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Reflecting Regional Conditions in Circular Bioeconomy Scenarios: A Multi-Criteria Approach for Matching Technologies and Regions

Almut Güldemund * **and Vanessa Zeller**

Material Flow Management and Resource Economy, Institute IWAR, Technical University of Darmstadt, Franziska-Braun-Straße 7, 64287 Darmstadt, Germany; v.zeller@iwar.tu-darmstadt.de

* Correspondence: a.gueldemund@iwar.tu-darmstadt.de

Abstract: The Circular Bioeconomy (CBE) combines the concepts of bioeconomy and a circular economy. As an alternative concept to the current fossil-based, linear economy, it describes an economy based on the efficient valorization of biomass. It is regional in nature and aims to improve sustainability. An analysis of the transition process, by identifying its success criteria and assessing its impacts through the modeling of technology-specific scenarios, is necessary to ensure that CBE concepts are sustainable. However, a comprehensive consideration of regional influences on both is lacking. Based on extensive literature research and an expert survey, we develop a multi-criteria approach where we (i) present a comprehensive catalog of CBE success criteria and discuss their region-specific characters and (ii) develop a methodology based on evaluation matrices that enable CBE technologies to be matched with regions. The matrices support the evaluation of technological and regional characteristics influencing successful CBE implementation. The results show that the success criteria "biomass resources", "technological", and "social" are perceived as highly important, and that most of the success criteria are both region- and technology-specific, highlighting the relevance of developing matrices to match them. We describe such matrices indicatively for the two broadest and most important success criteria clusters "social acceptance" and "biomass supply chain". With this, we substantiate the regional nature of CBE and raise the awareness on the importance of considering regional conditions in CBE transition processes. Furthermore, we provide practical guidance on how regional conditions can be reflected in the selection of technologies, e.g., in regional CBE technology scenarios.

Keywords: circular bioeconomy; CBE; regional; transition; technology scenario; success criteria; barriers and drivers; social acceptance; biomass supply chain

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1. Introduction

As a long-term target of the European Union (EU) [1] and of many countries worldwide [2], the bioeconomy (BE) is promoted as an economic concept that can replace the current fossil-based and linear economy with the aim of increasing sustainability [1]. The European Bioeconomy Strategy [1] describes the BE as a broad concept that covers all sectors and systems that produces biological resources or uses them to produce food, feed, bio-based products, bioenergy and services. In 2012, with the publication of the first BE strategy [3], the EU already committed itself to the goal of a transition towards BE. Since then, the potential negative impacts of the BE have also raised concerns. A main environmental concern relates to the resource base of the BE. It is expected that the growing demand for bio-based resources and the associated increase in primary production will potentially intensify production processes in agriculture, forestry, and aquaculture, as well as the competition for land [4]. This potentially intensifies environmental and social problems such as land use change, global warming [5], biodiversity loss [6], and threats to food security [7]. To prevent this, in the updated BE strategy of 2018 [1], the EU strengthened the focus on sustainability and circularity and defined it as key success factors of the BE. In parallel, the term circular bioeconomy (CBE) was established in the scientific literature in 2015. It describes the fusion of the two concepts of BE and the circular economy [8]. Stegman et al. [8] derive a definition from the elements that constitute the CBE: "the sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains, while also making use of residues and wastes and optimizing the value of biomass over time via cascading". Moreover, we hypothesize that CBE is a highly regional concept. For example, CBE concepts based on residual biomass are strongly predefined by its availability, which depends on regional conditions such as the agro-climatic environment, industry focus, and consumption patterns [9]. Further regional conditions exist, including biomass logistics, technological knowledge, and sensitivity to environmental impacts. Accordingly, the CBE approach of a given region is determined by its geographic location, natural resources, and economics.

Due to the aforementioned risk that the BE contradicts its vision of being a sustainable economic concept and instead might cause social and environmental damage when being implemented, careful planning of the transition process and its framework conditions is required. This equally applies for the CBE and can be achieved, for example, through the development of a comprehensive governance framework [10,11]. For this, a thorough understanding of the transition process is necessary [10]. Acknowledged methods to analyze the CBE transition process are, for example, (i) the identification of its drivers and barriers [12] or (ii) the assessment of its possible impacts. Many studies are available that identify drivers and barriers (see Table S1). However, most of them do not reflect regional conditions affecting these drivers and barriers. The potential impacts of a CBE transition process on the economy, society, and the environment can be assessed through explorative scenario analyses that depict potential CBE pathways [13–16]. For a precise model of certain development paths, it is necessary to integrate specific technological CBE innovations into the model. For example, Wydra et al. [16] examine possible transition pathways and interactions of distinct bio-based niches, i.e., bioplastics, biolubricants, and biofuels for road and aviation; Tsiropoulos et al. [14] investigate competitive and synergetic biomass uses within the energy, biotechnological, and chemical sectors using a technology-rich and technology-explicit model. However, the technology selection process in such CBE technology scenarios is often arbitrary and not sufficiently justified and documented. In the literature, we found rather vague justifications. For example, the selection was limited to technologies from certain economic sectors [14,15], to technologies with a direct substitution potential for fossil products [14,15], or to technologies with a high technology readiness level [13]. Conversely, we argue that in CBE scenario building, the selection of technologies should be based on an appropriate assessment of their potential for successful, sustainable implementation. Furthermore, following our hypothesis that CBE is a regional concept, we suggest that this potential should be assessed by taking regional conditions into account. Approaches for the evaluation of the potential success of CBE innovations that consider regional conditions have been proposed. For example, Salvador et al. [17] identify drivers and barriers for CBE businesses and present regional differences in these aspects. Croxatto Vega et al. [18] present an approach that allows the selection of an ideal technology for a given region based on economic and environmental criteria. However, concrete guidelines for region-specific technology selection in the context of CBE scenario building cannot be derived from these studies. For this purpose, the analysis by Salvador et al. [17] is not sufficiently refined in terms of both regionality and success criteria. The quantitative approach of Croxatto Vega et al. [18] is suitable to support an informed choice among a small number of technology options. However, intensive data requirements make it difficult to be applied to a large number of technology options for scenario building.

Accordingly, we address two research gaps: (i) Although there is extensive literature analyzing the potential for a successful CBE transition by identifying barriers and drivers, a comprehensive consideration of the role that regional conditions play in this context is lacking. (ii) Furthermore, we identify a lack of practical guidance for the reflection of regional conditions during the selection of CBE technologies in the context of CBE technology scenario building. Therefore, the objectives of this study are twofold: (i) The first objective is to compile a comprehensive catalog of CBE success criteria and to demonstrate the extent to which these success criteria are region-specific. In doing so, we aim to substantiate our hypothesis that the CBE is regional in nature and to broaden and deepen awareness and understanding of the important role that regional conditions play in CBE transition processes. (ii) The second objective of our study is to present a methodology for the selection of CBE technologies based on the reflection of their regional potential for a successful, sustainable implementation. The methodology is based on evaluation matrices that allow users to assess technological and regional conditions influencing the potential success of a specific CBE technology in a given region. Matching of CBE technologies with regions is thereby possible, preparing technology selection for the building of regional CBE technology scenarios.

The remaining sections of this study are structured as follows: Section 2 covers the applied materials and methods. It first provides an overview of the overall procedure and then describes each step of the procedure in detail. In Section 3, we provide for each step a comprehensive visualization of our results and provide a description and interpretation of them. In Section 4, we discuss our findings in the context of previous research, limitations, and uncertainties. Finally, Section 5 concludes to what extent our research questions have been answered and highlights the most important findings and their potential applications.

2. Materials and Methods

The first objective of the study is to demonstrate the importance of the regional context for the successful implementation of CBE technologies. With this in mind, in a first step, we identify success criteria for the implementation of CBE technologies from the literature and categorize them. We adopt a broad perspective that includes, among others, economic, environmental, and social factors both upstream and downstream of the CBE technology. We explicitly do not limit this first step to region-specific criteria. This allows for a comprehensive set of criteria that includes indicators from all sustainability dimensions and that may include region-specific factors that have not yet been identified as such. It also allows us to demonstrate later that most of the success criteria are indeed region-specific, which emphasizes the importance of this work. In a second step, we validate the CBE success criteria catalog through an expert survey.

The second objective of this study is to provide practical guidance for the selection of technologies in the context of CBE scenario building. Scenarios describe alternative future situations and paths to them [19] that can be analyzed, e.g., with integrated modelling frameworks [20]. One way to build scenarios is to identify key factors that have a central impact on future development and to define their possible states qualitatively or quantitatively. In BE scenarios, technology development is one of these key factors [19]. Therefore, an important step in scenario building is to identify relevant BE technologies and to decide which BE technologies should be included in a scenario [20]. We call this step technology scenario building. In the context of regional CBE scenario building, it is important to reflect regional conditions during the selection of CBE technologies. To do this, it is necessary to identify success criteria that are both technology- and region-specific, as these criteria must be carefully considered when selecting a CBE technology for a specific region. Therefore, in the third step, we categorize each CBE success criterion according to its territory and technology specificity. The final step considers only CBE success criteria that are both technology-specific and region-specific. In this step, we develop two evaluation matrices for each of the selected CPE success criteria clusters: the CBE Technology Evaluation Matrix and the CBE Region Evaluation Matrix. These matrices allow a separate evaluation of regional and technological characteristics and their potential influence on the respective success criteria cluster. By comparing the results of the two evaluation matrices, it is possible to match a CBE technology with a region regarding the criteria cluster. Figure 1. visualizes the described procedure. We call this procedure a multi-criteria approach. It is a structured approach that enables the evaluation of the complex goal of a successful, sustainable implementation of CBE technology options in a region. The approach breaks this complex goal down into detailed regional and technological criteria that are easy to evaluate.

