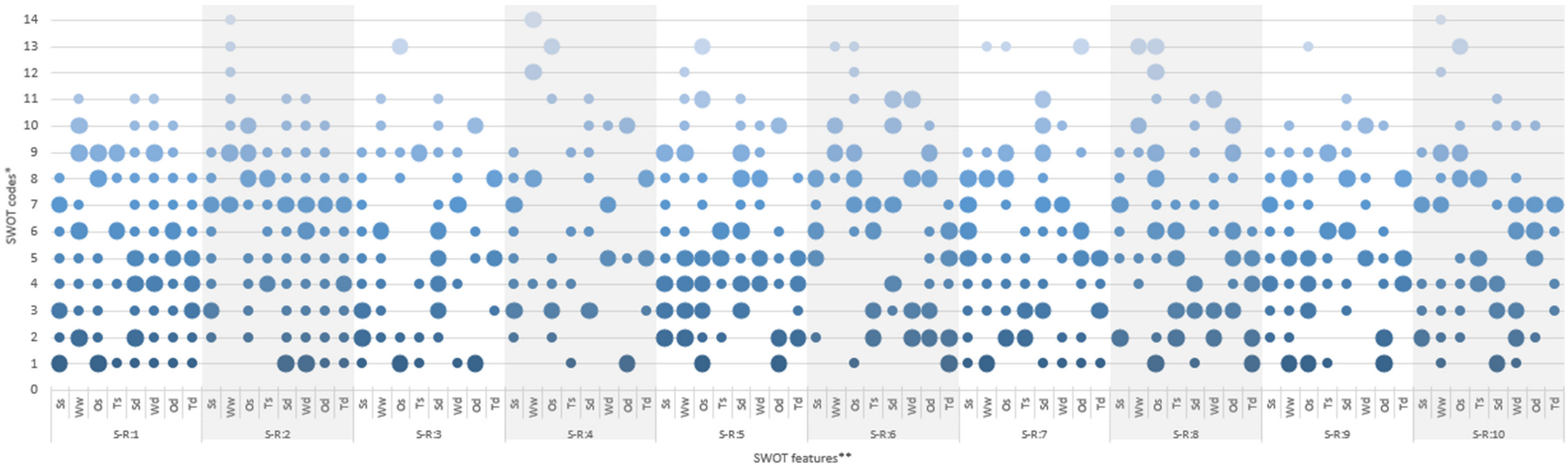

Figure A1. Clustered SWOT elements to formulate short run BSChs features to feed the Delphi questionnaire (larger circles represent the main elements while the smaller circles represent supporting elements)1. * SWOT codes correspond to the numbering of SWOT elements in Tables A1–A4, i.e., Ss-1 Inferior good at the heat market ** SWOT features correspond to the numbering of short run: immediate action BSCh features in Table 3; i.e., S-R:1. Increase in pellet production due to improved forest management.

Figure A2. Clustered SWOT elements to formulate long run BSChs features to feed the Delphi questionnaire (larger circles represent the main elements while the smaller circles represent supporting elements)1. * SWOT codes correspond to the numbering of SWOT elements in Tables A1–A4, i.e., Ss-1 Inferior good at the heat market ** SWOT features correspond to the numbering of short run: immediate action BSCh features in Table 3; i.e., L-R:1. BECCSU * could replace all forms of fossil CO_2 Increase in pellet production due to improved forest management)

Appendix B

Appendix B presents the detailed results from a short survey among biomass experts' network, collecting information on the behavior of BSChs during the lockdown period (more specifically, the period from February–October 2020, "the first wave") overlapping with the geographic area of the Delphi survey. The questionnaire had three short sections: disruptions in the energy sector, economic disturbances in biomass supply chains from the supply side (e.g., raw materials, labor, logistics), and disruptions from the demand side.

