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RESEARCH

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The circular bioeconomy: a driver for system integration

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Abstract

Background Human and earth system modeling, traditionally centered on the interplay between the energy system and the atmosphere, are facing a paradigm shift. The Intergovernmental Panel on Climate Change's mandate for comprehensive, cross-sectoral climate action emphasizes avoiding the vulnerabilities of narrow sectoral approaches. Our study explores the circular bioeconomy, highlighting the intricate interconnections among agriculture, forestry, aquaculture, technological advancements, and ecological recycling. Collectively, these sectors play a pivotal role in supplying essential resources to meet the food, material, and energy needs of a growing global population. We pose the pertinent question of what it takes to integrate these multifaceted sectors into a new era of holistic systems thinking and planning.

Results The foundation for discussion is provided by a novel graphical representation encompassing statistical data on food, materials, energy flows, and circularity. This representation aids in constructing an inventory of technological advancements and climate actions that have the potential to significantly reshape the structure and scale of the economic metabolism in the coming decades. In this context, the three dominant mega-trends—population dynamics, economic developments, and the climate crisis—compel us to address the potential consequences of the identified actions, all of which fall under the four categories of substitution, efficiency, sufficiency, and reliability measures. Substitution and efficiency measures currently dominate systems modeling. Including novel bio-based processes and circularity aspects might require only expanded system boundaries. Conversely, paradigm shifts in systems engineering are expected to center on sufficiency and reliability actions. Effectively assessing the impact of sufficiency measures will necessitate substantial progress in inter- and transdisciplinary collaboration, primarily due to their non-technological nature. In addition, placing emphasis on modeling the reliability and resilience of transformation pathways represents a distinct and emerging frontier that highlights the significance of an integrated network of networks.

Conclusions Existing and emerging circular bioeconomy practices can serve as prime examples of system integration. These practices facilitate the interconnection of complex biomass supply chain networks with other networks encompassing feedstock-independent renewable power, hydrogen, CO_2, water, and other biotic, abiotic, and intangible resources. Elevating the prominence of these connectors will empower policymakers to steer the amplification of synergies and mitigation of tradeoffs among systems, sectors, and goals.

Keywords Circular economy, Bioenergy, Renewables, Hydrogen, Efficiency, Substitution, Sufficiency, Resilience, Reliability, Sankey graph, Modeling, Flexibility, Planning, Network, Design

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Introduction

Problem statement and contribution

Various engineering, social science, and humanities fields are developing approaches to anticipate the long-term consequences of technological innovation and infrastructure development on society, the environment, and the economy. Previous evaluations of climate change mitigation and adaptation measures have primarily concentrated on energy system transformations. In the spotlight today, however, are potential synergies and tradeoffs between measures across different sectors. The combined complexity of the forestry, agriculture, and aquaculture sectors—collectively termed the bioeconomy—surpasses that of fossil fuel, nuclear, and feedstock-independent energy sectors. Furthermore, since the beginning of the 2020s, "circular bioeconomy" has been a preferred term, especially in European discussions. This term stresses the need to restructure the economy beyond, for example, substituting fossil fuel-based chemicals with bio-based chemicals and to depart from the respective sectors' "take, make, dispose" linearity.

A key task for technology assessment, impact assessment, and systems engineering scholars is anticipating the multifaceted interactions between the involved sectors and the aspects of a dynamically evolving circular bioeconomy, including the risks and opportunities of additional system integration, multisector, and multigoal coupling. Accomplishing this task requires demarcating the object under investigation and its system boundaries.

However, "[c]are must be taken in the beginning stages of theory (discipline) development not to narrow quickly, possibly precluding discoveries from broad range explorations" [1]. The "open mind" perspective can be beneficial for unraveling synergies between a broad range of societal transformation requirements set out in the United Nations' Sustainable Development Goals (SDGs), including taking affordable and clean energy and climate action, providing clean water and sanitation for all, ensuring responsible consumption and production, and working toward innovations in industry and infrastructure.

To avoid limiting the discursive space through a premature framing of the circular bioeconomy, we explore its multifaceted aspects through quantitative and qualitative methodologies designed to provide broad overviews of potentially relevant aspects. Based on the resulting broadened discursive spaces, we discuss the requirements for systems modeling of the circular bioeconomy with a focus on the risks and opportunities of system integration and multisector and multigoal coupling with and within the circular economy.

Background

In its latest Synthesis Report, the Intergovernmental Panel on Climate Change stresses the escalating risks, projected adverse impacts, related losses, and damages related to every increment of global warming. To secure a liveable and sustainable future for all, the report urges rapid and far-reaching transitions across all sectors and systems while warning about focusing on isolated sectors and risks. Such a focus would result in lock-ins of vulnerability, exposure, and risks that are difficult to change and must be "avoided by flexible, multi-sectoral, inclusive, long-term planning and implementation of [system-change] actions, with co-benefits to many sectors and systems" [2].

The Intergovernmental Panel on Climate Change tasked the Integrated Assessment Modeling Consortium with leading and facilitating the development of numerical experiments on the interactions of the human and earth systems. Since the 1970s, modeling of the earth system revolved around depicting atmospheric circulations and modeling of the human system around the deployment of fossil fuels [3, 4]. During the first oil crisis, in 1973, energy system models tested least-cost energy security policies, shifting their attention later to anticipating CO_2 emissions from energy deployment and determining how to achieve an economy-wide, carbon–neutral energy supply [5]. As a result, the first integrated assessment models (IAMs) found an apparent common denominator in greenhouse gas (GHG) emissions. Earth system models calculated GHGs causes and effects, while human system models estimated the costs and benefits of avoiding them.

With "climate action" and "clean energy for all" constituting only two of the 17 SDGs adopted by world leaders in 2015, however, this research domain must critically reflect on its ability to provide coherent policymaking advice with robust information. For example, the Alliance of Sustainable Universities in Austria recently scrutinized the abilities of a broad spectrum of quantitative and qualitative forward-looking approaches for exploring the interactions between SDG entities, including goals, targets, indicators, and policies. In this context, Horvath et al. [6] stress the relatively low interdisciplinary sensitivity of current simulation methods, which hinders more systemic research that could provide insights into relevant synergies and tradeoffs.

Recent high-level publications have provided a stock take on the major missing links of the incumbent IAMs. Quarton et al. [7] outline the conflicting roles of hydrogen in global energy scenarios. Welfle et al. [8] find that "IAMs do not/cannot capture the many other issues associated with sustainable bioenergy systems and the nuances between them." Nikas et al. [9] address the need for "conceptual and methodological bridges […] allowing an interdisciplinary integration and assessment of circularity, decarbonization, and sustainable development." The European Commission tasked the Joint Research Center and Pyka et al. [10, 11] with reviewing existing and emerging approaches for bioeconomy modeling. They highlight how this field is rooted in IAMs and highlight their "importance for providing information on different aspects [based on] their multisector and multidisciplinary nature."

Definitions

Kirchherr et al. [12] define the *circular economy* as an "economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes." A wealth of circular economy research and policy has emerged that focuses on upcycling non-biogenic materials, metals, and rare-earth elements, especially in electronic products [13], and, more recently, plastics and non-metallic minerals.

The concept of a *circular bioeconomy* addresses the wasteful use of biomass while encompassing the reduction, alternative use, recycling, and recovery of biological resources throughout the biomass value chain. By the definition of the European Commission, the *bioeconomy* includes "all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services. To be successful, the European bioeconomy needs to have sustainability and circularity at its heart" [14]. Circular bioeconomy research is trending both among practitioners and scholars. For example, the largest funding resource for research and development on related topics, the Bio-Based Industries Joint-Undertaking (a public–private partnership between the European Union and the Bio-Based Industries Consortium), was renamed the Circular Bio-Based Europe Joint Undertaking in 2021 [15]. The emergence of this terminology is reasonably recent in academia. Scopus reports the first journal publications with "circular bioeconomy" in their title, abstract, or keywords only in 2016, more than doubling yearly publication rates from four publications to almost 400 in 2022.[1] By the time of resubmission of this paper in April 2024, 1,641 publications were listed under this compound keyword.[2]

Compared to circular minerals and metals flows, however, the circularity of biomass flows adheres to different framework conditions. Biodegradability imposes limits on storing and re-using bio-based materials, and discharging or landfilling biodegradable waste creates other environmental and societal problems than landfilling minerals and metals. On the other hand, biomass is traded and deployed based on different functional contents: for example, its nutritional; energy value; structural strength; water content; or unquantifiable properties such as taste, smell, and appearance. The interaction of these framework conditions has led to a wealth of circular bioeconomy practices, such as nutrient recovery from wastewater treatment, paper recycling, and energy provision from biogas or sawmill residues. These practices integrate multiple systems (i.e., couple together different sectors), including water and sanitation, food provision, and wood-based building sectors. Consequently, *system integration* also referred to as *multisector coupling,* has been a foundational component of economic metabolism for many decades, prompting critical inquiry into its evolving role in the sustainable development landscape ahead.

