The 'bioeconomics vs bioeconomy' debate: beyond criticism, advancing research fronts

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Sandrine Allain[a], Jean-François Ruault[a], Marc Moraine[b], Sophie Madelrieux[a]

[a] University Grenoble Alpes, INRAE, LESSEM, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France.

[b] UMR Innovation, INRAE, CIRAD, Montpellier SupAgro, Univ Montpellier, 34060 Montpellier cedex 02, France

Corresponding author : Sandrine Allain sandrine.allain@inrae.fr

Abstract:

The case for solving the environmental crisis through a bioeconomic transition is gaining momentum. However, the content and aims of such a transition remain unclear, as this could target an economic sector, the analysis of economic activities, or society as a whole, especially in its relationship to the biosphere. This last possible object of transition – society – is where values, models and goals come into conflict. This study examines this confrontation through the lens of the 'bioeconomics vs bioeconomy' debate, in which proponents of bioeconomics have raised an arsenal of critiques against what they consider the simplistic promises of public and private promoters of the bioeconomy. We discuss these critiques, which are mainly macro in scale and/or narrative-centred, and argue for a complementary research effort that supports transition initiatives. This research could take place on three fronts: better understanding bioeconomic systems, evaluating bioeconomic transitions, and identifying how to implement these transitions.

Keywords: socio-technical transition; strong sustainability; agroecology; societal metabolism; sustainability trade-offs

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The case for solving the environmental crisis through a bioeconomic transition is gaining momentum. However, aims and content of such a transition remain unclear, as this could target an economic sector, the analysis of economic activities, or society as a whole, especially in its relationship to the biosphere. This last possible object of transition – society – is where values, models and goals come into conflict. This study examines this controversy through the lens of the 'bioeconomics vs bioeconomy' debate, in which proponents of bioeconomics have raised an arsenal of critiques against what they consider the simplistic promises of public and private promoters of the bioeconomy. We discuss these critiques, which are mainly macro in scale and/or narrative-centred, and argue for a complementary research effort that supports transition initiatives. This research could take place on three fronts: better understanding bioeconomic systems, evaluating bioeconomic transitions, and identifying how to implement these transitions.

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Introduction

Despite their similarity, the terms 'bioeconomy' and 'bioeconomics' follow two different conceptual and operational paths, with little mutual permeation. In simple terms, since the late 2000s, the former has been a popular paradigm for environmental policies, emphasizing the need for substituting fossil-resource-based energy and materials. In contrast, bioeconomics is a 50-year-old scientific paradigm that aims to anchor economic thought in biophysical foundations.

Today, these two paradigms are coming into conflict in an asymmetrical struggle. The bioeconomy-based rationale for policymaking largely ignores any bioeconomic antecedent and drives a colossal research effort (Lühmann, 2020). On the other side, proponents of the bioeconomics paradigm actively denounce bioeconomy strategies and public policies as a delusion (Giampietro, 2019) or as a 'hijacking' (Vivien, Nieddu, Befort, Debref, & Giampietro, 2019). This conflict is not surprising since the two paradigms point to virtually opposite directions for solving the environmental crisis. The bioeconomy adopts a pathway of economic growth supplied by large amounts of biomass (wood, crops, organic waste, manure, etc.) and the use of biotechnology in multiple sectors. In contrast, a bioeconomics programme (Georgescu-Roegen, 1971) argues for degrowth structured around new societal values (e.g. sobriety) and new social organization (e.g. conviviality), as well as low-tech innovations (e.g. agroecological practices). Of course, this is a schematic presentation of an antagonism that is more complex, and there are a spectrum of positions between the two: in terms of policymaking, the OECD, the US and the EU have different concepts of the bioeconomy that change over time (Levidow, Birch, & Papaioannou, 2012; Meyer, 2017); in the academic sphere, bioeconomics scholars oscillate between promoting a 'soft' or 'hard' transformation (Béfort et al., 2020; Vivien et al., 2019).