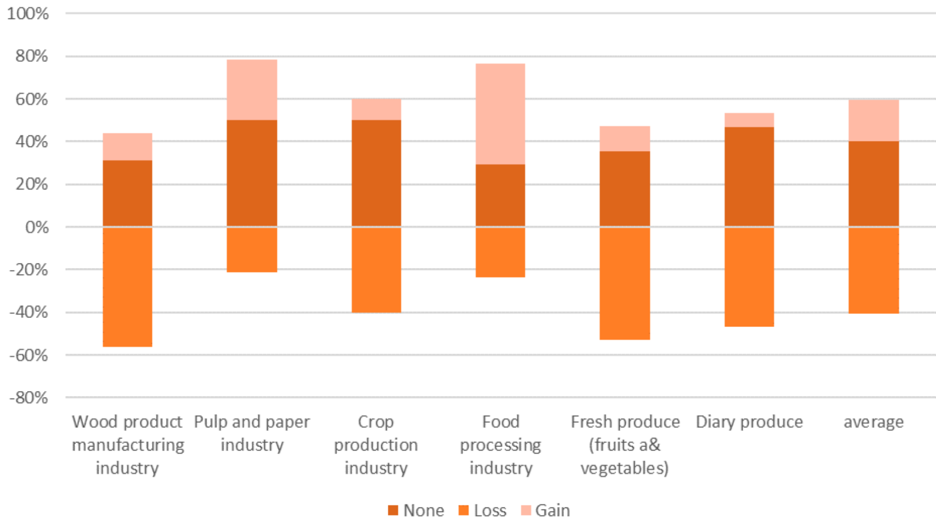

Figure A1. Aggregated results for economic disturbances in biomass supply chains from the demand side reported by experts.

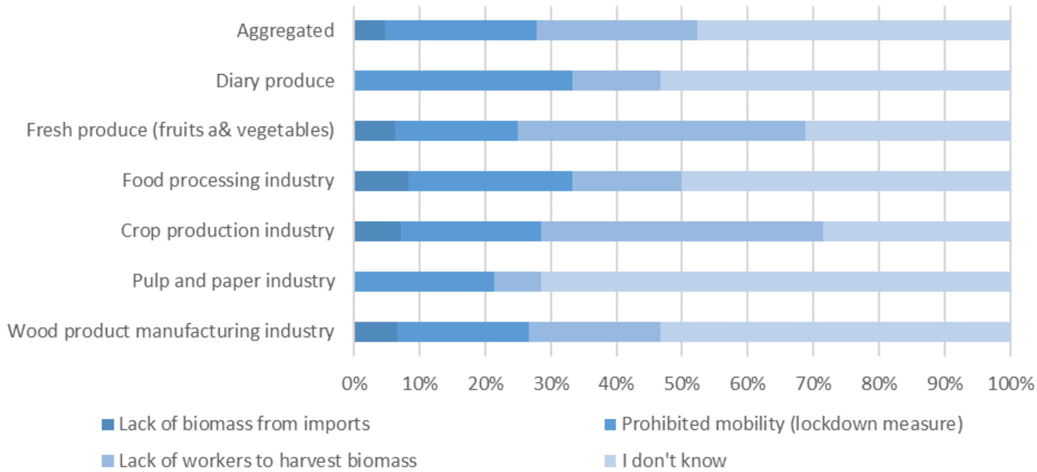

Figure A2. Reasons for negative disturbances on biomass supply chains from supply side reported by experts.