Paper outline

In the "Methodology" section, we outline the quantitative and qualitative methodology of this study. The findings are presented in the "Results" section. In the "Discussion" section we derive potential requirements for systems engineers, modelers, and other long-term planners who engage with multisector dynamics on a conceptual level. In the "Conclusion" section, we distill the guiding principles for circular bioeconomy planning activities.

Methodology

With this publication, we carefully broaden the discursive space for circular bioeconomy systems engineering to derive first requirements and guiding principles for the emerging research field. Therefore, we provide an overview of the status quo of the circular bioeconomy and its coupled sectors, by merging available Sankey graph data into a novel representation of economy-wide resource flows between the biosphere and the technosphere (Sect. "Status quo of resource flows between the biosphere and the technosphere"). This novel graphical representation is then used to explore qualitative expectations on how these resource flows might change in the upcoming decades (Sect. "Anticipating changes in the economic metabolism in the coming decades").

[1] www.scopus.com, *search result on February 4th, 2023.*

[2] www.scopus.com, *search result on April 22nd, 2024.*

Creating an overview of the status quo of relevant resource flows

Activities such as electricity production and energy consumption for transportation can be denoted as nodes in graph theory, and resource flows (e.g., solid fossil fuels or renewable electricity) can be denoted as edges (see, e.g., [16]). Resources typically flow from the input nodes from left to right, except for circular flows, which can loop back to the input nodes from right to left. The nodes are again grouped into node levels, giving the main process types, and edges are grouped into edge levels. In practice, theoretical graph data is stored in edge lists, with each row of a data sheet representing one edge flow between two nodes. Edge lists can describe, for example, different types of materials flowing through an industrial process or the overall economy and are typically illustrated in Sankey graphs.

Economy-wide material flow accounts (ewMFAs), based on the methodologies created by the Nobel laureate Wassily Leontief [17], provided the starting point for systemic material flow discussions on a national level. To date, Eurostat provides the most comprehensive ewMFA for Europe regarding metals, minerals, fossil fuels, and biomass and their respective emissions on a weight basis (see, e.g., Mayer et al. [18]). The work of Mayer et al. was continued in the EXIOBASE v3 database, which complements mass balances with energy- and monetary balances [19]. Global energy and associated chemical flows are monitored by different organizations, such as the International Energy Agency and Eurostat, both of which also provide interactive Sankey diagrams for illustrating the flows of renewable and fossil energy [20, 21]. Data sets and Sankey diagrams on forestry biomass date back to the beginning of the last decade [22]. For example, models of biomass flows, including agriculture and aquaculture, have been developed for the Austrian economy [23]. Only recently, however, have non-organic materials and energy flows been complemented in European statistics with thermodynamically balanced representations of biomass flows for food, material, and energy services [24–26].

This progress enables us to construct a unified database based solely on Eurostat data and illustrate this data in Sankey graphs. To this end, the following Eurostat data sets must be harmonized and unified:

- European Energy Flows Sankey diagram data found under the [nrg_bal_sd] handle in Eurostat;
- Eurostat Material Flow Accounting found under the [env_ac_mfa] handle, the Waste Management Statistics found under the [env_wassd] handle, and the [env_ac_sd] handle in Eurostat; and
- Eurostat Biomass Flow Sankey diagram data, which does not have a handle yet but can be accessed via the Joint Research Centre homepage.[3]

A well-thought-out meta-structure for the Sankey diagram was developed to ensure (1) a holistic depiction of energy, material, and biomass flows and (2) conciseness of the final visualization to fulfill its purpose of informing a broader audience. These two objectives can be balanced by grouping resource types that flow through the economy and the different processes through which the resources flow.

To harmonize and unify the underlying Eurostat data sets, we propose a novel meta-structure for circular bioeconomy edge lists, shown in the results section. The meta-structure is primarily inspired by the Circularity Gap Reports [27] and data on energy, materials, and biomass flows available on Eurostat [24–26]. The novel structure choice, harmonization methodology, and limitations of the resulting Sankey graphs are thoroughly discussed in the supplementary materials, including a review of existing Sankey graphs representing economy-wide flows of different resources. Edge lists, conversion and reattribution tables, and explanatory Sankey graphs are compiled in the supplementary sheets.

A quality examination of the potential economic metabolism changes

In the collaborative development of edge lists and subsequent analysis through the visualization of Sankey graphs, we sought to achieve a comprehensive mapping of anticipations concerning the structure and scope of the circular bioeconomy. The motivation for this study initially lays in the pursuit of quantitative modeling methodologies capable of accommodating potential alterations within the unified and coherent edge list. This, in turn, should have facilitated the creation of Sankey graph depictions projecting scenarios for the forthcoming decades. However, confronted with the multifarious complexities inherent to circular economy and bioeconomy modeling, as elucidated in recent comprehensive reviews [8, 9, 11], we opted to formulate qualitative scenario narratives instead. Drawing upon European data sets as our primary data source, these long-term projections are predominantly centered on tangible resource flows within the domains of energy, materials, and food. The

[3] https://datam.jrc.ec.europa.eu/datam/mashup/BIOMASS_FLOWS accessed 24.01.2024.

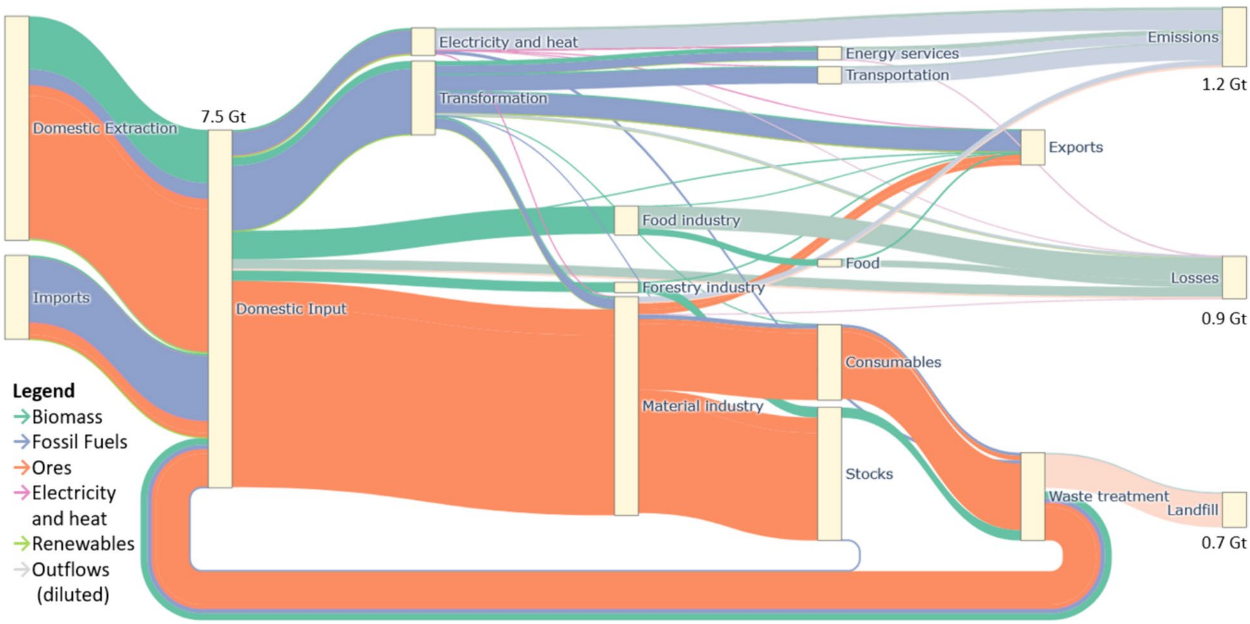

Fig. 1 EU27 resource flows 2017 based on mass content (1 Gt = 10^{12} kg). Electricity distribution and use cannot be meaningfully related to mass flows but are still included as one-dimensional lines to indicate their relevance based on energy content. Source: own illustration based on refs. [22–24]

