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Indicators for Urban Circular Bioeconomy Development

A Systematic Review of EU-Wide National Bioeconomy Monitoring Frameworks and Their Utility to Urban Policy-Makers

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Declaration of Authorship

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Management Summary

Indicators for Urban Circular Bioeconomy Development. A systematic review of EU-wide national bioeconomy monitoring frameworks and their utility to urban policy-makers

By combining principles of circularity with a transition to regenerative resource usage, the 2018 European bioeconomy strategy set a new vision for the continent's sustainable development. With it, the EU Bioeconomy Monitoring System, an indicator set used to monitor the progress of the circular bioeconomy, was launched. It is the most comprehensive such tool and its conceptualization involved the collaboration of several EU member states. For a successful, synergistic and efficient transition of the European economy to a circular bioeconomy, policy and action must indeed be aligned throughout governance levels. While both the European and national efforts are reflected within the Monitoring System, it remains unclear whether national strategies and indicator sets are also suitable for urban governments to align with. As urban policy-making takes the role of implementing the bioeconomy strategies, it is vital that it does not diverge from national and international efforts, causing inefficiencies and adverse effects on the bioeconomy transition.

This thesis aimed to investigate EU-wide national bioeconomy strategies and to examine the composition, features and topical coverage of their bioeconomy measuring tools. In a second step, the suitability of these tools as guidance for the development of consistent urban indicator sets was evaluated. The national bioeconomy strategies were collected and appraised through a systematic review process, and their indicator sets' forms and contents were examined. First, a factsheet and a quality appraisal of the single indicators gave insight into the construction of the indicator sets, then a heatmap of topical coverage was created showing areas of the bioeconomy tackled by the instruments.

Of the 27 member states, only nine had a dedicated bioeconomy strategy, and four among them proposed an indicator set. Assessing these sets revealed that particularly the tools proposed after the issuance of the 2018 bioeconomy strategy followed indicator development standards rigorously. They also included circularity principles in their notion of bioeconomy and combined indicators for a profound and multi-faceted analysis with substantial informative and policy-relevant value. These factors strongly improve the potential for alignment and coherence with urban-level bioeconomy monitoring

efforts. Nonetheless, urban governments cannot use them at face value, as the goal-setting and therefore the selection of single indicators, differs across policy levels.

Although it is not the aim of national measuring tools to perfectly provide for urban needs, the findings of this thesis give insight into the importance of and ways how national bioeconomy policies can support a uniform circular bioeconomy transition across the EU.

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List of Abbreviations

BMS	European Union Bioeconomy Monitoring System
CBE	Circular Bioeconomy
DPSIR	Drivers, pressures, state, impact and response model of intervention
EC	European Commission
EEA	European Environment Agency
EU	European Union
GHG	Greenhouse gas
SDGs	United Nations Sustainable Development Goals Agenda 2030
OECD	Organization for Economic Co-operation and Development

1 Introduction

During the past decade, rising awareness of the destructive impact of current production and consumption models on the environment and the integrity of global ecosystems has led to international efforts for sustainable development. On a global stage, the European Union (EU) has earned the status of ecological leader, thanks to its solid framework of environmental legislation (European Commission, 2018a; Le Cacheux & Laurent, 2015). Among others, the bioeconomy strategy, which aims to power the economy with regenerative resources, has leveled the ground for sustainable innovation on the continent (European Commission, 2012, 2018a). With its 2018 update, the need for the circular economy to become an integral component of a thriving bioeconomy was recognized for the first time, and the EU's ambition of transitioning towards a circular bioeconomy (CBE) was formulated. This strategy considers that the member states will develop a diversity of bioeconomy strategies and calls for their alignment and policy coherence (European Commission, 2018a).

While these frameworks are developed and agreed upon on international or national levels, implementation and monitoring of achievements trickle down to smaller, local entities (Woodbridge, 2015). Cities generally have high access to modern technology, supply of skilled workforce and geographic proximity of service providers, retailers and citizens. These are factors that favor collaboration and exchange between inhabitants, policy-makers and businesses. As such, they benefit urban societies through innovation and the development of new business models to tackle sustainable policy implementation (Ellen MacArthur Foundation, 2019a). Not only do cities have the capacity to fuel ecological change, they also depend on it to further support energy, resource and food security for their populations (Hetemäki et al., 2017). Urban areas currently host 55 percent of global populations and ongoing, rapid urbanization is forecasted to grow this figure to over two-thirds of the world population by 2050 (Ritchie & Roser, 2018). Therefore, cities are increasingly experiencing pressures on their infrastructure (Ellen MacArthur Foundation, 2019a; Hetemäki et al., 2017). With such impact potential and urgency for action, cities need to take on the responsibility to educate their citizens and labor force to set the foundations for the long-term viability of sustainable development.

The transition of a city's economy to become more bio-based and circular, thus a CBE, requires targeted action that fosters the desired outcomes. This means developing and aligning a fundamental understanding of the urban flows of organic materials and identifying system-wide solutions to loop them (Ellen MacArthur Foundation, 2017). Furthermore, regulation should be used to remove any gaps or flaws in policy-making to give businesses the necessary tools to strategically overcome barriers to the CBE and benefit from its opportunities (Ellen MacArthur Foundation, 2019b). Overall, however, efforts across policy-making levels must be coherent and aligned to achieve timely and collective success and avoid divergent, counterproductive developments (Robert et al., 2020). Robert et al. (2020) indicate that concepts related to the CBE vary across initiatives and over time and that collaboration crossing geographies and policy levels is essential in moving ahead uniformly in the EU. By highlighting *"the relevance of mutual learning, and of ensuring the coherence across scales"* (p. 14) they extended the responsibility of aligning inter- and intranational efforts to all entities involved.

1.1 Research Gap

In order to achieve the goals set by the EU's bioeconomy strategy and ensure alignment across policy levels, various tools must be leveraged to help streamline efforts and benefit from synergies in policy-making. Particularly relevant are assessment systems for the state and development of the CBE and for the successes and failures of policy-making practices (Eurostat, 2014). Such monitoring frameworks usually take the form of indicator sets that allow evaluating a combination of measures. With the right tools, their interpretation can give insight into the environmental and socio-economic impact of policies and systems and identify areas of weakness to address and respond to (European Commission, 2018b).

With its most recent bioeconomy strategy, the EU initiated the construction of the EU Bioeconomy Monitoring System (BMS) (Robert et al., 2020). This will be the most comprehensive bioeconomy indicator set that collects measures for EU-wide policy-making and is created in proximity with its member states (Giuntoli et al., 2020). Indeed, various members have developed their own strategies over the past years, which translate international commitments into national ones (European Commission, 2019a; Robert et al., 2020). As these are integrated with the BMS, the tool represents a unified understanding and set of strategic objectives that may be tailored to various policy levels within the Union and ensure comparability of progress across its regions (Robert et al., 2020).

However, the “local” level is mainly tackled in generic terms in the EU’s bioeconomy strategy and consequently in the BMS, despite being highly relevant for the implementation of CBE policy (Giuntoli et al., 2020). The focus, which is set on aligning national and international policy-making and monitoring systems, will therefore have to be expanded onto a local, urban level as well (Woodbridge, 2015). This is particularly important, as subsidiarity and proportionality principles limit the EU’s range of action and enable national, regional, or local governments to realize the strategic goals (European Committee of the Regions, 2017). Aligning with national and international bioeconomy strategies and policy-based measurement tools ultimately allows cities to benefit from readily established frameworks and coherently developed instruments (Woodbridge, 2015). It remains unclear, however, whether national developments in CBE policy-making successfully bridge the gap between international and local legislation and thus enable and support the CBE transition at an urban level.

1.2 Research Objective and Questions

This thesis acknowledges the roles and responsibilities of cities in implementing a sustainable, future-proof, and effective bio-based and circular economy (Swilling & Hajer, 2017; Woodbridge, 2015). Furthermore, it recognizes the needs of urban policy-makers to align monitoring efforts with national strategic goals (Robert et al., 2020). To gain clarity on the extent to which it is possible to align CBE monitoring approaches between cities and their nations, this thesis aims to describe the scope of indicator sets proposed by EU-wide national bioeconomy strategies and evaluate their suitability for urban-level needs. The intention is to identify to what extent urban policy-makers can orient themselves towards the national monitoring framework in creating their own CBE assessment tools. Ultimately, by studying their monitoring approaches, this thesis shall understand whether efforts by EU member states to promote the CBE are created in a way to favor scalability as well as alignment with urban needs and capacities.

The following set of research questions shall serve as guidance to achieve the objective of this research:

1. What are the features and compositional rationales of monitoring frameworks proposed by EU-wide national bioeconomy strategies and how extensive is their topic coverage?
2. Can cities in the EU find practical and purposeful tools in the existing national bioeconomy strategies that allow them to measure their CBE transition?

Answered in sequential order, these questions first give insight into the landscape of national bioeconomy monitoring frameworks and then allow to identify their suitability to urban-level needs. For this assessment, both the relevance of the proposed indicators to urban policy-makers and the methodological and functional soundness of the indicator sets will be considered.

1.3 Relevance and Domain Limitations

As governments prepare to mitigate worst-case scenarios of a looming climate crisis, efforts on all societal levels must be coordinated and unidirectional (Robert et al., 2020). Therefore, finding unambiguous answers to the stated research questions is essential to provide national policy-makers with a clear overview of the extent to which their CBE monitoring systems are useful to urban governance levels. The coherence of national policy-making and measurement tools with urban ones finds relevance in particular due to a current deficiency of city-level indicators, creating a barrier to the implementation of CBE-related concepts (Romano, 2019). While various non-governmental organizations have initiated developing indicator sets to fill this gap, their abundance and proliferation risks diluting the appropriate assessment of a subject with purposeless measures or statistically flawed ones (European Commission, 2018b; Eurostat, 2014). Furthermore, the lack of available and consistent monitoring frameworks leads to cities creating indicator sets on their own. While this is not problematic per se, the risk occurs that city-level strategies divert from national and international efforts and become counterproductive. Therefore, although the development of the BMS aligns EU-wide with national policies (Robert et al., 2020), proposing unscalable national indicator sets can jeopardize the efficiency of a holistic CBE transition within the various member states.

Both instances, national and urban governments, can draw benefits from clarity on this topic. Adjusting indicator sets for increased compatibility allows comparing practices with other cities or the state and streamlining the CBE transition by benefitting from synergies across policy levels. This facilitates a holistic approach to a subject that naturally crosses the scope of each single entity. Furthermore, new doors will open for collaboration with the private sector, which will benefit from increased coherence in the CBE transition in the form of new financial and business opportunities and clarity in regulatory approaches. This, in turn, has the potential to further fuel the CBE transition. Finally, this thesis builds on streams of research on the current political state of the CBE and contributes with a review and analysis of related urban and national policy-making.

To ensure the relevance, completeness and coherence of the findings of this research, its scope is delimited as described in the following paragraph.

For the identification of urban CBE policy-making needs, no real-life cases will be studied. By developing an understanding of such needs on available theoretic CBE research, rather than based on the study of an actual city, the goal is to provide a comprehensive assessment, covering all aspects of CBE, even those not yet solidified in practice. Furthermore, gaining enough insight into a specific city's needs for CBE monitoring tools exceeds the resources afforded to the completion of this thesis. Working on a real-life case will also reduce the transferability of the findings due to location-specific circumstances. The scope of this thesis further excludes ranking the various national bioeconomy strategies. Despite assessing each monitoring framework individually, the discussion and drawing of conclusions shall refer to the composite set of studied indicators and speak for EU member states as a whole. This is also necessary as a ranking implies a universally better fit of one tool over another. As all strategies carry an element of adaptation to their local circumstances, such grading is impossible to make. Finally, the bioeconomy strategies are discussed only regarding their monitoring frameworks. While it is necessary to consider other strategic elements, such as the strategic goals or the approach to circularity, conclusions on the strategies themselves will not be drawn.

This paper investigates the research objective in six chapters. The Introduction contextualizes the scope of the research and outlines its need and contribution to policy, business and academia. It also defines the research objective, questions and delimitations. The Literature Review investigates past research on indicator development, theoretical and practical notions of the CBE and urban sustainability and policy-making. This basis of knowledge informs decision-making related to the data analysis and the discussion of the findings and delineates the research gap presented in the introduction of the paper. The Methodology explains the systematic review approach conducted for data collection and evaluation. It also gives detailed information about the data analysis, which is split into an appraisal of the quality and composition of the indicator sets, as well as a heat map evaluation of their topical coverage. The study's Findings are presented in the subsequent chapter, which includes evidence from the collected data. In the Discussion, the findings are situated within prior research and elaborated in an argumentative manner to answer the research questions. In the final chapter, the Conclusion, the broader implications of the answers to the research questions are reflected upon and limitations and opportunities for further research identified.

2 Literature Review

This chapter summarizes and synthesizes information from publicly available sources to support answering the research questions stated in chapter 1.2. By reviewing academic articles and policy reports from various international organizations, the literature review aims to identify the conceptual structure in which the indicator set assessments are situated. To this end, the following subchapters investigate the domain of environmental indicators, the CBE, and urban sustainability and policy-making.

2.1 Environmental Indicators

Increasing urgency in environmental protection in the last decades of the 20th century resulted in a wide variety of environmental policy-making with the attempt of guiding worldwide economies towards sustainable development. As monitoring outcomes are an integral part of successful project implementation (Lynch & Cross, 1995; Ramos, Caeiro & Joanaz de Melo, 2004), these policies led to a proliferation of measurements for environmental well-being and progress towards sustainability targets (Smeets & Weterings, 1999). Such measurements are commonly referred to as environmental indicators, whereby this term goes beyond simple appraisal.

Various definitions for indicators were given in scientific literature and some common themes emerged across different studies: According to Hiremath, Balachandra, Kumar, Bansode & Murali (2013), as well as Smeets and Weterings (1999) and Ramos et al. (2004), indicators are tools to measure performance and monitor the progress made towards pre-defined targets. In order for these measures to be efficient in providing a clear, simple depiction of a complex reality, they quantify and aggregate collected information into a useful form to provide an operable model of the measured circumstance (Bracco, Tani, Çalıcıoğlu, Gomez San Juan & Bogdanski, 2019; Clarke & Wilson, 1994; European Commission, 2018b; Hammond, Adriaanse, Rodenburg, Bryant & Woodward, 1995; Hiremath et al., 2013; Smeets & Weterings, 1999). This is used to support management and decision-making in both public and private sectors (European Commission, 2018b) and serves the function of communication (Ramos et al., 2004; Smeets & Weterings, 1999). Indicators provide the information required to understand change and allow to exchange it between policy-makers and a wider audience (Bracco et al., 2019; Keirstead, 2007; Smeets & Weterings, 1999). As such, the core component of indicators lies in the message promoted with a measure, its use and meaningfulness for decision-makers and the resulting behavior it evokes as a response among policy-makers or managers and the public (Gabrielsen & Bosch, 2003; Smeets & Weterings, 1999). With the help of indicators, highly complex systems can therefore be summarized and evaluated with ease, a feature that makes them indispensable for effective estimations of circumstances, pressures on the environment and policy-making outcomes (Hammond et al., 1995).

This simplification of multivariate realities, however, has encountered widespread criticism among policy-makers and academics alike and must be considered when using indicators as a basis for decision-making. Indeed, Hiremath et al. (2013) pointed out that indicators do not give any information on the fluctuations and ambiguity in data over time, nor do they provide explanations or causal links to measured phenomena (Bracco et al., 2019; Hiremath et al., 2013). Hence, it is up to a user to draw relevant conclusions and take meaningful action based on the results (Heink & Kowarik, 2010).

The following subchapters provide further insight into various aspects of indicator features, usage types and presentations, as well as quality criteria relevant to purposeful indicator sets.

2.1.1 *Indicators*

Indicators can be qualitative or quantitative. Qualitative indicators are expressed in words and result from a quality assessment whereby precise statements that are often only applicable to a small sample can be made. Conversely, quantitative indicators are expressed in numbers with higher levels of potential generalization but results that need to be interpreted (Simister, 2017). Among quantitative indicators, the more common category, there are various modes of expressing a measurement: as counts and ratings, as reflections of change over time, as performance in comparison to an objective, or as binary dummy variables indicating the presence or absence of a feature (Bracco et al., 2019).

Furthermore, a distinction is made between direct and indirect indicators. The former category unambiguously links to the studied subject and informs specifically about the issue in question. The latter, also called proxy indicators, includes measures that serve as an approximation from which to derive conclusions on a subject (Eurostat, 2014). When measuring policy outcomes, proxy indicators, for instance, take the form of good practices. By indicating whether these are implemented or not, it is possible to draw conclusions on the quality of the outcome. Proxy indicators are generally used with highly complex topics that cannot be measured directly unless with excessive effort that cannot be frequently or systematically conducted (Bracco et al., 2019).

A final distinction identified by Eurostat (2014) is between objective and subjective indicators. Hereby, the author referred to the objectivity or subjectivity of both the measured substance and the assessment methods used to interpret the data.

2.1.2 *Indicator Frameworks*

While indicators are versatile and diversely applicable, their usefulness depends on their integration into a broader, underlying indicator framework and on the capacity of the user to interpret them (Wu & Wu, 2012). Wu and Wu (2012) defined indicator frameworks as *"conceptual structure[s] based on sustainability principles and used to facilitate indicator selection, development, and interpretation"* (p. 72). Rooting indicators within a coherent set of ideas, the indicator framework, allows defining the type of information to be retrieved and drawing meaning from simple measurements based on their contextual interconnections (Eurostat, 2014). As such, indicators only start expressing information once understood as relative to reference values and embedded in a pre-defined structure. In turn, these should both be informed by a system of knowledge surrounding a particular topic area (Bracco et al., 2019). It is, therefore, the intention, need, or open question underlying an issue that characterizes the typology of indicator being applied to a framework (Bracco et al., 2019; Eurostat, 2017). This further means that indicators should be as closely calibrated to the connected policy targets as possible (Hammond et al., 1995). Indeed, Eurostat (2014) highlighted the importance of indicator frameworks to be consistent with theory, relevant for politics, and contain measurable objectives.

The frameworks most typically applied in sustainability policy at a European level are the Drivers, Pressures, State, Impact and Response (DPSIR) model of intervention for environmental protection and the sustainable development framework. Both are briefly explained in the following paragraphs (Eurostat, 2014):

- **DSPIR framework**: Based on assessing a cause-effect relationship between different areas of a system, the Organization for Economic Co-operation and Development (OECD) defined the pressure, state, response framework which was later expanded to the DPSIR framework by the European Environment Agency (EEA) (Eurostat, 2014; Hammond et al., 1995). As the name suggests, this framework informs policy-makers on the *"(1) driving forces [or causes for environmental phenomena]; (2) the resulting environmental pressures; (3) the state of the environment; (4) the impacts resulting from changes in environmental quality and; (5) the societal responses to these changes in the environment"* (Smeets & Weterings, 1999, p. 6). The framework serves as a base for performing measurements that describe how the environment and society interact. The cause-effect relationship is established in both directions, from humans to the environment and back, given the interrelation of all elements. It is in these interdependencies that lie meaningful insights for policy-making (Gabrielsen & Bosch, 2003).

- **Sustainable development framework**: This framework resulted from a collaboration between the United Nations Economic Commission for Europe, the OECD and Eurostat and is partly based on the Brundtland Report's definition of sustainable development (Joint UNECE/Eurostat/OECD Task Force on Measuring Sustainable Development, 2013). The framework was built on three dimensions: the "here and now" accounting for the wellbeing of the current, local generation; the "later" referring to the wellbeing of local generations in the future and; the "elsewhere" considering the wellbeing of humans in other places (Eurostat, 2014). Within these dimensions, the framework assesses how developments over time and countries affect natural, social, economic and human capital (Joint UNECE/Eurostat/OECD Task Force on Measuring Sustainable Development, 2013).

2.1.3 *Indicator Functions*

Within an indicator framework, the various single indicators have a selection of different functions. When applied to environmental policy-making, indicators serve at least one of four purposes identified by Smeets and Weterings (1999) and later expanded upon by Gabrielsen and Bosch (2003) for the EEA. The following list was further completed with research by Hiremath et al. (2013), Keirstead (2007) and Hammond et al. (1995):

- **Inform**: Indicators provide insight into how well systems perform, highlighting which environmental problems must be tackled and how they change over time. With this information, policy-makers can conduct a situational assessment of the state of the environment.
- **Support**: By reducing the quantity of data needed when constructing and harmonizing databases, comparison, evaluation and prediction are facilitated. Forward-looking, so-called prospective indicators are operationalized to aid policy development by identifying critical environmental issues and showing what direction decision- and policy-making should pursue.
- **Monitor**: Indicators allow to quantify sustainability performance and keep track of the effects policy responses have on the environment. Such backward-looking or retrospective indicators allow evaluating the effectiveness of implemented policies and identifying corrective action if needed.
- **Educate**: Indicators make sustainability efforts more visible and transparent by facilitating the communication of policy targets and performance with various audiences. Therefore, they help grow environmental awareness among a population, increase public support for policy-makers, and allow for citizen participation in the public environmental sphere.