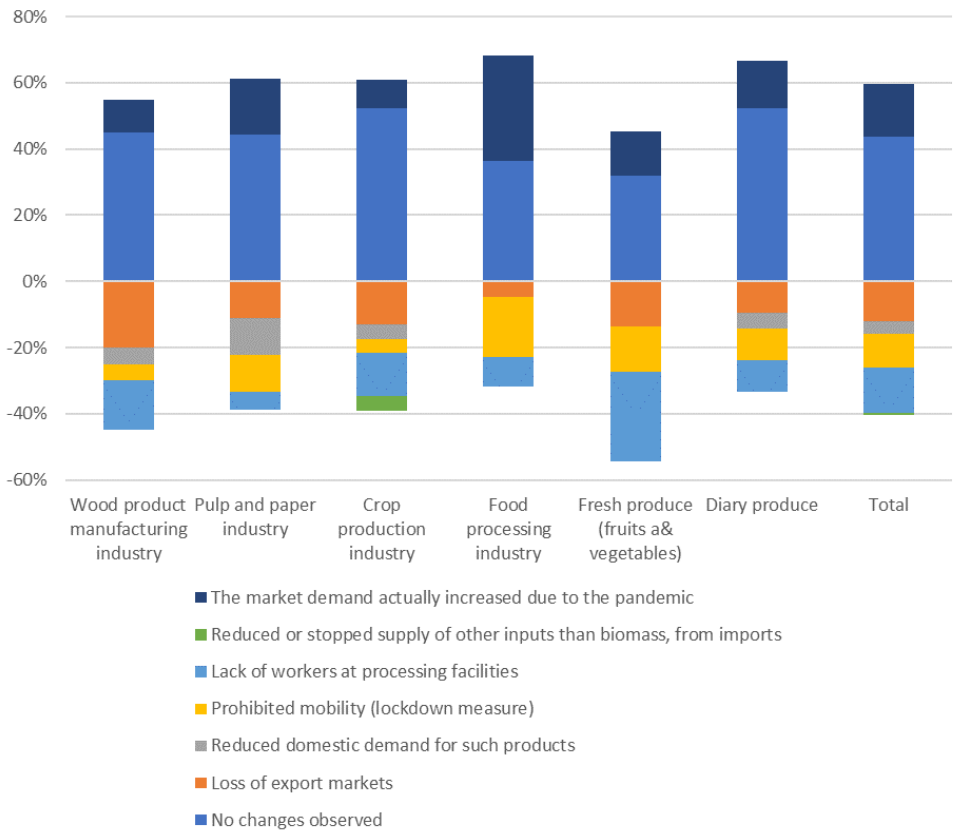

Figure A3. Aggregated results for economic disturbances in biomass supply chains from the supply side reported by experts.

Appendix C

Appendix C presents the detailed results from the Delphi study on the experts' consensus how various investments in biomass supply chains could contribute to the post-COVID19 recovery in three aspects: economic growth, job creation and building a more resilient and cleaner energy systems.

Table A5 indicates how investment directions were decided based on the expert opinion. Here, consensus was achieved in three future scenarios except for Back-to-Basics will enter the 2nd round only for those experts that did not choose to "Agree".

Table A5. Example of constituting consensus in experts' opinion (consensus range represented by values in italics) and interpreting results.

Likert-Scale		**Statement: Increasing Specific Bioenergy Demand (Bioheat, Bioelectricity, Liquid or Gaseous Biofuels for Transport) Would Generate Sufficient Economic Growth Through Investments by 2030.**			
verbal	numerical	Global Marketplace	Digital Reset	Back-to-Basics	Walled Gardens
Strongly disagree	1	3	2	3	2
Disagree	2	1	4	*4*	2
Undecided	3	*6*	*4*	*4*	*5*
Agree	4	*7*	*6*	*6*	*5*
Strongly agree	5	*5*	*6*	*4*	*7*
	Consensus	82%	73%	67%, double value	81%
Experts' opinion:	numerical	3.94	4.12	4 or 3.14	4.11
	verbal	Agree	Agree	No consensus: either agree or undecided	Agree

Table A6. Expert consensus on impact of investments in different biomass supply chains on economic growth *.

Biomass Supply Chains	**By 2023**				**By 2030**			
	Global Market Place	**Back to Basics**	**Digital Reset**	**Walled Gardens**	**Global Market Place**	**Back to Basics**	**Digital Reset**	**Walled Gardens**
1 New biomass supply chains from waste and by-streams	Strong to very strong	Weak	Weak	Moderate	Strong	*Moderate*	Moderate	*Moderate*
2 Growing terrestrial biomass (e.g., energy crops)	Weak	*Weak*	*Weak—No impact*	Weak	Moderate	Moderate	Moderate	Moderate
3 Forest biomass supply chains	Strong	Strong to very strong	Strong	Moderate to strong	Strong to very strong	*Strong*	*Strong to very strong*	Strong to very strong
4 Agricultural supply chains	Moderate to strong	*Strong*	*Moderate to strong*	*Moderate*	*Strong to very strong*	Moderate	Moderate	*Moderate*
5 Aquatic biomass (e.g., algae)	Weak	Weak	Weak to no impact	*Weak to no impact*	Weak	Weak	*Weak to no impact*	Weak

* Descriptions in regular font represent a consensus achieved in wave 1 of the survey, and descriptions in italics indicate a consensus in wave 2 of the survey.