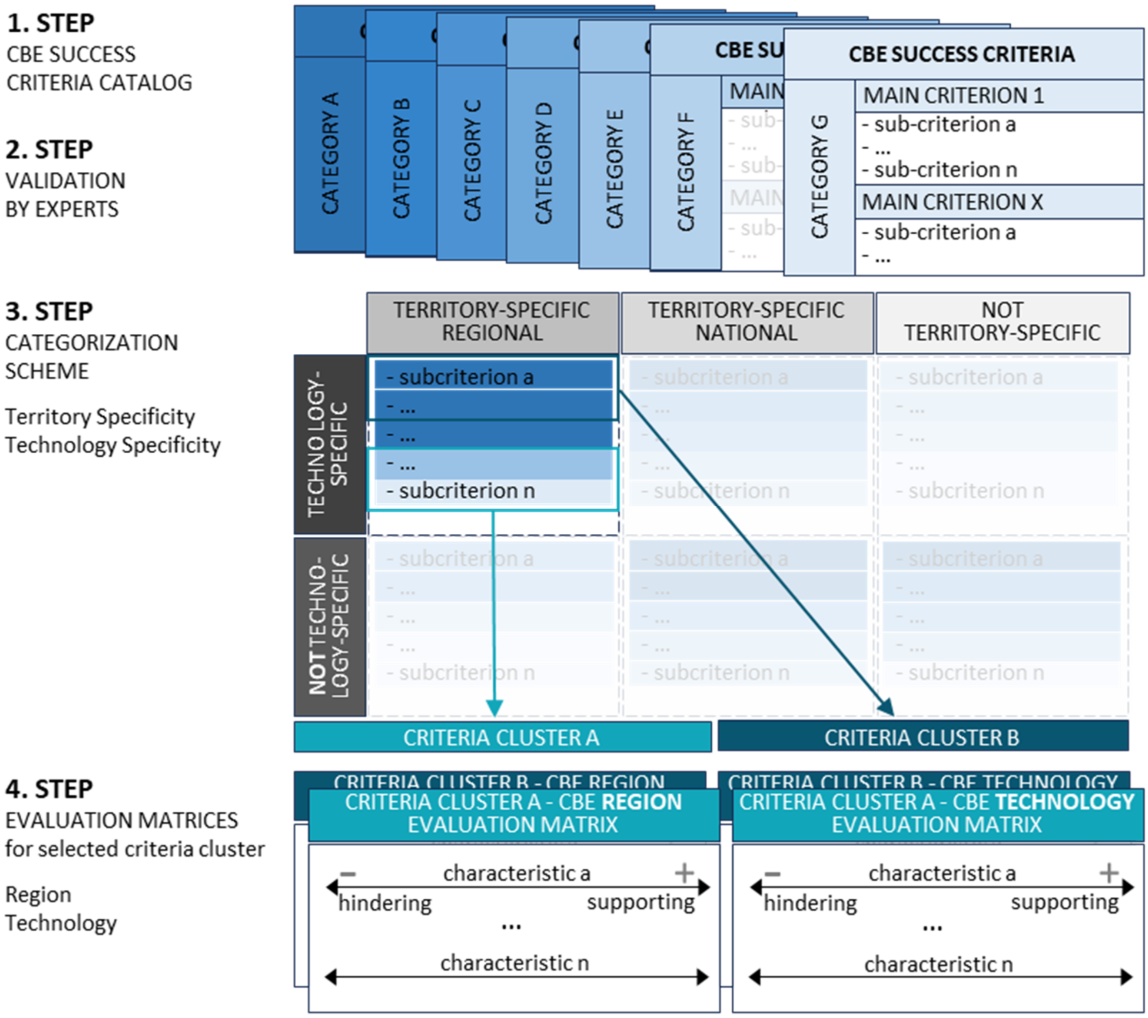

Figure 1. Visualization of the overall procedure.

2.1. Identification of Success Criteria for the Implementation of CBE Technologies

To identify criteria that influence the success of the sustainable implementation of CBE technologies, we conducted a literature review. By applying the search terms driver and barrier in combination with terms referring to the CBE, we received 286 results from the Web of Science database. We first scanned the titles and identified 28 studies as potentially relevant, from which we then read the abstracts to finally select 22 relevant peer-reviewed journal publications [10,17,21–40]. Table S1 in the Supplementary Material File S1 lists the selected studies, indicating bibliographic information and the context. Following a bottom-up approach, we first extract CBE success criteria from the publications and structure and categorize them afterwards. We compile the original citations in a comprehensive table (Supplementary Material File S2) and add a new column for each study. Related criteria from the different studies are grouped together in one row. For each row, we derive a generic term that stands for all quotations from this group and define it as the main criterion. In addition, sub-criteria are defined by deriving generic terms for specifications and details that deepen the understanding of the main criterion. Each main criterion with its sub-criteria are assigned to a superordinate criteria category. Further, we document the number of studies relating to each main criterion and sub-criterion and sort them in descending order, assuming this provides a first indication of their relevance. The main criteria and sub-criteria, as well as their categorization and sorting, are compiled in the CBE Success Criteria Catalog.

2.2. Validation of CBE Success Criteria

To validate and improve the results of the literature research, we conducted an expert survey. Five experts from three European countries answered a questionnaire (Supplementary Material File S1, Table S4) in which we present our CBE Success Criteria Catalog, including the categorization of the criteria. The experts provided feedback on whether they agreed with the catalog or whether and how they would add to the main criteria or sub-criteria or change their categorization or sorting. We merged the expert feedback into one document and changed the criteria list accordingly (Supplementary File S1, Table S4).

2.3. Categorization of CBE Success Criteria into Region- and Technology-Specific Criteria

To identify CBE success criteria that are both technology- and region-specific, we created a categorization scheme that classifies CBE success criteria according to their territory and technology specificity. We consider criteria to be territory- or technology-specific, which can either have different states for different territories/technologies or which can be of different importance to different territories/technologies. For the purposes of this study, we distinguish territories at national and regional level and define a region as a territorially contiguous and delimited area at the sub-national level, smaller than NUTS 0 level (NUTS—European Nomenclature of Territorial Units [41]). This means that a region can be, for example, a NUTS 1, 2, or 3 region; a sub-region thereof; or a conglomerate of sub-regions of different NUTS 1, 2, or 3 regions. For each sub-criterion, we research aspects that clearly indicate their territory and technology specificity. For instance, the availability of residual biomass depends on regional factors, such as agro-economic productivity patterns or industrial focus. This clearly indicates that this criterion can adopt different states in different regions. A further example is the fact that water depletion is more important in water-scarce regions. This demonstrates how the criterion of water depletion is of varying importance in different regions. If we find such aspects for a criterion, we categorize it as region-/technology-specific. If we find aspects that indicate territorial differentiation only at the national level, but not at the regional level, we classify this criterion as being territory-specific at the national level. If no such aspect could be identified, the criterion is determined to be not territory-/technology-specific. In Section 3, we present the rationale for the categorization decisions.

2.4. Development of Evaluation Matrices for Regions and Technologies to Allow the Matching of Regions and CBE Technologies Regarding Selected CBE Success Criteria Clusters

To demonstrate the evaluation and matching process, we select two success criteria clusters: the first cluster examines the topic of social acceptance and consumer awareness, while the second cluster looks at the topic of the biomass supply chain.

In order to compile the CBE Technology and the CBE Region Evaluation Matrix for the two clusters, we conducted two further literature searches in Web of Science. For the first cluster, we combined search terms referring to social acceptance, region, and the BE. A more specific search referring to the CBE was not successful. We excluded mismatches by scanning titles and abstracts and added further publications from the reference lists of suitable publications during the reading process. The list of 17 publications [42–58] that was finally considered to compile the matrices is summarized in Table S2. For the second cluster, we used a combination of search terms referring to residual biomass, accessibility, and region. Scanning of titles and abstracts helped to exclude mismatches. As this search provided mainly studies on supply chains for forestry and agricultural residues, but few for industrial by-products and wastes, we included publications from another search with terms related to biobased industrial by-products and supply chain. The final list of 23 publications [59–81] used for the matrices' compilation can be taken from Table S3.

To construct the matrices, we extract from the literature characteristics of both CBE conversion technologies and regions that influence social acceptance and the biomass supply chain, respectively. For each characteristic, we indicate whether it is more likely to increase or decrease the potential for a CBE.

3. Results

3.1. CBE Success Criteria Catalog

From the literature review and the expert survey, we receive 19 main criteria and 76 sub-criteria that influence the success of CBE (see Table 1). We categorize them into the seven criteria categories: biomass resource, technological, environmental, economic, political and legislation, social, and methodological.

Table 1. CBE Success Criteria Catalog: criteria that influence the success of the implementation of CBE technologies sorted by relevance; results from the literature review and expert survey.

CRITERIA CATEGORY	main criterion (no. of publications mentioning criterium) {expert comments (no. of experts)} - sub-criterion (no. of publications mentioning criterium) {expert comments (no. of experts)}
BIOMASS RESOURCE	biomass availability (20) - sustainably available biomass (5) {should be first (2)} - temporal fluctuation in biomass availability (7) - competing biomass uses | security of biomass supply in the long term (7) - local biomass availability (1) {is important (1); should be fourth (1)}
	biomass quality (6) - no standardization of qualities | changes in composition (1) {is important (1)} - sensitivity to toxicants in biomass (1)

TECHNOLOGICAL	logistics and supply chain (17)
	- storage and transportation (5)
	    - bulk density of biomass {should be added (1)}
	    - loading and offloading of biomass {should be added (1)}
	- space for/position of facility (4)
	- waste/by-product separation and collection systems (4)
	- distribution of biomass availability (point vs. non-point sources *) (1) {should be moved from biomass availability to here (1)}

	availability of technology (17) - technology efficiency | conversion rates (5) {should be first (1)} - complexity of technology | ease of adoption (1) {should be second after maturity (1)} - successful technology showcases (3) {should be ranked higher (1)} - maturity of technology | need for scale up (7) - availability of processing industry and start-ups in the region {should be added (1)}
	availability of knowledge/expertise | R&D (11) - local tradition of knowledge (1) {should be first (2)} - locally based scientific institutions (2) - advances in sciences (e.g., biological and CIT) (1)