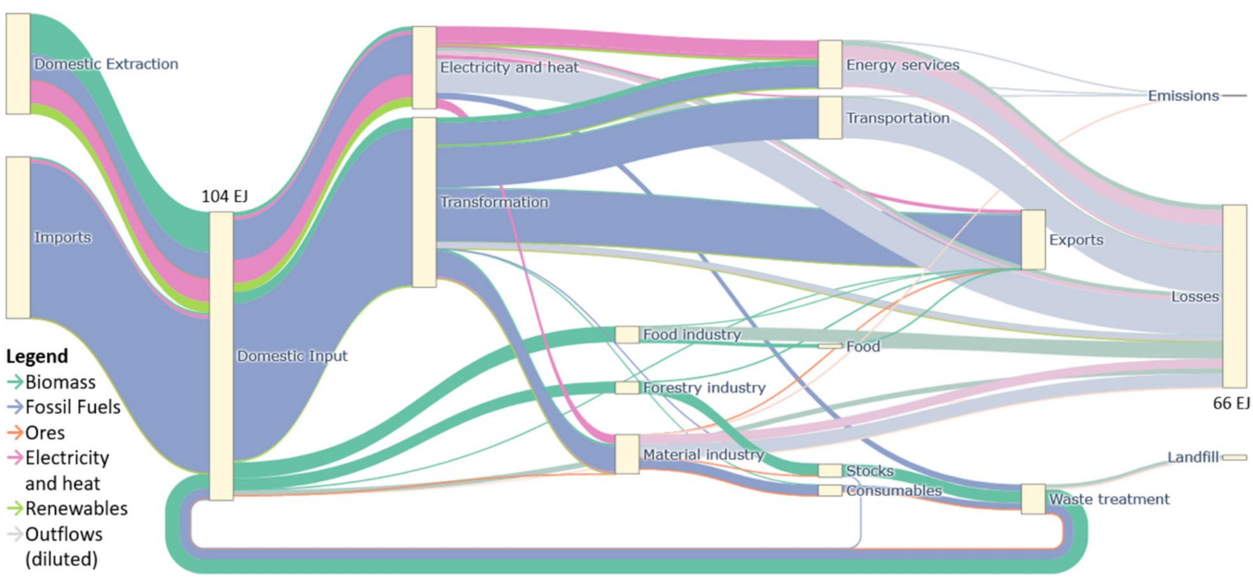

Fig. 2 EU27 resource flows for 2017 based on energy content (1 EJ = 10^{18} J). Ores and emissions cannot be meaningfully illustrated in energy flows but are still shown as one-dimensional lines to indicate their relevance based on mass content. Source: own illustration based on refs. [22–24]

outcome of this endeavor is an inventory of circular bioeconomy processes and emerging trends. Although not exhaustive, this inventory serves as a valuable resource for deliberating the prerequisites that warrant consideration in the planning of circular bioeconomy strategies and the integration of multiple sectors.

Table 1 Optimal grouping of node levels, nodes, edge levels and edges for the Sankey diagram illustration

Node levels and nodes	Edge levels and edges
Sourcing	**Fossil fuels**
Imports	Liquid fossil fuels
Domestic extraction	Gaseous fossil fuels
Availability	Solid fossil fuels
Domestic inputs	Other fossil fuels
Pre-processing	**Electricity and heat**
Electricity and heat	From fossil fuels
Transformation	From nuclear power
Processing	From renewables
Food industry	**Minerals**
Forestry industry	Mineral ores
Material industry	Non-metallic ores
Societal needs	**Biomass**
Transportation	Forestry biomass
Energy services	Agriculture biomass
Food	Fisheries biomass
Consumables	**Carbon dioxide**
Stocks	From fossil fuels
Loopbacks	From biomass
Exports	
Waste treatment	
Outflows	
Emissions	
Losses	
Landfill	

Source: own elaboration based on the Circularity Gap Reports and Eurostat data [24–27]

Results

Status quo of resource flows between the biosphere and the technosphere

Using the openly accessible Eurostat data and a novel merging procedure, we generated first-of-its-kind unified Sankey diagrams representing the current state of the circular bioeconomy in the 27 member states of the European Union (EU27) based on both energy and mass values (Figs. 1 and 2, respectively). The meta-structure outlined in Table 1 is inspired by the Circularity Gap Reports [27] and the data available on Eurostat [24–26]. The meta-structure follows the two objectives of a holistic depiction of energy, material, and biomass flows and conciseness of the final visualization to inspire the discussion on expected long-term changes in the economic metabolism.

The integrated Sankey diagrams were conceived with the explicit purpose of facilitating discourse concerning forthcoming developments and trends in strategic planning for the circular bioeconomy. By its nature, material flow accounting tends to underestimate the importance of renewable electricity, while energy flow analysis fails to adequately capture critical mass-related aspects, such as the associated emissions. Furthermore, it is imperative for our research to encompass various dimensions, such as the non-energy use of fossil fuels, particularly in relation to the materials derived from minerals, metals, and biomass, as these factors assume paramount significance within our analytical framework.

The illustrations in Figs. 1 and 2 advance the state-of-the-art by including aspects of the economic metabolism that are underrepresented in Sankey graphs found in the literature [18, 19, 22, 23, 26]. We provide a combined graph of energy, material, and food flows, which is necessary to capture the potential extent of the circular bioeconomy. The integration of hitherto segregated energy, material, and biomass flow assessments necessitated the advancement of the current state-of-the-art in the following ways:

1. a shift in focus toward fundamental societal requirements or the fundamental rationale underpinning the preservation of resource streams;
2. the inclusion of mechanisms for quantifying resources that are either circulated within the system or dissipated as waste (i.e., outflows); and
3. the depiction of resource flows in accordance with their distinct functional units, thus affording a more granular and nuanced representation of the data.

Energy flow accounting clarifies what specific resource flows are used for (i.e., the basic societal needs). They differentiate between residential heating, transportation, the service sector, and the industry sector on the highest agglomeration level. Non-energy use of fossil fuels—for plastics and chemicals and, volumetrically most relevant, for providing road infrastructure [28]—is considered an additional societal need. Arguably, the industry sector produces goods used by society (consumables) or deployed in the building or appliances stock to cover societal needs either as a one–off or continuously. Unlike energy flow accounting, however, ewMFAs traditionally focus on the processes rather than the final resource deployment. Haas et al. [29] propose a graphical depiction of comprehensive energy and mass balance of the economy, with a higher resolution of the end-use sectors going beyond the agglomerations "materials used" and "material in stock." Their work focuses mainly on determining the circularity of the metabolism (i.e., measuring the waste streams that loop back as inputs). It was from their work that circularity gap research emerged [18, 30–32]. The Circularity Gap Reports differentiate between societal needs for housing, communication, mobility, healthcare, services, consumables, and nutrition

[32]. In contrast, the developed agglomerations (illustrated in Figs. 1 and 2) aim to provide a quicker overview to discuss relevant significant changes in the upcoming decades.

Furthermore, the presented Sankey graphs are informed by the circularity gap literature concerning resource flows after their final deployment. Waste treatment for recycling, landfilling, emissions, and other losses (e.g., through dispersion into the environment) are resource flows that must be sufficiently represented in energy and biomass accountings. Emissions from the energy system however, which are not part of the energy and biomass flow accountings, can be derived from environmental edge lists. For example, circular flows for biomass are illustrated for wood-processing industries [22, 33].

Trivial conversion rates, such as zero tons per gigajoule for electricity, were applied and are explained in the supplementary materials. Still, we recommend a coherent conversion between functional units of all material and energy flows to foster a broader perspective. However, this perspective remains limited in regard to other resource flows and functional units that might be relevant for framing the circular bioeconomy. We briefly review the state-of-the-art accounting for additional resource flows in the supplementary materials. Other resources flowing through the economy include bulk water, airflow, flows of plant macronutrients, physical and cognitive labor, and monetary, time, and land resources, which are not in the scope of the current publication. Identifying these limitations informs the qualitative scenario exploration presented in the next section.