Table A7. Expert consensus on impact of investments in technology and infrastructure on economic growth *.

Type of Investment	**By 2023**				**By 2030**			
	Global Market Place	**Back to Basics**	**Digital Reset**	**Walled Gardens**	**Global Market Place**	**Back to Basics**	**Digital Reset**	**Walled Gardens**
1 Investment programs for preferred bioenergy technologies coupled with targeted biomass supply chains	Strong	Moderate	Moderate	Strong to moderate	Strong to very strong	Strong to moderate	Strong	Moderate
2 Programs supporting all technologies and biomass supply chains	Strong	Moderate to weak	Moderate	Moderate	Strong to very strong	Moderate	Moderate to strong	Moderate
3 Investment in biomass logistic-distribution centers (bio-hubs)	Moderate to strong	Moderate	Weak	Moderate	Strong	Moderate to strong	Moderate to strong	Moderate to strong
4 Investments in upgrading the existing agricultural collection and processing centers into bio-hubs	Moderate	Moderate	Moderate to weak	Moderate	Moderate to strong	Moderate to strong	Moderate to strong	Moderate to strong
5 Investments in small scale, decentralized bioenergy facilities, coupled with substitution of fossil fuel use, fit for a local supply chain	Strong	Moderate	Moderate to strong	Moderate	Strong to very strong	Strong	Strong	Strong to very strong
6 Investments in large scale, centralized bioenergy facilities, coupled with substitution of fossil fuel power plants (coal, gas) or a biorefinery	Moderate	Weak	Weak to no impact	Moderate	Strong to very strong	Weak to moderate	Moderate	Moderate to weak

* Descriptions in regular font represent a consensus achieved in wave 1 of the survey, and descriptions in italics indicate a consensus in wave 2 of the survey.

Table A8. Expert consensus on investments related to the biomass supply chains to create jobs under different scenarios and timeframe *.

Type of Investment	By 2023				By 2030			
	Global Market Place	Back to Basics	Digital Reset	Walled Gardens	Global Market Place	Back to Basics	Digital Reset	Walled Gardens
1 Investment in information exchange points to inform the market players how to add value to the unused biomass with a portfolio of financing schemes	Probably not to possibly	Probably not	Probably to definitively not	Probably not	Probably not to possibly	Possibly	Probably not to possibly	Probably not to possibly
2 Market incentive programs for replacing fossil fuel heating and cooling with biomass in agriculture (e.g., stables, greenhouses), post-harvest (e.g., drying, cooling), primary processing (e.g., dairy, juices, spirits)	Possibly	Possibly	Possibly to probably not	Possibly	Possibly	*Possibly*	*Possibly*	No consensus
3 Investments in replacing fossil fuels in public institutions with a biofuel with the highest multiplier effect in jobs	Probably not to possibly	Possibly to probably not	Probably not	Possibly to probably not	Possibly	Possibly	Possibly	Probably yes to possibly
4 Investment in re-skilling of unemployed workers due to the COVID-19 for biomass supply related jobs	Probably not	Probably not	*Possibly to probably not*	Probably not	Probably not	Possibly	Probably not	Probably not
5 Investments in establishment of biomass logistic-distribution centers to stabilize the biomass supply market: secure supply, quality, price and sustainability	Probably not	Probably not	Probably not	Possibly to probably not	Possibly to probably not	*Possibly to probably not*	Possibly	Possibly
6 Investments in planting biomass for bioenergy within a bioeconomy, in general	Probably not	Probably to definitively not	Probably not	Possibly to probably not	No consensus	Possibly	No consensus	Possibly
7 Investments in planting biomass for bioenergy within a bioeconomy at non utilized agricultural land	*Possibly to probably not*	*Probably to definitively not*	Probably not	Possibly to probably not	Probably not	*Possibly*	*Probably not*	Probably yes
8 Investments in planting additional biomass as a part sustainable intensification of agriculture (intercropping, agri-forestry)	Possibly to probably not	Probably to definitively not	Probably not	Probably not	Probably not	*Possibly*	Probably not	*Possibly*
9 Increased demand for bioenergy would increase jobs in biomass supply chains	Probably yes	Possibly	Probably yes to possibly	*Probably yes to possibly*	Probably yes	Probably yes	Probably yes	Probably yes

* Descriptions in regular font represent a consensus achieved in wave 1 of the survey, and descriptions in italics indicate a consensus in wave 2 of the survey.