Apart from their inherent qualities outlined in the list above, goal-setting and intentions by the user of an indicator set is another defining aspect of the operationalization of indicators (Feller-Länzlinger, Haefeli, Rieder, Biebricher & Weber, 2010). While Eurostat (2014) distinguished only between performance assessment and descriptive tools (described further in the following list), other authors have recognized various other uses supported by indicators. For instance, Shen, Jorge Ochoa, Shah & Zhang (2011) proposed classifying indicators as explanatory tools that inform about the momentary state of the environment, pilot tools that support policy-making and indicators used for performance assessment. The EEA, on the other hand, classified uses of indicators in the following five distinct categories (Gabrielsen & Bosch, 2003; Smeets & Weterings, 1999):

1. **Descriptive / contextual / situational**: These indicators give insight into a specific current condition. To improve the communicative value of a

descriptive indicator, the measure is often put in comparison with another variable or is represented as it changes over time.

2. **Performance / normative / progress**: These indicators can be composed of the same measures as descriptive ones but are presented in relation to policy targets or approximations of desirable sustainability levels. As such, they indicate the distance between the currently measured values and a desirable future situation or other types of reference conditions. These indicators, which assess the relation between policy response and the state, pressure or impact dimensions of the DPSIR framework, are particularly relevant when policy outcomes are connected to the accountability of specific groups or individuals.
3. **Efficiency**: Efficiency indicators depict the link between human activities and environmental pressures (drivers and pressures of the DPSIR framework). As such, a nation's environmental efficiency can be measured in terms of resources used or emissions and waste generated per unit of output, for instance.
4. **Policy effectiveness**: Such indicators depict how the environment changes under the influence of specific policies. They are therefore used to understand ongoing developments better.
5. **Total welfare**: Indicators for total welfare inform about the overall sustainability that can be measured from economic, environmental and social developments.

The various types of indicators can be used in combination. While some might point towards emerging phenomena, others can provide further explanations for them (Eurostat, 2014).

2.1.4 *Presentation and Indices*

Since indicators are used to better understand complex realities, using a single indicator can often be meaningless or highly misleading. Indicators are, therefore, typically used in combination with each other to shed light on all different facets of a phenomenon being studied (Feller-Länzlinger et al., 2010). The following paragraphs list various ways how indicators can be grouped and presented to enhance their usefulness for policy-makers.

Indicator sets are collections of various indicators covering a broad field of interest or political area and work in synergy to provide in-depth information on interconnected systems (Eurostat, 2014). The selection of indicators within the set is tied to a carefully pre-defined reference framework that combines theory and policy-making, as explained in chapter 2.1.2 (Wu & Wu, 2012). While each indicator measures a specific aspect of the subject analyzed, within an indicator set its meaningfulness extends beyond the single value and emerges once indicators are understood in relation to each other (European Commission, 2018b; Eurostat, 2014). Therefore, it is necessary to avoid diluting information uptake by including duplicates or redundant indicators in the set (Bossel, 1996). To make entire indicator sets more concise or digestible and increase their communicative value, they are often complemented with a reduced set of headline indicators representing the larger set (European Commission, 2018b).

Under the umbrella of indicator sets, scoreboards refer to condensed sets of key parameters used to measure progress and performance towards pre-defined targets (Eurostat, 2014). On the other hand, dashboards do not serve a normative function but rather display information drawn from a selection of areas of interest (Bracco et al., 2019). Dashboards are useful when combining different aspects of a subject would misguide interpretation. In fact, they present single indicators separately (rather than combined in one figure) so that underlying causes for phenomena can be identified (Stiglitz, Sen & Fitoussi, 2009).

However, indicator sets can be challenging to interpret, especially when the single values differ in the direction of change or amplitude or when phenomena cannot be understood by their individual components (Bracco et al., 2019). For this reason, parameters and indicators are often mathematically aggregated or weighted to obtain composite or aggregate indices. These are single measures that give insight into multidimensional, abstract concepts (European Commission, 2018b; Eurostat, 2014; Nardo et al., 2008). As such, composite indices can provide a concise but clear, holistic picture of the characteristics of a studied subject (Wu & Wu, 2012).

The main pitfall of using indices is that their creation is a complex process (selecting component indicators, normalizing, aggregating and weighting them) and based on a methodology that is prone to misrepresentations and bias and does not always fulfill rigorous scientific requirements (Böhringer & Jochem, 2007). Furthermore, if poorly constructed, composite indicators might combine various measures that should instead be studied separately. This leads to misleading result interpretations and over-simplification of an analysis (Nardo et al., 2008). It is, therefore, recommendable not to use composite indices when information can be displayed as distinct indicators in a more practicable way (Eurostat, 2014). Furthermore, it is imperative to use a sound and clearly defined methodology in the composition of indices that allows disaggregating measures to their single components without losing information (European Commission, 2018b).

Footprint-type or consumption-based indicators serve as a communication tool to gauge the sustainability of production and consumption patterns accessible to the wider public. They aggregate several environmental and economic concerns and generally extend to a wider geographical area, connecting a local and global view on policy-making (Bracco et al., 2019). Giljum, Lutter, Bruckner & Aparcana (2013) listed four types of footprints for the Sustainable Europe Research Institute: material, water, land, and carbon.

Finally, adjusted economic measures are indicators that correct or expand conventional indicators of economic performance, such as the gross domestic product, with elements of an environmental or social dimension (Bracco et al., 2019)

2.1.5 *Quality*

As described in previous subchapters, indicators are utensils that serve various functions from situational description and communication to support for decision- and policy-making (Feller-Länzlinger et al., 2010; Gabrielsen & Bosch, 2003). As such, the creation and selection of indicators for an indicator set must be purposefully made and follow rigorous processes to ensure truthful, reliable and meaningful interpretations of results (Eurostat, 2014). Amongst sets of quality criteria relevant to indicator development, the European Statistical System (2019) proposes 15 non-binding quality principles for statistical procedures in the European Statistics Code of Practice (see European Statistical System & Eurostat, 2017). Adherence to these quality criteria during indicator development or the composition of indicator sets ensures their integration into EU-wide statistical standards and therefore increases their relevance and utility for policy-makers within the EU (Eurostat, 2017).

Based on the consultation of academic literature and institutional quality guidelines (including the European Statistical System), several quality criteria for indicators and indicator sets could be identified. A first consideration to be made for indicator quality assessment is the indicator's relevance in the context of use (Eurostat, 2014). This implies that a clear link can be drawn between a measured item and a non-measurable construct it aims to inform about (Feller-Länzlinger et al., 2010). In order for indicators to be representative of an issue of interest, they must be responsive to change and policy intervention and be connected to a clear conceptual framework (Gabrielsen & Bosch, 2003; Moreno Pires, Fidélis & Ramos, 2014; Wu & Wu, 2012). A scientifically sound and well-documented methodology should be applied to construct this framework that aligns the indicator with theoretical consensus and policy-making practice (European Commission, 2018b; European Statistical System, 2019; Hiremath et al., 2013). With regards to the utility of indicators, quality criteria are determined by the indicators' comparability with reference values, their adaptability to contextual needs, the possibility to indicate developments over time, their ease of use and interpretability by various audiences (the communicative value) (European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Gabrielsen & Bosch, 2003). To be readily applicable, however, data accessibility must be granted at a tenable cost and with regular, reliable updates (Bracco et al., 2019; European Statistical System, 2019; Eurostat, 2014; Zavadskas, Kaklauskas, Šaparauskas & Kalibatas, 2007). All these quality criteria ought to be considered when constructing indicator sets, whereby it is crucial for selected indicators within an indicator set to complement each other and operate synergically. In this way, they represent the phenomenon under study integrally, comprehensively and coherently with the lowest possible number of single measures (Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007).

From the literature review of these indicator quality criteria, four characteristics emerged as relevant when considering the selection or creation of indicators: (1) relevance, defined as the appropriateness of the indicators to the researched item; (2) utility, the usefulness, functionality and benefit of an indicator to its user; (3) methodological soundness, referring to how transparently and reliably the indicator was created; and (4) measurability, indicating the reliability and timely availability of required data. A fifth category collecting quality criteria for the composition of entire indicator sets was also identified. Appendix 1 lists the quality criteria and various scientific and institutional sources that support them, as allocated to one of the five categories.

While the information given in this chapter serves as guidance for the assessment of features and compositional rationales of national bioeconomy indicator sets, the following chapters review existing literature on urban CBE. The goal is to determine the topics an urban CBE measurement tool ideally covers.

2.2 The Circular Bioeconomy

With the conceptualization of the bioeconomy in the EU's bioeconomy strategy in 2012, the groundwork was laid to transition the EU towards a sustainable, post-petroleum society that strives within planetary boundaries of resource regeneration (European Commission, 2012). Then, defined as the *"renewable segment of the circular economy"* in the 2018 update of the bioeconomy strategy, the necessity and potential of a sustainable, circular bioeconomy to reach global climate targets was recognized (European Commission, 2018a). As such, the concept is closely linked with international sustainability agendas such as the United Nations Sustainable Development Goals Agenda 2030 (SDG). It also aims to support the Paris Agreement by reducing greenhouse gas (GHG) emissions and modernizing the EU's industries with greener value chains (European Commission, 2018a; Stegmann, Londo & Junginger, 2020).

According to the EC (2018a), the bioeconomy interlinks ecosystems on land and water, including the ecosystem services they provide. It also encompasses the part of the primary sector that produces resources of biological origin and all industrial and economic sectors that use them. The bioeconomy, therefore, spans all systems and sectors directly linked to biological resources, as well as their practices and functions. The key in defining bio-based products lies in their entire or partial derivation from materials with biological origins, with the exception of those materials that are fossilized or embedded in geological formations. Hence, the bioeconomy comprises only materials that are inherently regenerative (European Commission, 2012). Several institutions, researchers and policy-makers adopt these descriptions, converting them into widely accepted and policy-relevant notions of the bioeconomy (e.g. Ellen MacArthur Foundation, 2017; Temmes & Peck, 2019).

The following chapters further elaborate on defining aspects of the bioeconomy and its connection to circularity. Then they dissect and map the value chain of a "desirable" CBE.

2.2.1 *Circular Bioeconomy Features*

Although, Temmes and Peck (2019) pointed out a lack of conceptual clarity and consensus on a definition of the bioeconomy, commonalities across the literature indicate convergence on its sustainable ideas surrounding resource origin and usage. The resources used in the bioeconomy are drawn from biological origin, so-called biomass, and are renewable in nature (Antikainen et al., 2017; World Economic Forum & Ellen MacArthur Foundation, 2017). Furthermore, knowledge-based and innovative biotechnological intervention results in the production, usage, processing, and distribution of such resources (Venkata Mohan, Dahiya, Amulya, Katakojwala & Vanitha, 2019). Therefore, advancing the bioeconomy requires support by funding and appropriate policy-making and is enabled through collaboration between policy-makers, researchers, and other stakeholders (Carus & Dammer, 2018; European Commission, 2012). By replacing non-renewable material, chemical and energy sources with renewable ones as inputs to various industries, the bioeconomy facilitates cross-sectoral transformative features with the potential to enhance sustainability beyond its own reach (Temmes & Peck, 2019). In fact, it is documented that the regenerative nature of bio-based resources and their products (from healthy food to fuels and chemicals) can make agriculture and industry more sustainable. This is enabled by reducing GHG emissions, improving waste valorization and biodiversity conservation (Carus & Dammer, 2018; Temmes & Peck, 2019). With necessary policy support and access to innovation, rural economies are stimulated through new business opportunities and the creation of jobs (Carus & Dammer, 2018; European Commission, 2018a; Hetemäki et al., 2017).

As a resource-focused concept, though, the bioeconomy also faces limits in effectively shifting production methods to more sustainable ones if other topics such as economic growth are not addressed simultaneously (D'Amato, Veijonaho & Toppinen, 2020). Indeed, as Giampietro's (2019) research showed, nature's limited availability of resources and high regeneration times inherently pose boundaries to the prevailing paradigm of continuous economic growth. This implies that the potential benefits of using biomass as a resource in lowering GHG emissions, for example, might rapidly be evened out or overturned by its excessive and wasteful usage (D'Amato et al., 2020; Stegmann et al., 2020). Striving within planetary boundaries, therefore, also means a shift towards more balanced production and consumption models. It means decoupling economic growth from energy and resource consumption and minimizing trade-offs between biomass production and the depletion of natural capital. This includes ecosystem services, such as cultural spaces, climate regulation and provisioning (Hetemäki et al., 2017; Venkata Mohan et al., 2019).

The bioeconomy strategy's circularity update in 2018 served to avoid such externalities connected to unsustainable practices and modernize the primary and secondary sectors (European Commission, 2018a). Society's reliance on natural capital and the ecosystem services it provides was, therefore, accounted for by circular utilization of resources and the regeneration of biodiverse and healthy, thus resilient ecosystems (Hetemäki et al., 2017; Palahí et al., 2020). In fact, by combining circularity with the bioeconomy, essential steps towards improving the sustainability of both concepts were made (Carus & Dammer, 2018; Venkata Mohan et al., 2019). As such, the CBE can be defined as the area of the economy where circularity and bioeconomy work in synergy.

To avoid conceptual ambiguity throughout this thesis and align understanding across scientific research and policy application, the following subchapters dissect the lifecycle of biomass and describe its desirable, circular value chain. A visual mapping, based on research from Carus and Dammer (2018), Ellen MacArthur Foundation (2013), EC (2018a), Smyth and Horan (2015), as well as the World Economic Forum and Ellen MacArthur Foundation (2017), can be found in Appendix 2.

2.2.2 *Sourcing*

Defined as the *"biodegradable fraction of products, waste and residues from biological origin [...]"*, biomass is the core resource harvested, transformed and consumed in the bioeconomy (European Parliament & Council of the European Union, 2009, p. 27). As a regenerative resource, it originates from the biosphere, where land and marine ecosystems use water, carbon and energy from the sun as nourishment in the production of biological raw materials (Carus & Dammer, 2018; Palahí et al., 2020). These energy-rich materials are then captured by activities in the primary production sector, such as agriculture, forestry or fishery (Ellen MacArthur Foundation, 2013; European Commission, 2018a). At this stage, sustainable production on land and sea is an essential component of the CBE as it underpins the sustainability of the bioeconomy and the potential of future circularity (European Commission, 2018a).

Currently, approximately 13 billion tonnes of biomass are annually collected from the global biosphere, material destined to be processed into food, animal feed, bioenergy, chemicals and materials (World Economic Forum & Ellen MacArthur Foundation, 2017). While rapid and constant urbanization implies that increasing amounts of biomass will be consumed in cities, the main production sites of biomass are still principally found in rural areas (Ellen MacArthur Foundation, 2017). Therefore, a functional and sustainable CBE needs the ability to close the loop between geographically distant and structurally different authorities. This favors both areas' economies, provides products and services to each region and regenerates the natural capital where exploited. As such, an urban CBE cannot be implemented and monitored without regard for its rural components (Palahí et al., 2020).

2.2.3 *Transformation and Utilization*

In a next step, the biomass finds its way to the secondary production sector, where it is processed to create three types of goods: variations of bioenergy, food and animal feed, as well as chemicals and materials, which can be further processed to a variety of products (Carus & Dammer, 2018; Ellen MacArthur Foundation, 2013). Adhering to the idea of making the bioeconomy circular and sustainable, increased value must be retrieved from raw material to use resources efficiently and minimize waste (Antikainen et al., 2017).

Cascading and value optimization

A way to increase resource efficiency while keeping demand for virgin raw material low, thus extending biomass availability within a system, is via the implementation of cascading use of biomass (Carus & Dammer, 2018). This practice, applied to the CBE, indicates the sequential use of biomass for different purposes over time, meaning that a product created within the bioeconomy finds at least one more usage as a material or energy source before reaching its end-of-life (Olsson et al., 2018; Stegmann et al., 2020). This is typically done by recycling, remanufacturing or reusing products and materials, as well as their waste and residues (Carus & Dammer, 2018; Ellen MacArthur Foundation, 2013). As the possibility for cascading depends on the value that can be retrieved from used products, processing fresh biomass into high-value products first, allows for higher value optimization over its lifetime and a longer usage time (Stegmann et al., 2020). Conversely, if fresh biomass is processed into low-value products, the resource quality is not efficiently maximized and is faster consumed (Carus & Dammer, 2018). Figure 1 visualizes how the cascading of biomass interlinks with the bio-based value pyramid and how resource quality deteriorates from each step of the cascade to the next. Material and chemical applications of fresh biomass would enable optimal value retrieval through cascading before reaching end-of-life as a source of energy (Stegmann et al., 2020).

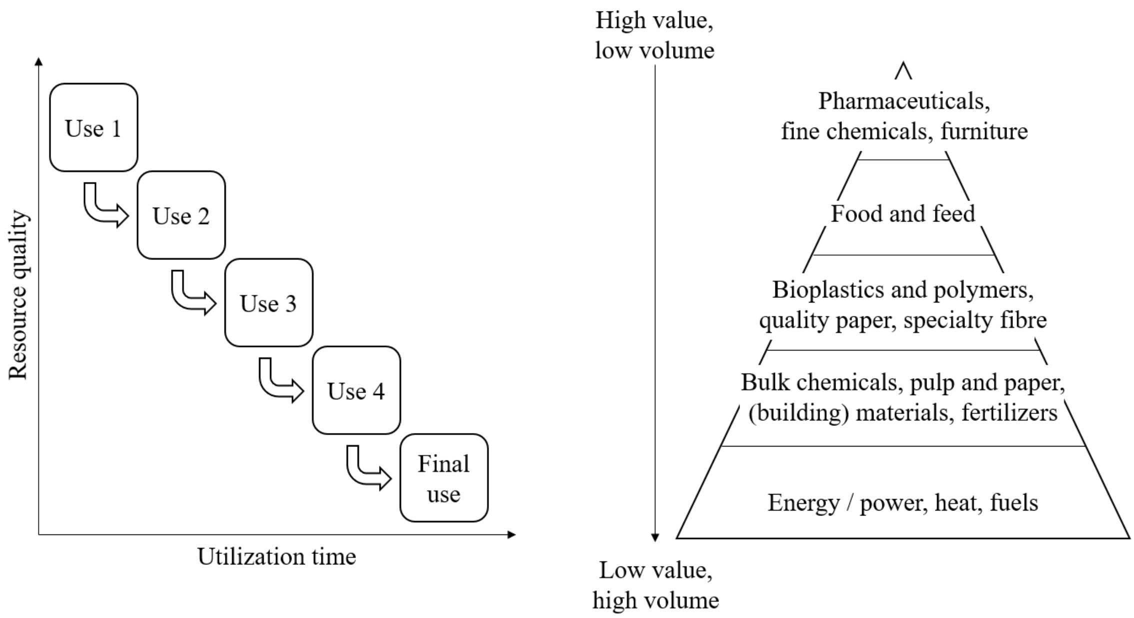

Figure 1: Link between cascading and the bio-based value pyramid (adapted from Antikainen et al., 2017, p. 18; Stegmann et al., 2020, p. 6)

Though options for further usage decrease as biomass application moves down the value pyramid, strictly maximizing cascading options by following the value pyramid has its trade-offs (Stegmann et al., 2020). Not only can needs for well-developed and expensive infrastructure hinder the viability of cascading, accumulation of toxins and other critical substances along the cascade can also impede a product from being further used before reaching its end-of-life (Carus & Dammer, 2018; Stegmann et al., 2020). Furthermore, cascading is only sustainable as long as required industrial processes, including collection and transportation of waste and residues, cause less negative impact on the environment than using virgin biomass. This implies that any cascading step must be justifiable (Carus & Dammer, 2018). Olsson et al. (2018) point out that this concept, meant to improve resource flows, is gaining acceptance as a simple hierarchy. This can become problematic because, if imposed as policy, it can lead to unwanted consequences such as a tendency towards a negotiation economy and unstable policy structures.

With CBE aiming to increase the bioeconomy's sustainability, the objective should not be to maximize cascading blindly but to optimize eco-efficiency in the bioeconomy and the value of biomass over time. Adapting CBE practices to local contexts, needs and capacities becomes vital in ensuring that the bioeconomy develops with consideration for the economic, environmental and social pillars of sustainability (Carus & Dammer, 2018; Stegmann et al., 2020).

Biorefineries

Various circular activities take place during the industrial production process in integrated biorefineries, the factories where biomass is processed into marketable products and energy (de Jong, Higson, Walsh & Wellisch, 2012; Gnansounou & Pandey, 2017). Ideally, co-production of different functional streams from the same biomass, coupled with internal recovery loops of waste and residues, for instance as energy sources, allows for efficient and sustainable resource valorization (de Jong et al., 2012; Zabaniotou, 2017). To enable practices such as cascading, therefore, biorefineries should have the capacity to utilize multiple types of inputs and to perform different processes and products simultaneously (Zabaniotou, 2017). This combination of multiple conversion technologies for biomass in one refinery decreases production costs and allows for more flexibility in resource usage and output (de Jong et al., 2012; Stegmann et al., 2020). Therefore, to support the CBE transition, biorefineries must be updated from mono-process and mono-output to multi-process and multi-output ones (Temmes & Peck, 2019). Furthermore, co-locating biorefineries with pre-existing facilities involved in bioprocessing is essential to benefit from cost savings and synergies in developing biorefining infrastructure (World Economic Forum & Ellen MacArthur Foundation, 2017).