Table 1. *Cont.*

ENVIRONMENTAL	potential to mitigate/increase environmental issues ** (14) {sub-criteria should not be ranked (3)} - climate change - biodiversity ǀ ecosystems - land use (change) - soil and water quality - resource scarcity (resource efficiency ǀ circularity) - water depletion {should be added (1)} - waste generation
	sensitivity towards environmental changes/issues *** (3) - climate change - potential for adapting to climate change through plant breeding {should be added (1)} - soil conditions - water scarcity - land availability {should be added (1)}
ECONOMIC	profitability and markets (18) - knowledge of customer's needs (3) {should be first (1)} - market demand ǀ unfavorable markets (6) {should be second (1)} - competitiveness (with fossil counterparts) (7) {should be third (1)} - fluctuations in fossil fuel prices (1) - value creation from waste/by-products (4) {should be fourth (1)} - cost-effectiveness (6) {should be fifth (1)} - economic benefits due to multiple product outputs (3) {should be sixth (1)} - immature markets ǀ need to develop new markets (4) {should be seventh (1)} - business diversification (3) {should be eighth (1)}
	investment (15) - need for financial investment ǀ lack of financial resources (11) - public incentives and subsidies (8) - private investors' interest (5)

	operational costs (9)
	- costs of raw material, esp. biomass (6)
	  - costs of harvesting biomass {should be added (1)}
	- supply chain costs, esp. logistic costs (4)
	  - costs of loading/offloading {should be added (1)}
	  - costs of storing and handling biomass {should be added (1)}
	  - costs of waste disposal {should be added (1)}
	- personnel costs {should be added (1)}

	general socio-economic development (3) - population development (2) - economic crises (1) {should be equal to first (1)} - prioritization of local economy {should be added (1)}

Table 1. *Cont.*

POLITICAL AND LEGISLATIVE	policies, legislation, and standards (18)
	- existence ǀ lack of supporting policies and legislation (15)
	  - carbon costs {should be added (1)}
	  - blending mandates {should be added (1)}
	- unfavorable ǀ inadequate ǀ inconsistent policies and legislation (10)
	- normative tools such as technical standards and certifications (1)
	- availability and direction of regional policies and legislation (1)

	policy implementation (8) - uncertainties in future legislation (predictable, less turbulent) (3) {should be first (1)} - ineffectual execution (4) - excessive bureaucracy (2)
SOCIAL	jobs and labor (15) {should be first (1)} - availability of skilled labor and training (10) {is important (1)} - job creation (in rural areas) (6) - labor conditions (1)
	social acceptance (production) (12) {should be second (1)} - competition for biomass with food production (5) - interfering civil society ǀ culture of participation (3) - promotion ǀ information ǀ involvement to increase acceptance (3) - NIMBYism (2) - impacts on human health (1)
	company culture ǀ regional culture (11) {should be third (1)} - commitment to sustainability, esp. environ. protection (4) - vision-driven culture ǀ willingness to change (4) - willingness to cooperate (2) - closed-loop thinking (2) - innovative, agile, imaginative, and creative (1)
	consumer awareness (product) (14) {should be fourth (1)} - consumers' perceptions of product quality (e.g., non-primary cycle) (4) {should be first (1)} - consumers' reluctance to change (1) {should be second (1)} - green consumerism (bio-based and waste valorization) (9) - willingness to pay a premium for "green" products {should be added (1)} - awareness of CBE products (6) - regionality of products (2)
	cooperation (16) {should be fifth (1)} - stakeholder involvement (7) - cooperation between primary producers {should be added (1)} - clusters and networks (7)

Table 1. *Cont.*

METHODO-LOGICAL	uncertainties in environmental and economic assessments (3) - availability of data for econ./environ. evaluations (2) {should be first (1)} - availability of (standardized) methodologies (3) - availability of results (1)

* e.g., beet pulp from a big sugar factory as a point source vs. biowaste from households as a non-point source. ** e.g., a CBE product has the potential to replace a fossil-based product and thereby to reduce climate change impacts; experts suggest not ranking different environmental impacts, as their relevance depends on the type of biomass. *** e.g., the production of a CBE product is threatened by climate change, as the crops whose residues are valorized can no longer be cultivated under changing climate conditions; experts suggest not ranking different environmental impacts, as their relevance depends on the type of biomass.

The main criterion we found to be mentioned most frequently in the literature, with 20 studies referring to it, is biomass availability. This is particularly remarkable as this criterion has a comparatively narrow scope, while other main criteria cover a broader range of sub-criteria. Furthermore, there is a high level of awareness towards the criteria of profitability and markets, as well as policies, legislation, and standards, with 18 studies relating to each. Two criteria, logistics and supply chain and availability of technology, are also frequently mentioned, with 17 studies each, demonstrating the high relevance of technological aspects. The social category comprises many criteria with medium to high rankings, which indicates that this category as a whole receives a high level of attention. The social category is the only one for which one of the experts proposed a change in the sorting of the main criteria, stating that there is a lack of consensus in the scientific bioeconomy community. The environmental category seems to be of rather low importance, comprising only two main criteria with medium and low rankings. This is surprising as the transition to a CBE is mainly motivated by the environmental problems associated with a linear and fossil-based economy. It is further remarkable that the potential of CBE to influence the environment (negatively or positively) attracts far more attention than the potential for environmental changes to jeopardize the successful implementation of CBE. It is also worth mentioning that three of the five experts suggest not ranking the environmental indicators, as their relevance is highly biomass-specific.

3.2. Categorization Scheme—Territory and Technology Specificity of CBE Success Criteria

To identify those success criteria that are both region- and technology-specific, we categorize all sub-criteria accordingly. Figure 2 shows the result of this categorization process. The sub-criteria are categorized as either territory-specific at the regional or national level or as non-territory-specific and as either technology-specific or non-technology-specific. It appears that the vast majority of the criteria are technology-specific. Only criteria relating to general socio-economic developments, policy implementation, and the culture of businesses and regions were classified as independent of the technology under consideration. The majority of technology-specific factors are found to be territory-specific, with more factors being territory-specific at the regional level than only up to the national level. This demonstrates how important it is to match regions and technologies to increase the success of a CBE transition and to strengthen the plausibility of regional CBE scenarios.

In terms of the biomass resource category, we have, on the one hand, criteria referring to the locally, sustainably available, and usable biomass potential and its supply chain. We classify these criteria as region-specific, as (i) the availability of different biomass categories and their spatial density varies from region to region (see also Section 3.4); (ii) the use of biomass, especially biogenic residues, and therefore competing demands for biomass are region-specific; and (iii) the infrastructure and organization of the biomass supply chain vary regionally, including transport and storage capacities and the organization of collection, separation, and pre-treatment systems for biogenic residues. On the other hand, there are criteria from the biomass resource category that are rather biomass-specific than territory-specific, such as quality aspects and temporal fluctuations, which we classify as non-territory-specific.

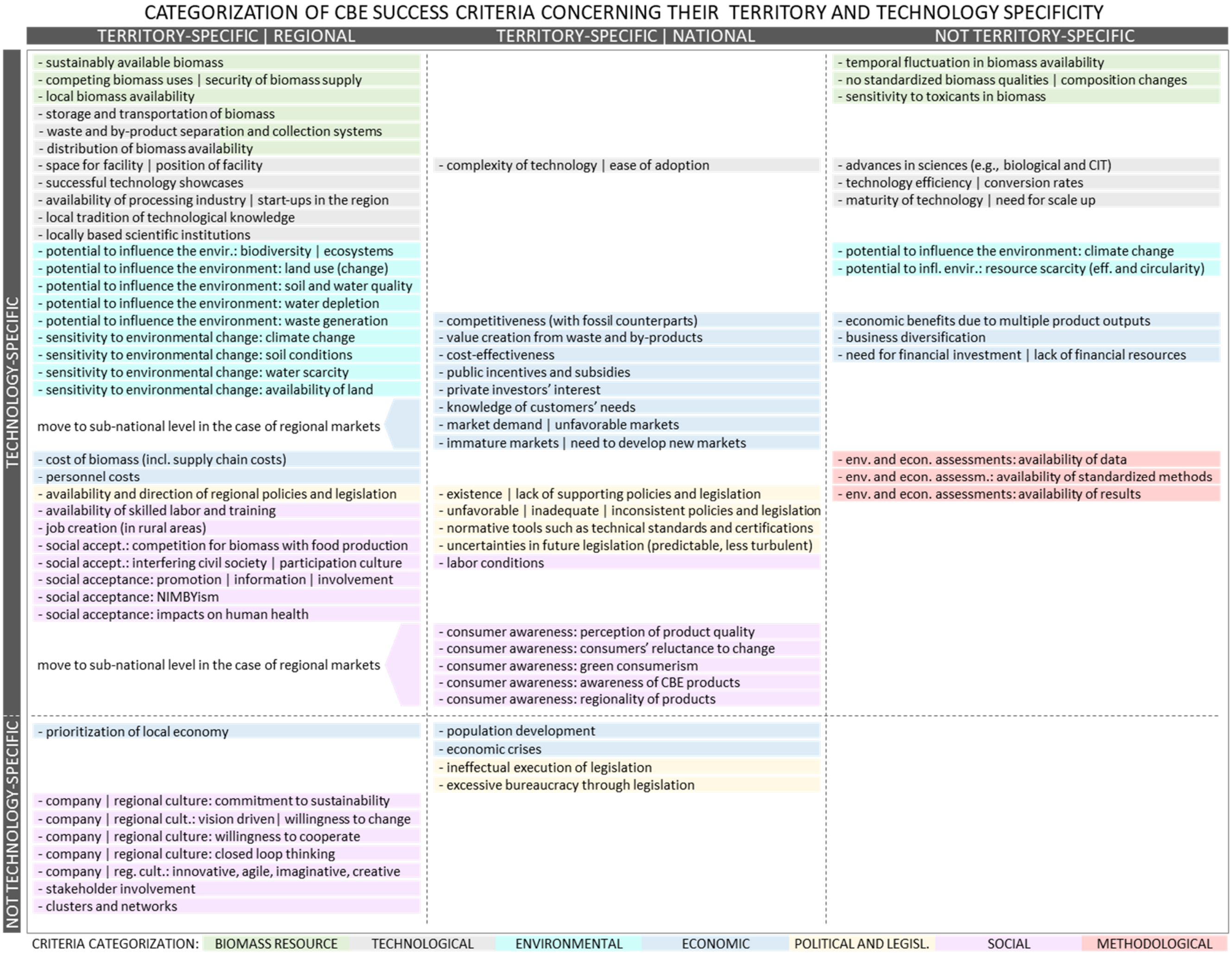

Figure 2. CBE success sub-criteria categorized according to their territory and technology specificity.