The idea of a 'bioeconomic transition' is nonetheless rapidly gaining ground (e.g. Asada, Krisztin, di Fulvio, Kraxner, & Stern, 2020; Béfort et al., 2020; de Schutter et al., 2019; Lynch, Klaassen, van Wassenaer, & Broerse, 2020; Palmer, Burton, & Haskins, 2020; Wydra et al., 2021). Just like many other sustainability related concepts, many questions remain unsolved while words disseminate in scientific and policy arenas. The 'bioeconomic transition' hence offers diverse understandings, among which: the rediscovery of the multiple uses and sources of biomass after decades of specialization (Colonna et al., 2019; Daviron, 2019); a push for coordinating multiple innovations based on living organisms and establishing a new strategic economic sector around these (e.g. Wydra et al., 2021); a call for broad changes in lifestyles and consumption standards to slow down the environmental crisis (e.g. de Schutter et al., 2019). While such plurality is inherent to the democratic exercise in which multiple values meet and mutually enrich or oppose each other, it also contributes to expanding the diversity of approaches to the bioeconomic transition. The results of these different approaches are linked to specific assumptions and lead to incomparable analyses. Still, they flow between the scientific sphere and the political arena and generate in the end confusion about the ins and outs of different innovations flying the flag for a bioeconomic transition.. This confusion also acts as a barrier for stakeholders to position different types of innovations and initiatives within a broader transition process.

Clarifying the 'bioeconomics vs bioeconomy' debate could help settle certain points for a wide range of stakeholders – researchers included – in the aim of encouraging a more sustainable economy. This could raise awareness of the counterproductive side effects of many promoted solutions, as well as provide incentives to explore new policy and research directions that fit the magnitude of current social and environmental challenges. To this end, this study has two aims. First, it defines the 'bioeconomy boom' as a multifaceted and multidirectional process for transition, which, in many cases, is a fallacious project for reducing society's footprint on the planet, including fossil fuel use. Second, it draws from the large critical arsenal focusing on the bioeconomy to put forward a set of proposals for initiatives with the objective of 'strong sustainability' (Ekins, Simon, Deutsch, Folke, & De Groot, 2003; Neumayer, 2003). Based on a normative and reflexive approach to sustainability transitions (Susur & Karakaya, 2021), we (1) present the competing arguments for a bioeconomic transition, (2) describe the different critiques of the dominant bioeconomy paradigm, and (3) identify avenues of research to support a transition that is strongly sustainable.

The examples in this paper relate largely to agricultural biomass production, valorisation and consumption, due to the authors' domain of expertise (agriculture and agroecology, from the perspectives of farming systems and ecological economics). The agricultural sector is a good entry point to offer insights into the bioeconomic transition more generally as it combines significant biomass production and extensive land coverage, subject to controversies in terms of the allocation between food, feed, fibre and fuel uses. Agriculture also embraces diverse products and production systems, including closed-loop systems, such as integrated crop–livestock systems.

1. Competing claims about the bioeconomic transition

The definition of the bioeconomy has been the subject of numerous academic contributions, especially in the last 10 years (Bugge, Hansen, & Klitkou, 2016; Hausknost, Schriefl, Lauk, & Kalt, 2017; Levidow et al., 2012; McCormick & Kautto, 2013; Meyer, 2017; Vivien et al., 2019). Many classifications have been proposed (see Table 1 for a selective review), revealing the role of narratives and their political content. Our intention is not to provide an additional typology of definitions and visions of the bioeconomic transition, but to attempt to give the context for our analysis of the 'bioeconomy vs bioeconomics' debate.

[Tab. 1 Here]

Within the existing literature on the bioeconomic transition, a first macrolevel of distinction lies in *what* is being transformed: an economic sector (1.1), the economic science paradigm (1.2), or society as a whole in its relationship with the environment (1.3).

1.1. First object of transition: an economic sector

In most strategic planning literature, the bioeconomy corresponds to an *economic sector* that includes the activities that produce, transform and value living matter. This definition has been promoted by international organizations such as the OECD and deployed in EU and national strategies. For instance, Wreford et al. (2019) interpret the bioeconomic transition in New Zealand as the emergence of a *new* bioeconomic sector consisting of high-value products, such as biotechnology or pharmaceuticals, and waste-recovery processes, which is expected to take precedence over an *old* bioeconomic sector (food, fibre and energy). A similar conception is found in a Dutch case study by Bosman & Rotmans (2016), which describes a pyramid of biomass value: low-value/high-volume biofuels at the bottom, and high-value/low-volume pharmaceuticals and fine chemistry at the top.

When the bioeconomic transition is conceived as the emergence of a new economic sector, one element of division lies in what are considered the most valuable products, economic sectors and production processes (Bauer, 2018; Dietz, Boerner, Foerster, & von Braun, 2018). In some cases, the transition is considered to be driven by the challenge of substituting fossil fuels with bioresources, encouraging an energy-centred transition; in other cases, new technologies based on living organisms are promoted as they offer high added value (Bauer, 2018). The food sector often occupies a marginal position and is mainly regarded as a provider of potentially valuable waste or as a land-use competitor.