Anticipating changes in the economic metabolism in the coming decades

In the following, we reflect on the illustrations in Figs. 1 and 2. What changes can we expect in the illustrated resource flows between now and the year 2050? We differentiate between changes induced by macro-drivers (Sect. "Anticipating macro-drivers and mega-trends") and those driven by social, technical, and organizational innovation in energy flows (Sect. "Anticipating changing energy flows"), material flows (Sect. "Anticipating changing material flows"), and food flows (Sect. "Anticipating change in economy-wide food flows"). We are particularly interested in potential changes that significantly impact mass and energy volumes and in how these changes are depicted in existing modeling practices.

Anticipating macro-drivers and mega-trends

System engineers striving to inform policymakers and stakeholders are interested in potential changes, visible in changing flow weights and types in the presented Sankey graphs over the upcoming decades and in the longer term. For exploring energy system scenarios, the shared socioeconomic pathways (SSPs) [35] are broadly accepted as a set of possibly relevant macro-developments. They address two interlinked macro-drivers, namely demographic and economic drivers, also called pressures in social transition research (see Geels [34]).

Human *population dynamics* are one of the significant uncertainties that must be addressed before decisions regarding infrastructure investment and system design can be made. The SSPs are closely linked to education rates in the population, which in turn affect factors such as fertility, mortality, income, and equality. Population dynamics also include a spatial dimension. They differ between countries, regions, and urban and rural areas, all succumbing to migration. All SSPs assume overall population growth until 2030–2040, followed by further growth, stagnation, or gradual decline [35]. However, they exclude discontinuous developments, such as doomsday scenarios (see, e.g., [36]), and the collapse of large-scale organizational structures, which systems engineering aims to avoid in the first place.

Economic developments are represented as countries' and regions' gross domestic product (GDP). In combination with purchasing-power parity, GDP can provide insights into the overall resource intensity of the population. Furthermore, the Gini index helps provide more exact estimates of resource consumption based on income distribution within the population [37]. The economic distribution affects overall fertility, mortality, and the risk of revolutions and wars, potentially leading to the collapse of humanity's self-organization capacity. All SSPs assume GDP growth but differentiate between improving and worsening income inequality [35].

On the abstraction level of the present study and considering the SDGs and Paris Goals, we must consider the phasing out of fossil fuels, including coal, oil, and natural gas, and its primary rationale, the climate crisis, as an additional relevant macro-development (i.e., *changing environmental pressures*). Climate change mitigation requires GHG emissions to be stopped completely and possibly the reversion of GHG flows by negative emission strategies. For the European economic metabolism, as illustrated in Figs. 1 and 2, domestic inputs and subsequent resource flows with high GHG relevance account to 15% on a mass basis and 52% on an energy basis. In addition to climate change mitigation, adaptation is required to adjust to consequences, including rising sea levels, increasing temperatures, and severe weather events, especially by investing in resilience [38]. In combination, the outlined mega-trends do not simply require a transition, but demand far-reaching transformational change fueled by significant technological, organizational, and societal advancements.

The three mega-trend categories—(1) demographic drivers, (2) macro-economic developments, and (3) changing environmental pressures—set the overall framework conditions and need for circular bioeconomy systems engineering. The long-term trends will affect the resource flows illustrated in Figs. 1 and 2, "creating windows of opportunity" [39] for social, technical, and organizational innovation in energy, materials, and food flows.

Anticipating changing energy flows

European domestic resource input for energy production and consumption accounted for about 84×10^{18}J in 2017. This input mainly included oil, coal, and gas imports (57×10^{18}J). Fossil fuels are primarily transformed into transport fuels, electricity, and heat or used for materials processing, with transformation losses of about 14×10^{18}J. The remaining 70×10^{18}J are deployed for exports (20×10^{18}J), non-energy use (4×10^{18}J), energy (3×10^{18}J), or directly for various societal needs. Transportation, including road and rail transport and aviation, require 16×10^{18}J, mostly provided via oil products. Industry consumes another 10×10^{18}J, and households, services, and agriculture another 17×10^{18}J. Households require energy mainly for residential heating. Other services include appliances for cooking, washing, lighting, hot water, and communication [21].

Modeling the impact of system-change actions on energy flows has a long history. It is an established academic field with extensive scientific literature and long-term scenarios developed and deployed for policymaking. According to current reviews, most models focus on energy resource substitution and efficiency measures [40–43]. More recently, however, more attention has been given to system integration, primarily through sector coupling between the power sector, heating, and transportation, which can provide valuable flexibility for variable renewable electricity production [44, 45]. The anticipation of different types of consumers and sufficiency measures mainly relates to social and spatial planning topics. Furthermore, topics that have mostly been overlooked in current modeling efforts include decentralization, energy security, market organization, regional responsibilities, and development [42, 46–48].

Energy and CO_2 intensity of European residential heating are expected to decrease through improved building insulation, renovation, and technology substitution measures. Integration measures will shape the resource flows directed toward households through sector coupling based on heat pumps and district heating expansion [49]. While this could decrease overall energy demand for heating, sector coupling and accelerating digitalization will significantly boost electricity demand for transportation and communication. The conversion of electricity into hydrogen via electrolysis can provide a dense, storable energy carrier that can be applied in hard-to-abate sectors. Relevant hard-to-abate sectors include especially industry based on high-temperature heat, maritime transport, and aviation. Furthermore, green hydrogen (i.e., hydrogen produced via electrolysis from renewable electricity) can be stored with higher energy densities than renewable electricity, for example, after conversion or mixing with synthetic natural gas in the existing natural gas infrastructure. The green hydrogen economy is expected to develop significantly in the following decades but has yet to be consistently reflected in energy system modeling [7]. Green hydrogen deployment is also discussed for sectors that are not hard-to-abate (i.e., sectors that can be directly electrified). In these sectors, however, direct electrification is usually significantly cheaper and thus economically more feasible than the production of hydrogen-based electrofuels. Still, electrofuels can be used for road transportation and heating, with the potential risk of "lock[ing]-in a fossil-fuel dependency if e-fuels fall short of expectations" [50].

At least in Europe, liquid and gaseous biofuels for transportation are currently perceived as transition technologies. Policies to ban combustion engines for road transportation after 2035 are being discussed [51]. Biofuels might become relevant as bunker fuels for shipping and bio-based kerosene for aviation, but the competing long-term vision is to electrify, directly or indirectly, via hydrogen. Overall, residential heating demand will probably decrease due to the implementation of efficiency measures. Still, the effects must be anticipated of substituting large numbers of fossil fuel-based heating devices with wood chips and wood pellets boilers, district heating, combined heat and power, and electrification via heat pumps. The European Commission promotes efficient district heating, and "it is therefore assumed that European D.H. [district heating] markets will grow in the future" [52]. District heating market expansion is also taking into account industrial excess heat integration [53]. Furthermore, we expect large-scale bioelectricity-only production to focus on carbon capturing, sequestration, and storage in the upcoming decades. European annual storage capacities, mainly in deep saline aquifers, are estimated to be around 1×10^{12} kg_{CO2} [54]. Negative emission technologies, including bioenergy-based carbon capturing, sequestration, and storage and direct air capture, would contribute to novel stocks, potentially visible in the Sankey graphs for 2050 and beyond. However, due to a lack of potential business models and the