Once the path through a biorefinery is complete, the resulting chemicals, materials, bio-products, food, feed and bio-energy are dispatched through retail and service to reach the consumers (Ellen MacArthur Foundation, 2013). From this stage on in a CBE, most of the products are kept in use through sharing, repairing and maintenance, looped back into the production cycle or recovered for their energetic value (World Economic Forum & Ellen MacArthur Foundation, 2017). For bio-energy and biofuels, as well as most cosmetics, paints, coatings and detergents, however, the consumption stage is the final one (Carus, 2017; Carus & Dammer, 2018).

2.2.4 *End-of-Life Options*

For all other products, the consumption stage of the value chain represents the start of a new life. Where biomass as waste or residues can be valorized and in what form depends on its properties and quality (World Economic Forum & Ellen MacArthur Foundation, 2017). Waste products stemming from higher-value products in the value pyramid inherently have more potential to be looped with circular practices than low-value products (Stegmann et al., 2020). Furthermore, intensive usage of products by consumers can affect their potential to be cascaded, for instance, when bioplastics become contaminated with hazardous materials. Accordingly, maintaining the quality and purity of biomass from collection to recovery allows for a more prolonged, high-value re-application of biomass (World Economic Forum & Ellen MacArthur Foundation, 2017).

To ensure this, successful implementation of a CBE at the end-of-life stage of organic matter requires a locally integrated, complete and functioning waste management system (Ellen MacArthur Foundation, 2017). This includes practices that range from waste collection and sorting for improved material recovery to the development of infrastructure and human capacity for more efficient processing of waste to avoid landfill (Stegmann et al., 2020). The waste collection, separation and processing stages of the value chain are vital in enabling cascading flows of organic matter and the recovery of energy and nutrients, which in turn generate vast economic savings for cities (World Economic Forum & Ellen MacArthur Foundation, 2017). According to the Ellen MacArthur Foundation (2018), up to 85 percent of organic waste can be collected and processed with well-implemented separation schemes. In order to function, however, locally customized approaches to the management of various waste streams are fundamental (Ellen MacArthur Foundation, 2017).

Urban organic waste includes: (1) solid waste, such as food waste from households and commercial centers; (2) agricultural and horticultural wastes which include wastes from activities in gardens and public parks, as well as manure; (3) agro-industrial waste generated in industries that process organic products; and (4) sludge and bio-solids which include human excreta and waste water (Cofie, Adam-Bradford & Drechsel, 2006). Saveyn and Eder (2014) added industrially processed biological materials to these four categories, stressing that some of them lose their biodegradability during chemical modification procedures. As highlighted in the following paragraphs, each waste category follows different valorization paths (Vis & Pfau, 2016).

The waste hierarchy

Figure 2 shows various waste treatment options from the most favorable, waste prevention, to the least preferable, disposal. The preferential waste treatment scheme proposed by this waste hierarchy is an integral part of the EU's circular economy action plan and is also applicable to organic waste (European Commission, 2015). Furthermore, the proposition of this sequence of waste treatment aligns with the cascading use of biomass. Both concepts aim to retain the quality of resources whereby waste from high-value products has more potential to be cascaded via higher levels of the waste hierarchy than waste consisting of low-value biomass (Stegmann et al., 2020). While the waste hierarchy optimizes the environmental outcome of waste treatment, it must be noted that it neglects the social, economic and logistical dimensions pertinent to waste management (Papargyropoulou, Lozano, Steinberger, Wright & bin Ujang, 2014). As a result, similarly to cascading, there must be flexibility and purpose in applying the concept.

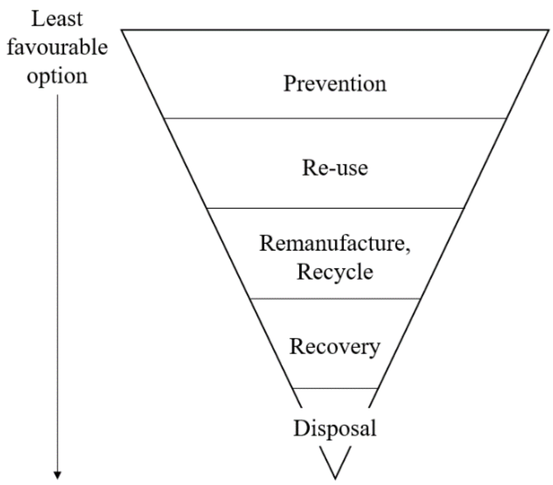

Figure 2: Waste hierarchy (adapted from Papargyropoulou et al., 2014, p. 3)

The first level of the waste hierarchy, waste prevention, differs from waste management on a temporal level: it is the component of the hierarchy that tries to decrease the generation of waste and with it, the need for waste management (Papargyropoulou et al., 2014). Preventing waste from being generated is the top priority in the hierarchy and must be followed by any actor and step along the value chain. Typically, in the production of goods, the focus lies on efficient usage of input materials and the redistribution or looping of residual by-products. Furthermore, designing products for circularity by avoiding hazardous materials and not mixing biodegradable with non-biodegradable materials, are practices that, along with repairability and durability of products enhance circular properties of industrial outputs (Department for Environment, Food and Rural

Affairs, 2011). For consumers, prevention practices span: not over-purchasing, sharing, maintaining and repairing bio-based products, whereby awareness creation and incentivizing consumers along the value chain are crucial to successful waste prevention (Gustavsson, Cederberg, Sonesson, van Otterdijk & Meybeck, 2011). Particular attention should also be paid to food waste, one of the most significant socio-economic issues within the bioeconomy (Principato, Mattia, Di Leo & Pratesi, 2021). Having a clear understanding of the amount of required food and food surplus as a safety net for a given population results in decreased amounts of wasted food (Papargyropoulou et al., 2014).

The following steps in the waste hierarchy: re-use, remanufacture, and recycling pertain to cascading biomass usage as described in chapter 2.2.3. These practices apply to waste and residue side-streams that can be re-fed into the cycle at an earlier production or consumption stage along the entire value chain (Carus & Dammer, 2018). In order to re-use or redistribute unused products, thus extending their lifetime, repairing, refurbishing and maintaining them in shape is vital (Department for Environment, Food and Rural Affairs, 2011). Furthermore, functioning and efficient return and collection logistics must be implemented (World Economic Forum & Ellen MacArthur Foundation, 2017). If products break or become unable to fulfill their purpose, their single components can be used to manufacture new products or can be broken down and recycled as new raw materials (Ellen MacArthur Foundation, 2013). Given the perishability of food, cascading food waste takes a slightly different form. Food surplus shall be "re-used" to feed people suffering from food poverty via redistribution networks and food banks, "remanufactured" as animal feed and "recycled" for its nutritional and energetic value via composting or anaerobic digestion (explained in the next paragraph) (Papargyropoulou et al., 2014).

Following the organic value pyramid (see Figure 1), during the recycling process of organic material, multiple outputs should be co-created in integrated biorefineries to optimize biomass value retrieval (Smyth & Horan, 2015; Stegmann et al., 2020). In a first step, high-value biochemical feedstock in the form of chemicals or materials, including bioplastics, is retrieved from the biomass (Smyth & Horan, 2015). As a lower-value application, the remaining biomass is treated with anaerobic digestion or composting to extract the nutrient value contained in it (Ellen MacArthur Foundation, 2013). Composting describes the mainly aerobic process of biological decomposition. Over time, tiny organisms transform organic materials into humus which plays a vital role in land regeneration and helps heal and fertilize the soil. In anaerobic digestion, micro-organisms decompose biodegradable material in an environment lacking oxygen. In that way, nutrient-rich organic fertilizers called digestates, as well as renewable energy as a by-product in the form of biogas are created (World Economic Forum & Ellen MacArthur Foundation, 2017). CO_2 emissions caused during these processes can also be recycled and captured as nutrients for plants via photosynthesis and be re-fed into the biosphere (Carus, 2017). Combining various treatment procedures as well as waste-flows in integrated biorefineries, therefore, creates an economically beneficial system. By taking advantage of synergies, it closes the bioeconomy loop while simultaneously decreasing needs and thus costs and externalities connected to extracting more virgin biomass from the environment (Ellen MacArthur Foundation, 2017).

The next step of the waste hierarchy refers to the low-value recovery of energetic properties from unavoidable biomass waste (Papargyropoulou et al., 2014). Energy recovery, together with the next practice, disposal, forms the final steps for cascading use, past which the biomass cannot be further valorized (Carus & Dammer, 2018). As a by-product of anaerobic digestion, biogas is won and can be fed into the gas grid or be transformed into electricity, ideally powering the same biorefinery responsible for its extraction. A wide array of organic materials can undergo anaerobic digestion, which, combined with its potential to replace synthetic fertilizers and fossil-based material, makes this practice a versatile, renewable and inherently circular catalyst for the bioeconomy (World Economic Forum & Ellen MacArthur Foundation, 2017). Energy recovery also includes incineration of organic materials if energy is retrieved during the process (Department for Environment, Food and Rural Affairs, 2011).

Collected organic waste and residues can also find their final destination in an incineration plant without energy recovery or in landfill. These two options of the waste hierarchy are the least desirable as the value inherent to the biomass is entirely lost. This is considered to be leakage and should be strictly avoided (Ellen MacArthur Foundation, 2013). In the EU, an average of 40 percent of organic waste reaches landfills, where it significantly contributes to methane emissions, a GHG with an effect 28 times greater than that of CO_2 (Ellen MacArthur Foundation, 2017). However, solutions exist to capture such GHG emissions and to generate electricity and thermal energy with them.

Wherever capacity for such technologies exists, the opportunity arises to convert a wasteful landfill into a circular energy-recovery facility and improve available infrastructure, rather than creating entirely new one (World Economic Forum & Ellen MacArthur Foundation, 2017).

With a better understanding of the functioning of the CBE, the next chapter investigates the role of CBE in urban contexts and how its development can be assisted by policy-making.

2.3 Urban Sustainability and Policy-Making

While their territories and populations grow, cities have to find ways to manage their bioeconomy to accommodate increasing energy, food, water and material needs (Hetemäki et al., 2017). Attempting to respond to urbanization while limiting its environmental impact is at the core of urban sustainability (Hiremath et al., 2013). Consequently, by addressing economic, social and environmental concerns through appropriate governance, cities can effectively confront opportunities and challenges arising from their bioeconomy (World Economic Forum & Ellen MacArthur Foundation, 2017). Simultaneously, urban areas become increasingly decisive in activities beyond mitigating pressures linked to their growth. As nodal points of innovative productive structures, research activities and human development, city governments have the tools and responsibilities to drive sustainable and ecological development (Romano, 2019).

The following subchapters elaborate on the form the CBE takes in urban areas, the barriers its development faces and the tools urban policy-makers can use to support it.

2.3.1 *Urban Circular Bioeconomy*

Social, cultural, political and economic realities have always been reflected by the physical urban landscape and a city's use of resources, economic productivity and wellbeing. The ever-increasing consumption patterns and expansion of commodified and privatized urban services accumulating from the early 1980s onwards have left strongly ingrained, destructive and self-perpetuating traces in today's urban infrastructure and regulatory spheres (Swilling & Hajer, 2017). At a time when international agreements and national socio-cultural shifts increasingly demand the inclusion of sustainable development to economic growth (for instance with SDG 11), city governments are recognized to hold responsibilities for leading such change (Romano, 2019; United Nations Sustainable Development Group, 2020).

Indeed, scholars agree that innovation and implementation of sustainable practices mainly take place on a regional and urban scale (Bezama, Ingrao, O'Keeffe & Thrän, 2019; Swilling & Hajer, 2017; Woodbridge, 2015). This is the case as city governments have the possibility to use a variety of policy levers to capture and influence the needs and concerns of business and urban citizens alike (Ellen MacArthur Foundation, 2019b). Furthermore, cities concentrate the availability of technology and skilled workforce and are hubs for experimentation and innovation. Responsible for 60 percent of public investments in OECD countries, their investment choices significantly influence the development of sustainable practices, key industrial sectors, and urban infrastructure (Romano, 2019). Among others, through industrial transformations such as the CBE, cities can accelerate such sustainable development. Envisioning a sustainable future of cities, Swilling and Hajer (2017) proposed the definition of livable urbanism. The concept envisages an aspiration that goes *"beyond 'minimising damage' to 'restoration' of nature by the way urban developments are designed and inserted into sustainable bioeconomic regions in ways that enhance both productivity and wellbeing"* (p. 3).

By acknowledging the need for regional integration of urban developments, this vision highlights the significance of the "local" component of CBE. Stegmann et al. (2020) supported this claim by arguing that close cooperation among local players in public institutions, research, agriculture and the industry is essential to enabling strategies that work towards a resource-efficient and circular bio-based economy. Involving local communities and implementing sustainable practices on a local level is also promoted by the United Nations to achieve the SDGs as it is more conducive to reaching truly balanced, rounded and coherent sustainability (United Nations Sustainable Development Group, 2020). This not only means adapting policy and practices such as waste collection systems to local capabilities and contexts but also leveraging opportunities and synergies among various parts of the CBE provided by innovative, sustainable solutions (World Economic Forum & Ellen MacArthur Foundation, 2017).

An essential factor challenging local integration is the urban-rural dichotomy that indicates the physical and psychological distance of urban dwellers from the countryside and nature despite their dependence on rural productivity (Palahí et al., 2020).

Overcoming these distances is vital to establishing a CBE as it means that cities and countrysides connect their economies and production-consumption cycles. Collectively, they can create infrastructure and industrial processes for circular generation, processing and usage of regenerative resources and transform currently unsustainable, costly practices into efficient and sustainable ones (Hiremath et al., 2013; Palahí et al., 2020). The EC's (2018a) bioeconomy strategy describes benefits for rural and coastal areas linked to the bioeconomy development in terms of job creation and economic growth, given the increased investment in knowledge, skills, new business models and innovation.

When such collaborations between companies and institutions in geographic proximity occur, regional bioeconomy clusters are formed (Stegmann et al., 2020). Such clusters are linked to an increased potential for innovative industrial development, productivity and efficiency and are a core indicator of the maturity of bioeconomy development across regions in Europe (Haarich, 2017; Porter, 1998). These clusters' productivity, scope, and focus depend on many factors, such as the type of active participants (e.g. agricultural players versus players in waste management) or their geographic location (e.g. proximity to waterways versus landlocked). Other influences are given by the type of input used (imported versus local or fresh biomass versus organic waste) and output produced (high- to low-value) (Stegmann et al., 2020).

Central to a bioeconomy cluster are biorefineries. As introduced in chapter 2.2.3, biorefineries are described as various applications and technologies that process natural resources through thermo- or biochemical conversion into building blocks of future products such as fuels or materials (Haarich, 2017). In order to mimic the global carbon cycle and therefore become sustainable and profitable, biorefining technologies ideally prevent waste creation. So-called "integrated" biorefineries can do this by generating multiple outputs simultaneously, re-using residues from other value streams, and having the capacity to process value from various sources of waste (Zabaniotou, 2017). Although bioeconomy clusters and integrated biorefineries are seeing momentum, particularly in the European north, most projects are still in the early stages of development and operate with restricted scope (Haarich, 2017; Stegmann et al., 2020).

These transformative visions and developments clearly show that cities have great economic opportunities linked to the CBE and sustainable development. Indeed, the EC recognizes the need and potential for cities to become hubs of CBE, calculating considerable savings of money, GHG emissions and the creation of jobs linked to its development (European Commission, 2018a). Practices such as waste valorization and subsequent regeneration of resources replacing fossil-based raw materials as well as the application of circular principles are sources of business opportunities under the sustainable development paradigm.

2.3.2 *Implementation Barriers and Consequences*

Nonetheless, this potential is not currently seized by a majority of municipalities in the EU, nor is circularity embraced as an economic opportunity. Besides worsening negative economic consequences, this neglect also bears a heavy impact on the environment. The processing of waste water streams as well as the organic fraction of municipal solid waste, for instance, is seen as a costly practice and often neglected (Dale Samset & Accorigi, 2020). Consequently, high amounts of organic materials reach landfills or run off through water bodies, generating GHG emissions and destabilizing entire ecosystems. Strong links have also been found with causes of severe health-related issues, loss of biodiversity and the depletion of nutrients from soils in rural areas (Dale Samset & Accorigi, 2020; Ellen MacArthur Foundation, 2017). Consequently, these soils cannot sustain the current high levels of exploitation through industrial food systems and mass production. Increased usage of synthetic fertilizers incurs land degradation, which further compounds the loss of biodiversity and with it, the loss of ecosystem services, including the provision of healthy food and climate regulation (Palahí et al., 2020; World Economic Forum & Ellen MacArthur Foundation, 2017). This, ultimately, converts urbanization, which has the potential of being an opportunity for economic and social growth, into the challenge to sustain food, material and energy security for growing populations (Hetemäki et al., 2017).

Among other structural problems lies the issue that a wide variety of ecosystem services nature provides, particularly those related to climate regulation and provisioning of raw materials can currently be benefitted from at no cost. Their abuse at the hands of business operations and industrial activities leads to disruptions of natural nutrient and carbon cycles and pollution through toxins and GHG emissions, as described above. This, in turn, causes significant damage to the environment and imbalances in the very same life-supporting ecosystems (World Economic Forum & Ellen MacArthur Foundation, 2017). By not accounting for this natural capital, businesses cannot identify their true asset value and the damage caused to nature by their operations (Palahí et al., 2020). Furthermore, as pollution does not have to be compensated for, the cost-saving potential of the bioeconomy is mostly neglected, which ultimately tilts the economy towards the usage of non-regenerative, polluting systems and creates an uneven competition between bio-based and fossil-derived products (Palahí et al., 2020; World Economic Forum & Ellen MacArthur Foundation, 2017). Mispriced externalities finally also misinform consumer choices, limiting the demand for sustainable versions of the same product (Palahí et al., 2020).

Similarly, misplaced subsidies and incentive systems promote highly CBE-averse practices and behaviors. Currently high and growing energy and fossil fuel subsidies in most EU countries hinder the investment in and uptake of modern, green technologies in the energy sector and therefore, their decarbonization (European Commission, 2020). Subsidies for waste incineration divert recyclable materials to less preferable waste treatment options, while ineffective incentive systems and demand structures lead fresh biomass to be disproportionately used for its energetic value rather than for higher-value applications (Carus & Dammer, 2018; Hetemäki et al., 2017).

These barriers to the CBE transition are imposed by unsustainable growth paradigms observed by Swilling and Hajer (2017) to be increasingly replaced by sustainable development.

2.3.3 *Policy Levers and Implementation Tools*

Despite sustainability requirements and practices needing to remain adaptive and reflective, it is crucial that policy-making strategically supports the transition from a linear non-renewable economy towards a CBE (Hetemäki et al., 2017). This transition has to result from close cooperation between governments creating the regulatory operating environment and businesses making use of investments to establish business operations (Hetemäki et al., 2017). As such, urban policy-makers function as facilitators, promoters and enablers of the CBE and create coherent structures for its development (Romano, 2019). This includes setting and managing a regulatory framework and engaging and incentivizing stakeholders through targeted action (Ellen MacArthur Foundation, 2019b).

Dietz, Börner, Förster & von Braun (2018) highlighted the importance of governments in guiding the development of the CBE through both enabling and constraining governance. The former mechanism is necessary to remove policy barriers. The latter limits the effect of socio-economic structures connected to fossil-dependent development paths, which reinforce the non-renewable, linear status quo and disincentivize markets from shifting to CBE. Similarly, to achieve an ideal state of the bioeconomy, the OECD (2018) split available policy tools into three types of instruments: (1) regulatory command and control instruments, which include permits, quotas, standards, and requirements; (2) economic instruments, such as taxes, fees, subsidies, externality pricing and fines; and (3) information and voluntary instruments, referring to labels and certifications or negotiated agreements. Likewise, the Ellen MacArthur Foundation (2019b) identified financial support, fiscal measures, legislation, and regulation as relevant policy levers. However, it also added the creation of a shared vision and engagement of stakeholders through awareness-raising, public-private partnerships and capacity building. Furthermore, the Foundation expanded on urban management instruments that span urban planning, asset management and public procurement (Ellen MacArthur Foundation, 2019b). This last category of levers is particularly essential in shaping the physical urban structures and infrastructure and determining how assets, especially in CBE-relevant areas, such as building, transportation and waste management, are used. Therefore, decisions related to urban planning can either support or hinder the development of the CBE in the long run (Romano, 2019; Swilling & Hajer, 2017).