1.2. Second object of transition: the economic thought

Another conception of the bioeconomic transition consists of setting a new *scientific paradigm that reinvents economic thought*, based on Georgescu-Roegen's bioeconomics (Georgescu-Roegen, 1971; Mayumi, 2009). Bioeconomics is an attempt to reframe economic science and embed it within the theory of biological evolution and thermodynamic principles. The goal of the transition is a paradigm shift in the analysis of economic activities: from the economy being an independent and self-reproducing system (i.e. a machine with its own laws) to being embedded in resource systems and institutions (hence affected by biological, physical and social laws). An important feature of bioeconomics literature is the renewal rate of funds (Couix, 2020). Funds are considered the agents of a transformative process, delivering services but not transformed in the process (Georgescu-Roegen, 1971): e.g. the soil for the transformation of seeds into harvestable crops; the mill for the transformation of grain into flour. Both the soil and the mill need energy to carry out the transformative process, which occurs only at a specific rate. This rate can eventually grow with the aid of add-ons or technological advances, but the latter would in turn require new material and/or energy inputs, relying on the use of other funds.

Most bioeconomy literature overlooks the bioeconomics paradigm, despite its anteriority and pivotal role in heterodox economics (and especially ecological economics: see Costanza, Stern, Fisher, He, & Ma, 2004; Melgar-Melgar & Hall, 2020; Røpke, 2004). Hence, a sense of usurpation has coloured the recent writings of the heirs of bioeconomics (Giampietro, 2019; Vivien et al., 2019). Their main grievance is that this omission has led governmental bioeconomy development strategies to neglect the insights brought by bioeconomics theory (see section 2).

1.3. Third object of transition: human societies

This leads into the third possible object of the bioeconomic transition: *society and its relationship to the environment*. Here, the normative assumptions of the different bioeconomic narratives come into conflict, as the direction of change, its ends and its means become central. Vivien et al. (2019) point out that the different bioeconomic narratives embed incompatible visions of societal relationships to living organisms, especially in terms of reliance on technology and the management of uncertainty and feedback from ecological systems. They also show that narratives support either ‘weak’ or ‘strong’ sustainability conceptions, i.e. the possibility or impossibility of substituting natural capital with manufactured capital. The merit of these authors is to tackle the question of the purpose of the bioeconomic transition: continuous economic growth or the survival of the human species (requiring degrowth). Most studies are more ambiguous, remaining on the level of narratives (see Tab. 1). In these cases, the debate appears mainly around the means and models for a bioeconomic transition. Of these, Levidow et al. (2012) distinguish a life-science, biotechnology-based bioeconomy and an agroecological, integrative bioeconomy: two visions that compete in the policies of international organizations. Bugge et al. (2016) reveal three main strands in bioeconomic research works: a biotechnology vision, a bioresource vision or a bioecology vision.

The debate surfaces mainly in terms of the societal-related transition (1.3), although not independently of the other two objects of the bioeconomic transition (economic sector, 1.1, and economic thought, 1.2.). For instance, the bioeconomics paradigm supports a political programme that includes the abandonment of weapons, the development of organic agriculture, more moderate lifestyles and an end to excessive consumption (Georgescu-Roegen, 1979). This programme continues to stimulate discussion in the scientific community and has been adopted by the political degrowth movement. It has links with non-mainstream narratives of a societal bioeconomic transition that highlight sufficiency, moderation and biophysical limitations (Hausknost et al., 2017; Levidow, 2015b; Vivien et al., 2019). By contrast, the mainstream narratives of international organizations and national strategies point at the emergence of the bioeconomic sector (of green chemistry, bio-sourced materials, bioenergy production among others), seen as the corner stone of a societal model valuing ‘green’ employment and ‘green’ growth. The question of the sector's ability to mitigate the environmental crisis is often not asked; risks of making it worse are kept off the radar (Ruault, Dupré la Tour, Evette, Allain, & Callois, 2022). The result can resemble a dialogue of the deaf, yet the ‘bioeconomics vs bioeconomy’ debate is worth detailing to gain a more critical and differentiated understanding of the bioeconomic transition.