Criteria from the technological category are partly territory-specific at both regional and national levels, but also partly territory-independent. Criteria referring to the regional availability of technological knowledge and experience we classify to be region-specific. Aspects relating to advances in technological development (science, maturity, and efficiency) are classified as territory-independent based on the assumption that these advances, once implemented in standard technological solutions, can be applied globally. However, we argue that the complexity and investment costs of a technology are perceived differently in different regions of the world. For example, highly complex and costly technologies are difficult to be financed, operated, and maintained in rural areas in countries of the global south, whereas this may be less problematic in the surroundings of a modern industrial park.

Environmental factors are mostly region-dependent. Impacts caused or mitigated by CBE technologies can be divided into local impacts such as biodiversity loss, land use change, soil and water quality, etc., and global impacts such as climate change and resource scarcity. Conversely, the environmental changes that influence the success of CBE technology implementation are generally region-specific. For example, while GHG emissions lead to the global effect of climate change, their effects differ regionally. In some regions, droughts due to climate change might lead to a deterioration of cultivation conditions for specific crops; in other regions, higher temperatures might lead to an expansion of potentially cultivable plants.

Economic success factors mostly depend on national conditions. For example, the cost-effectiveness and the competitiveness of innovative biobased products depend on factors like public subsidies or prices of competing (fossil-based) products. Whether a waste can be used as a resource for specific value chains depends on national legislation. The interest of private investors in innovative projects depends, among other factors, on the political stability of a country. Furthermore, we argue that market conditions vary usually at the national level. However, we also consider that some biobased products might be traded on regional markets. In this case, the market-related factors should be seen as region-dependent. Economic benefits through business diversification and multiproduct outputs, for example, in biorefineries, seem to be possible regardless of the region.

Policies and legislation are primarily implemented at the national or supranational level, leading to national differences in the supportiveness of policies and legislation. However, some relevant policies or legislation might also be implemented at the regional level. Regarding social criteria, we argue that the social acceptance for production sites is region-dependent, while the consumer awareness plays a role at the national level in the case of international markets. In the case of regional markets, differences in consumer acceptance are also relevant at the regional level. Finally, we argue that all methodological aspects that are relevant to assess the economic and environmental potential of CBE technologies are territory-independent.

For our further analysis, we consider only those success criteria that are both region-specific and technology-specific. We identify four relevant clusters (see Table S5): (i) a cluster of the regional biomass supply chain that includes criteria referring to the availability, accessibility, deliverability, and costs of biomass and covers aspects of technological knowledge to process the biomass; (ii) a cluster of regional environmental impacts, (iii) a cluster of regional policies and legislation; and (iv) a cluster of regional social acceptance and consumer awareness that also includes selected economic aspects. We acknowledge that all four clusters are highly relevant and recommend their consideration when selecting technologies for CBE scenarios at the regional scale. However, the remaining part of the study that presents the methodological approach to match CBE technologies with regions is limited to two of the four criteria clusters. This sufficiently demonstrates the procedure of the method and its value so that it can be applied to the other criteria clusters in subsequent studies. We chose the broadest and most relevant criteria clusters (i) biomass supply chain and (iv) social acceptance and consumer awareness. As shown in Table S5, these criteria clusters contain most of the region- and technology-specific sub-criteria and achieve the highest rankings of the sub-criteria belonging to these criteria clusters.

3.3. Social Acceptance and Consumer Awareness

CBE concepts aim at a holistic transition that involves technological and economic changes, which affect large parts of the economy and societies' modes of living. Broad acceptance or rather contribution to this transition by different stakeholders and particularly by the civil society is necessary: as neighbors of CBE plants, as consumers of CBE products, and as an active political force. That the acceptance of a technology in general and not only in its concrete implementation is of decisive importance is demonstrated by those cases in which the skepticism of civil society led to the delay or cancellation of projects and to a decrease in political support. In the context of BE, the example of BECCS is of relevance. Although BECCS is applied as a mitigation strategy in all 2 °C compatible SSP scenarios, due to public protests, several CCS projects have been suspended or terminated, R&D funding has been reduced, and the German government has not yet included BECCS in its long-term climate strategy [48].

From a regional perspective, it is important to recognize that the social acceptance of BE concepts and their technologies can vary from region to region. For example, support for forest-based biorefineries in the state of Maine, USA, in general was found to be different than in a subgroup that included only mill towns with existing pulp and paper facilities [55]. Additionally, the comparison of public acceptance of biorefineries and aquaponics in a transition region compared to a non-transition region showed regional differences [53]. Particularly, familiarity or previous exposure to similar technologies appears to be a factor that favors support and is strongly region-dependent [42,52,57]. A body of literature furthermore acknowledges that various socio-demographic factors, such as gender, age, level of education and income, size of the place of residence, or the affiliation with certain social groups, correlate with the acceptance of BE [46,51,55,57,58]. The prevalence of these factors varies regionally, which is particularly evident for some factors, for example, the distinction between eastern and western Germany or between rural and urban areas, as considered by Eversberg and Fritz [46]. This suggests that the different ways how people react to manifestations of the BE is an expression of embodied collective experiences that differ along socio-demographic and regional characteristics.

It is also important to understand that citizens do not assess the BE in a generalized but in a differentiated way. Their acceptance depends on the specific technology [42,53,54]. The literature distinguishes different BE visions that are supported by different societal or stakeholder groups [43,44,49,51]. The BE visions can be differentiated according to their relationship to nature (controlling/dominating vs. preserving/protecting), their attitude towards growth (rejecting vs. demanding), their trust in technological innovations, and their openness to change. Accordingly, these visions differ in terms of the envisaged technologies. For example, genetically modified crops would be supported by a vision that believes in the controllability of nature through technological innovation, while a vision that tends to distrust technological innovation and sees the protection of nature as a priority would reject it. Regarding technology acceptance, the distinction between different acceptance dimensions is also important. Three dimensions of social acceptance were first introduced by Wüstenhagen et al. [82] and have been referred to frequently since then [47,55,56]: (i) "socio-political acceptance", which reflects the acceptance of the idea of the BE in general; (ii) "community acceptance", which describes the acceptance of the consequences for oneself and one's environment and which is closely related to the NIMBYism phenomenon; and (iii) "market acceptance", which refers to the acceptance of consumer products and services offered by the BE [47].

Since the social acceptance of CBE depends on both the technology and region, it is important to consider this factor when matching regions with CBE technologies. The underlying question is whether a specific technology is more likely to experience acceptance or rejection from a specific region.

In the following two sections, we will therefore present an approach that helps to (i) derive statements about the acceptability of a CBE technology from its technological characteristics (Section 3.3.1) and (ii) estimate how perceptions of a technology might be shaped in a particular region (Section 3.3.2).

3.3.1. CBE Technology Evaluation Matrix—Social Acceptance and Consumer Awareness

To enable an evaluation of the acceptability of a given technology, we create the CBE Technology Evaluation Matrix (Figure 3). As a first step, we derive from the literature detailed technological factors that influence social acceptance [17,42,43,48,50–53,55,57,58]. We define whether each factor leads rather to an increase or decrease in acceptability and display this accordingly along the horizontal axis of the matrix. Furthermore, we arrange the factors that reflect the three dimensions of acceptance (community, socio-political, and consumer) along the vertical axis. A clear demarcation is not possible and reasonable here. For example, ethical and social aspects can have influences on both social-political and consumer acceptance.

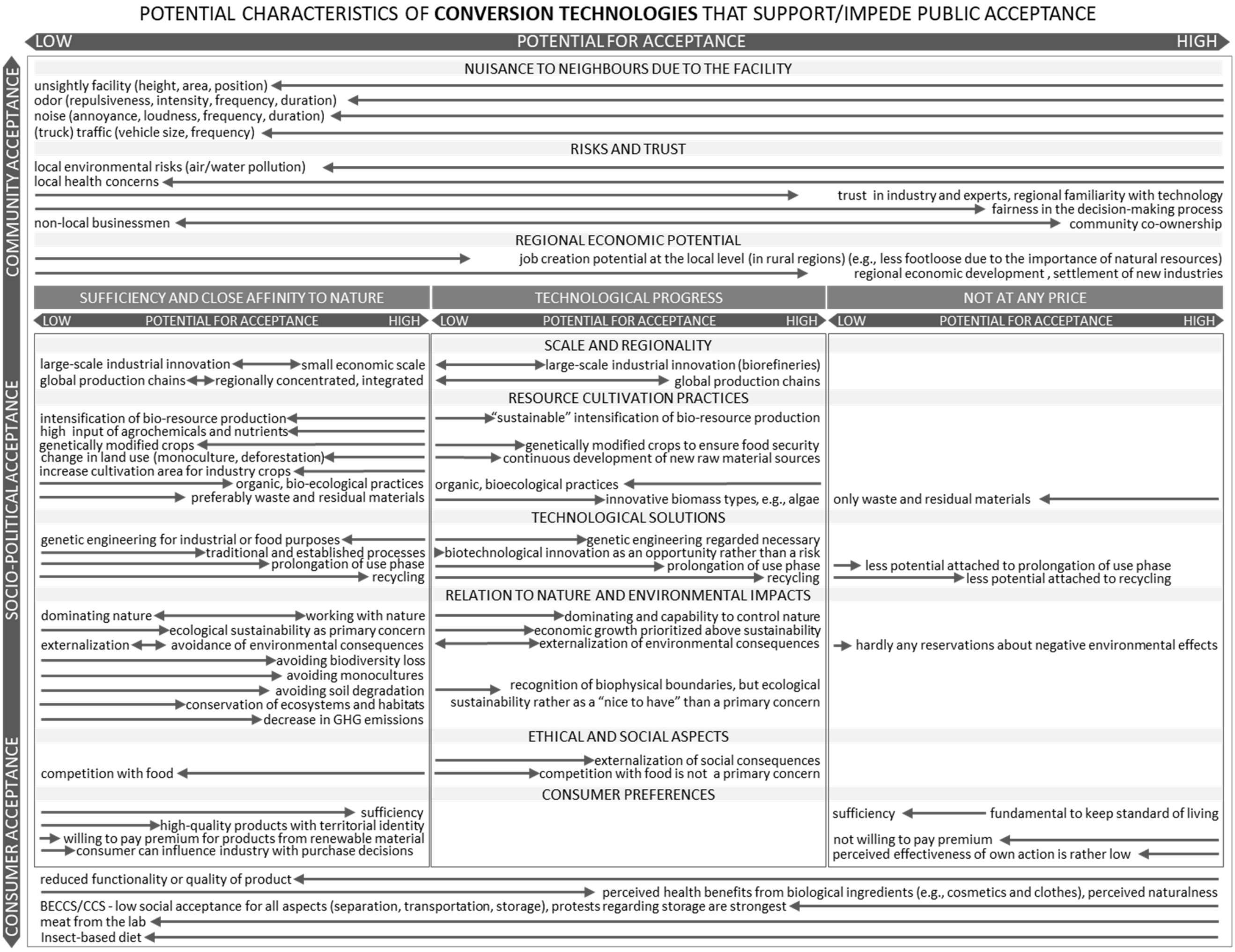

Figure 3. CBE Technology Evaluation Matrix—Social Acceptance and Consumer Awareness: evaluating the characteristics of a CBE technology that affect its acceptance potential.