Acknowledging the complexity of systemic changes required for a CBE also means realizing that the transition is rooted in technological advancement (Wilts & Steger, 2019). Accordingly, another way of creating a CBE enabling environment is by supporting local research, development and innovation programs (Hetemäki et al., 2017). As part of the Horizon 2020 Framework Programme (2019), a challenge was issued to facilitate more investments in projects advancing urban CBE strategies. Many CBE projects suffer from a lack of access to financing, particularly in the early stages of development because sustainable technological advancements are expensive and bear a variety of business-, regulation- and market-related risks (Hetemäki et al., 2017; Leoussis & Brzezicka, 2017). This applies particularly to disruptive, cross-cutting research that merges political, economic, environmental and foresight research with biotechnology, chemistry and engineering (Hetemäki et al., 2017). Solutions for urban policy-makers to support such innovation include minimizing transaction costs and removing administrative, legal and other market barriers for mainstreaming CBE investments. These investments foster innovative technologies and can drive a transition towards a CBE by creating favorable market conditions and increasing consumer awareness and demand for bio-based products (Kardung et al., 2021).

On a regulatory level, policies that share or reduce innovation risks should be in place, while the public sector should support highly risky investments (Hetemäki et al., 2017). As an approach to ensuring risk diversification, the European Circular Bioeconomy Fund, an investment fund that collects capital for a CBE transformation for the European economy, offers investors risk adequate returns (European Circular Bioeconomy Fund, 2021). Simultaneously, this fund, set up by the EC and the European Investment Bank, gives innovative but already slightly matured businesses in CBE access to finance in the form of equity or debt (European Circular Economy Stakeholder Platform, 2019). Further initiatives are, however, required to support early-stage projects and enable important innovations to reach the economy in the first place (Leoussis & Brzezicka, 2017).

Finally, moving from a non-renewable, linear economy to a CBE requires the contribution and support of businesses and society at large (Palahí et al., 2020). To gain widespread buy-in, CBE strategies must be supported by aligned policy and incentive systems that establish a CBE enabling environment (Hermann, 2021). Streamlining strategic priorities and enabling incentive systems tackling GHG emissions, for instance, includes measures to direct economies towards low-carbon practices. This can be done by increasing carbon prices, removing producer and consumer subsidies for the consumption of fossil-based products, targeting unsustainable economic sectors with policies that incentivize them to become greener and enabling circular practices through appropriate financial support (Hetemäki et al., 2017).

2.3.4 *Aligning Assessment Efforts*

To make targeted use of such governance methods, policy-makers must be able to assess how vastly a CBE is developed in their area of governance, detect faulty developments and streamline corrective action (European Commission, 2017). Indicator sets for the CBE bear the benefit of easing the evaluation of progress and identification of areas with the need for policy intervention on a cross-sectoral and cross-policy level (Robert et al., 2020). However, the validity and applicability of such assessment systems are constrained by a variety of factors ranging from data availability at a city level to the alignment with local capacities and strategic objectives (Robert et al., 2020; Romano, 2019).

Such alignment efforts were started by the EC (2018a), which in its updated bioeconomy strategy included an action (Action 3.2) aiming to create an EU-wide, coherent CBE monitoring framework, the BMS mentioned in chapter 1.1. Although it specifically stated that cities should become “CBE hubs”, it remains open to what extent such efforts can trickle down to the local, implementation-oriented level, given that local governance is only superficially addressed by the bioeconomy strategy (Giuntoli et al., 2020). To account for specific urban level challenges, such measures should ideally combine evaluations for CBE success, the amount and type of governance aimed at the CBE transformation and their outcomes (Wilts & Steger, 2019).

As the OECD found in a report about the circular economy, in the absence of practicable tools, cities likely initiate their own indicator development (Romano, 2019). Creating a tailored assessment tool for a city's specific needs bears various benefits, mainly connected to the autonomy in defining goals, contributions, and measurement approaches. Another alternative are assessment tools prepared by non-governmental organizations. Indeed, the advancement of the CBE has spurred the creation of a variety of other indicator frameworks in recent years that enable measurements and evaluations of the CBE at various levels of the private and public sectors (Ecorys, 2019). These are attractive to urban policy-makers because they are often adaptable and usually easily accessible. However, their usage bears the risk of implementing a misaligned set of measures that loses its relevance and instructive capacities (Eurostat, 2017). Diverging from national bioeconomy alignment also means decreasing the possibility of benefitting from synergies in activities such as data collection and might result in the pursuit of counterproductive CBE development (European Commission, 2018b; Robert et al., 2020).

The drawback of using a readily existing indicator framework, rather than a purposefully created one, can therefore manifest in the faulty interpretation and operationalization of resulting measures or their inefficient, unfocused application (Eurostat, 2014). Among other reasons, national governments do, therefore, not aim to create an indicator set that perfectly fits several governance levels. Nonetheless, setting the base for regional alignment within their tools allows for unidirectional efforts and a holistic approach to measuring the CBE across the EU, its member states and local players (Robert et al., 2020).

2.4 Conceptual Framework

The evaluation of EU-wide national CBE strategy assessment tools and whether these are fit for use at an urban governance level necessarily has to take a multi-disciplinary approach. It must tie statistics, politics, business and ecology, and be situated where EU-wide and national policy-making intersects with local economic realities. As such, this thesis is embedded within three research areas: (1) notions of indicator theory and practice; (2) CBE research; and (3) an urban policy context. The knowledge synthesized in this literature review informed the methodology and analysis processes as depicted in Figure 3.

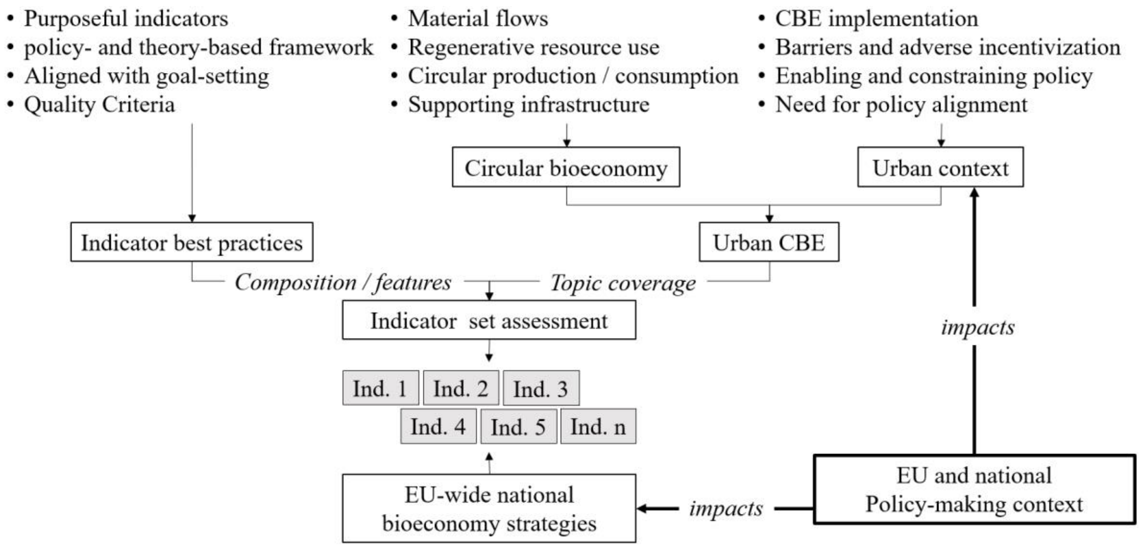

Figure 3: Conceptual Framework

To conduct this research, the guidance given by theory and best practices for the composition and usage of high-quality indicator sets influenced the evaluation of the compositional rationales of national assessment tools. It also allowed to better understand the sets' features and potential to be scalable to urban policy levels. Judging an indicator sets' links to policy-making and goal-setting as well as purpose and quality must be considered for a top-level assessment of the monitoring frameworks.

On the other hand, the CBE and urban context represent the topics of interest to be measured by urban policy-makers. The assessment of the indicator sets' content is guided by parameters such as circular and regenerative processes and material flows, as well as urban CBE vision, barriers and policy levers. Accounting for these topic areas allows gaining comprehensive insight into the breadth and depth of the indicator set contents.

The next chapter outlines the methodology adopted to conduct the indicator set collection, assessment and analysis to answer both research questions.

3 Methodology

Two separate workstreams led to the elaboration of the research objective of this thesis. In the first one, all tools required to assess the nationwide bioeconomy indicator sets were created. These comprised a factsheet about their features, a quality assessment tool and a topical assessment framework. The second workstream consisted of the indicator set analysis and included all steps required to assess their features, components and covered topics to determine their suitability for urban policy-making. As the second workstream was constructed on the first one, they were conducted sequentially.

This chapter outlines the methodology adopted for the elaboration of both workstreams. The process included four steps: (1) identification and specification of indicator set aspects relevant for urban policy-making; (2) construction of the factsheet and quality and topical assessment frameworks; (3) indicator set collection; and (4) indicator set analysis, whereby steps one and two were integrated into workstream one and steps three and four in workstream two.

3.1 Workstream One: Assessment Tools

The first workstream mainly served as a preliminary step for the research conducted in the second workstream. It transformed knowledge gained from the literature review into an operable conceptual basis and created a connection between secondary and primary research. It resulted in the basis for the assessment of composition, features and topics covered of national bioeconomy indicator sets.

3.1.1 *Composition and Features*

An indicator set factsheet and a quality assessment tool were created to better understand how the various collected indicator sets were built and whether they fulfill essential requirements for coherent indicator development.

The factsheet

Besides the title and year of issuance of the respective bioeconomy strategies, four items resulted from the literature as relevant to creating purposeful and thorough indicator sets. These items were listed in the indicator sets' factsheets as the criteria to be assessed. Their rationales are explained in the following list:

1. **The strategic goals**: For an indicator set to give a comprehensive, rounded and parsimonious view on the studied subject and appropriately assist policy-

making, its components must be aligned with the strategy's goal-setting (Feller-Länzlinger et al., 2010).

2. **The approach to circularity**: The approach to circularity taken by a bioeconomy strategy can significantly influence the features of its assessment tool. Its relevance was given by the aim of this thesis to evaluate how bioeconomy indicator sets allow measuring the CBE.
3. **Framework**: This item served to identify the rationale behind the indicator framework on which the assessment tool is built and determine whether it is rooted in both policy-making and theory.
4. **Indicators**: The single components of the indicator sets were assessed based on their: typology, indicator sources, data sources and collection frequency, scalability and aggregation level. These aspects resulted as relevant from the literature to give insight into the interconnectedness of the various measures, their flexibility and scientific rigor.

The factsheets, including filled-in information of the collected indicator sets, can be found in Appendix 3.

The quality assessment tool

The quality assessment tool was based on the quality criteria retrieved from the literature in chapter 2.1.5. It was used for the data analysis in the same form as presented in Appendix 1.

3.1.2 *Topical Coverage*

Based on the literature review, a topical assessment framework was created to better understand the extent of topics covered by indicators in the various bioeconomy assessment tools.

Before composing the assessment framework for the topical coverage of the collected indicator sets, however, the framework's purpose had to be aligned with the users' needs (Feller-Länzlinger et al., 2010). This included identifying the primary audience (urban policy-makers) and measuring objectives (the urban transition towards a CBE). Next, a set of 54 keywords and key phrases derived from the literature were collected to compose a framework capable of reflecting the multidimensionality of urban CBE and interconnecting its various components (Nardo et al., 2008). From this set, duplicates and ambiguous terms were combed out by combining topics and assimilating concepts. 36 components resulted from this activity, each describing one facet of urban CBE. For a more structured analysis, an information architecture exercise was used to thematically group these components into six categories, each falling under one of three aspects of urban CBE. This enabled a systematic analysis of single components but also of entire areas of urban CBE. The three aspects cover the CBE, governance mechanisms, and sustainability outcomes, which in combination enable accounting for specific urban-level challenges as defined by Wilts and Steger (2019).

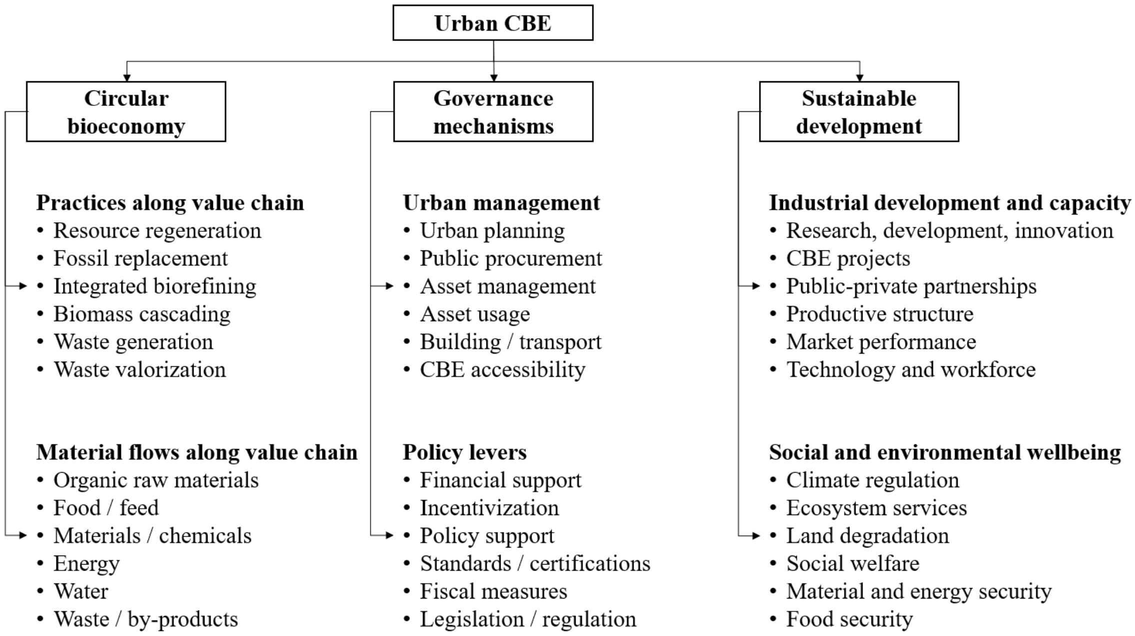

Figure 4: Structure of the indicator set assessment framework

As visible in Figure 4, the components related to the aspect: “CBE” focused on both categories, “material flows” as well as “practices along the value chain”, spanning from resource to waste material. The aspect: “governance mechanisms” encompassed both the management and shaping of the physical urban landscape as well as policy levers of financial or regulatory nature. Finally, “sustainable development” spanned components relating to economic performance and development, as well as social and environmental sustainability.

Once identified, the 36 components were operationalized (see Appendix 4) to gain a more specific and unambiguous overview of the analyzed facets and to provide a clear definition of what each of them aimed to assess. This concluded workstream one and set the basis on which to collect and examine national bioeconomy indicators in workstream two.

3.2 Workstream Two: Indicator Set Assessments

With a complete and operationalized assessment basis, the second workstream entailed the collection of EU-wide national bioeconomy strategies, their indicator sets, and the evaluation of their fit for urban CBE measurements.

3.2.1 *Research Design*

As this thesis aims to identify compatibilities and gaps between indicator sets currently available at a national level and the needs of urban policy makers for a measuring tool, it consists of applied research. As such, an evaluative research design, as defined by Wollman (2012), was adopted.

The method applied to analyze available indicator sets in a scientifically sound manner was adapted from a systematic review. This procedure aims to collect, appraise, extract and utilize information from existing literature surrounding a specific topic in a categorical manner (Grant & Booth, 2009). Similarly, this thesis: collected EU-wide national bioeconomy strategies, appraised their approach to bioeconomy monitoring, extracted information from the indicator sets they proposed and used it to answer the research questions. The Cochrane Collaboration based the process for systematic literature reviews on the steps outlined in Table 1 (Bilotta, Milner & Boyd, 2014; Higgins et al., 2019). A description of how each step was applied in this thesis is further illustrated in the same table. The subchapters following Table 1 provide further detail regarding the sampling, data collection and analysis methods applied throughout the research process.

Table 1: Systematic review process (adapted from Bilotta et al., 2014, p. 69)

Steps of a systematic review	Adapted to the present thesis
1. Formulate question	*See chapter 1.2*
2. Develop protocol	• Definition of search criteria and platforms for EU-wide national bioeconomy strategies *See chapter 3.2.2*
3. Conduct search	• Collection of national bioeconomy strategies
4. Select studies	• Identification of strategies that propose an indicator or monitoring framework for the bioeconomy transition • Dismissal of strategies without monitoring framework

5. Appraise studies	• Appraisal of strategic goals, approach to circularity and structure of the proposed indicator frameworks and sets (see Appendix 3) • Control of the quality of each indicator set (see Appendix 1)
6. Extract data	• Extraction of indicators from each set and matching with components of the topical assessment framework (see Appendix 5)
7. Analyze and interpret	• Description of the indicator sets, based on the extracted data • Completion of a heat map analysis to identify intensity and gaps in how the collected indicator sets cover the areas of relevance to urban CBE policy-making • Evaluation of the appropriateness and meaningfulness of national indicator sets for CBE assessment at an urban level with consideration for the appraisal in step 5
8. Disseminate and update review	• Submission of the thesis

3.2.2 *Sampling and Data Collection*

For the scope of this research, data collection referred to steps two through four of the process laid out in Table 1. The indicator sets proposed by the national bioeconomy strategies of EU member states were understood as data that had to be collected and analyzed to answer the research questions. As the questions specifically refer to the EU member states' officially adopted national bioeconomy strategies, these strategies represented the population under study. For data collection, the sample was equated to the population as a restriction of data sources would have compromised the relevance of the findings. Moreover, the number of bioeconomy strategies in existence during the research process allowed the assessment of the entire population. As such, purposive sampling in the form of a census, as defined by the OECD (2007), was applied (Black, 2009).

Defining and accessing this population was done by designing a structured and intentional research strategy in line with a systematic review. Two parameters were applied: (1) the nations under analysis had to be EU member states during the period of research (August 2021); and (2) they had to have an officially adopted bioeconomy strategy. The identification of this population was conducted referencing the EC's (2019a) Bioeconomy Country Dashboard, which lists countries with a *"Dedicated*

Bioeconomy Strategy at national level" (sec. Bioeconomy country dashboard). Although slightly outdated, this was the last systematic review conducted by the EC on national bioeconomy strategies and was therefore adhered to. Out of the 27 member states, one-third fulfilled both conditions. Therefore, the strategies that constituted the population were those issued by Austria, Finland, France, Germany, Ireland, Italy, Latvia, the Netherlands, and Spain.

Each national bioeconomy strategy was then collected through desk research and screened for any information on bioeconomy assessment approaches. Three different scenarios were encountered and, where needed, mitigated:

1. The national bioeconomy strategy directly included an indicator set. This set was used for the data analysis. (In the Finnish bioeconomy strategy, an indicator set is proposed which slightly differs from the indicators the country actively applies through its statistical database (Natural Resources Institute Finland, 2021). The latter was, therefore, the one referred to in this thesis).
2. The national bioeconomy referred to a separate document for an indicator set or further explanations about the indicator set. These documents were searched for on the same website as the one which issued the bioeconomy strategy, usually a government website. For this research, Boolean strings were used on Google, with a timeframe for results that spanned from the year the national bioeconomy strategy was issued to the present. The Boolean strings were created to search only the indicated website, based on keywords retrieved from the bioeconomy strategy and with parsimonious Boolean operators.
3. There was no reference to monitoring efforts in the bioeconomy strategy. In this case, the same website as the one which issued the bioeconomy strategy was searched for possible measuring tools. For this research, the following Boolean string was used on Google, whereby the keyword "bioeconomy" was spelled as found in the national bioeconomy strategy and the keyword "indicat*" was replaced with the synonyms "monitor*", "assess*" and "evaluat*": *site:[selected website] "bioeconomy" AND "indicat*"*. Again, the timespan was set to the period from the issuance of the strategy to the present.

3.2.3 *Data Analysis*

Data analysis referred to steps five through seven of the proposed process (see Table 1). During the data analysis, the goal was to scrutinize national-level indicator sets and determine whether urban policy-makers can use them to assess their city's CBE development.

With the factsheet, the indicator sets were first appraised based on their features and compositions to better understand indicator structure and thoroughness. While the extraction of information to the factsheets was conducted without valuation, the indicator set features served as supportive or constraining arguments during the data interpretation.

The quality evaluation of the indicator sets was based on a grading of the single quality criteria for each indicator set on a three-point Likert scale (1 = clearly not met; 2 = ambiguous; 3 = clearly met). Only three points were chosen to reduce bias in the quality grading. Indeed, by not further subdividing the quality grading, the overall quality could be concluded to be high, low or ambiguous, which sufficed to draw conclusions within this research. The quality assessment was based on the perspective of an urban policy-maker and therefore gives insight into the indicator sets' quality to city-level governance.