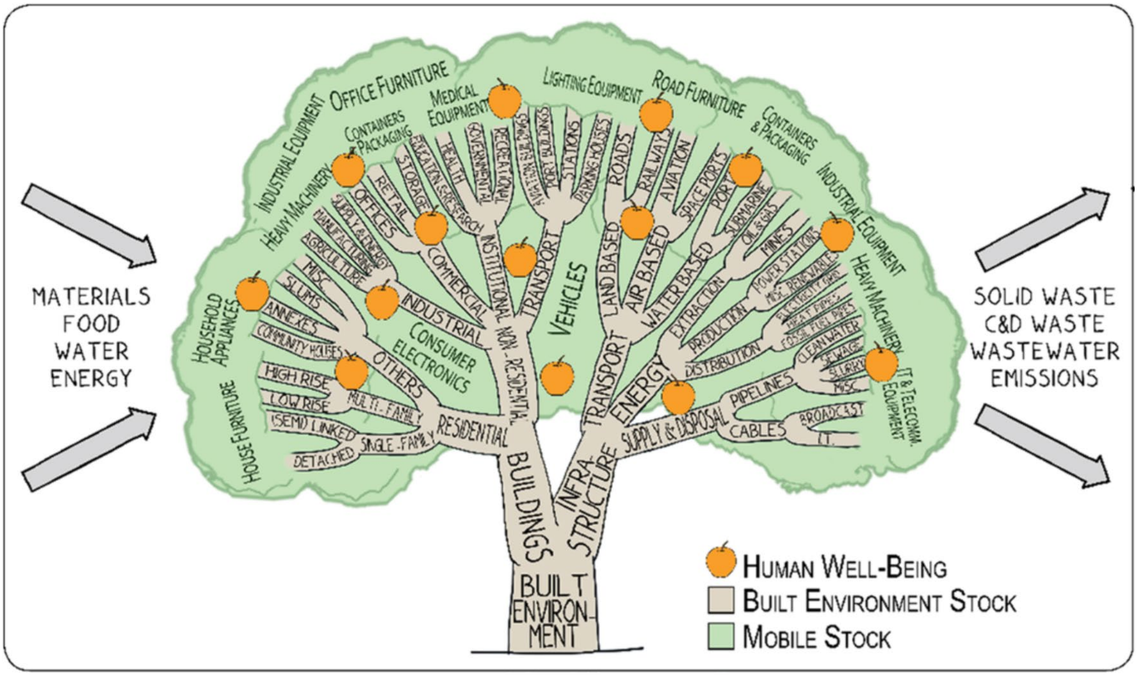

Fig. 3 Anthropogenic stocks as a tree. Branches represent the end-use categories of the built environment stock, and foliage represents the mobile stock categories. Source: Reprinted with permission from Lanau et al. [56]. Copyright 2023 American Chemical Society

need for more public policy support and regulations for storing carbon [55], the potential contribution of negative CO_2 emissions technologies is subject to significant uncertainties.

Collective energy flow substitution trends might visually alter the Sankey graphs in the long term by mostly removing fossil fuel flows and CO_2 emissions to the atmosphere. Therefore, the resource input based on mass content will significantly decrease but increase in total based on energy content. In the long term, electricity from wind, photovoltaic systems, and renewable electricity-based auxiliary fuels are expected to dominate the resource supply for all energy needs. Bioenergy for industrial and residential heat, electricity, and transportation may still be essential as a transition technology and beyond. However, we expect the role of bioenergy to be less occupied by substituting fossil fuels and more by integrating measures to improve overall system reliability [45]. Measures include integrating variable renewable energy generation and flexible bioenergy, green hydrogen, and bioenergy to form stable carbohydrates; integrating negative emission services; and improving the integration between biomass flows for energy, materials, food, and circular use of by-products and wastes.

Anticipating changing material flows

Biomass, abiotic, fossil material, and respective circular flows are subject to the built environment, mobile stocks, and consumables. Systems engineers consider trends for these resources less frequently than they do energy flows [9]. Lanau et al. [56] provide an accounting for "[m]aterials accumulated in the anthroposphere in the form of buildings, infrastructure, and consumer goods […]" based on a thorough literature review of built environment stocks and material flow analysis. Their resulting typology is vividly illustrated in the form of the anthropogenic stocks tree (Fig. 3). The typology mainly differentiates between (a) the built environment, including buildings and infrastructure; and (b) the mobile stock, including machinery and electronic equipment.

Direct GHG emissions from resource extraction, supply, manufacturing, deployment, and waste management are part of a broad range of negative environmental and social impacts. Critical changes in landscapes, hydrology, and biodiversity occur throughout the material extraction-to-disposal value chain, but the negative effects weigh disproportionally more on countries that benefit the least from these resources, specifically for metals and rare earths [57].

European resource inputs for the material industry mainly consist of ores, especially non-metallic minerals (about 3.6×10^{12} kg). Significantly lower fractions consist of biomass (about 0.4×10^{12} kg), metal ores (approximately 0.3×10^{12} kg), and materials based on fossil fuels (approximately 0.1×10^{12} kg) [25]. Wiedenhofer et al. [58] modeled global future developments of material flows, considering existing stocks, maintenance, and replacement based on virgin resources. Material stocks are dominated mainly by concrete, sand and gravel, asphalt, and bricks used in the built environment and infrastructure. Wiedenhofer et al. found that per capita stock accumulation in industrialized regions is slowing down, potentially indicating saturation in the upcoming decades. However, "even if material stocks are saturated, their operation, maintenance and replacements of stocks will require continuous material and energy inputs" [58].

Thus, the impact of recycling practices and technologies will become more visible in the overall economic metabolism resource flows. In addition to improving recovery rates, prolonged lifetimes and equitable deployment of the in-stock materials are essential to reduce the pressure of material accumulation. Still, and from a thermodynamic perspective, these resource-efficiency measures cannot replace sufficiency-related system changes. Simply put, "closing material loops completely is incompatible with physical growth" [59].

Sufficiency measures will be required. Such measures mostly differentiate between collaborative consumption and conscious non-consumption. Sharing can also be categorized as an efficiency measure; however, sharing can lead to similar adverse effects of fueling additional overall consumption due to greater accessibility and lower costs of shared services and products. Community initiatives and commercial practices contribute to the so-called sharing economy. Other sufficiency actions include conscious non-consumption, anti-consumption, voluntary simplicity, minimalism, and sufficiency lifestyles. Respective sufficiency measures are based on social innovations and are mainly discussed as individual contributions, which rarely find their way into models and policy [60].

While we expect circular flows for metals and in-stock non-metallic minerals to increase significantly, we anticipate some potentially relevant resource substitution effects. Materials are mainly flowing into the construction sectors. Bio-based construction materials such as glue-laminated beams and cross-laminated timber are engineered wood products with more predictable mechanical performance. These products along with bamboo could "lead to downscaling of cement, steel, aggregate, limestone, and iron ore mining and production" while providing opportunities for large-scale and maintained carbon sinks [61]. Current bio-based insulation materials include panels, bales, fibers, loose fills from cotton, flax and hemp, cork, wood, and sheep wool [62]. If bio-based building and insulation materials are used extensively as alternatives and carbon sinks, their end-of-life treatment practices, including energy conversion will boom as well.

Furthermore, on the infrastructure side of the built environment, bitumen for road construction exhibits high substitution potentials. Bitumen accounts for about a fifth of fossil fuel material consumption. However, due to low market prices for fossil-based bitumen and the dominant market position of refineries, the substitution with bio-based bitumen is at relatively low technological readiness levels.[4] Furthermore, polymers, solvents, surfactants, and lubricants complement the material use of fossil fuels. Bio-based alternatives are already dominant for surfactants. These chemicals are used for washing and generally dilute into the hydrosphere. Bio-based lubricants, solvents, and especially plastics could contribute to a visible shift in economy-wide resource flows. Bio-based plastics' recyclability or environmental degradability will determine their market success. [28, 63]

In the long run, we anticipate additional, novel abiotic material flows to substitute current material flows. CO_2 sequestration and utilization from biomass combustion and direct air capture fueled by renewable electricity will create new market segments and, ultimately, new sectors. Concrete building materials, platform chemicals, polymers, and fuels can be derived from captured CO_2 [64], theoretically allowing for large-scale and automatized production. Although currently at relatively low technological and market readiness levels, carbon substrates based on nanotechnologies exhibit promising properties for material applications, for example, in construction, electronics, and medicine. Carbon substrates include "graphite, molybdenum disulphide, graphene, graphene oxide (GO), carbon nanotubes (CNTs), carbon nanofibres (CNFs) and hornbeam leaves" [65]. The market entry, diffusion velocity, and magnitude of these substrates are subject to significant uncertainties, although they could significantly alter the economic metabolism.

Anticipating change in economy-wide food flows

Biomass flows from forestry are currently mainly covering energy and material needs. In contrast, biomass from agriculture, fishery, and aquaculture primarily supplies food directly or indirectly via livestock and animal meat production. About 0.5×10^{12} kg of agricultural biomass, including 8% imports, was provided to the European Union metabolism in 2017. Almost 80% of agrarian biomass is deployed for animal feed and bedding. Animal production exhibits a low overall conversion rate of about 13% on a mass basis to animal-based food for domestic consumption and exports. The remaining 20% of agricultural biomass is almost entirely made available as a

[4] https://www.uu.nl/en/research/copernicus-institute-of-sustainable-development/chaplin-xl, accessed 27.02.2023.

plant-based food, exhibiting significant food waste from retail, households, and others (nearly 20%). In comparison to agricultural biomass, and on a mass basis, aquatic-based food flows are vanishingly low (approximately 0.5% of agrarian biomass flows). [26]

Helander et al., for example, model and compare the effect of dietary changes and food waste reduction [66]. Sustainable and healthy diets are based on significantly reducing meat, fish, sugar, and alcohol. Instead, protein and nutrient requirements are mainly satisfied by an increased intake of vegetables, fruits, pulses, beans, and nuts. The modeling results suggest that, for the case of Germany, the resource-saving potential of the currently prevailing policy focus on food waste reduction should be complemented with policy measures for dietary shifts [66].