Based on the assumption that different BE visions also differ in the perception of specific technical aspects, we researched the studies of Hempel et al. [50,51] and Bugge et al. [43] and obtained technological factors on which there is no consensus across the visions. We adapt the categorization of Hempel et al. [51] to build three BE visions: (i) the "sufficiency and close affinity to nature" vision focuses on ecological interrelationships and prioritizes the prevention of negative environmental impacts over economic growth; (ii) the "technological progress" vision believes in the controllability of nature through innovative technologies and thus in the possibility of achieving economic growth within planetary boundaries; and (iii) "not at any price" is a vision that gives priority to preserving the current standards of living and opposes anything that potentially compromises this standard and therefore appears not to endorse any bioeconomic transition [50,51]. In order to harmonize the visions with those of Bugge et al. [43], we assume, as suggested by Eversberg and Fritz [46], that the vision "sufficiency and close affinity to nature" corresponds with the vision "bio-ecology" and that the vision "technological progress" corresponds with the "bio-technology" vision. We position the obtained factors within the evaluation matrix by dividing the horizontal acceptance axis into three subsections, each reflecting the different views of the three BE visions. We find that the visions differ primarily in the assessment of factors from the socio-political dimension and partly from the consumer acceptance dimension.

The presented CBE Technology Evaluation Matrix for Social Acceptance can be used to assess the acceptance potential of a particular technology. A user of the matrix needs to indicate for each factor the extent to which the technology corresponds to that factor. In this way, step by step, an overall picture of the acceptance potential emerges, which differentiates between the three acceptance dimensions and the three BE visions.

3.3.2. CBE Region Evaluation Matrix—Social Acceptance and Consumer Awareness

To estimate how the perception of a certain CBE technology might be shaped in a specific region, it is helpful to look at the perception, evaluation, and action patterns that the region's population applies to post-fossil transformation in general and to relate them to the specific BE visions. The habitually applied patterns are based on internalized dispositions gained from lived experience, also referred to as "mentalities". Eversberg and Fritz [46] identify eleven types of mentalities and group them into three broader camps: (i) the "ecosocial camp" comprises mentalities that are clearly pro-ecological, pro-transformative und skeptical of economic growth; (ii) the "liberal–escalatory camp" includes mentalities with contented, optimistic views and consumerist attitudes that are positive towards growth; (iii) in the "authoritarian–fossilists camp" mentalities are represented that are dominated by feelings of loss and threat, and that unconditionally adhere to the status quo and oppose any kind of change. The different mentalities are plotted within a three-dimensional socio-ecological option space characterized by the dimensions "technology", "growth", and "fossilism". The first two dimensions range between rejection/skepticism/criticism and support/trust/focus/claim towards high-tech innovation and economic growth, respectively. The third dimension describes a continuum of views ranging from those who acknowledge the need for de-fossilization as a consequence of the need for climate protection to those who reject de-fossilization in principle or as soon as it affects the standard of living [46]. The three mentality camps are further assigned to the BE visions that they support: the "sufficiency and close to nature" vision is supported by the "eco-social camp", the "technological progress" vision by the "liberal–escalatory camp" and the "not at any price" vision by the "authoritarian–fossilist camp" (a detailed description for each of the 11 mentalities can be taken from Figure S1).

The authors also relate the mentalities to different socio-economic contexts to show how approval and rejection of different transformation options are distributed across different social groups. The considered socio-demographic factors are gender, age, educational level, employment (e.g., part time, full time, retired), occupational group (e.g., workers, professionals, low-grade managers, service occupations, self-employed, never worked), net monthly household income, size of the place of residence (e.g., metropolis, city, village), residential status (own/rent flat or house), household type/size (e.g., single person, shared flat, single parent, childless couples, families), and the size of the living space [45,46].

Mentalities that favor sufficiency over growth and are skeptical towards technologies (e.g., from the eco-social camp) are typically represented by women, older people, people that are retired or work part time, those who have low household incomes, and those living in cities. Mentalities that support growth and technology (e.g., from the liberal–escalatory camp) occur often among men, very young people, and those still receiving an education, from high-income households, in full-time employment, and living in villages. Fossilist mentalities arise strongest among men, people from the age group of 30–39, and those that live in villages, work full time, and in manual jobs. Detailed information on the mentalities and associated socio-economic characteristics can be taken from Figure 4 [46].

We suggest that an examination of the socio-demographic characteristics of a region and their comparison with the sample average could help to derive justified initial assumptions about the distribution of different mentalities within a region. Socio-demographic data at the regional level should be mostly accessible. For Germany, the census database [83] provides relevant data at the NUTS 2 level. Since mentalities are related to BE visions and since these visions can be linked to the approval/disapproval of technological characteristics, we argue that it is possible to broadly match a CBE technology with a region in terms of social acceptance.

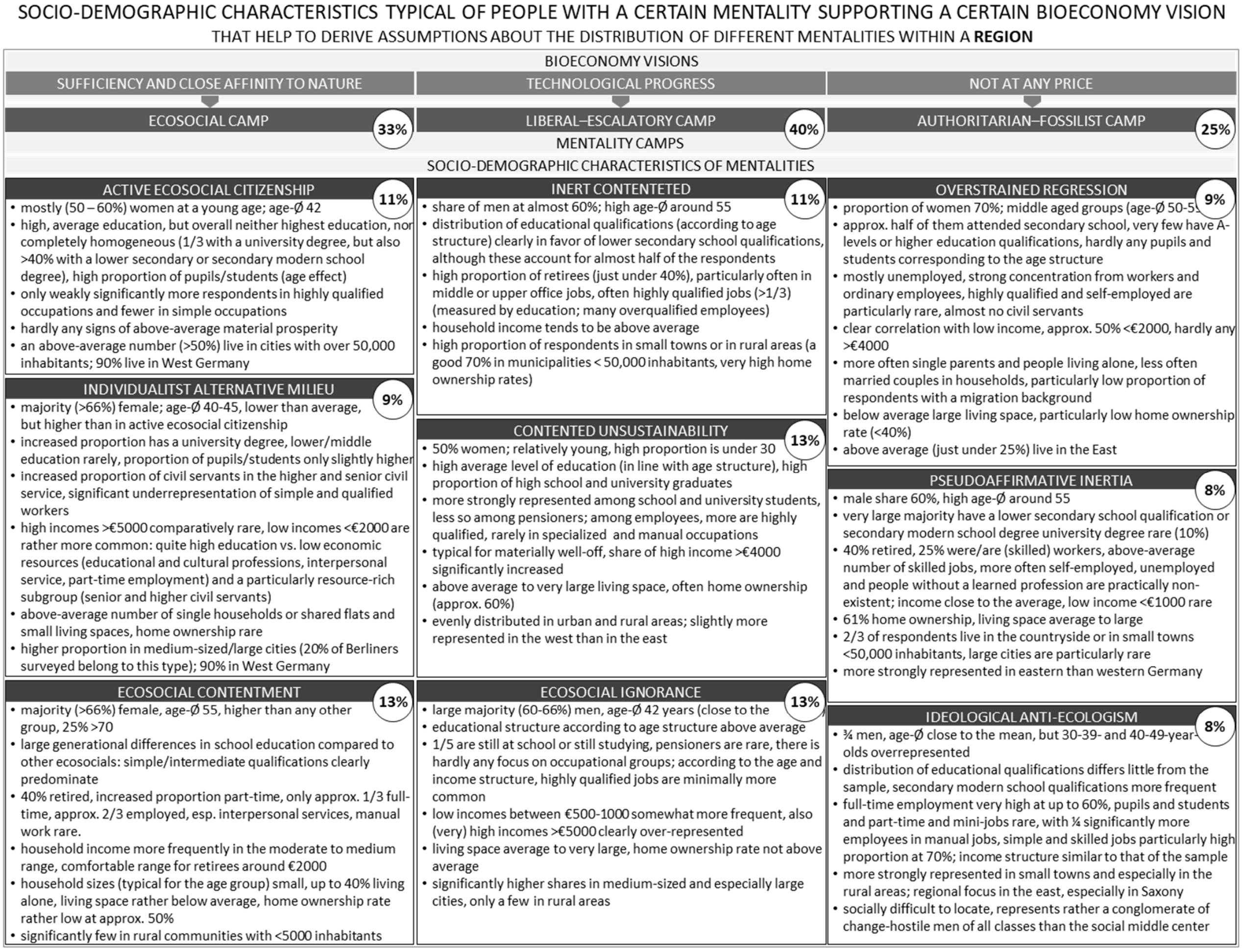

Figure 4. CBE Region Evaluation Matrix—Social Acceptance and Consumer Awareness: socio-economic characteristics of specific mentalities found in Germany belonging to broader mentality camps and supporting certain BE visions. Percentages give shares in the German population. Own compilation of information taken from [45,46].