With the quality assessment completed, the next step was to analyze the breadth and depth of urban CBE topic coverage within the indicator sets. Therefore, each indicator was extracted and matched with one component of the assessment framework (see Appendix 5). Where available in the bioeconomy strategy or attached documents, specifications and explanations for the various indicators were considered to guide this attribution process. Each match of an indicator with a component resulted in one point for that component. Therefore, the total points per component reflected the number of times it was represented within an indicator set. Therefore, the breadth was assessed by the number of different components covered by an indicator set, while the depth was reflected by the quantity of indicators attributed to a single component. The three following issues arose during the assessment:

1. Some sets were constructed as a series of measures that were applied to a variety of sectors. As the disaggregation of a measure to sectors is simply a question of scalability, each measure and each sector was only counted once to not overrepresent them.

2. Two indicators lacked conceptual clarity. As both still resulted as broadly attributable to a framework component, they were included in the assessment.

To summarize this assessment, a heat map was created to visualize how often the various components, categories and dimensions were covered by the indicator sets individually and collectively.

As the quality and topical assessments included an unavoidable amount of bias, both procedures were conducted three times, whereby divergent results were investigated and aligned.

The three types of content assessments (factsheet, quality grading and topical coverage) were then studied in combination with each other to evaluate the appropriateness, meaningfulness and relevance of nation-wide indicator sets for urban policy-makers. Answering the research questions required weighing findings with each other and the support of specific information retrieved from the study of the assessment tools. Although the quantification of present versus absent quality criteria and topical components streamlined data extraction from the indicator sets, the data assessment did not pursue their quantitative understanding. Hence, a qualitative approach was adopted by this methodology in answering the research questions.

The findings retrieved with the above methodology are outlined in the following chapter and supported by visualizations of the data analysis.

4 Findings

This chapter lays out the salient observations made during the assessment framework creation, data collection and analysis. They encompass four areas, which also represent the structure of this chapter: (1) the national strategies and their monitoring systems; (2) the indicator set appraisal; (3) the indicators' content assessment; and (4) composite findings from joint observations of the above points.

4.1 National Strategies and Monitoring Systems

One of the most pertinent and clear findings that emerged from the data collection is that the development of national bioeconomy strategies is not yet a widespread practice across the EU member states. While most of the 27 states had some amount of policy initiatives related to the bioeconomy, only nine had officially adopted a dedicated bioeconomy strategy at the time of the EC's (2019a) review: Austria, Finland, France, Germany, Ireland, Italy, Latvia, the Netherlands and Spain.

The availability and scope of measuring tools accompanying the strategies seem to follow the extensiveness of elaboration of the strategy itself. While strategies, such as those of Germany or Italy include an extensive set of indicators, others do not propose any – or, as was the case with Finland and Spain, include a rather superficial one. Similarly, only the German and Finnish strategies, and to a lesser extent the Italian one, offer explanations and rationales for their monitoring frameworks. Although the Austrian and French strategies reference external documents or action plans for their monitoring approaches, these were not found with the systematic research. Meanwhile, the Dutch strategy, a relatively broad policy statement, does not mention any monitoring approach at all. Similarly, the Latvian and Irish strategies do not refer to any monitoring systems tailored to the bioeconomy strategy. It resulted, therefore, that the only EU member states proposing an accessible measuring framework for the implementation of their bioeconomy strategy were Finland, Germany, Italy and Spain.

The next subchapters present findings emerging from the assessment of these four monitoring frameworks.

4.2 Indicator Set Appraisal

As visible in Appendix 3, where data for this subchapter is summarized, three different approaches were applied to the construction of the analyzed indicator sets:

1. **Finland and Spain**: A series of measures was applied to a series of sectors, resulting in a matrix of items to assess. The Spanish tool also includes two non-sectoral measuring categories.
2. **Germany**: Strategic and integrative goals were defined in the domains of social, environmental and economic sustainability. These were split into criteria and matched with indicators.
3. **Italy**: Measuring categories were set and matched with fitting indicators. No reference was given to the source of these categories.

Among the four, the German set resulted in being the most elaborate one in terms of quantity and variety of indicators presented, as well as in terms of provided explanations. It gives a rounded view of the bioeconomy, clearly links the indicators to the strategy's goals, and adheres to sustainability frameworks supported by both policy-making and academia. Italy as well follows up on several of its strategic goals in the indicator set. The Finnish and Spanish indicators broadly cover the strategic goals of growth in competitiveness and competence of the bioeconomy with growth and output-oriented measures. Both these indicator sets, however, lack a clearly policy- and theory-based indicator framework.

In terms of coverage of the circular economy within the single indicators, the frameworks vary. Both Italy and Spain pointed out the importance of circularity in their bioeconomy strategies. However, while Italy included it in the strategy's overarching goals as well as indicator set, Spain only mentioned it in the introduction and did not follow up on it throughout the rest of the strategy. Circularity is also not reflected within the Spanish monitoring framework, besides by implication in the category *"Metric tons of processed waste %"* (Secretería de Estado de Investigación, desarrollo e innovación, 2016, p. 45). The Italian indicator set's direct circularity measures tackle energy, water and waste only, while indirect interpretation of various other measures may shed light onto a wider area of circular materials and practices. The German indicator set is the one that most thoroughly follows up on its goal of making the bioeconomy more circular, as it takes a more profound and holistic approach to circularity measures. While it does not explicitly disaggregate its measures onto the circularity of various sectors of the bioeconomy, the circular practices are represented in footprint type indicators regarding material, water and ecosystem usage. Furthermore, various indicators refer to the degradation and regeneration of resources and the circulation of CO_2 within ecosystems. Finally, the German circularity indicators are also directed towards economic aspects of the bioeconomy. Such measures include the productivity of resources, revenues generated by circular firms, or ISO 14001 certifications, which environmental management systems that incorporate circular principles can receive (International Organization for Standardization, 2015). Finally, Finland did not mention circularity in its bioeconomy strategy at all and consequently did not present any measures for it in its monitoring approach.

Next to the coverage of the circular economy and the fundamental indicator set composition, strengths and flaws emerged from the feature and quality assessment of the single indicators. Both the Finnish and Spanish indicator sets, using only a few measures, rely on quantitative, direct and descriptive indicators and therefore present a lack of variety in their typology. In both cases, the indicators only serve a descriptive and performance-oriented function, thus limiting the potential for interpretation of cause-effect relationships. Additionally, they are scalable only to the various sectors and not to other policy-making levels. While the Spanish set does not disclose any information about the data source and collection frequency, the Finnish one links to the national statistics database that gives more specific references of data sources, as well as explanations to the data collection and calculation methods (Natural Resources Institute Finland, 2021). Furthermore, the Spanish strategy lacks definitions of the objects to measure within the various categories, which creates ambiguity in their understanding and application. For instance, it combines the measure of "employee numbers" with the item: "sustainability indicators" but gives no further insight into how to measure an appropriate figure.

The opposite is the case with Germany and Italy. Both list specific indicators and indicator sources in their monitoring frameworks, and with it, assist the correct understanding of the measurement object and application. In contrast to Finland and Spain, these sets also include an explicit statement of scalability to international, national, regional and local contexts for Germany and national and regional contexts for Italy. These frameworks include both quantitative and qualitative measures, as well as direct and indirect ones. Descriptive measures are accompanied by performance, efficiency, policy effectiveness and, in the case of Germany, also total welfare measures, allowing a more multifaceted analysis. The German set extensively presents data sources and data collection regularity and offers various sets for headline and specific indicators, thus allowing to aggregate values. Meanwhile, the Italian set does not aggregate its measures and states that the tool was created based on areas with guaranteed data availability.

Table 2: Quality assessment of indicator sets based on criteria in Appendix 1

Country	Relevance				Utility							Methodologically sound					Measurability			Indicator sets		Total
	Aligned with audience	Representative	Accuracy / reliability	Responsive	Shows development	Useful for planning	Comparable	Causal explanations	Adaptable to context	Easy to interpret	Implementable	Sound statistics	Scientific framework	Supported by policy	Stated methodology	Impartial sources	Affordability	Data regularity	Data accessibility	Parsimonious	Complementary	
Finland	1	1	1	3	2	1	1	1	2	2	3	1	1	3	2	3	N/A	3	3	1	2	37
Germany	2	2	3	3	2	2	2	3	3	3	3	3	3	3	3	3	N/A	2	3	2	3	53
Italy	2	2	2	3	3	2	2	3	3	3	3	3	2	3	2	3	N/A	3	3	2	3	52
Spain	1	1	1	3	2	1	N/A	1	2	2	2	1	1	3	1	N/A	N/A	N/A	N/A	1	2	25

The quality assessment in Table 2 reflects the above-stated findings, whereby higher ratings reflect indicator sets with higher quality from the perspective of urban policy-makers. It shows that various pitfalls, particularly in the categories "relevance" and "utility", compromised the quality of Finland's and Spain's indicators. Several criteria for these two frameworks were "clearly not met". Furthermore, it shows that the lack of supportive documentation to the indicator set impacted the quality rating of the Spanish assessment tool. Consideration must also be given an assessment of the reliability of the Finnish measures by the Natural Resources Institute Finland that stated: *"In many sectors, there are plenty of factors reducing the reliability of the results. That is why the current bioeconomy calculations do not meet the quality criteria for official statistics"* (Sauvula-Seppälä & Hautakangas, 2019, p. 1). A similar assessment of the Spanish framework was made by the EC (2019a), stating that Spain's national statistics system would not be able to obtain objective numbers about its bioeconomy. Hence the low scores in "methodological soundness".

Regarding quality rating, the German and Italian tools scored similarly, whereby the differences lie in certain criteria being ambiguously represented versus "clearly met". No quality criterion was "clearly not met" by these frameworks.

4.3 Content Assessment

The thoroughness of the features and composition of the indicator sets was also reflected in the breadth and depth of urban CBE topics covered by them.

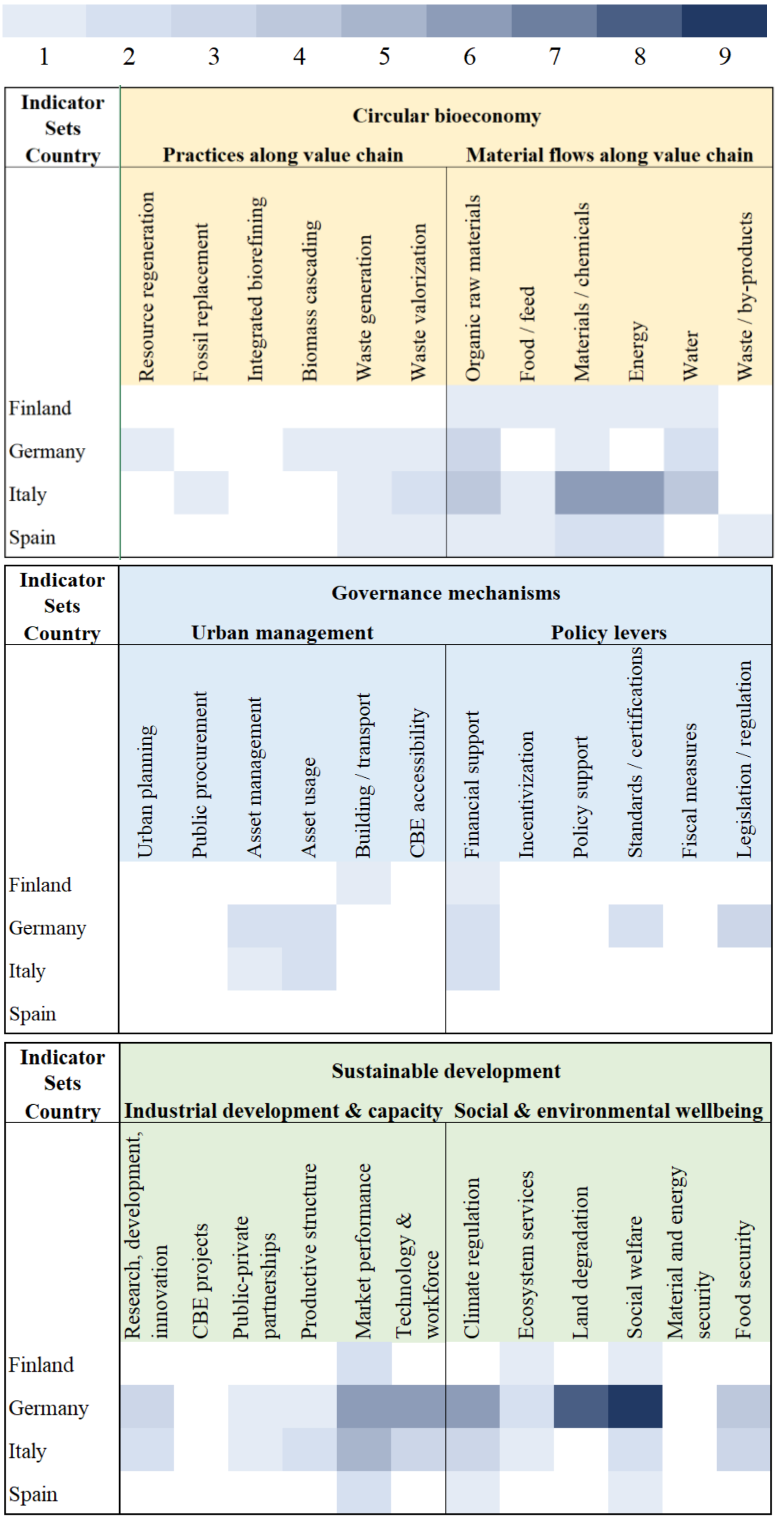

Figure 5: Heat maps of the indicator assessment

As the heatmaps in Figure 5 show, the tools of Finland and Spain differ significantly from those of Germany and Italy. The former group hardly touched upon any "governance mechanism" available to policy-makers, and the few indicators proposed on the two axes of their measurement matrices (industrial sectors versus socio-economic measures) can be clearly viewed. Furthermore, as the light-colored tiles indicate a low number of indicators pertaining to a given component, it became evident that the measured aspects were mainly expressed as aggregations or superficially studied.

Conversely, the German and Italian indicator sets spread more vastly across the topics, albeit still presenting a low focus on "governance mechanisms". A convergence of indicators in the aspect of "sustainable development" for the German tool showed a clear link to its framework, which is based on the three sustainability pillars. The Italian framework, which is split into key performance indicators, sectors and sustainability indicators, showed a more even distribution across the categories. While some relevant urban CBE components were still not covered by these indicator sets, more depth, particularly in the aspect of "sustainable development", could be observed. In the areas of the regeneration of natural resources and the utilization of natural materials as biomass, the German indicator set covered slightly more components than the Italian counterpart. Both sets included at least one indicator referring to waste and valorization options. Although it is one of the goals of the German strategy to establish a sustainable base of raw materials, the replacement of fossil-based materials was not covered at all.

When assessing coverage across all four frameworks together, a dominant focus on "material flows" and "social and environmental wellbeing" also became apparent. Conversely, while all four indicator sets considered "organic raw materials", they widely underrepresented the CBE-essential practices of "biomass cascading", as well as "resource regeneration" and "fossil replacement".

Strikingly, as many as 80 percent of the tiles are colored with the three lightest shades of blue, meaning that very often, only few indicators referred to a specific component. On the other hand, items such as "social welfare" and "market performance" overall, but also "land degradation" in the case of Germany, stood out for the importance given to them by the bioeconomy monitoring systems. Further, profound coverage, although not to the same extent across frameworks, could be observed for the material flows of "organic raw materials" and "materials / chemicals", as well as "energy", "technology and workforce" and "climate regulation". Interestingly, the components of "asset management" and "asset usage" were exclusively filled with indicators regarding the management and usage of land, and the component "technology and workforce" was only covered by workforce-related indicators and not by any technology-related ones.

Finally, a complete lack of focus on specific components was also found in parts of the assessment framework. Apart from both categories pertaining to the aspect of "governance mechanisms", the category of "practices along value chain" also displays low coverage. This is particularly important, as the components that represent circularity in the most direct way across the topic coverage assessment framework are within this category. Furthermore, none of the frameworks that were notably created to assess the bioeconomy include any indicators to monitor "integrated biorefining" and only one tackles the replacement of fossil-based materials. Similarly, the German framework's lack of inclusion of “food / feed” and “energy” resulted in two crucial aspects of the bioeconomy being omitted from an otherwise thoroughly constructed tool. In the aspect of “sustainable development”, the lack of monitoring “CBE projects” and generally low number of economic indicators besides “market performance” are evidence of a higher focus on the economic performance rather than structure and development of the economy. A final measure that did not appear in any of the frameworks is “material and energy security”. Nonetheless, this is a topic of very high relevance when transitioning an economy from non-renewable to regenerative resources while aiming to maintain living standards and economic growth.

4.4 Composite Findings

Although the studied population was relatively small compared to the number of EU member states that can still adopt a bioeconomy strategy, a few trends seemed to appear between the topical coverage and features of the indicator sets. The more recently the strategies were adopted, the more elaborate were the monitoring frameworks, the higher the congruence between the strategic goals and selected indicators, and the more prominent the principles of circularity. Similarly, the two oldest strategies received the lowest quality ratings, whereby the more recent one, Spain, ranked lowest due to the lack of clarification and rationale for the chosen measures.

Hardly any difference could be observed between the recency of the strategy and its focus on “governance mechanisms”. Although the more recent ones did make slightly more references to such components, the lack of governance measures was still in stark contrast to the coverage of other aspects of the assessment framework.

The next chapter evaluates these findings in order to answer the research questions. To this end, the various indicator sets are examined through a critical lens and compared with learnings drawn from the literature.

5 Discussion

This chapter aims to fulfill the thesis' research objectives of describing the scope of indicator sets proposed by EU member states and evaluating their fit for urban-level CBE measurement. In this quest, exhaustive and argumentative answers to the research questions are formulated in chapters 5.2 and 5.3. Before that, the assessment framework used to analyze the topic coverage (see Figure 4) is discussed. Although it is not part of the findings, this serves to better understand its structure and logic and consequently creates a more coherent basis on which to draw conclusions about the indicator sets.

5.1 The Assessment Framework

To draw meaning from the findings described in chapter 4, the goals pursued by urban policy-makers for the evaluation of their CBE transition must be considered. Goal-setting influences a tool's form, presentation, composition, and benefits sought and varies from user to user (Feller-Länzlinger et al., 2010). While cities have to identify and operationalize their own specific goals to pursue the CBE and consequently their monitoring tools, what they have in common is their role as implementers of the CBE (Woodbridge, 2015). This is indicative of the need for measuring instruments that give insight into the state and sustainability of the CBE development and the appropriateness of policy-making to advance it (Wilts & Steger, 2019). Therefore, the subject to measure, reflected in the topical coverage assessment framework, is the dynamic between urban governance and its effectiveness in supporting the transition towards CBE and the resulting environmental, social, and economic impacts. This also sets the function of policy-making in relation to that of business within the CBE transition. Results emerging from the assessment of the urban CBE transition shall help urban policy-makers identify issues and gaps in the urban CBE landscape and implement policy-making to effectively promote innovation and development by the private sector to correct them.

The interest in CBE monitoring for urban policy-making is, thus, not limited to having a statistical account of the CBE transition or its environmental impact, but to gain a differentiated perspective on the contribution of the CBE to the livability of a city and the structural mechanics impacting it. Therefore, to a possible extent, the three aspects of the assessment framework were conceptualized to be strongly interlinked and in line with an urban, interconnected perspective on CBE. The links between the three aspects are explained in the following paragraphs.

At the core are components relating to the CBE. In two categories, the content assessment is geared towards aspects of circular "material flows" and "practices" connected to the CBE. Using indicators that pertain to these components serves policy-makers to assess the extent to which production and consumption models within their cities use regenerative sources and follow circular principles. Moreover, gaps or deficits shall emerge through indicators in these components, which should subsequently be studied to reveal the need and potential for corrective action.

The potential for such action, as well as its efficacy, can be measured through governance mechanisms. This aspect collects tools at the disposal of urban policy-makers, from managing physical spaces to financial and regulatory levers. As identified by Swilling and Hajer (2017), these tools can both enable and support the development of the CBE through the development of business opportunities, innovation and workforce readiness, as well as hinder adverse structural pressures. Furthermore, components under this aspect of urban CBE allow detection and removal of barriers to CBE development ingrained in faulty or outdated incentive systems.

Finally, the components under the aspect of sustainable development hold a two-fold function. On one hand, they can measure a city's overall sustainable development and detect positive or negative impacts of policy-making and CBE activities. This is particularly important for policy-makers to detect areas where CBE development comes at the cost of environmental, social, or economic wellbeing. As the CBE is not a guarantee for sustainability, its progress must be held in check by sustainable development measures. On the other hand, measures in the sustainable development aspect can monitor the availability of CBE enabling human, environmental and industrial resources.

However, there are flaws in the construction of this assessment framework. During the assessment of the collected indicator sets, certain components of the framework, such as "social welfare", "land degradation", and "market performance", accumulated particularly large amounts of indicators. This might indicate a relatively strong focus on these components in the various indicator sets at the national level, or that the assessment framework aggregates too many distinct aspects into single components. Similarly, the components "asset management" and "asset usage" were only matched with indicators referring to “land” as an asset, and the component “technology and workforce” was only matched with workforce-related indicators. In these cases, including various concepts in the same component is likely to have obfuscated the actual extent of topic coverage. Definitive conclusions on the depth of topic coverage must be made carefully since the amounts of possible indicators per component differ.