In addition to the outlined efficiency and sufficiency improvements, potentially relevant substitution effects can be anticipated. Mariutti et al. [67] outline alternative food sources to improve health and guarantee access and food intake. Sources include edible insects such as crickets, grasshoppers, mealworms, and pseudo-cereal and grains such as amaranth, quinoa, chia, and sorghum. Grasses and herbaceous perennials such as "miscanthus are excellent protein producers on par with, e.g., soybean due to much higher total biomass production" [68]. Macro- and micro-algae [69] and fungi [70] are also widely discussed as promising food and supplement alternatives. On lower technological and market readiness levels, Granato et al. [71] investigated hemicellulose content from wood, finding that "functional carbohydrates and polyphenol-rich extracts can be obtained and further used in food." Ultimately, even non-biological synthesis of sugars and glycerols from pure CO_2, for example, via direct air capture, could be used to feed society [72].

Other trends that are not presentable in the full economic metabolism Sankey graphs include changes in the spatiality of agricultural biomass production and its supply patterns. Food production should be intensified in urban areas—for example, in vertical farms [73] and nature-based solutions—recovering water [74], nutrients, materials, and energy [75]. Greener cities could benefit from synergies, for example, between improved resource efficiency through controlled environments and reduced logistical requirements; air and drinking water quality; and meaningful work for differently skilled labor. The multiple benefits have been validated in demonstrations and case studies: for example, in Nicholls et al. and Orsini et al. [76, 77]. Urban agriculture includes vertical farms such as roof-top gardens, indoor farming with artificial lighting, community gardens, allotment gardens, and different forms of aquaponics.

Nevertheless, European rural and industrial agriculture will need to be de-intensified to reduce its negative impacts on the environment and ecosystems. Impacts include eutrophication through mineral fertilizer uses and run-off, biodiversity loss through large-scale monocultures and the application of chemical crop protectants, and depletion of water reserves through exhaustive irrigation practices. External water, nutrient, and energy input should be reduced by increasing the input of contextual knowledge. Struik and Kuyper [78] describe complex intercropping systems and other alternative agroecological systems as "trait-based ecology." Such systems manage a "proper balance between the architectural above-ground and below-ground characteristics of intercrops based on accurate knowledge of the dynamics of weather conditions, temporal and spatial availability of resources" [78]. Furthermore, down-scaling of farming operations could be supported by geographic information systems-based planning, cropping, harvesting; mobile, connected services; and communal, flexible biorefineries capable of processing different inputs to a more extensive portfolio of intermediaries and products. Down-scaling would, in return, reduce environmental and ecosystem pressure while boosting resource democratization; increased participation of diverse stakeholder groups throughout the entire supply chain creates the opportunity for co-determination through multilevel governance. [79]

Furthermore, Giampietro and Haas et al. [59, 80] highlight the importance of better understanding ecological funds' recycling capacity. So far, we have mainly addressed societal funds (the technosphere), including labor, technologies, and infrastructure capable of reducing entropy through recycling and upcycling. But a functioning biosphere—the ecological fund—also contributes to entropy reduction through circular flows fueled by sunlight and biodiversity. Work performed by ecological funds, including water purification, recycling of nutrients, and, equally important, recycling of carbon and CO_2, could not be illustrated as circular flows in our Sankey graphs due to limited data availability. Practices that could result in controlled circular flows via the biosphere, and thus also improved accounting, include carbon farming, recirculation of bio-based fertilizer and biochar, reforestation, forest restoration, and afforestation [81–83].

Discussion

The Sankey diagrams presented in Sect. "Status quo of resource flows between the biosphere and the technosphere" and the qualitative scenario analysis undertaken in Sect. "Anticipating changes in the economic metabolism in the coming decades" underscore the intricate interconnections among resource flows, specifically concerning the domains of sustenance, materials, and energy provisioning. The outcomes of these analyses elucidate the current limitations with regard to our capacity to comprehensively depict resource streams that may come under the purview of the circular bioeconomy and multisector integration in the forthcoming decades. Nonetheless, using the inventory of anticipated alterations in the overall resource flows and drawing upon a comprehensive review of existing system modeling endeavors, we can discern the prerequisites that ought to inform the engineering of circular bioeconomy systems.

These anticipated long-term alterations in the resource flows can be divided into four primary categories:

1. **Substitution:** Using alternative resources to achieve the same outcome.
2. **Efficiency:** Achieving more with less, such as reducing waste or making better use of resources.
3. **Sufficiency:** Rethinking what is necessary by questioning the urgency of resource consumption and considering non-consumptive options.
4. **Reliability:** Creating processes that do not fail, often achieved through integrating systems to distribute surplus resources to cover shortages.

Beyond the overarching macroeconomic, demographic, and environmental trends that have been outlined, we anticipate a confluence of substitution, efficiency, sufficiency, and reliability actions that is poised to exert substantial influence over the dynamics of energy, material, and food flows within the economic ecosystem.

In this section, we delve deeper into the study's findings, with particular emphasis on the prevailing emphasis on substitution and efficiency measures. We then derive prospective imperatives that should inform the endeavors of systems engineers, modelers, and other long-term strategists engaged in conceptual explorations of the circular bioeconomy and its multisector dynamics.

Genesis of system-change actions in quantitative forward-looking approaches

Substitution actions

IAMs, bridging earth and human system dynamics, focus primarily on GHG emissions. Central to IAMs are energy system models, essential in the science–policy interface. These models depict pathways for replacing fossil fuels with renewable energy sources, drawing on Nikolai Kondratiev and Josef A. Schumpeter's theories of S-shaped technology diffusion curves [84]. Diffusion curves are used to explain the evolution of energy consumption from human labor to draught animals, traditional mills, wood combustion, and then to coal, oil, and natural gas, leading to modern photovoltaic electricity and advanced bioenergy sources. While fostering techno-optimism, the concept of technology diffusion tends to overlook the adverse societal impacts of these "evolutionary reconfiguration processes" [85]. Conversely, narratives focusing on substitution may inadvertently shift attention away from the exigency of the climate crisis. A direct substitution scenario would have to assume not only remarkable advancements in learning and expansion of emerging technologies, but also a swift societal consensus on the designation of extensive regions for renewable energy production and transmission and their use in the synthesis of materials and food. Such a strategy is not merely impracticable, however; it may also be counterproductive. It risks perpetuating entrenched structural issues from one technological regime to another, a topic we explore in depth in this section.

Efficiency actions

In addition to substitution actions, efficiency improvements represent a cornerstone of industrial evolution. The inaugural Sankey diagram, published in 1896, depicted the thermal efficiency of steam engines [86], playing a pivotal role in the rapid industrialization, particularly in Germany [87]. While efficiency improvements in the industrial sector often lead to substantial economic benefits for individual stakeholders, the impact in other domains, such as household electricity consumption, heating, and transportation, is less pronounced. In these sectors, the cost savings from efficiency enhancements are frequently minimal or dispersed over time, necessitating supplementary incentives and support mechanisms for their adoption. The effectiveness of these incentives is largely contingent upon social dynamics, as modeled in agent-based models, which predominantly focus on individual technologies, substitution, and efficiency actions [88]. Conversely, models representing the broader energy system or the whole economy generally employ optimization algorithms based on partial or general market equilibrium [40]. These models inherently assume a rational and cost-efficient resource allocation under ideal market conditions. However, the validity of this "traditional neoclassical economic paradigm" in long-term transformation analysis has been increasingly scrutinized over recent decades, primarily due to its exclusive emphasis on relative prices and the consequent neglect of other critical factors, including behavioral, political, social, and technological aspects [48].