3.4. Biomass Supply Chain

The successful implementation of CBE technologies depends on an adequate supply of sustainable biomass. While economies of scale favor large conversion plants, biomass supply costs can become a significant cost driver as supply distances increase, favoring smaller conversion plants. Accordingly, there is a need to optimize the relationship between plant size and a cost-effective biomass supply system [74]. Several studies focus on optimizing the costs (partially including environmental and social costs) of the biomass supply chain in order to find the optimal location and/or size of the plant [68,72,73,81,84–86]. This indicates the relevance of considering biomass supply chain characteristics in spatial BE planning. Large-scale CBE plants require a secure, preferably year-round supply from a robust, efficient, and cost-effective biomass supply chain to ensure uninterrupted operation [75]. However, biomass supply chains are highly complex [26,35,38]. They involve many processing steps and stakeholders and depend on numerous external conditions. An exemplary corn stover feedstock supply system for cellulosic biorefineries includes harvesting, windrowing, baling, field bale collection, field edge stacking, transportation to and handling at a central storage facility, and transportation to the biorefinery [75]. This complexity, in combination with underdeveloped supply chain logistics, results in high logistic costs for biomass [35,38,65,77,80], which is a major challenge for the economic feasibility of biomass utilization [64,65]. This is especially valid for residual biomass streams, which are often more spatially dispersed, more contaminated, and of lower quality in terms of chemical composition and energy content than first-generation biomass [81].

It is acknowledged that differences occur in the potential of regions to provide sufficient biomass for a given CBE technology, primarily because different residual biomasses are available in different regions. Regions have unique agro-economic productivity patterns due to different agro-climatic conditions [70]. This results in different types of agricultural and forestry residues available in the region. For example, in subtropical and tropical areas, the processing of sugar cane results in the availability of sugar cane bagasse [62]. Around the Mediterranean, the processing of citrus fruits generates significant amounts of citrus waste [71]. In the boreal zone, dense forests have a high potential to provide forest residues [60,76]. In addition, the population density or consumption patterns of a region influence the availability of some municipal waste streams [9], whereas the industrial focus of a region influences the availability and types of industrial wastes and by-products [9].

In addition to the regional availability of a particular residual biomass, there are also region-specific factors that influence the accessibility and deliverability of that biomass. Tyndall et al. [77] state that the availability of biomass to a defined market "is a function of several unique, dynamic, and regionally variable technological, environmental, infrastructural, economic, and social factors". The examples below illustrate the region-specific nature of each factor category. In established and diversified forest regions, there is a high availability of technology such as harvesting equipment and specialized transportation systems [77]. The potential environmental impacts of residue removal, such as erosion, nutrient loss and habitat degradation, vary by location [63,77]. The density and condition of a region's transportation infrastructure affect the biomass supply chain [61,75,81]. Different levels of competition for biomass lead to different economic situations for new utilization paths in different regions [77,81]. A social factor is, for example, personnel trained to operate specific equipment, which is more likely to be available in specialized regions [77]. These dynamic and region-specific supply chain conditions cumulate in temporally and regionally varying residual biomass prices [87]. For example, in 2017, cereal straw prices varied by about 35% between two German states during certain months [87]. Therefore, it is crucial to consider the regional biomass supply chain conditions in regional CBE planning.

The viability of a biomass supply chain is certainly more influenced by the choice of region than by the characteristics of the chosen CBE technology. However, technologies also have characteristics that affect supply chain requirements or flexibility. First and foremost, the CBE technology defines what residual biomass is needed. This selected biomass comes with specific characteristics influencing the supply chain, like seasonality [65], spatial dispersion [61,80], or transportation and storage properties [61,64,65,72,74,80]. In addition, CBE technologies differ in their quality requirements for the biomass [61,64,65] and the required biomass amounts [64]. For example, low-capacity, high-value conversion pathways, such as biopharmaceuticals, are likely to require lower volumes of higher quality biomass compared to large-scale bioenergy uses. Accordingly, technological characteristics have an impact on the viability of the supply chain.

As demonstrated above, a viable biomass supply chain is dependent on both the region and the CBE technology. Therefore, in the following two sections, we present an approach that allows to match a CBE technology with a region in terms of an adequate supply of biomass. First, the characteristics of a given CBE technology that affect the biomass supply chain can be evaluated using the CBE Technology Evaluation Matrix (Figure 5). In a second step, the Region Evaluation Matrix (Figure 6) can be applied to evaluate characteristics of a given region in terms of a supply chain for the chosen residual biomass type.

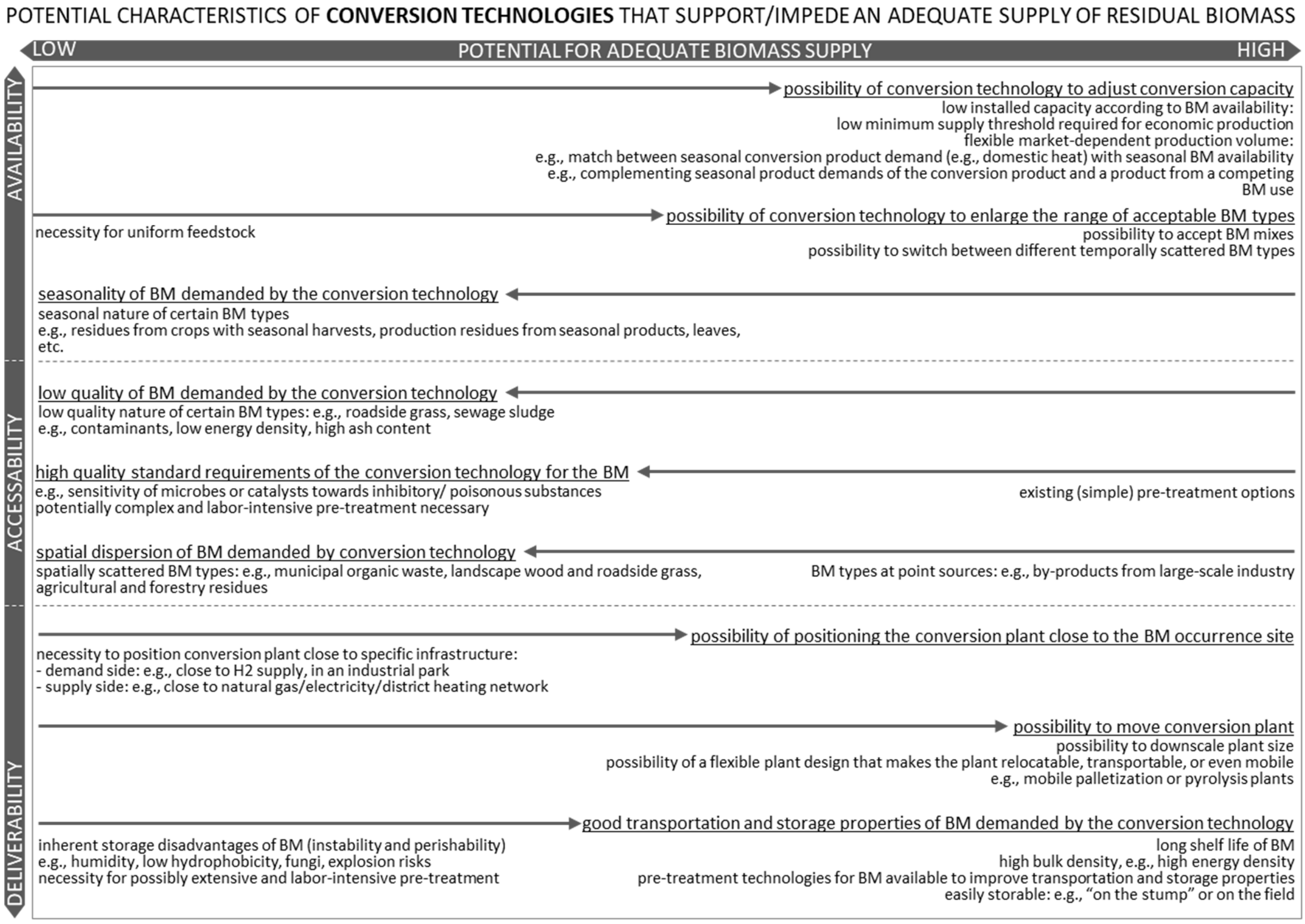

Figure 5. CBE Technology Evaluation Matrix for Biomass Supply Chains: evaluating the characteristics of a CBE technology that affect the viability of the biomass supply chain.

From the literature, we derive characteristics that influence the biomass supply chain and indicate whether they support or hinder an adequate biomass supply. To explain the characteristics, we provide examples of how they could be shaped in a technology or region. We further categorize each characteristic along the vertical axes as affecting either biomass availability, accessibility, or deliverability. We define each term as follows: biomass availability describes the general existence of a biomass at a certain period of time in a certain geographical area; biomass accessibility describes the attainability of an available biomass for a CBE conversion technology in terms of the reachability, extractability, obtainability, and usability; and biomass deliverability describes the feasibility of overcoming the discrepancy in space and time between the point of occurrence and the point of utilization of an available and accessible biomass.

By first qualitatively assessing the supply chain characteristics of a CBE technology and then of a region, it is possible to compare the results and thereby derive a qualified guess as to whether a CBE technology and a region match in terms of biomass supply chain aspects. We recommend comparing technological and regional characteristics step by step in terms of biomass availability, accessibility, and deliverability. In this way, it is possible to gradually uncover the potential of a CBE technology to mitigate unfavorable conditions of a region or, conversely, the potential of a favorable region to meet the challenging demands of a CBE technology.

Figure 6. CBE Region Evaluation Matrix for Biomass Supply Chains: evaluating the characteristics of a region that affect the viability of the biomass supply chain for a given biomass.

3.4.1. CBE Technology Evaluation Matrix—Biomass Supply Chain

The CBE Technology Evaluation Matrix provides a comprehensive set of technological characteristics that influence the viability of the biomass supply chain. It can be used to qualitatively evaluate a particular CBE technology in terms of biomass supply chain aspects. To demonstrate the value and applicability of the matrix, some of the technological characteristics are discussed in more detail below. We assume that for a given technology, the range of applicable residual biomass types is predefined. Therefore, biomass-specific characteristics are also addressed in this matrix.