5.2 National Bioeconomy Monitoring Tools

During the systematic review of EU-wide national bioeconomy strategies conducted by the EC in 2019, only nine member states, excluding the United Kingdom, had an officially adopted bioeconomy strategy (European Commission, 2019a). Considering that the first EU-wide bioeconomy strategy called for member states to develop their own bioeconomy in 2012 (European Commission, 2012), this is a remarkably low amount. The absence of more dedicated bioeconomy strategies can be partly explained by several member states having implemented related strategies or bioeconomy policy initiatives. Another part of the EU-27, especially the states with a strategy under development during the 2019 national bioeconomy strategy review, might have since joined the nine pioneering countries.

Even so, the nine member states whose strategies were investigated propose vastly different levels of elaboration. Many of the documents resemble policy statements more than strategies, while elaborate action plans and monitoring frameworks accompany others. Drawing conclusions on reasons for this disparity exceeds this thesis's scope and might require clearly delineating what shall be considered a “dedicated bioeconomy strategy” and contemplating national and international requirements towards them. For the scope of this thesis, the EC’s (2019a) evaluation was referred to and the strategies were collected accordingly.

Relevant to this discussion is that the lack of nationwide guidance on the development of the bioeconomy has resulted in several cities advancing their own local initiatives (Romano, 2019). Cities such as Amsterdam or Milan have taken leading roles in implementing organic waste valorization systems and repeatedly serve as case examples in research on CBE (e.g. World Economic Forum & Ellen MacArthur Foundation, 2017). By developing their CBE and CBE measuring tools before nation-wide efforts, cities risk misaligning local and national efforts rather than sharing them. This impedes gaining comprehensive insight into the state of the CBE transition and urban-level responsibilities, as well as clearly identifying areas of improvement. Without nation-wide alignment, systemic errors in the CBE transition might remain undetected, lead to inefficiency and wasted resources, and render states, cities and businesses unable to effectively work towards reaching agreements in sustainable development. Consequently, as stated in the research gap in chapter 1.1, it should be in the states' interest to close this gap, create a bioeconomy strategy and make its usability span policy-making levels with clearly communicated goals. This ultimately means creating a national tool to measure and evaluate the CBE, which is simultaneously applicable to urban areas as well.

5.2.1 *Monitoring Approaches*

While there is already a small amount of dedicated national bioeconomy strategies, the number of strategies including a monitoring framework accessible online is further limited. The availability of the indicator set does not seem to be bound to the recency of the strategy, as both the oldest and youngest policy documents present one. However, the level of detail and alignment to the overall policy goals varies significantly across the years.

The high level of simplification without elaboration on the framework in the case of Spain poses issues on various levels. The few measures used limit the extent to which insight into the bioeconomy can be gained, making it likely that the economic productivity of the bioeconomy sectors will become the primary measure of success of the CBE. As established in the literature review, the bioeconomy on its own is not a guarantee for sustainability (Carus & Dammer, 2018). Therefore, the lack of a selection of environmental and social measures results in the neglect of very significant factors needed to advance the CBE transition. Furthermore, the lack of more diverse indicators and the presence of confusing indicators (e.g. measure of "employee numbers" applied to the category of "sustainability indicators") also hinder policy-makers from reaching conclusions on the measured items.

As described in chapter 5.1, strong links exist between activities and materials of the "CBE", "governance mechanisms" and social, environmental and economic "sustainable development". Having a thorough understanding of these links and appropriate measures allows them to be seen in relation to one another and to deduce the origins of issues or policy effectiveness. The limitations on the informative value of the

Finnish and Spanish frameworks are further compounded by the usage of only quantitative and descriptive measures. While these measures can be used in isolation and interpreted to some extent, their combination with qualitative measures and performance, efficiency, policy effectiveness, and total welfare measures could create a complete and coherent perspective on the subject of investigation. Finally, although the Finnish and Spanish frameworks align with the strategy's objectives and goals, the few indicators used do not shed any light on the progress made or decision-making impacts, and if so, very ambiguously. This factor weakens the sets' adherence to the indicator-development best practice of rooting indicator frameworks in theory and policy-making. Furthermore, it reduces the indicators' policy-support and monitoring functions (Eurostat, 2014; Smeets & Weterings, 1999).

The Italian and German monitoring sets perform relatively better in terms of indicator variety and diversity of measured aspects. Both include measures that cross the boundaries of one topic area. This allows an interdisciplinary approach to CBE monitoring and integration of various complementary measures within categories or aspects of their indicator frameworks. All these factors enhance the utility of the frameworks to policy-makers.

These elaborations trickle down to the quality assessment of the indicator frameworks. As visible in Table 2, the Italian and German frameworks reached reasonably high ratings, losing points mainly in the areas of "relevance" and "utility". This is justifiable as this assessment aimed to perceive how high the frameworks' quality is for urban policy-makers and the goals pursued with the tools by nations versus cities naturally differ. Consistently high are also the scores in "methodological soundness" and "measurability", whereby those strategies with stated data sources (Finland, Germany and Italy) and an attached rationale (Finland and Germany) reached a higher score. The Spanish framework's lack of written support for its indicator set also becomes visible in the quality rating, where several categories were neither "clearly met" nor "clearly not met" or "ambiguous". These results indicate that an explanation of rationales behind measures, in particular stating their interrelations, can significantly impact the quality of an indicator set. For urban policy-makers, more insight into how to utilize a national assessment tool increases their chances of avoiding externally created indicator sets.

The indicator functions of informing and educating an audience are fulfilled, based on their composition and features in varying degrees, by the four indicator sets. Conversely, the functions of policy-support and outcome monitoring are mostly followed up by the more extensive and cross-sectional German and Italian sets.

5.2.2 *Approach to Circularity*

Among the main aspects needing clear alignment between cities and nations is how the circular economy and the bioeconomy are defined in policy-making. According to the updated bioeconomy strategy, circularity is meant to be understood as integral to the bioeconomy (European Commission, 2018a). To provide coherence across the continent national bioeconomy strategies and their urban counterparts should equally incorporate the principles of circularity. The four monitoring frameworks that were analyzed for this thesis take very different approaches to circularity. Again, the approaches can be broadly grouped from the Spanish and Finnish frameworks, which hardly mention the concept, to the German and Italian ones, which integrate it in strategic goals and indicators.

Issued in 2014, the Finnish bioeconomy strategy was adopted before the European Circular Economy Action Plan. Although the circular economy and the biocycle were already fairly well-known concepts in European policy-making (see Ellen MacArthur Foundation, 2013), this might be the reason why circularity did not yet find its way into the country's bioeconomy strategy. The Spanish strategy, however, was adopted in 2016, approximately one year after the European Circular Economy Action Plan. Nonetheless, the connection with the bioeconomy was not yet made. Both strategies adopted after the EC's updated bioeconomy strategy, thus after the official integration of circularity in the bioeconomy, include circular principles in their goals as well as indicators. Since Germany and Italy have merged circularity into their bioeconomy strategies, identifying which of these measures directly or indirectly informs about circularity is somewhat ambiguous. Nonetheless, both monitoring frameworks have advanced the notion of bioeconomy by accounting for its inherently circular features, setting a direction for future developments in CBE monitoring.

This hints at a paradigm shift in how the circular economy and the bioeconomy have become increasingly understood as intertwined in sustainable development since 2018. The recency and still unsolidified nature of this new understanding of the CBE is reflected in the four national bioeconomy strategies, particularly in the form of a lack of unidirectional approach within and across indicator sets. Furthermore, the circular economy has experienced rapid proliferation and development in policy-making separate from the bioeconomy itself. As such, the concept has enjoyed widespread adoption without necessarily being integrated into the bioeconomy. Indeed, as several sources see the bioeconomy as an inherent part of the circular economy rather than the opposite way (Stegmann et al., 2020), this might be a reason for the late uptake of circularity within the bioeconomy strategies.

5.2.3 *Topic Coverage*

Across the four indicator sets on the heatmap in Figure 5 the topic coverage is visibly linked with their underlying indicator framework. While the aspects of "sustainable development" and the "CBE" are represented to some extent by all indicator sets, they lack focus on "governance mechanisms". This might be due to the audience of the assessed indicator sets, which are national governments. Although the roles in developing the CBE overlap and policy effectiveness measures are also necessary for national governors, states generally take a leading role in goal-setting and monitoring. In contrast, the implementation of the goals falls under the responsibility of regions or cities (Woodbridge, 2015). As a follow-up on the progress towards reaching the set goals, these national indicator sets can therefore be observed to monitor areas of resource usage and consumption as well as impacts on the economy and environment. On the other hand, they tackle the implementation and success of specific policy measures less intensely.

Another salient finding is the generally low amount of indicators per component, particularly for the Finnish and Spanish indicator sets. Understanding this observation as evidence of superficiality across the indicator sets must be considered with a significant caveat. Different components of the assessment framework encompass a variable amount of facets of the CBE that could potentially be measured. For instance, the component "materials / chemicals" naturally encompasses a wider range of biomass usage types than "food / feed". For this reason, it is not possible to reasonably attribute the same number of indicators to all components. As a result, several components might include exceptionally high numbers of indicators, while others are saturated with only a few. Seeing low numbers attributed to a component is therefore not necessarily a sign of superficiality. Another necessary consideration pertains to the choice of attributing each indicator to only one component. While some indicators might have fit several components through direct or indirect links, each indicator was only allocated once to its most directly represented component. This implies that more components might be represented in the indicator frameworks than the heat map shows.

The following subchapters further dissect findings related to the topic coverage across the three aspects of the assessment framework.

Circular bioeconomy

At first glance, the heatmap for this aspect of the assessment framework in Figure 5 shows a relatively thorough coverage of the category of the "material flows along value chain". However, it is also visible that most tiles are colored with very bright shades, indicating that most components are referred to with few indicators except in the Italian indicator set. Minding the caveat mentioned above, a more detailed analysis must be conducted before concluding the breadth and depth of topical coverage.

A rather unilateral perspective of the material flows across the indicator sets can be observed when further dissecting what indicators were allocated to the components of this category. In fact, the Finnish, Spanish, and to a lesser extent, the Italian indicators allocated to the category of "material flows" were retrieved from a sectoral disaggregation of measures. As such, one single measure, for instance "output" in the Finnish example, appears once for each type of material. This can be misleading since an output measurement that is disaggregated on industrial sectors does not give profound evidence on material flows across the value chain. Furthermore, the components in the "material flows" category are operationalized in Appendix 4 to reflect "circularity". However, most indicators allocated to these categories, while clearly pertaining to "material flows", do not allow insight into the circularity of the flows. Within this category, Italy addresses only the components of "energy" and "water" in further detail. Nonetheless, the Italian sectoral disaggregation of measures presents relatively higher diversity than the Finnish or Spanish ones. Indeed, Italy's measures referencing the various sectors are based on many more diverse indicators referring to the overall bioeconomy. These span areas from economic sustainability over employment and innovation to material productivity.

Although German indicators such as material or forest footprints aggregate various related measurements into one number, the country's indicator set barely touches upon the material flows of its bioeconomy. Strikingly, relevant sectors such as "food /

feed" and "energy" are not tackled at all. This is likely due to the German indicator set being built around the three pillars of sustainability which led to a clear majority of attributable indicators to components under the aspect of "sustainable development". Nonetheless, several measures might be indirectly linked to various materials, too. Furthermore, the lack of industry-specific indicators might be attributable to the goal-setting of the strategy as well. As a national framework, industry-specific development is not centered, whereby attention is brought to supporting sustainable sourcing and human and economic capacity development.

Similarly, the small number of indicators giving insight into the "practices along value chain" across indicator sets could be due to the strategies' goals. Nonetheless, Italian and German goals such as strengthening the bioindustry potential and developing bioeconomy solutions seem to indicate a lack of indicators for bioeconomy practices.

Sustainable development

Within the CBE aspect of "sustainable development", the German focus on the sustainability pillars is clearly visible on the heat map. Roughly half of the German indicators allocated to the assessment framework are collected in the category of "social and environmental wellbeing" and one-fourth in "industrial development and capacity". As discussed in chapter 5.1, this spurs the question of whether the components within these two categories are differentiated enough. The assessment framework was built independently from the national bioeconomy strategies and monitoring frameworks to preserve a neutral view on urban CBE measuring needs. Nonetheless, crowded components might indicate the need to be further split into more specific topic areas. In the case of "social welfare", which is matched with nine indicators from the German set spanning salaries, employment and equality, the question emerges whether these three subtopics should not be observed separately for a more nuanced view on the topic coverage.

Similarly, across all four monitoring frameworks, the highest number of indicators is allocated to "market performance". Here as well, splitting the category into various subcategories, for example growth, competitiveness and productivity, might shed light on aspects of the market performance that are specifically referred to. Conversely, connecting various subtopics into one component only, has the advantage of reflecting the broader parts of sustainable development that are focused on in particular. As such, it can be stated that across all four indicator frameworks, the economic performance of the bioeconomy is seen as a rather relevant subject of study.

Further to subdividing single components, other factors impact the attribution of indicators within the assessment framework. Several German and Italian indicators can lead to various interpretations, which create a certain level of bias when allocating an indicator to a specific component. The indicator *"proportion of revenues by eco- and circular economy firms out of total revenues"* taken from the German indicator set was allocated to the component of "market performance" as the direct object of study is the contribution to the total industrial revenues (Egenolf & Bringezu, 2018, p. 16). Nonetheless, as an indirect indicator, this measure can also give insight into the development of the "productive structure". An accumulation of indicators within one component might thus skew the perception of topic coverage throughout the assessment framework as only one among multiple usage types per indicator is included in the assessment. This could also explain the lack of indicators for the component of "material and energy security" for instance, where a combination of the Italian indirect indicators: *"final energy consumption"*, *"energy use efficiency"* and *"energy productivity"* might give an idea on whether a population's needs for energy can be covered with energy from biological origins (Italian Committee for Biosafety, Biotechnology and Sciences of Life, 2019, p. 83).

Therefore, giving more insight into the usage of indirect indicators is essential to improve the applicability of an indicator set. This is also true for its scaling to an urban governance level. It can be concluded that topic coverage of "sustainable development" is among the more extensive across the assessment framework, particularly for the German and Italian tools.

Governance mechanisms

The aspect with the least coverage across all indicator frameworks is "governance mechanisms". As the studied indicator sets were established at the national level, this is not surprising for the category "urban management". On the other hand, "policy levers" are tools that can be used at a national level as well, and as described in chapters 2.3.3 and 5.1, are the primary operating tool to influence and monitor the development of the CBE. The neglect of issues such as adverse subsidies and unpaid externalities detected in the literature review can drastically hinder the sustainable development of a CBE and could be detected with indicators for policy levers.

The German framework is the one with most indicators pertaining to these categories. However, in this case as well, the specific measures attributed to the components have to be scrutinized. Indeed, the indicators pertaining to "legislation / regulation" tackle working hours, child labor and land rights. While these categories fit the given component, they only inform about CBE by implication and with the support of additional context. As such, a simple glance at the heat map might give a false impression of the representativeness of the German framework for urban needs.

A similar conclusion can be drawn within the category of "urban management". All six indicators allocated to the components of "asset management" and "asset usage" refer to land as an asset. However, both components are operationalized to include land, buildings, roads and bridges, as well as water and sewage systems, in line with the elaborations made by the Ellen MacArthur Foundation (2019b). Consequently, the allocation of indicators to these components does not necessarily disclose the specifics of areas tackled by the various indicators.

5.3 Monitoring Frameworks for Cities

With a complete analysis of the EU-wide monitoring frameworks, this thesis also aims to judge the extent to which urban policy-makers in the EU can find adequate measuring tools for their city's CBE development in the existing national bioeconomy strategies. At first glance, the small number of such strategies and the even smaller number of indicator sets reflect a CBE that is still in its initial stages of development. Furthermore, EU member states' strategies and monitoring sets differ in content and depth, based on their own needs, capacities, and goal-settings. Similarly, it is impossible to define what the ideal monitoring set looks like at urban level. As Carus and Dammer (2018) stated in their research, CBE practices must be thoughtfully applied to ensure their contribution to sustainability. This highlights the need for tailored indicator sets which is intensified by the fact that local circumstances, from CBE barriers to capacity for improvement, differ for various nations and cities. Therefore, it becomes clear that various entities see a very different use in CBE development and pursue different strategies (Dietz et al., 2018). As such, the question to answer shall not strictly assume that cities must find appropriate monitoring frameworks in national strategies. Instead, it focuses on the possibility of finding adequate and flexibly implementable measures within them that enable the alignment of local with national efforts across Europe.

5.3.1 *Scalability*

The first consideration concerns the scalability of the indicators from the national to the local level. This is essential to understanding whether a measure, even if laid out for a different audience and goal than given in the urban context, can easily but effectively be adapted to local needs. The German and Italian indicator sets explicitly mention scalability to local and regional circumstances, respectively. However, in the Italian statement, there is no further indication of which specific indicators can be re-adapted and how. On the other hand, the German indicator set indicates the scalability of each indicator, whereby the scalability only refers to the national and international levels and never to regions or cities. The indicator elaborations provided by the national government do not clarify whether this indication merely refers to the indicator's scalability as it is denoted or if it also incorporates an estimation of the measurability and data access on the various governance levels. If the latter is the case, the possibility for urban policy-makers to orient themselves at the national level is significantly compromised. However, studying the single measures shows that most indicators can be adapted to local levels, provided the necessary data collection infrastructure is available. Similarly, the Finnish and Spanish measuring frameworks are scalable from the national to the local level as well, given that measures such as "output", "value-added", or "numbers of employees" can easily be measured within cities.

However, scalability is simply a precondition to the possibility for cities to use the given indicators and is, therefore, not proof of their utility and relevance on its own. When considering how urban needs can be accounted for in the adaptation of an indicator set, other technical factors about the monitoring framework also come into play. When applying indicators used by another audience, the new users must be able to modify the sets to their local contexts and needs. This includes weighing the evaluation of various aspects more or less than others or expanding or reducing aspects to be measured. To this end, the possibility of aggregating or disaggregating information into a suitable form matters (Bracco et al., 2019). While it seems that a larger pool of indicators to select from (e.g. the German and Italian sets) might support these needs, research by Hiremath et al. (2013) showed that only a small number of indicators is usually applied by local authorities rather than an entire coherent set. Consequently, this highlights the need for parsimony in adapting an indicator set to urban needs and to consider the creation of a selection of headline indicators with the subsequent possibility of further investigation through baseline indicators.

The vast difference in complexity and content coverage visibly set the German and Italian indicator sets apart from the Finnish and Spanish ones. Therefore, a further investigation must be made into how these differences impact the frameworks' adaptability, usability and flexibility in an urban context.

5.3.2 *Complexity*

One strength of the German and Italian indicator sets is their multi-perspective framework which effectively allows interconnecting various domains of the CBE development. To an extent, they effectively account for the interdependencies of CBE aspects by measuring progress, efficiency, policy effectiveness and total welfare. Their frameworks, which link to both CBE theory and policy-making, are, therefore, complemented with indicators that describe a phenomenon and allow for its context-specific interpretation (Eurostat, 2014). Including indicators with a plurality of purposes is a goal-oriented consideration to make when implementing a framework in an urban context with the aim of increasing the relevance and utility of indicator sets.

A multitude of indicators also offers the opportunity of tailoring the set of measures used to contextual specificities as described in chapter 5.3.1. With more available indicators, a city can decide which ones to take into its own set and what aspects to add. Furthermore, urban policy-makers can take strategic decisions on measures to aggregate into a single one or to disaggregate to gain more detailed perspectives on measured subjects. There are caveats, however, that must be minded when adapting an indicator from a pre-existing one. A more complex indicator set, particularly if its framework is policy-relevant and academically supported, gives the impression of being comprehensive and appropriate as a reference. Nonetheless, policy-makers at an urban level must remain aware of their own specific needs and the limitations of the reference set. That also means to complete the assembling of indicators with other sources, for instance, to fill the gap of "governance mechanism"-related measures.

Furthermore, more flexibility and diversity in adapting the set to urban needs given by complex indicator sets may lead to essential connections and control measures getting lost. This comes at the risk of significantly lowering the communicative value and the ability to draw conclusions from the measurements. Another risk attached to adapting indicator sets from complex ones is diluting the subject of measure. With a higher quantity of possible interlinked indicators from which to choose, it is possible to lose the focus on the specific intentions of urban policy-makers in monitoring local CBE developments. For instance, relying on the German indicator set might lead a city to equally focus on "sustainable development", neglecting other relevant aspects of the CBE, such as "fossil replacement" or "integrated biorefining".