Circularity aspects are another blind spot in current IAMs, which "poorly represent resources and their uses" [9]. These considerations are grounded in the concept of resource-efficient valorization of residues and waste. IAMs typically presuppose the resource efficiency inherent in the linear economy, framed within the "take, make, dispose" lifecycle. Adopting a circular economy model in IAMs would not necessarily constitute a paradigm shift, as it could adhere to similar efficiency principles, albeit within significantly expanded system boundaries. Integrating circular resource flows through both technological and ecological recycling would still markedly transform our understanding of the overall economic metabolism. Furthermore, the potential impacts of novel resource flows and their respective value chains—encompassing sourcing, production, consumption, and waste management—could be substantial in the forthcoming decades, provided circularity aspects are accorded greater significance.

It is therefore essential that technological recycling is adequately represented in existing modeling frameworks and augmented by the notion of ecological recycling. Giampietro [80] distinguishes between (a) societal funds, or the technosphere, encompassing labor, technologies, and infrastructure that contribute to entropy reduction through processes such as recycling and upcycling; and (b) ecological funds, or the biosphere, which can fulfill a similar role, contingent upon its functional and healthy state.

In the late nineteenth century, predating the publication of the first Sankey diagram, a seminal observation by the British economist William Stanley Jevons articulated the counterintuitive effects of the "economic use of fuels" on consumption, now recognized as the Jevons paradox (Jevons 1865 in [89]). Sorrell [89] delineates various forms of rebound effects associated with this paradox, including embodied energy effects, where the production of more efficient technologies necessitates additional resource input; re-spending effects, whereby consumers allocate savings to purchase additional goods; output effects, wherein producers amplify output by leveraging cost savings; and energy market effects, where reduced energy prices lead to increased consumption. Similarly, Castro et al. [90] examined circular rebound effects, noting that systemic changes such as enhanced productivity and consumption often undercut the benefits of circular economy strategies.

These rebound effects can manifest as direct, indirect, or systemic—also known as economy-wide—effects and are contingent upon specific technologies and contextual factors, rendering their quantification challenging. In energy economics, efficiency measures are often termed the "fifth fuel," following coal, oil, gas, and renewable energy. It is therefore unsurprising that a complex array of beneficial and detrimental impacts on the environment and society accompanies their diffusion. Despite the Jevons paradox being identified over 160 years ago, it is only in the early twenty-first century that rebound effects have garnered substantial attention, leaving many economic, societal, and psychological questions open for exploration and debate [91].

Sufficiency actions

The inventory presented herein, alongside preceding sections, underscores the emphasis of systems engineering on substitution and efficiency initiatives, particularly in the context of decoupling economic growth from CO_2 emissions. A mere decade and a half ago, Rockström et al. [92] successfully contextualized climate change as one of nine critical "planetary boundaries," encompassing issues such as biodiversity loss, biogeochemical flow boundaries, and land use changes. In 2017, Kate Raworth [93] expanded upon this concept by juxtaposing the "ecological ceiling" with a "social foundation," encompassing twelve fundamental societal needs beyond energy, food, and housing, including peace and justice, health, and social equity. The formidable challenge of our era lies in satisfying these foundational needs while concurrently learning to avoid exceeding ecological limits, a task symbolized by the "doughnut" model. This representation is poised to guide the next wave of modelers and forward-thinking qualitative researchers. To meet the foundational needs of a global population of seven billion, the world's provisioning systems would need to achieve an efficiency increase ranging between two- and sixfold [94]. Given projections of the world population potentially reaching eleven billion in the coming decades, additional, complementary actions are imperative.

As such, sufficiency and degrowth represent alternative paradigms to traditional economic growth, emphasizing the need to reduce overall consumption and prioritize well-being and sustainability. Sufficiency involves consciously limiting consumption to meet basic needs, while degrowth calls for a deliberate reduction in economic output to reduce environmental and social impacts. The notion of degrowth entered the academic discourse in 2008 with the conference in Paris on Economic Degrowth for Ecological Sustainability and Social Equity [95]. Moreover, supported by quantitative methods in line with the doughnut economy narrative, O'Neill et al. [94] found that "resource use could be reduced significantly in many wealthy countries without affecting social outcomes, while also achieving a more equitable distribution among countries."

The preceding discussion has revealed that sufficiency measures have only recently penetrated academic discourse. Integrating these measures into modeling energy, the circular economy, and the circular bioeconomy presents challenges, primarily due to their predominantly non-technical nature. Such innovations are mainly social and organizational. It is therefore essential for scholars, particularly those in the humanities and social sciences, to be at the forefront of inter- and transdisciplinary research. This involvement is crucial to discern which sufficiency improvements are socially tenable and to devise strategies for their realization.

Reliability actions

We wish to highlight a distinct category of system-change actions from our inventory that does not neatly align with substitution, efficiency, or sufficiency paradigms. Addressing this fourth type of action and its role in comprehensive economy-wide modeling is challenging due to a lack of consensus on terminology. Concepts such as resilience, stability, safety, and robustness might aptly encapsulate transformation pathways aimed at fulfilling social foundations without exceeding ecological limits, as discussed in Sect. "Sufficiency actions", even in the face of unforeseen disturbances. These terms, drawn from various disciplines, are instrumental in formulating guiding principles for this measure of system change. For circular bioeconomy systems engineering, we propose the term "reliability" to describe this approach, setting it apart from analogous concepts in other fields.

For example, energy system flexibilization is often considered to efficiently valorize surplus resources, for example, storing power produced from photovoltaics on exceptionally sunny days, in order not to waste it, or to sell it at low market prices (e.g., [96–98]). However, flexibility also fulfills a second, equally important function: to offer reliability by mitigating resource scarcity and stabilizing the grid. For example, planning for power grid expansion has traditionally pursued resource efficiency and system reliability in equal measure, resulting in flexibility with anticipation of a continuously growing share of renewables [99]. In general, networks for different energy carriers [100], physical goods [101], investments [102], information [103], or food webs in ecosystems [104] are found to exhibit both the potential for efficient resource allocation and a capacity to react to external disturbances, thus improving their stability.

In ecosystem modeling, network-specific mechanisms such as the coordination of heterogeneous constituents to improve ecosystem resilience are well-researched [104]. These mechanisms have been investigated quantitatively for their network stabilizing effect "from cells to systems" [105]. It has been shown that network topology, density, heterogeneity, and symmetry all affect the resilience of a system [104]. Resilience engineering aims to plan systems that exhibit respective characteristics, with the robustness of networks, independent of their scale, being the goal [103, 105]. This scientific realm provides metrics and modeling frameworks to design system reliability: for example, in the anticipation of individual supply chain shocks [100, 101], chemical process systems engineering [106], classical flexibility analysis [107], management of portfolios [108, 109], and food webs and economic networks [110].

In energy system model design, the focus is often on ensuring system reliability through climate change mitigation, adaptation, and cost-effective social acceptance. However, explicit mention of reliability objectives post-design is scarce. For circular bioeconomy engineering, reliability is crucial. Technologies such as combined bioenergy plants, renewable gas storage, wood pellet and green hydrogen trade, biorefineries, and versatile conversion technologies exemplify system flexibilization. They facilitate resource shifting across time, space, and sectors, balancing scarcities and surpluses, thereby enhancing both reliability and efficiency. To fully leverage these benefits in systems engineering, it will be essential to prioritize the multisector coupling capabilities of the circular bioeconomy.

Model framework design, especially of energy system models, primarily seeks to ascertain system reliability objectives through mitigation and adaptation goals concerning climate change impacts or social acceptance through adequate system cost developments. Beyond the design, however, reliability objectives are rarely mentioned explicitly in these frameworks, despite the multifaceted uncertainties underlying the long-term projections of entire sectors and economies [111]. For circular bioeconomy engineering, this aspect could play a pivotal role. Examples for system flexibilization include combined bioenergy heat and power plants, the storage of renewable gases, the storage and trade of wood pellets and green hydrogen, biorefineries producing biomaterials, food and energy products, and conversion technologies that can handle a variety of heterogenous, low-quality biomass inputs and produce a spectrum of products. Such technologies and infrastructure enable the shifting of resources through time, space, and between sectors, to balance scarcities with surpluses, improving reliability and efficiency simultaneously. To seize the opportunities of these technologies in systems engineering, we must move the multisector coupling service of the circular bioeconomy into the spotlight.