One of the technological characteristics that could support a sufficient supply of residual biomass is the potential to adjust the installed conversion capacity. Limiting the capacity in accordance with the regional biomass availability helps to decrease transportation distances, to avoid biomass shortages, and to prevent installed overcapacities. As said before, it is reasonable to optimize the plant size by considering both the economies of scale and the biomass supply distances [74]. If the minimum supply threshold for economic viable production is relatively low for a given CBE technology, the potential to downshift the installed capacity in favor of a viable biomass supply increases. A CBE technology may also have the freedom to temporarily adjust the production volume. For instance, a company may produce a product that is demanded only during a specific season, such as domestic heating, and therefore may shut down production outside of that period. If this seasonal demand furthermore coincides with the seasonal availability of a combination of residual biomass types, there is great potential for a suitable configuration of a regional biomass supply chain.

Another option for the CBE technology to increase the available feedstock quantity is to enlarge the range of acceptable biomass types. Either the technology is able to convert a mixture of different biomass types simultaneously or it can switch between different biomass types from time to time. Depending on the requirements of the CBE technology, chemical-physical characteristics can be derived that must be fulfilled by potential feedstocks. These characteristics can be used to find suitable residual biomass types, e.g., from biomass databases like those proposed by Black et al. [62]. The matching process between CBE technology and biomasses can also be supported by tools such as the Bio2Match Tool [88]. They are designed to propose an optimal match between biomass resource and conversion technology and are backed by databases containing extensive information on the specific requirements of a conversion technology for its feedstock and the characteristics of different biomass types.

Particularly in the case of spatially dispersed biomass types, the ability to move a conversion plant could help limit transportation costs. This would eliminate the need for frequent transportation of biomass to the conversion facility. Instead, the mobile plant is moved to where the biomass is located. This further allows an increase in the overall biomass supply radius. Commercialized mobile conversion plants exist as palletization [74] and pyrolysis plants [80]. For example, Yazan et al. [80] investigate the economic and environmental sustainability of different supply chain designs for mobile and fixed pyrolysis plants fed with second-generation lignocellulosic biomass and find that the mobile plant performs slightly better, but that the number of set-ups for the plant should be kept small.

Further technological characteristics influencing the biomass supply chain are shown in Figure 5 in the CBE Technology Evaluation Matrix. For example, biomass-specific characteristics, such as seasonality, quality, spatial dispersion, and transportation and storage properties, are described.

3.4.2. CBE Region Evaluation Matrix—Biomass Supply Chain

Regional characteristics affecting the supply of biomass to a CBE technology are compiled in the CBE Region Evaluation Matrix. Following the approach of the previous section, we discuss below how selected characteristics potentially affect a biomass supply chain and to what extent they are region-dependent.

As previously stated, different regions provide different residual biomass types. Thus, the initial step in matching a CBE technology with a region is to demonstrate that the regional availability of the demanded biomass is quantitatively sufficient. Methods to quantify the potential of different types of residual biomass at a regional level have been proposed [9,89]. Potential analyses often consider not only the availability of residual biomass but also various technical, economic, and environmental limitations of its extractability. These are reflected in corresponding terms for the biomass potential, i.e., technical, economic, and environmental potential [90]. In our CBE Region Evaluation Matrix, we reflect regionally varying restrictions for the accessibility of the demanded biomass, i.e., environmental, technical, and social constraints. Regional potential analyses often stop at theoretical or technical potential, neglecting economic, environmental, or social constraints [86,89,91]. If environmental constraints are included, they are often not considered as region-specific variables. For instance, when applying a "sustainable extraction rate" for straw, average values from the literature are used [9]. However, Paredes-Sánchez et al. [92] demonstrate that it is possible and relevant to consider region-specific techno-economic and environmental constraints for the extraction of forest residues by applying spatial data on the slope, erosion risk, and carbon content in soil. These are conditions that are typically reflected in environmental residual biomass potentials (see e.g., also [93]). In our literature analysis, however, we identified further environmental impacts that can be caused by the removal of residues from agricultural or forestry land, i.e., disturbances of water and nutrient cycles, biodiversity losses, as well as habitat and travel corridor losses. The sensitivity towards these impacts depends on spatial conditions and should be considered in the calculation of environmental potentials through factors valid for the specific region. Furthermore, it is important to acknowledge, that residual biomass potentials are not static but can change over time in the long term. For example, changes in agro-climatic production conditions like temperature- and rainfall patterns or changes in the frequency of natural interruptions like droughts, wind- and hailstorms, frost, floods, wildfires have the potential to change a region's agricultural and forestry production patterns [61,73,78]. In addition, the implementation of more efficient production methods in agriculture and forestry can lead to increased yields [62,70,74]. For instance, the use of high-quality seeds, potentially including GMOs, or precision farming are methods that are under development and have the potential to increase yields and thus the amount of residual biomass in the future. In certain regions, the latest technology in agriculture and forestry, e.g., in terms of mechanized processes or optimized cropping and fertilization patterns, may not yet be applied. When calculating future regional biomass potentials, it is therefore necessary to consider the possible development of a region towards the use of more modern production techniques. Additionally, it is important to note that the literature values on yields have limited applicability to other regions or time periods.

In terms of accessibility, the regional competition for biomass plays an important role. Increasing competition can result in increased transportation distances or the need to exploit biomass with limited accessibility. Both result in high biomass prices. If it is not possible to supply all the competing uses of biomass in a cost-effective way, there is a risk of installed overcapacity. Existing uses, especially in-plant uses, are often prioritized, making it difficult for new technologies to compete. For example, forest residues are often used by plantation or sawmill owners as feedstock for in-plant CHP facilities so that they do not enter the market in the first place [81]. Zimmer et al. [81] find that an existing demand is a decisive factor for the siting of a biofuel production facility; in some of the regions with highest forest density, they find the lowest potential for biofuel production due to the consumption of forest residues in existing CHP plants. The competitiveness of other uses and their level of biomass demand depends on the regional market for their product. If a competing use serves an expanding market, such as the wood pellet market [77], it is likely that the regional competition for the biomass will increase over time. Conversely, current competition may also come from shrinking industries, such as the pulp and paper industry [79], or from industries that are targeted to be downsized in the future, such as livestock production, making the release of residual biomass likely over time. Competing uses may also be exposed to fluctuating product markets, such as the electricity market. In these cases, a market-driven choice between two competing biomass utilization paths within a flexible and combined production system may be advantageous. For example, Black et al. [62] note that comparable to some sugar mills currently choose between sugar and ethanol production depending on market conditions, it is likely that future sugarcane bagasse utilization will switch between bioethanol and bioelectricity production.

Further regional characteristics influencing the biomass supply chain can be taken from the CBE Region Evaluation Matrix in Figure 6. In the category of biomass accessibility, we further describe regional characteristics that influence the willingness of biomass owners to provide the demanded biomass and the regional supply chain costs. In the deliverability category, we consider regional characteristics such as the availability of specialized equipment and centralized points for collection, storage, and pre-treatment, as well as the availability of infrastructure for transportation and product distribution.

4. Discussion

We have conducted an intensive literature search and an expert survey to (i) develop a comprehensive catalog of CBE success criteria that reflects and substantiates the regional nature of CBE; and to (ii) evolve a new methodology based on evaluation matrices that allows CBE technologies to be matched with CBE regions.

A body of literature exists on success criteria for CBE. However, our CBE Success Criteria Catalog complements the existing literature as it is more comprehensive and detailed than any other that we are aware of in the context of the CBE transition. Furthermore, it suggests a ranking of criteria by relevance. The criteria catalog reflects a broad spectrum of success criteria from seven categories: biomass resource, technological, environmental, economic, political and legislation, social, and methodological. The categories are similar to those of the PESTEL analysis (based on Aguilar et al. [94]) but are supplemented by the categories biomass resource and methodological. The PESTEL analysis is a well-known tool that has also been applied by some of the studies used to research success criteria (see Table S1) [23,34,38]. Other studies use categorization principles based on the SWOT matrix [25,35,39] or distinguish internal and external drivers [23,30]. We used a bottom-up approach to research success criteria from the literature. Accordingly, we did not pre-structure the expected results to ensure that influencing factors from all relevant areas are covered. Criteria categories were created after the research was completed by clustering the identified criteria and deriving an appropriate category for each cluster. This implies the uncertainty that important criteria or entire categories are not covered by our catalog. However, the fact that the derived categories match those of the established PESTEL method indicates that the most important categories are captured. Furthermore, to validate and complete our catalog, we conducted an expert survey with five experts from three European countries. Although a larger number of experts from a wider geographical area would have been desirable to provide more comprehensive feedback with a more international perspective, the expert survey is a valuable contribution to the validation of our results. Our criteria catalog suggests a ranking of criteria by relevance, which is derived from the number of studies and experts relating to each criterion. While we acknowledge that the number of references does not necessarily correlate with its relevance, it can at least be an indicator of the attention it receives in the scientific community. Only one expert suggested changing the ranking of the main criteria, and only for the social criteria category. This indicates that the ranking at the level of main criteria is consensual.

Our categorization scheme classifies success criteria based on their technology and territory specificity. However, the determination of whether a criterion is territory-specific at the national or regional level can be subject to ambiguity. For example, we determined the sub-criterion “value creation from waste and by-products” to be territory-specific at the national level because the usability of a waste depends on national legislation. However, the potential for value creation from waste is not only determined by the legal framework but also by economic conditions affecting the profitability, such as regional residual biomass costs. A more systematic categorization approach based on the scientific literature that examines and demonstrates regional differences in the criterion under consideration would help to achieve a more valid and verified categorization. In the scope of this extensive literature review with 76 sub-criteria, it was not possible to substantiate the decision for each criterion. Still, this could be an interesting topic for future research. Another discussion point is the consideration of exclusively region- and technology-specific criteria in the matching process. We argue that only criteria that affect both technologies and regions have an impact on the compatibility of a technology with a region. However, some criteria initially classified to be not region-specific play a role during the matching process. For example, we include the temporal fluctuation of biomass or the biomass quality in the evaluation matrix. The reason for this is that these criteria have, in combination with region-specific characteristics, an influence on the compatibility of region and technology. For instance, a technology that uses a low-quality, temporally varying biomass, yet requires a constant supply of biomass pre-treated to a high level of purity has a greater chance of success in a region where a supply chain for this biomass already exists, with central points for collection, pre-treatment, and storage. Nevertheless, we suggest that an initial focus on region- and technology-specific criteria helps to establish an effective workflow. Examining broad criteria clusters during the development of the evaluation matrices allows related criteria that were initially excluded from the further analysis to be reconsidered.