Table A9. Expert consensus on contributions of investments in biomass supply chains on creating a clean, resilient energy *.

Type of Investment	By 2023				By 2030			
	Global Marketplace	Back to Basics	Digital Reset	Walled Gardens	Global Marketplace	Back to Basics	Digital Reset	Walled Gardens
1 Investing in research to select biomass supply chains appropriate for a country	Disagree	Undecided to disagree	Undecided to disagree	Undecided to disagree	Undecided	Undecided to agree	Undecided	Undecided
2 Investment in establishment of locally available biomass supply chains to facilitate a targeted fossil fuel replacement or power grid flexibility	Disagree to undecided	Undecided	Undecided to disagree	Undecided	Agree	Undecided to agree	Undecided	Undecided to agree
3 Investment in diversification of conversion technologies to accommodate local biomass supply	Undecided	Undecided to disagree	Undecided to disagree	Undecided	Undecided	Undecided	Undecided	Agree to undecided
4 Investment in R&D to increase efficiency in the bioenergy system relying on local biomass supply	Disagree	Undecided to disagree	Undecided	Undecided	Undecided	Undecided	Undecided	Undecided to agree
5 Investment in biomass logistic-distribution centers (bio-hubs) to stabilize the biomass supply market: secure supply, quality, price and sustainability	Undecided	*Disagree*	Undecided	Undecided to disagree	Undecided to Agree	Undecided	Undecided to Agree	Undecided
6 Investment programs for preferred bioenergy technologies coupled with targeted biomass supply chains	Undecided	Undecided to disagree	Undecided	Undecided to disagree	Agree	Undecided to agree	*Undecided to Agree*	Undecided to agree
7 Investments in upgrading the existing agricultural collection and processing centers (e.g., flour mills, oil mills, vineries, dry fruits and nuts . . .) into bio-hubs to mobilize waste- and side-streams	Undecided to disagree	Undecided to disagree	Undecided to disagree	Undecided to disagree	Agree to undecided	Undecided to agree	Undecided	Undecided to agree
8 Investments in small scale, decentralized bioenergy facilities, coupled with substitution of fossil fuel use, fit for a local supply chain	Undecided	*Undecided to disagree*	Undecided to disagree	Undecided	Agree	Agree	Undecided	Agree to strongly agree
9 Investments in large scale, centralized bioenergy facilities, coupled with substitution of fossil fuel power plants (coal, gas) or a biorefinery	Undecided	*Undecided to disagree*	Disagree	Disagree	Agree to Strongly Agree	*Undecided to agree-*	Undecided	Undecided to agree

* Descriptions in regular font represent a consensus achieved in wave 1 of the survey, and descriptions in italics indicate a consensus in wave 2 of the survey.

Table A10. Expert consensus if the increasing specific bioenergy demand (bioheat, bioelectricity, liquid or gaseous biofuels for transport) would generate sufficient economic growth, jobs and clean and resilient energy systems through investments.

Goal:	By 2023				By 2030			
	Global Marketplace	**Back to Basics**	**Digital Reset**	**Walled Gardens**	**Global Marketplace**	**Back to Basics**	**Digital Reset**	**Walled Gardens**
1 Economic growth	Disagree	Disagree	Disagree	Strongly disagree	Agree	Agree	Agree	Strongly agree
2 Jobs	Disagree to undecided	Disagree to undecided	Disagree to undecided	Disagree to undecided	Strongly agree to agree	Agree	Agree	Agree to undecided
3 Clean and resilient energy systems	Disagree to undecided	Strongly disagree	No consensus	Disagree	Agree to undecided	Agree to undecided	Undecided	Agree to undecided

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