2. The ‘bioeconomy vs bioeconomics’ debate

Although this debate is asymmetric, with the bioeconomy currently having the upper hand, it exists because both philosophies share common ground. They focus on a common object of transition: society and its relationship to the environment. The rationale behind bioeconomics is intrinsically normative and fixes ecological sustainability, universal needs and social justice as the aim of the transition. In contrast, the rationale behind the bioeconomy focuses on the emergence of innovations and their capacity to be scaled up, giving less importance to ecological and social justice goals. Another commonality is that they both take a macroscale, global approach, whether referring to planetary boundaries, decarbonization of the economy, energy efficiency, or economic competitiveness.

The debate consists in fact of a list of bioeconomy critiques emerging from different fields, all sharing the aim of contesting the capacity of the bioeconomy to solve or even temper the environmental crisis. ‘Bioeconomics’, although it fostered the most vivid reactions to bioeceonomy strategies, would be too restrictive: other critiques raised by evolutionary economics, regulation theory, industrial ecology, innovation and sustainability research, among others, are also included in our analysis and extend or complement the bioeconomics argument in several respects. But for clarity, in this study, we define the debate as between:

- *a bioeconomic**s** transition*: a societal transformation in which the economy is re-embedded within planetary boundaries and ecological constraints
- a *bioeconom**y** transition*: a political priority on expanding the use of bioresources and/or biotechnology to emancipate economic development from fossil fuel use.

In the followings, we list up the different strands of critiques addressed to the idea of a bioeconomy transition. There is no formal answer to these critiques since they are hardly considered by bioeconomy proponents; to them, core challenges are the feasibility, efficiency and social acceptability of the bioeconomy transition, not its validity. Nonetheless, the tension between the two types of transition is insightful and paves the path to defining new research fronts.

2.1. The bioeconomy transition as the continuation of the industrial regime

The notion of "regime" is manifold, and disentangling it is not the purpose of this article. The conceptualizations used to critically analyse the bioeconomy transition include: socio-technical regimes (Befort, 2020; Magrini, Béfort, & Nieddu, 2019), accumulation regimes and food regimes (Allaire & Daviron, 2017; Levidow, 2015b), and socio-metabolic regimes (Giampietro, 2019; Haas, Krausmann, Wiedenhofer, Lauk, & Mayer, 2020; Vivien et al., 2019). Any regime is characterized by structural interactions between subsystems, self-reinforcement processes, and power relations that allow it to change only under specific circumstances. Changes from one regime to another are alternatively called transitions (e.g. socio-technical transitions, socio-metabolic transitions) or crises. Roughly speaking, the industrial regime can be described as a specific mode of socio-ecological organization aiming to emancipate Western societies from the constraints of biomass and living systems as energy suppliers (Giampietro, 2019; Krausmann, Fischer-Kowalski, Schandl, & Eisenmenger, 2008). The ascendancy of the industrial regime relies on the expanding use of fossil fuels in every productive sector (including agriculture), on technological breakthroughs for the extraction and use of these fuels, and specific modes of labour organization and consumption (Allaire & Daviron, 2017; Krausmann et al., 2008). Some authors draw links between the increasing dependence of Western societies on energy and the expansion of capitalism (Allaire & Daviron, 2017; Görg et al., 2019), or even consider that capitalist ideology constitutes the original driver, before industrialization, of the environmental crisis (Moore, 2017). The general critique we examine here is that the bioeconomy transition is not able to challenge the current industrial regime, which is based on an extractive mode of resource use and the objectification of the natural environment.

One set of critiques express doubt about the transformative capacity of bioeconomy policies and ask for substantial add-ons. This line of critique recalls that of 'greenwashing', highlighted by Birner (2018). For instance, Béfort et al. (2020) warn of the risk that bioeconomy policies would result only in a change in raw materials and the mere 'biologicalization' (p. 439) of the productive system. In a longer-term perspective, Allaire and Daviron (2017) observe the evolution of Western society's relationship to biomass: they note changes in hegemonies, labour organization and political attitudes towards modes of biomass production and use, but not such profound changes as to prompt the destabilization of the current regime. They write: *"The chemical industry, which played such an important role in the emergence of the agricultural model of the 20th century, sees biomass as a new source of raw materials, just as coal and oil used to be, with the risk of transposing the same mining logic to it"* (p 76, translation from French by authors).

This critique views the current regime as locked in place, hence gradual or one-off changes are like a drop in the ocean. Without restrictions and incentives to change modes of resource extraction, processing and consumption, a bioeconomy approach cannot solve the environmental crisis generated by accelerated industrialization since World War II (Béfort et al., 2020). In the case of agricultural biomass production, Vanloqueren and Baret (2009) call for public intervention to open up the development of agroecological innovations in contrast to the technological regime that prevails in agricultural research. Magrini et al. (2019) point to the risk that giving too much incentive to one dominant agricultural transition model may prevent, through various reinforcement mechanisms, other legitimate development options and hence shrink the future adaptability of agricultural systems.