With the goal of providing practical guidance in selecting appropriate CBE technologies for a given region, we developed a matching approach based on CBE Technology and Region Evaluation Matrices. One limitation of our matching approach is that the evaluation matrices have only been developed for the two broadest and most relevant of the four identified criteria clusters. However, we acknowledge the importance of all four clusters and recommend considering them when selecting CBE technologies. Therefore, we suggest addressing the construction of the evaluation matrices for the two clusters “regional environmental impacts” and “regional policies and legislation” in future research. Another limitation that reduces the practicality of the matching approach is that its application can be time-consuming. Particularly, in the case of building CBE transition scenarios, it is questionable whether matching each conceivable technology to each of the four identified criteria clusters is feasible. However, compared to a quantitative assessment approach proposed for example by Croxatto Vega et al. [18] for singling out an ideal technology for a given region based on TEA and LCA, our qualitative approach is less time- and data-consuming and therefore more suitable for a selection among a variety of technology options. In turn, it lacks the precision of a quantitative method. Our matching approach is limited to the provision, discussion, and interpretation of regional and technological characteristics. When applying the approach, it is additionally necessary to evaluate the investigated technologies and regions based on all characteristics from the evaluation matrices. Future research could provide guidance on how to determine the characteristics of a region or technology. For example, to assess a region’s potential for an adequate biomass supply, it is necessary to examine the regional competition for the desired biomass by investigating the development of current and future uses. Such further practices, though, are not addressed in this study. We do, however, provide some literature recommendations, e.g., on methods for quantifying the availability of residual biomass at the regional level or how to proceed when selecting specific biomass types for a given technology.

For the criteria clusters biomass supply chain and social acceptance and consumer awareness, we exemplarily develop the evaluation matrices. The evaluation matrices for the biomass supply chain can be used to assess regional and technological characteristics influencing the availability, accessibility, and deliverability of biomass. They are supposed to reflect biomass supply chain characteristics for all types of residual biomass, i.e., agricultural and forest residues, municipal waste, and industrial by-products and wastes. However, our initial literature search revealed a research focus on forest and agricultural residues. In order to include aspects that are specific to industrial by-products and wastes, we conducted a further literature search that explicitly looked for biobased industrial by-products. However, we identified only five further studies [62,66,67,69,71] fitting our scope, mainly in the context of industrial symbiosis. One reason for this could be that the supply chain for agricultural and forestry residues is often more complex. They are spatially scattered and there is no pressure to dispose of them. On the contrary, there may be concerns about their removal. Furthermore, they require harvesting. Among these reasons, the potential of forestry and agricultural residues is currently often not being fully exploited, and the investigation and optimization of their supply chain is of greater scientific interest. Therefore, our evaluation matrices for biomass supply chains may be better suited to investigate supply chains for agricultural and forestry residues than for industrial by-products and wastes.

The evaluation matrices for social acceptance and consumer awareness help to estimate the acceptance potential of a given technology in a specific region. It is important to consider the potential for social resistance to CBE technologies early in the planning process because civil society tends to support different visions of the BE than BE experts from industry, politics, and science [44]. For example, Dieken et al. [44] find in their literature review that among various groups, such as “government and political actors”, “industry and commerce”, “media”, or “research”, only the group “citizens and consumers” supports a "bio-ecology vision" similar to the "sufficiency and close affinity to nature" vision of Hempel et al. [51]. A reason for these differences lies in the way the BE is assessed. While experts apply BE-specific evaluation criteria based on specific technological and economic aspects, civil society tends to evaluate the BE not in isolation, but against a system of evaluation patterns that are habitually applied to economic, environmental, and social problems [46]. This is also reflected in our technology evaluation matrix. It shows that the various bioeconomy visions differ primarily in the socio-political acceptance dimension. This suggests that social groups, and therefore regions, differ in their acceptance mainly in terms of fundamentally different perceptions. Since socio-political perceptions are less amenable to influence than, for example, concerns relating to community acceptance, it is recommended to consider them as serious, possibly well-founded, and legitimate criticism that should be integrated with its region-specific expressions into decision-making processes of early CBE planning. The technology evaluation matrix indicates that different social groups have conflicting opinions about certain technological characteristics. For instance, the "sufficiency and close affinity to nature" vision favors small technological scales over large industrial ones to avoid potential environmental impacts, while the "technological progress" vision takes the opposite view and prioritizes the potential for economies of scale. Therefore, it is necessary to identify early in the implementation process of CBE technologies which acceptance issues can potentially arise in a certain region and to accompany its implementation process accordingly. The prediction of social acceptance is difficult. Even though we propose an approach to deduce how mentalities are distributed in a region, it is subject to potential uncertainty and inaccuracy. The correlation between mentalities and socio-demographic characteristics provided by Eversberg et al. [46] is based on survey data from Germany. Its direct applicability to other countries is very limited. They use this correlation to gain insights about which socio-economic milieus are behind the mentalities; they did not discuss whether the reverse prediction from milieus to mentalities, as proposed in our study, is also plausible. Furthermore, it is difficult to derive from the distribution of single socio-demographic factors a picture about social milieus. Moreover, the differences in the socio-demographic characteristics between the region and the sample average can be very small, not allowing any assumption about the prevalence of specific BE mentalities; this applies particularly to large and diverse regions. Even if it is possible to shed light on the prevalence of mentalities in a region, it is not clear which mentalities will actively articulate their acceptance or resistance, for example, in the form of participation or protests. This applies even though we know which mentalities are more likely to actively participate and which are less likely to do so. This is especially true as the acceptance of a person can vary between the individual acceptance dimensions. A technology that is accepted from a socio-political perspective may still face opposition from a community acceptance point of view (NIMBYism). Furthermore, acceptance can be influenced by various measures. This means that the acceptance within a region does not only depend on the initial mentalities of its population but it can be influenced and change over time, adding uncertainty to any prediction. For example, public participation in planning, equity in decision-making processes, transparent information, and co-ownership by the community can improve acceptance [47,52,55]. Therefore, the proposed approach to predict a region's affinity to one of the three BE visions should be seen as a first attempt, which has the advantage of being able to be conducted as desktop research. It should, however, be supplemented by more precise approaches such as region- and technology-specific surveys or the investigation of the civil society's involvement during the implementation of similar technologies in a comparable region.

5. Conclusions

The first objective of this study was to examine the influence of regional conditions on the potential success of a CBE transition. To achieve this, we have successfully developed a comprehensive catalog of CBE success criteria and discussed the regional specificity of each criterion. The CBE Success Criteria Catalog presents success criteria from a broad set of criteria categories, i.e., biomass resource, technological, environmental, economic, political and legislation, social, and methodological, which allows for a thorough analysis of the macro environment along the entire CBE supply chain. Within the categorization scheme, we classify success criteria based on their technology and territory specificity. The scheme supports a reflection on the importance of regional characteristics for the success of CBE implementations. As the majority of success criteria turned out to be region-specific, we consider our initial hypothesis to be proven and conclude that the CBE is a highly regional concept whose successful implementation depends strongly on regional conditions. This finding highlights the importance of reflecting regional conditions in effective CBE transition planning. A practical implication of our findings is therefore the recommendation to complement national and transnational BE strategies with regional policies, as they have the potential to address the specific characteristics of a given region. Our set of region-specific CBE success criteria can serve as a starting point for the development of regional strategies by supporting a thorough analysis of the regional drivers and barriers that affect the CBE transition and by indicating in which areas a strategy needs to be region-specific.

The second objective was to provide practical guidance for the reflection of regional conditions during the selection of CBE technologies in regional CBE scenarios. For this purpose, we developed evaluation matrices that support the assessment of regions and technologies based on very detailed characteristics affecting the successful implementation of CBE technologies. Exemplarily, we provide such matrices for the two broadest and most important success criteria clusters: social acceptance and biomass supply chain. The comparison of technological and regional characteristics makes it possible to match CBE technologies and regions, thus preparing the region-specific selection of technologies for CBE scenarios. The matching approach is suitable for further practical application, e.g., to support decisions on which CBE technologies should receive regional funding or be considered in regional policies. It could further support regional development planning by identifying development needs related to key region-specific success criteria.

Our evaluation matrices for the biomass supply chain present characteristics in terms of biomass availability, accessibility, and deliverability and consider technological, legal, economic, social, and environmental aspects. By comparing the evaluation results of a region with those of a technology, it is possible to determine the potential of a CBE technology to compensate for unfavorable conditions in a region or, vice versa, the capability of an advantageous region to cope with the demanding requirements of a CBE technology. The evaluation matrices for social acceptance and consumer awareness can be used to estimate how the acceptance of a given CBE technology might evolve in a particular region. Our summary and combination of the results from the current literature on social acceptance in the context of BE makes this scientific field more accessible to more technology-oriented stakeholders. By combining the concept of different bioeconomy visions including technological characteristics with the concept of different mentalities of people with certain socio-economic characteristics, the potential acceptance of certain social groups towards certain technological characteristics can be derived. Since social resistance can prevent the large-scale introduction of technologies, its potential occurrence must be considered early in CBE planning and in realistic CBE transition scenarios.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16072935/s1, Supplementary Material File S1: Table S1. Selected peer-reviewed journal publications used to identify success criteria for the implementation of CBE technologies; Table S2. Selected (peer-reviewed) journal publications used to identify aspects influencing the social acceptance and consumer awareness for a CBE technology within a region; Table S3. Selected peer-reviewed journal publications used to identify aspects influencing the availability and the supply chain of biomass for the utilization of a CBE technology within a region; Table S4. Comparison of the CBE criteria catalog before and after the changes resulting from the expert survey; Table S5. Attribution of region- and technology-specific sub-criteria to the four criteria clusters; Figure S1. Descriptions of social camps and mentalities from our own compilation of information taken from [45,46]. Supplementary Material File S2: Results from the literature search on CBE success criteria: detailed CBE Criteria Catalog. Supplementary Material File S3: Results from the expert survey: validated and improved detailed CBE Criteria Catalog. Supplementary Material File S4: Questionnaire for the expert survey.

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