Therefore, for a city to reference the German or Italian indicator sets, diversity of indicator types and a solid scientific basis provide a coherent and relevant base for a new indicator set. Nonetheless, the city-specific needs are not necessarily represented by these national bioeconomy strategies and might have to be provided for separately. In doing so, urban policy-makers need to ensure that interlinkages between single measures remain consistent, thus maintaining the purpose and utility of the set.

5.3.3 *Simplicity*

Simpler indicator sets, such as the Finnish and Spanish ones, reduce the risk of diluting the adapted indicator set and come with the benefit of a straightforward and easy-to-use indicator framework. Furthermore, comparison across cities and with country-wide measures is easily feasible and interpretable. Nonetheless, the flaws in quality and scope and the lack of interconnectedness between the measures that affect these two indicator sets will inevitably be reproduced. With both sets having five or fewer measures, there is hardly any indicator diversity that would allow cities to create a tailored and balanced indicator set fit to be used according to their needs. Although different cities may focus on sectoral applications of measures in line with their local productive structure, it is inevitable that an effective and policy-relevant measurement tool for a city would have to be expanded significantly. A variety of additional measures would be required to fulfill measuring purposes that go beyond the description of a status quo. Sticking to the measures currently proposed by the Finnish and Spanish governments alone would result in low levels of interpretability and skew the focus towards economic production measures. As stated before, this does not necessarily fit the purpose of developing the bioeconomy sustainably, nor in a circular manner.

5.3.4 *Indicator Fit for Urban Policy-Making*

Viewed across the four frameworks, various conclusions can be drawn. Firstly, the CBE monitoring landscape is currently in its initial stages. Much progress still has to take place, spanning from the alignment of the notions of CBE to the structuring of an indicator set that can be applied in a variety of contexts. Secondly, the more recent the indicator sets, the more they seem to conform to integrating circularity in the bioeconomy and to theoretical and practical necessities in indicator developments. As such, the older sets of indicators composed by Finland and Spain are not comparable to the more recent ones from Germany and Italy based on their extensiveness of measures, quality requirements and integration in scientific and political structures. Furthermore, while the amount and depth of coverage of topics that cities may require to measure are only partially covered by all four sets, the older ones lack depth across all aspects of the urban CBE.

It must be considered that it is not the aspiration of the national frameworks to create an instrument with the perfect fit for urban use since national goals differ from urban ones and no one indicator set can fit multiple cities at once. Nonetheless, it is favorable for EU member states to develop strategies that enable implementation on an urban level and comparability across cities. As part of that, creating monitoring frameworks that are easily scalable to cities is an important step.

A higher level of compatibility can be found between the German and Italian frameworks. These tools offer policy-makers more potential for adaptation to local contexts, and with a variety of interrelated measures, the possibility to weigh indicators from different areas. Furthermore, by incorporating an EU-aligned notion and corresponding measures of CBE, these instruments open the possibility of aligning city-wide, regional, national and international efforts and measurement categories. Nonetheless, both instruments include factors that might complicate their applicability to city-wide CBE monitoring. Such issues include a misplaced topical focus point, lack of topical coverage or lack of theoretical explanations.

Taking these and other flaws into account, the two monitoring frameworks do, however, provide versatile tools that enable contextual and meaningful analysis of measures through a variety of indicators. Furthermore, their indicator frameworks, particularly the German one, are constructed in a policy-relevant and theoretically sound manner and completed with indicators that meet quality requirements. While they do not provide a rounded and indiscriminately relevant tool to be used by any city across the EU, these tools can serve as informative bases for the construction of a tailored CBE indicator set for urban policy-makers. Although adapted to German and Italian policy-goals, they also set basic elements of consistency with the BMS, which may trickle down to local policy-making.

The next chapter concludes this thesis with a summary of the research questions and their answers. It also provides insight into the implications this research has on policy-making, the private sector and the academic field. Finally, an elaboration of the limitations faced throughout the research process and corresponding opportunities for further research close this paper.

6 Conclusion

This thesis investigated to what extent cities can find a purposeful monitoring framework for the development of their local CBE in EU-wide national bioeconomy strategies. Based on a systematic review of the indicator sets of these strategies, it can be concluded that their development is still in the early stages. More recent ones, however, propose high-quality and politically relevant tools that, to some extent, are available for urban policy-makers to benefit from. These conclusions are based on a two-fold assessment: First, the collected frameworks were scrutinized for their composition and features, then dissected to investigate the topical coverage. Both results served to identify the fit of the indicator sets for use by urban policy-makers.

These elaborations served to find answers to the following two research questions, which served as guidance throughout the thesis:

1. What are the features and compositional rationales of monitoring frameworks proposed by EU-wide national bioeconomy strategies and how extensive is their topic coverage?
2. Can cities in the EU find practical and purposeful tools in the existing national bioeconomy strategies that allow them to measure their CBE transition?

The results indicate that the more recent and complex monitoring frameworks follow up on various critical considerations better than the older and simpler ones. Such considerations include rooting the underlying indicator frameworks in both theory and policy-making practice, including indicator diversity for a more conclusive monitoring approach, aligning definitions of the CBE with EU-wide policy-making, and finally, covering a more comprehensive range of topic areas. The difference between the indicator sets issued before the circular update of the European bioeconomy strategy and those issued after, therefore, goes beyond the difference in approach to circularity. As the older ones lack coherence with essential features for the development of high-quality indicator sets, their frameworks do not allow for a versatile and comprehensive assessment of CBE development. The high focus on economic measures further bears the risk of neglecting the importance of social and environmental sustainability for CBE development.

The more recent frameworks find relevance in guiding the composition of tailor-made indicator sets for urban policy-making by fulfilling the above requirements. In doing so, they allow the notion of circularity to transfer within the bioeconomy from an EU-wide strategy down to an urban implementation plan. As such, alignment of policy-making and measurements surrounding the circularity of the bioeconomy can be created, which serve a more holistic and coherent European CBE transition. Nonetheless, despite a better fit of the German and Italian indicator set, recommending their use at an urban level requires caution. Both frameworks are based on a locally relevant framework and reflect various measures with differing breadth and depth that might be less meaningful at the urban level. Furthermore, all four indicator sets lack insight into the effectiveness of governance mechanisms. This has to be compensated for by urban policy-makers.

6.1 Implications

The urgency with which sustainable development has to be tackled and the collective efforts required for it apply to the CBE, too. In particular, emphasis must be put on the alignment and coherence of goal-setting and strategic efforts across policy-making levels. Furthermore, efforts in promoting the sustainable development of the CBE are interconnected with high-quality and comprehensive monitoring frameworks and a balanced selection of representative measures. In light of the findings of this thesis, this leads to a variety of considerations to make for future development of national bioeconomy strategies and monitoring frameworks, as well as considerations for presently existing ones.

With the findings from this thesis, policy-makers gain insight into how to successfully set the basic structures to implement CBE monitoring in a future-oriented and efficient way. This entails creating policy-relevant tools that are suitable for multiple levels of governance. More aligned policy-making and monitoring tools create benefits in the form of synergies in data collection and evaluation and direct comparability of measures across regions. The present research can support future strategic planning for the bioeconomy by instructing national policy-makers on their strategy's guiding function for local CBE development. With it, the policy-makers can identify areas of relevance to other policy-making levels and create monitoring sets that are in line with EU-wide requirements and with the measuring capabilities and needs of the cities. This means that future indicator sets can be created to compensate for currently lacking items, such as indicators for governance mechanisms or CBE practices, and replicate valuable features such as policy- and theory-based indicator frameworks.

Being aware of the interconnectedness of various policy levels and creating indicator sets that are implementable on them allows to avoid counterproductive misalignments in bioeconomy efforts and accelerate the sustainable CBE transition locally and internationally. This is especially relevant as the current low amount of existing bioeconomy monitoring frameworks leaves many cities across the EU lacking guidance for local policy and measurement development. This nourishes the probability of misaligning local CBE developments with each other, the state and the wider EU. Among the few existing sets, the present research found that the ones proposed in recent years fulfill many fundamental requirements for their use in urban areas. Nonetheless, those frameworks that already exist, particularly the Finnish and Spanish ones, can utilize the findings of this research in a future update. To this end, the need to collaborate with cities and fill the current lack of topic coverage and indicator features is emphasized.

Effectively monitoring the CBE development as well as using enabling and restrictive governance allows setting favorable conditions for the implementation of CBE. Therefore, a thorough implementation of a CBE strategy and monitoring approach supports the development of business opportunities and innovation that can accelerate the reaching of strategic goals. If such policy-making and goals are uniformly applied across cities and nations, the conditions for businesses to seize opportunities and collaborate with urban governments are enhanced. As such, creating new bioeconomy monitoring frameworks or updating existing ones at the national level with accountability for the findings of this thesis has benefits that trickle down to the public and private sectors.

Contributions to the body of knowledge encompass a situational analysis of how best practices in indicator development and the notion of CBE are represented and incorporated in bioeconomy monitoring approaches of EU member states. This gives insight into the current state of development of CBE-related policy-making and the evolution of sustainable development in the EU. To this end, a definition of the CBE and a set of quality criteria were assembled from available literature. Furthermore, this thesis created an assessment framework for the evaluation of topical coverage of CBE aspects that are relevant for urban policy-makers. While these tools are not the final output of this thesis and need further refinement, they serve as contributions to the synthesis of knowledge from a variety of sources.

6.2 Limitations and Opportunities for Further Research

A variety of limitations must be acknowledged to have compromised the validity of the findings of this thesis. They can be grouped into three categories: limitations linked to the urban focus, data analysis instruments and data availability. The following subchapters will elaborate on them and propose opportunities for further research on the topic areas, where applicable.

6.2.1 *Urban Focus*

The objective of centering urban policy-making in the identification of CBE measurement needs was motivated by a variety of sources indicating the role of cities as implementers (e.g. Woodbridge, 2015) and the current lack of adequate indicators (e.g. Romano, 2019). However, the research process showed that the CBE cannot be efficiently measured confined by an urban perspective but requires the inclusion of interplays with rural areas, regions and the country of origin. This means that an effective monitoring set for urban CBE cannot be entirely isolated from these other governing entities. Furthermore, all cities have varying needs and capabilities to leverage in the development of the CBE. Considering this limitation, the assessment was based on generally valid aspects, such as indicator quality criteria or topic coverage areas that emerged from the literature to be relevant for cities. Nonetheless, this results in a potential lack of specificity or transferability of the results.

While the focus on urban areas can provide valuable insights across various aspects studied in this thesis, a similar study may be conducted for specific cities in the future to gain more practical, location-specific results. This would entail a study of the specific needs and capacities of the selected city. Potentially, research might be conducted to identify the prevailing needs and capabilities of a selection of cities, based on which transferability of results would apply to that specific sample. More research might be conducted to expand on area limitation and tackle regions, rather than cities or the combination of urban and rural areas.

6.2.2 *Data Analysis Instruments*

Achieving the objective of identifying the utility of national indicator sets to urban needs resulted throughout the research process to require a variety of steps that in themselves may be the subjects of a separate study. The assessment framework of topical coverage of the studied indicator sets, for instance, was created based on the literature review. The derivation and dissection level of topics to components, therefore, includes an inevitable amount of arbitrariness. Furthermore, while quantification of the topic coverage with subsequent investigation allowed for an efficient and comparative analysis, the research process showed that the assessment framework did not equally suit the assessment of all indicator sets. While it allows drawing conclusions within the scope of this thesis, a more profound study of such an assessment framework might increase the validity of the findings. Concerning the quality assessment of the various indicators, an inevitable amount of arbitrariness must be acknowledged, as the lack of specification on the construction of some indicator sets did not allow for their detailed analysis. This issue was mitigated by simplifying the ranking of quality criteria to a three-point Likert scale. Furthermore, due to limited capacity in the scope of this thesis, the topic and quality assessments were conducted by only one researcher. Both processes were repeated multiple times at a distance in order to reduce subjectivity.

Nonetheless, the availability of multiple researchers would increase the objectivity of the results. Similarly, focusing a study on the creation of a topic coverage assessment framework for urban CBE needs or the quality grading of EU-wide national CBE indicator sets would lead to more neutral results. An individual, qualitative assessment per indicator set would also allow tackling each study with a tailored approach rather than with one unified assessment framework. Such research might be conducted in the future to gain a clearer understanding of the discussed topics.

6.2.3 *Data Availability*

The last systematic review of EU-wide national bioeconomy strategy development was conducted in 2019 (European Commission, 2019a). Despite being slightly outdated, this list was referred to due to its methodological reliability and because it allows differentiating between what the EC considers to be a “dedicated bioeconomy strategy” versus “bioeconomy policy initiative” or “related strategy”.

Furthermore, the systematic review resulted in the collection of four monitoring frameworks, whereby only two of them included thorough elaborations on the various indicators and reflections on the framework compositions. As a result, the usefulness of the collected data of half of the sample was significantly compromised. This limits the dependability of the indicator set assessments. Given this limitation, the goal was to avoid interpreting the indicator sets that lack further elaborations, which would have created a bias in their assessment. For this reason, all indicators across the monitoring frameworks were regarded as direct indicators, thus referring to one specific object of measure. As such, all indicators were attributed to only one component of the assessment framework, despite their potential indirect relationship to other components. While this limited the amount of bias affecting the attribution, indirect indicators were neglected in the assessment.

Further research might be conducted to discover more profoundly how the indicators within national indicator sets are interrelated and to what extent they manage to synergistically inform and support policy-making and the broader public on CBE development. Furthermore, research might also tackle the study of bioeconomy-related policies in EU member states that do not have a dedicated bioeconomy strategy as identified by the EC (2019a). As these countries also require monitoring policy implementation and progress, gaining a clear understanding of other approaches to the bioeconomy might complement the findings of this thesis with insights into the remaining EU member states.

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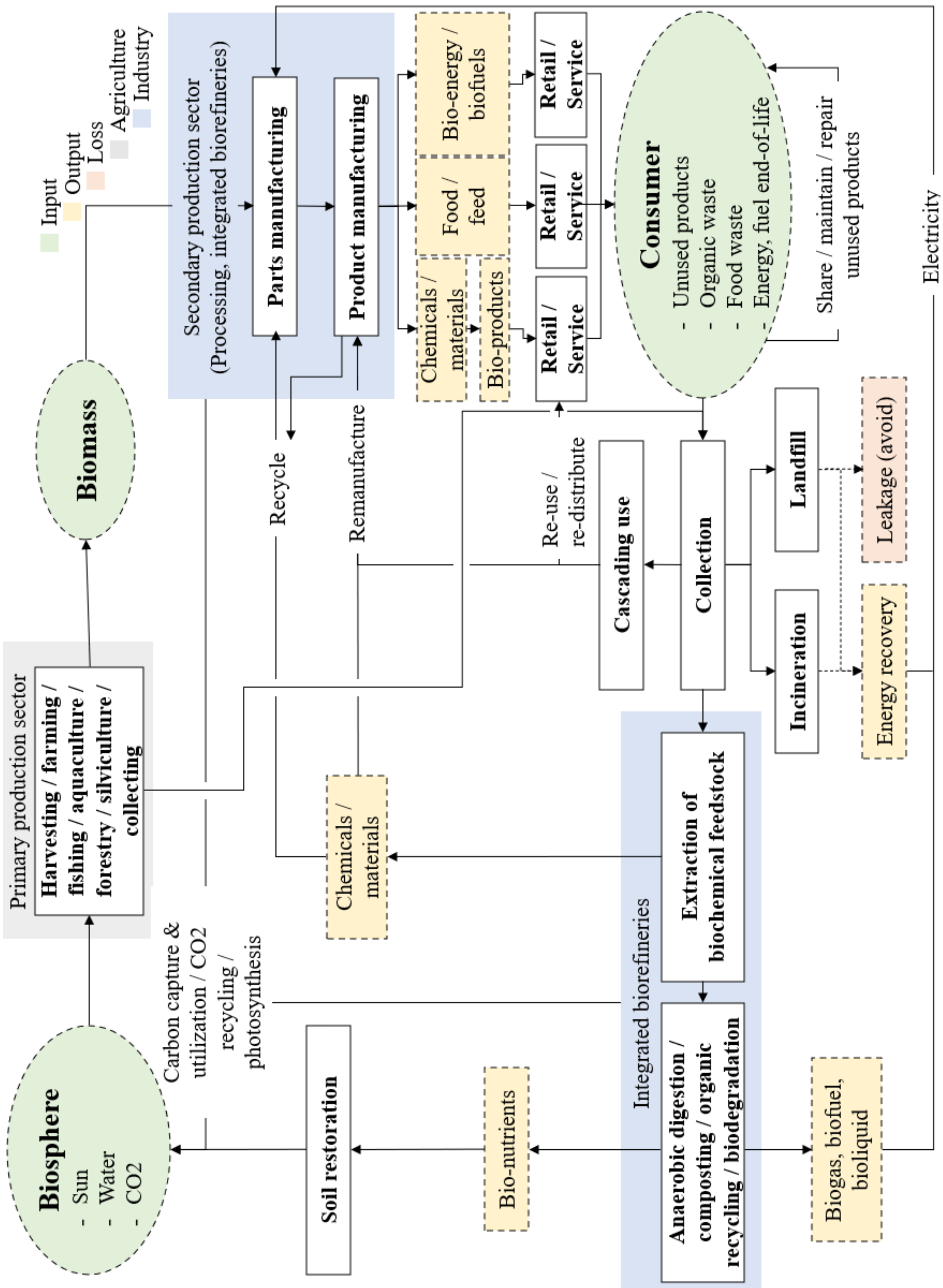
8 Appendix

Appendix 1: Quality Criteria for Indicators

Category	Criterion	Author
Relevance	Aligned with interests of audience	(Feller-Länzlinger et al., 2010; Gabrielsen & Bosch, 2003; Hiremath et al., 2013)
	Representative of: • studied issue • area or phenomenon of interest • socio-political or geographic context • local needs • policy target	(European Commission, 2018b; Eurostat, 2014; Gabrielsen & Bosch, 2003; Hiremath et al., 2013; Moreno Pires et al., 2014; Shen et al., 2011; Zavadskas et al., 2007)
	Accuracy and reliability	(European Statistical System, 2019)
	Responsive to change and policy intervention	(Eurostat, 2014)
Utility	Indicative of development over relevant timespan	(Eurostat, 2014; Gabrielsen & Bosch, 2003)
	Useful for planning and policy-making	(Hiremath et al., 2013)
	Comparable with: • reference values and policy targets • other indicators • geographical areas	(European Statistical System, 2019; Eurostat, 2014; Gabrielsen & Bosch, 2003)
	Supported by causal explanations	(Gabrielsen & Bosch, 2003)
	Adaptable to contextual needs	(European Commission, 2018b)
	Easy to interpret by policy-makers, public and stakeholders	(European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Gabrielsen & Bosch, 2003)
	Readily implementable	(Hiremath et al., 2013)

Methodologically sound	Based on sound statistical procedures	(European Statistical System, 2019; Gabrielsen & Bosch, 2003)
	Founded in a scientifically constructed framework, based on: • existing agreed definitions • classifications • standards • recommendations • best practices	(European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Gabrielsen & Bosch, 2003; Hiremath et al., 2013; Wu & Wu, 2012; Zavadskas et al., 2007)
	Supported by policy-makers	(European Commission, 2018b; Hiremath et al., 2013)
	Based on documented and accessible methodological procedure including clearly identified assumptions and sources	(European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Feller-Länzlinger et al., 2010; Hammond et al., 1995)
	Derived from impartial and independent sources	(European Statistical System, 2019)
Measurability	Availability of cost-effective measurements and data collection	(European Statistical System, 2019; Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007)
	Calculated from regularly and reliably updated data	(European Statistical System, 2019; Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007)
	Calculated from accessible data	(Bracco et al., 2019; European Statistical System, 2019; Zavadskas et al., 2007)
Indicator sets	Parsimonious	(Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007)
	Constructed from complementary and coherent indicators	(Eurostat, 2014)

Appendix 2: Mapping of the Circular Bioeconomy
(adapted from Carus & Dammer, 2018; Ellen MacArthur Foundation, 2013; European Commission, 2018a; Smyth & Horan, 2015; World Economic Forum & Ellen MacArthur Foundation, 2017)



Appendix 3: National Bioeconomy Strategy and Indicator Framework Factsheets

FINLAND

(Biotalous, 2014; Natural Resources Institute Finland, 2021; Sauvula-Seppälä & Hautakangas, 2019)

Strategy:	Sustainable growth from bioeconomy – The Finnish Bioeconomy Strategy
Year:	2014
Goals:	1. Competitive operating environment for bioeconomy 2. New business from bioeconomy 3. A strong bioeconomy competence base 4. Accessibility and sustainability of biomass *No separate goal-setting for indicators*
Circularity	Not mentioned throughout the report
Framework	• Five measurement categories related to the bioeconomy *(output, value-added, investments, exports, employment)* • Each measure is applied to total bioeconomy or various industries and branches *(food, forestry, chemical / pharmaceutical, energy, construction, water, ecosystem services)*
Indicators	• Nomenclature: All quantitative, direct, objective • Indicator types: Solely descriptive and performance indicators • Indicator source: Statistics Finland • Data source: Statistics Finland, Finnish Environment Institute, Thule Institute, Luonnontila.fi • Data collection frequency: yearly measures • Scalability: total bioeconomy, industry and industry branches • Aggregation: measures disaggregated to the sectoral level