Circular bioeconomy as a driver for system integration

The Sankey diagrams and our comprehensive inventory of circular bioeconomy innovations illustrate the interconnectivity among the food, material, and energy sectors. Furthermore, the supplementary materials highlight the intricacies of various resource flows, encompassing elements such as power, heat, biomass, non-metallic

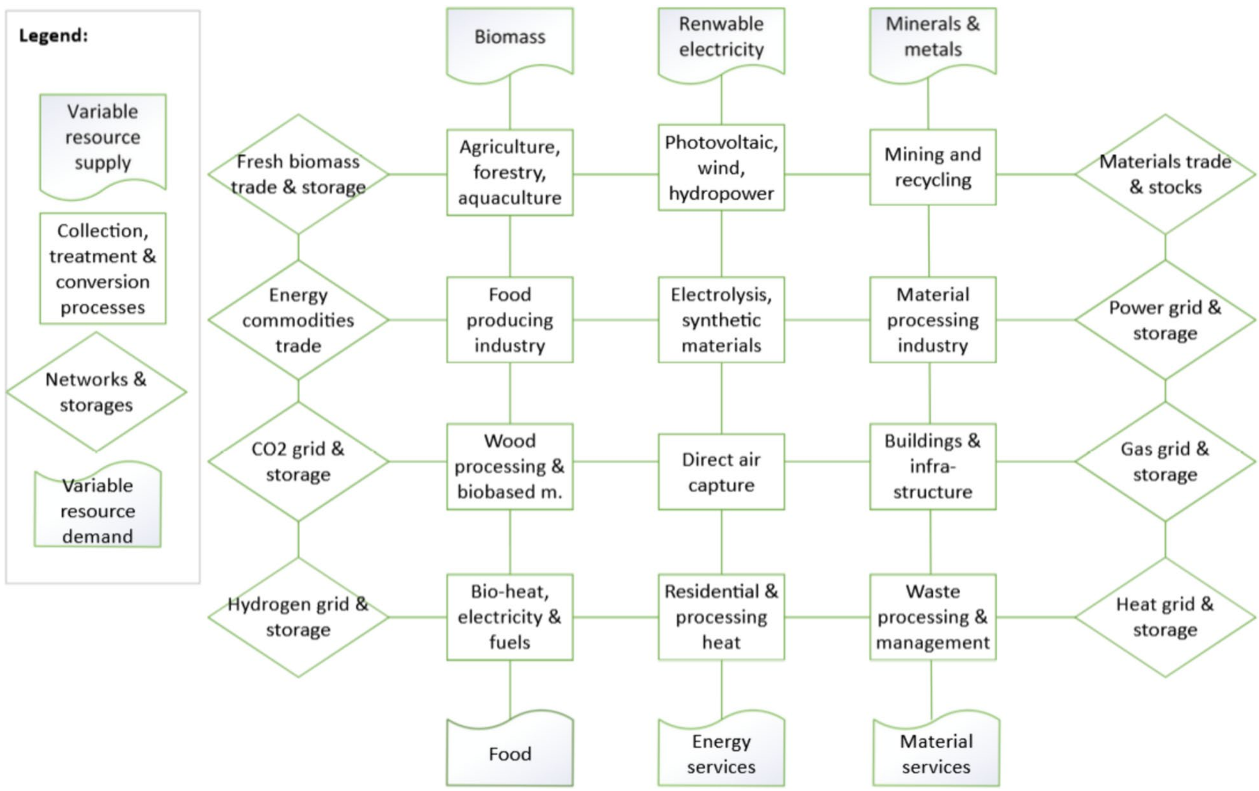

Fig. 4 Network of network engineering concept for developing resource-shifting strategies supported by a circular bioeconomy. Source: own illustration

and metallic ores, water, air, CO_2, labor, and money. Recent shifts in the biomass supply chain literature, moving from linear perspectives to networked approaches [112–114], are particularly noteworthy. This paradigm shift facilitates the incorporation of varied resource inflows and product outflows, duly considering residues, by-products, and circular flows intrinsic to the circular bioeconomy.

We advocate for a holistic modeling approach that interlinks biomass supply chain networks with independent renewable electricity networks and networks revolving around other critical resources such as minerals, CO_2, and water. We propose the term "network of network engineering" for this methodology, drawing inspiration from the concept, foundational principles, research trajectories, and practical implications inherent in system of system engineering, as conceptualized by Keating et al. [1]. Alternative terms, reflecting similar concepts, might include "coupled multilayer networks," "system integration," "multicarrier systems," "whole system," "multisector coupling," and "multisector dynamics." Selected examples from our inventory serve as illustrative connectors in the depicted network of networks, as shown in Fig. 4.

This research underscores the importance of comprehensive modeling encompassing energy, materials, biomass, and circular flows within the circular bioeconomy framework. By interlinking diverse resource flows, the circular bioeconomy necessitates being conceptualized and modeled as a facilitator for system integration. There is a burgeoning need for innovative models and methodologies to explore the capability of these networks to shift resources temporally, spatially, between sectors, and between systems, thereby enhancing both resource efficiency and system reliability. In contrast, the emerging field of multisector dynamics research in the US focuses explicitly on the tradeoffs of multisector and multilayer networks, including safety issues, security threats, and cascading and interconnected failures, often summarized as systemic risks [115, 116]. Network of network engineering should provide the foundation for objectively analyzing these beneficial and detrimental consequences of system integration together. Resulting guidance is vital for formulating robust and coherent policies that can effectively amplify synergies and mitigate tradeoffs among sectors, systems, and objectives.

Conclusion

This study presents a comprehensive survey of the circular bioeconomy, using Sankey diagrams that amalgamate statistical data on food, material, and energy flows to discern emerging trends that could significantly reshape the current economic metabolism. The study recognizes that traditional systems engineering and modeling have predominantly focused on substituting fossil fuels with renewable energy and biomass and enhancing efficiency within constrained system boundaries. We highlight the urgent need to broaden these system boundaries to include both technological and ecological recycling, suggesting that such expansion can be achieved without departing from the efficiency-centric approach characterizing current modeling frameworks.

Contrastingly, future paradigm shifts in systems engineering will probably revolve around sufficiency and reliability actions. The former will necessitate groundbreaking strides in inter- and transdisciplinary collaboration, with the daunting task of reaching consensus on sufficiency levels and equitable resource distribution and prioritization. These are monumental, non-technological challenges requiring ongoing participatory renegotiation. Such collaborative efforts could profoundly influence resource flow magnitudes, ensuring societal needs are met without surpassing ecological limits.

While often implicitly present, measures enhancing system resilience, robustness, or reliability are not explicitly addressed in long-term and economy-wide modeling efforts. Insights from ecosystem modeling and related disciplines have highlighted the significance of flexible nodes and the shifting of resources across time, space, and systems as crucial for resilience. In the realm of the circular bioeconomy, biomass supply chain networks, characterized by diverse inputs and outputs, clearly intersect with networks for feedstock-independent renewable power, CO_2, water, and various other biotic, abiotic, and intangible resources. On the one hand, this network of networks introduces heightened systemic risks for potential cascading failures; on the other hand, it offers opportunities for efficiency enhancements while maintaining reliability. Elevating the prominence of the connectors provided by the circular bioeconomy will empower policymakers to steer the amplification of synergies and mitigation of tradeoffs among systems, sectors, and goals.

Abbreviations

ewMFA	Economy-wide material flow account
GDP	Gross domestic product
GHG	Greenhouse gas
IMA	Integrated assessment model
SDG	Sustainable development goal
SSP	Shared socioeconomic pathway

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author contributions

Fabian Schipfer: conceptualization, funding acquisition, project administration, methodology, formal analysis, investigation, writing—original draft, review and editing, data curation, formal analysis. Pralhad Burli: writing—original draft, review and editing. Christiane Hennig: writing—original draft, resources. Uwe Fritsche: writing—original draft, review and editing, resources. Svetlana Proskurina: writing—review and editing. Fabian Stricker: investigation, software, visualization. Maria Wirth: writing—original draft, review and editing. Sebastian Serna-Loaiza: writing—review and editing.

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Availability of data and materials

Data published in this article are open-source and available online. We thoroughly discuss the structure, harmonization methodology, and limitations of the resulting Sankey graphs in the supplementary materials. We also thoroughly review existing Sankey graphs representing economy-wide flows of different resources. Edge lists, conversion and reattribution tables, and explanatory Sankey graphs can be found in the supplementary sheets.

Declarations

Ethical approval and consent to participate

Not applicable.

Consent for publication

Consent for use of images has been granted.

Competing interests

The authors declare that they have no competing interests.

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