Continued on next page

GERMANY

(Bundesregierung, 2020; Egenolf & Bringezu, 2018)

Strategy:	National Bioeconomy Strategy
Year:	2020
Goals:	1. Develop bioeconomy solutions for the 2030 Agenda for Sustainable Development 2. Recognise and harness the potential of the bioeconomy within ecological boundaries 3. Enhance and apply biological knowledge 4. Establish a sustainable raw material base for industry 5. Promote Germany as the leading location for innovation in the bioeconomy 6. Involve society in the bioeconomy and strengthen national and international collaboration *Separate goal-setting for indicators*
Circularity	Ingrained in the second policy guideline of the bioeconomy strategy: *"Using biogenic raw materials for a sustainable, circular economy"* (Bundesregierung, 2020, p. 5)
Framework	• 15 specific goals attributable to the three sustainable dimensions *(environment, society, economy)* • 4 integrative goals (merging two or more sustainable dimensions) *(rural development, food security, avoidance of national and international land degradation, sustainable production, infrastructure and consumption)* • Each goal is split into one or more criteria that match SDGs • Each criterion is assigned an indicator
Indicators	• Nomenclature: Qualitative, quantitative, direct, indirect, objective • Indicator types: Descriptive, performance, efficiency, policy effectiveness • Indicator and data sources: Destatis, Eurostat, ILO, Alliance 8.7, World Bank, FAO, German Patent and Trademark Office, Eco Innovation Observatory, various German ministries, IPCC, IIASA, OECD, WHO, WaterGAP, IUCN, CBD, LandSHIFT, BLE, BioSt-NachVO, IRP • Data collection frequency: regularly updated unless specified • Scalability: international, national, regional / sectoral, local • Aggregation: Headline indicators (based on integrative goals), Specific indicators (based on specific goals), base data

ITALY

(Italian Committee for Biosafety, Biotechnology and Sciences of Life, 2019)

Strategy:	BIT II Bioeconomy in Italy – A new Bioeconomy strategy for a sustainable Italy
Year:	2019
Goals:	1. To increase current Italian Bioeconomy turnover and jobs by 15% by 2030 while increasing the level of circularity in the economy 2. Boosting sustainable and locally routed economic growth by bridging gaps between research and economic sectors 3. Supporting alignment of EU, national, regional policies, regulations and coordination of local stakeholders 4. Ensuring that the Bioeconomy reconciles technological advances and progress without undermining environment conservation and the resilience of the ecosystems 5. Promoting knowledge-based economic activities & policy making 6. Supporting cross-disciplinary education and training for researchers as well as for technical careers 7. Catalyzing informal learning, tertiary education and technology / knowledge transfer to support jobs in the wider Bioeconomy 8. Promoting the Bioeconomy in the Mediterranean [...] to improve Mediterranean primary production and bioindustry potential [...] *No separate goal-setting for indicators*
Circularity	Ingrained in the general objective of the bioeconomy strategy: *" To increase current Italian Bioeconomy turnover and jobs by 15% by 2030, while increasing the level of circularity in the economy"* (Italian Committee for Biosafety, Biotechnology and Sciences of Life, 2019, p. 61)
Framework	• 8 national and/or regional key performance indicator criteria with between two and eight indicators each *(biomass availability, productive structure, employment structure, human capacity, innovation, investment, demographics, markets)* • 5 sustainability objectives (based on one or two sustainable dimensions), each with two or more indicators *(Ensuring food security, managing natural resources sustainably, reducing dependence on non-renewable resources, coping with climate change, enhancing economic growth)* • Most indicators are applicable to a list of bioeconomy sectors
Indicators	• Nomenclature: Qualitative, quantitative, direct, indirect, objective • Indicator types: Descriptive, performance, efficiency, policy effectiveness • Indicator sources: EU key performance indicators • Data sources: national and Eurostat • Data collection frequency: N/A, but indicators based on availability • Scalability: national, regional, sectoral • Aggregation: two separate indicator sets without aggregation

SPAIN

(European Commission, 2019b; Secretería de Estado de Investigación, desarrollo e innovación, 2016)

Strategy: Estrategia Española de Bioeconomía – Horizonte 2030

Year: 2016

Goals:

1. To enhance the competitiveness and internationalisation of Spanish companies operating in the realm of resources of biological origin, and to create new economic activities and new jobs by generating knowledge and adapting it to new scientific and technological developments, responding to the demands of the productive sectors and of consumers
2. To maintain the Spanish bioeconomy as an essential part of our economic activity and position it as an area of knowledge-based strategic innovation among the leaders in an international context
3. To assist in attaining all the bioeconomy's development potential to a horizon of the coming 15 years in Spain, based on social and environmental sustainability and on technological, organisational and management innovation as a tool for resolving problems and to make the most of market openings

No separate goal-setting for indicators

Circularity Supporting the transition to a circular economy is stated as an objective in the introduction but not reaffirmed later in the document.

Framework

- Four measurement categories related to the bioeconomy *(final production, value-added, employment numbers, exports)*
- Each measure is applied to ten aspects *(agriculture, food industry, forestry products, industrial chemicals, pharmaceutical and nutritional by-products, biofuel, renewable energy of biological origin, other rural services, metric tons of processed waste, sustainability indicators)*

Indicators

- Nomenclature: All quantitative, direct, objective
- Indicator types: Solely descriptive and performance indicators
- Indicator sources: N/A
- Data sources: N/A
- Data collection frequency: N/A
- Scalability: sectoral, depending on data availability, national or regional
- Aggregation: measures disaggregated to the sectoral level

Appendix 4: Component Exemplification of the Topical Assessment Framework

Dimension: Circular bioeconomy

Components		Notes
Practices along value chain	Resource regeneration	The extent to which natural resources are depleted versus regenerated
	Fossil replacement	The extent to which the usage of regenerative resources replaces fossil ones
	Integrated biorefining	The extent to which biorefineries are present in cities and the extent of processing, as well as input/output capabilities
	Biomass cascading	The extent to which biomass is transformed with respect for the value pyramid
	Waste generation	Measures related to sources, types and quantities of waste generated by consumers
	Waste valorization	The extent to which nutrients, materials and energy are retrieved in the end-of-life stages of biomass
Material flows along value chain	Organic raw materials	Measures related to origin, availability, circular usage and externalities linked to regenerative resources at the sourcing stage (before transformation)
	Food / feed	Measures related to circular usage and externalities linked to food and feed at the transformation / consumption stage (before end-of-life)
	Materials / chemicals	Measures related to circular usage and externalities linked to bio-materials and bio-chemicals at the transformation / consumption stage (before end-of-life)
	Energy	Measures related to circular usage and externalities linked to bio-energy at the transformation / consumption stage (before end-of-life). This includes its sustainable sourcing and retrieval from biomass
	Water	Measures related to circular usage and externalities linked to water as a resource and waste-product carrier
	Waste / by-products	Measures related to circular usage and externalities linked to organic waste and industrial by-product usage and their transformation / disposal In contrast to the component “waste valorization”, this category focuses on the circularity of waste material flows rather than the industrial practices of value retrieval.

Dimension: Governance mechanisms

Components		Notes
Urban management	Urban planning	The extent to which the physical development of a city supports and reinforces the CBE strategy
	Public procurement	The extent to which purchases by the public sector supports and reinforces the CBE strategy
	Asset management	The extent to which the management of city-owned land, buildings, roads and bridges, as well as water and sewage systems, supports and reinforces the CBE strategy
	Asset usage	The extent to which city-owned assets are productively used in support of and in line with the CBE strategy
	Building and transportation	The extent to which building and transportation infrastructure and services support and reinforce the CBE strategy
	CBE accessibility	The extent to which urban services and infrastructure supporting and reinforcing the CBE strategy are available and accessible to inhabitants
Regulatory measures	Financial support	The extent to which grants and investments support and accelerate the CBE transition, particularly in high-risk areas
	Incentivization	The extent to which subsidies and other incentive systems support CBE competitiveness and transition
	Policy support	The extent to which policy-making supports and accelerates the industrial and social CBE transition
	Standards / certifications	The extent to which standards and certifications supported by policy-making steer industrial and social practices towards compatibility with CBE
	Fiscal measures	The extent to which taxes, charges, fees and fines hinder CBE adverse practices and related externalities
	Legislation / regulation	The extent to which by-laws, regulations and bans hinder CBE adverse practices and related externalities

Dimension: Sustainable development

Components		Notes
Industrial development and capacity	Research, development, innovation	The extent of CBE research and development conducted in an urban area, access to it and resulting innovations that support and accelerate the CBE transition. Includes intellectual property rights
	CBE projects	The amount of and extent to which ongoing and completed CBE projects in an urban area support and accelerate the CBE transition
	Public-private partnerships	The extent to which partnerships crossing the private and public sector support and accelerate the CBE transition
	Productive structure	The extent to which businesses and clusters supporting and accelerating the CBE transition are present in an urban area and can benefit from synergies with each other
	Market performance	The extent to which the CBE contributes to urban economic growth
	Technology and workforce	The extent to which technology and skilled workforce is available or being developed to support and accelerate the CBE transition *Includes human development and capacity, but not employment numbers, which are covered in "Social welfare".*
Social and environmental wellbeing	Climate regulation	The extent to which urban CBE impacts climate change
	Ecosystem services	The extent to which urban CBE impacts the availability of ecosystem services and biodiversity
	Land degradation	The extent to which urban CBE impacts land degradation
	Social welfare	The extent to which urban CBE impacts social welfare (including employment, education, equality, access to aid, etc.) of urban populations
	Material and energy security	The extent to which urban CBE impacts the security and safety of material and energy supplies for its population
	Food security	The extent to which urban CBE impacts the security and safety of food supplies for its population

Appendix 5: Indicator and Assessment Framework Matching

FINLAND

5 measures:

Measure	Component	Rationale
Output	Counted once for each sector	output measures material flow
Value added	Market performance	Counted once, aggregate value
Investments	Financial support	Counted once, aggregate value
Exports	Market performance	Counted once, aggregate value
Employment	Social welfare	Counted once, aggregate value

8 sectors:

Sector	Component	Rationale
Food sector total	Food / feed	Measures material flow
Forest sector total	Organic raw materials	Measures material flow
Other industry	Materials / chemicals	Exemplified online with “chemicals, pharmaceuticals”
Energy	Energy	Measures material flow
Construction	Building / transport	Measures material flow
Water treatment & supply	Water	Measures material flow
Bioeconomy services	Ecosystem services	Measures material flow
Total bioeconomy	dismissed	Aggregate value

GERMANY (translated from German)

Social sustainability

Indicator	Component	Rationale
Number and quota of apprentices	Technology and Workforce	Measures workforce development
Number of employees, who participated at a work-related, non-formal further education program	Technology and Workforce	Measures workforce development
Number of accidents and deaths at work	Technology and Workforce	Measures workforce safety
Child labor / forced labor	Legislation / regulation	By definition
Average completed working hours	Legislation / regulation	By definition
Number of female / transgender employees	Social welfare	Measures equal opportunities
Gender-related pay-gap	Social welfare	Measures equal opportunities
Proportion of disabled employees	Social welfare	Measures equal opportunities
Proportion of migrant employees	Social welfare	Measures equal opportunities
Number of employees with collective agreements	Technology and Workforce	By definition
Number of employees in trade unions	Technology and Workforce	By definition
Engagement of stakeholders in strategy development (qualitative)	Productive structure	Measures how businesses operate

Cooperation as part of PPP projects, research projects and NGOs (qualitative)	Private-public partnerships	By definition
Aspects of patent protection (qualitative)	Research, development, innovation	Protects and furthers innovation
Access to knowledge (qualitative)	Research, development, innovation	By definition
Rooting and implementation of land rights in the legal system (qualitative)	Legislation / regulation	By definition

Economic sustainability

Indicator	Component	Rationale
Number of employees in full-time employment	Social welfare	By definition
Employees with a temporary contract	Social welfare	By definition
Number of informal employments	Social welfare	By definition
Number of employees by qualification	Technology and Workforce	By definition
Number of employees below existential minimum	Social welfare	By definition
Average monthly salaries	Social welfare	By definition
Gini-coefficient	Social welfare	By definition
Product-related Global Competitiveness Index	Market performance	By definition
Staff-related Global Competitiveness Index	Market performance	By definition
Value added of selected bioeconomy sectors	Market performance	By definition
Proportion of revenues by eco- and circular economy firms out of total revenues	Market performance	By definition
Number of firms registered under ISO 14001	Standards / certifications	By definition
Number of patents related to eco-innovations	Research, development, innovation	By definition
Number of promoted research and development projects in SMEs	Financial support	Measures funding for SMEs
Maximum amount of eligible costs for SMEs	Financial support	By definition

Ecological sustainability

Indicator	Component	Rationale
Quantity and Type of GHG emissions	Climate regulation	Measures climate regulation
Amount of CO_2 captured in grasslands and forests	Climate regulation	Measures climate regulation
Total emissions by pollutant	Climate regulation	Measures pollution
Fine dust emissions ($PM_{2,5}$)	Climate regulation	Measures pollution
Quantity of phosphorus and nitrogen in ground and surface water	Climate regulation	Measures pollution
Extraction of ground and surface water	Water	Measures material flow
Water scarcity index	Food security	Measures issue related to nutrition
Diversity by presence of indicator species	Ecosystem services	By definition

Quantity of invasive species on total diversity	Ecosystem services	By definition
Diversity of utilized crop species	Organic raw materials	Measures raw material output
Quantity of genetically modified organisms	Organic raw materials	Measures material flow
Proportion of grassland on total agricultural land	Asset usage	By definition
Proportion of protected area on total area	Asset management	By definition
Type and quantity of utilized chemicals	Land degradation	By definition
Proportion of organic CO_2 in the soil	Resource regeneration	Measures fertility of the soil
Dry bulk density	Land degradation	By definition
Average yearly land degradation	Land degradation	By definition

Sustainability indicators for integrative goals

Indicator	Component	Rationale
Access of rural areas to public transport	Dismissed	Outside the scope of urban CBE
Number of full-time employees in rural areas	Dismissed	Outside the scope of urban CBE
Added value of selected bioeconomy sectors in rural areas	Dismissed	Outside the scope of urban CBE
Development of consumer prices for food	Food security	By definition
FAO indicators for food security	Food security	By definition
Proportion of food consumption that can be covered by national production	Food security	By definition
Proportion of usage types to total land surface	Asset management	By definition
Proportion of degraded acreage	Land degradation	By definition
Direct loss of agricultural land	Land degradation	By definition
Direct loss of forest area	Land degradation	By definition
Indirect loss of agricultural land	Land degradation	By definition
Indirect loss of forest area	Land degradation	By definition
(Acreage) land footprint	Asset usage	Measures usage
Forest footprint	Organic raw materials	Measures usage
Water footprint	Water	Measures usage
GHG footprint	Climate regulation	Measures pollution
Material footprint	Materials / chemicals	Measures usage
GDP per resource utilization	Market performance	By definition
Total raw material productivity	Market performance	Measures economic output
Quantity of waste	Waste generation	By definition
Recycling rate of municipal waste	Waste valorization	By definition
Usage factor of biomass	Biomass cascading	By definition
Proportion of consumer products with sustainability certifications	Standards / certifications	By definition

ITALY

Key performance indicators at national and regional level

Indicator	Component	Rationale
Agricultural biomass production [kg/capita] - import of agricultural biomass	Organic raw materials	measures material flow

Blue biomass production [kg/capita] - import of blue biomass	Organic raw materials	measures material flow
Forestry biomass production [kg/capita] - import of forestry biomass	Organic raw materials	measures material flow
Waste biomass production (including OFMSW) [kg/capita] - import of waste biomass	Waste generation	By definition
Firms in total Bioeconomy sectors [% of total firms]	Productive structure	By definition
Firms in Bioeconomy subsectors [% of total firms]	Dismissed	Aggregate value
Innovative start up in total Bioeconomy sectors [% of total innovative start up]	Productive structure	By definition
Innovative start up in Bioeconomy subsectors [% of total innovative start up]	Dismissed	Aggregate value
Employment in total Bioeconomy sectors [% of total employment]	Social welfare	By definition
Employment in Bioeconomy subsectors [% of total employment]	Dismissed	Aggregate value
Tertiary education [% of total population]	Technology and workforce	By definition
R&D employment in total Bioeconomy sectors [% of total employment]	Technology and workforce	By definition
R&D employment in Bioeconomy subsectors [% of total employment]	Dismissed	Aggregate value
University courses in Bioeconomy sectors [% of total university courses]	Technology and workforce	By definition
Research Institute in Bioeconomy sectors [% of total Research Institutes]	Research, development, innovation	By definition
IPRs (patent, trademark, design) applications in total Bioeconomy sectors [number of application per 1000 employees]	Research, development, innovation	By definition
IPRs (patent, trademark, design) applications in Bioeconomy subsectors [number of application per 1000 employees]	Dismissed	Aggregate value
Private R&D expenditure [index (EU=1)]	Financial support	By definition
Public R&D expenditure [index (EU=1)]	Financial support	By definition
Population growth [% year]	Dismissed	Not bioeconomy specific
Population 15-65 years [% of total population]	Dismissed	Not bioeconomy specific
GDP (PPP) [index (EU=1)]	Public-private partnerships	By definition
Turnover of total Bioeconomy sectors	Market performance	By definition
Turnover of Bioeconomy subsectors	Dismissed	Aggregate value
Value added of total Bioeconomy sectors	Market performance	By definition
Value added of Bioeconomy subsectors	Dismissed	Aggregate value
Exports of total Bioeconomy sectors related goods [% of total exports]	Market performance	By definition
Exports of Bioeconomy subsectors related goods [% of total exports]	Dismissed	Aggregate value
Imports of total Bioeconomy sectors related goods [% of total exports]	Market performance	By definition
Imports of Bioeconomy subsectors related goods [% of total exports]	Dismissed	Aggregate value

Bioeconomy sectors

Indicator	Component	Rationale
Primary biomass sectors: Agriculture, paper industry, forestry, fisheries and aquaculture	Organic raw materials	measures material flow
Food industries, beverages and tobacco	Food / feed	By definition
Water cycle	Water	By definition
Biodegradable waste recovery and management	Waste valorization	By definition
Bio furniture	Materials / chemicals	By definition
Bio textile & clothing	Materials / chemicals	By definition
Bio plastics and rubber	Materials / chemicals	By definition
Bio apparel	Materials / chemicals	By definition
Bio energy	Energy	By definition
Bio chemicals	Materials / chemicals	By definition
Bio fuels	Energy	By definition
Bio pharmaceuticals	Materials / chemicals	By definition

Sustainability indicators

Indicator	Component	Rationale
Change in food price volatility	Food security	By definition
Change in macronutrient intake / availability	Food security	By definition
Change in malnutrition or risk of hunger	Food security	By definition
Change in freshwater availability	Water	Measures material flow
Level of water pollution	Climate regulation	Measures climate regulation
Change in land use intensity	Asset usage	By definition
Land productivity	Asset usage	By definition
Rate of biodiversity loss	Ecosystem services	By definition
Secondary material price changes	Waste valorization	Measures value from organic waste
Organic waste diverted from landfills	Waste / by-products	By definition
forest area subject to planning and certified surface	Asset management	By definition
Water productivity	Water	By definition
Water use efficiency	Water	By definition
Final energy consumption	Energy	By definition
Energy intensity of the economy	Energy	By definition
Share of renewable energy in gross final energy consumption	Fossil replacement	By definition
Energy productivity	Energy	By definition
Energy use efficiency	Energy	By definition
Change in greenhouse emissions	Climate regulation	Measures climate regulation
Level of emission of air pollutants	Climate regulation	Measures climate regulation
Change in employment rate	Social welfare	By definition
Job creation in skilled/unskilled labor	Market performance	Measures competitiveness

SPAIN

4 measures:

Measure	**Component**	**Rationale**
Final production	Counted once for each sector	output measures material flow
Added value	Market performance	Counted once, aggregate value
Employee numbers	Social welfare	Counted once, aggregate value
Exports	Market performance	Counted once, aggregate value

8 sectors:

Sector	**Component**	**Rationale**
Agriculture	Organic raw materials	Measures material flow
Food industry	Food / feed	Measures material flow
Forestry products	Materials / chemicals	Measures material flow
Industrial chemicals	Materials / chemicals	Measures material flow
Pharmaceutical and nutritional by-products	Waste / by-products	Measures material flow
Biofuels	Energy	Measures material flow
Renewable energy or biological origin	Energy	Measures material flow
Other rural area services	Dismissed	Outside the scope of urban CBE
Metric tons of processed waste %	Once: Waste generation Once: Waste valorization	Combined with final production Combined with added value
Sustainability Indicators	Climate change	Lack of specification for this aspect, closest approximation