Other scholars adopt a more pessimistic view: they argue that bioeconomy policies not only recast but reinforce and even extend the harmful extractivist logic of the industrial regime. For example, Pahun et al. (2018) show how easily nature changed status through the (re)discovery of its multiple uses from 'overexploited' to 'mis-exploited', becoming an object of intensification and (genetic) optimization. Birch, Levidow, & Papaioannou (2010) and Levidow (2015b) assert that the early bioeconomy agendas and narratives in Europe and the OECD, especially those of the 'knowledge-based bioeconomy', succeeded in introducing a neoliberal, productivity-led vision of natural resources and associated knowledge. Another study identifies the emergence of a new type of capital, 'sustainable capital': *"Regardless of labour's role, some natural resources are seen as inherently sustainable and/or eco-efficient because they are renewable (…) Life itself is characterized as capital, forever renewable and forever productive. Thus nature is meant to sustain capitalism through its own inherent renewability"* (Birch et al., 2010, pp. 2902–2903). More than ten years later, the diagnosis of Tordjman (2021) extends this, contending that nature has become a new 'fictitious commodity' (sensu Polanyi). These different authors warn that the bioeconomy transition has gained social and political acceptance through two important characteristics – renewability and natural origin – erroneously used as synonyms of sustainability. In this line of critique, the bioeconomy transition is therefore not only insufficient and unconvincing; it signals the worsening of the environmental crisis.

2.2. The bioeconomy transition rests on fallacious hypotheses

Bioeconomy policies are based on two main pillars: substitution and decoupling. These arguments are not exclusive to bioeconomy policies and fuel as well circular economy principles. Because circular economy and bioeconomy are more and more considered as a whole (e.g. the OECD directorate for Science, Technology and Industry, speaking about 'circular bioeconomy', Philp & Winickoff, 2018), we will also use insights from the circular economy literature.

Substitution is a shortcut for the substitution of non-renewable resources with renewable ones. Very often, it covers only the substitution of fossil fuels with renewable energies. The substitution principle is often driven by the consideration of the depletion of fossil fuels and/or their increase in price rather than an ecological objective, and has led to biofuel policies in Europe and the US (Dietz et al., 2018; McCormick & Kautto, 2013). From an industrial point of view, substitution involves the use of biomaterials and the development of biorefineries to generate bioenergy and new products (Bauer, 2018; McCormick & Kautto, 2013), which also means, from an economic point of view, capturing a market share from non-renewable products and fossil fuels. In a review of different bioeconomy strategies (OECD, EU, various German landers, Sweden and the US), Meyer (2017) considers that these differ only in the extent to which they envision substitution: 'unspecified bio-based economy', 'reduced dependence on fossil resources' and 'moving towards a post-fossil age' (p. 9). A similar argument underlies the policy of developing reuse activities, i.e. activities in which inputs are waste streams from another activity: the hypothesis is that secondary products will substitute for primary products (Zink & Geyer, 2017), hence lowering the extraction of resources and the generation of waste.

The second pillar – decoupling - refers to the decoupling of the relationship between two variables: non-renewable/vulnerable resource use or ecological impacts and Gross Domestic Product or well-being (see e.g. the OECD Environmental Strategy, the UNEP report Decoupling Natural Resource Use and Environmental Impacts from Economic Growth, the EU Roadmap to a Resource-efficient Europe, or the UN Sustainable Development Goals). The general idea is summed up in the motto "doing more with less", which is expected to be enabled by technological innovation (at least). Decoupling posits that there is room for improvement in efficiency: optimizing processes would allow limiting our environmental footprint per capita without compromising our consumption levels. Decoupling generally associates with multiple and cascading uses of resources – be they 'bio' or not – and innovations in technologies (e.g. precision agriculture, DeLay, Thompson, & Mintert, s. d.) or logistic chains (for instance industrial symbioses, Earley, 2015). Once again, bioeconomy and circular economy appear to be the two sides of the same coin (Giampietro, 2019). Indeed, as far as the full circularity of the economy seems unreachable, the bioeconomy is expected to provide the necessary inputs to the productive system, so that renewability is achieved within an imperfect circular economy (Temmes & Peck, 2020). At the same time, recycling within bioeconomic sectors is expected to overcome potential problems of biomass availability and waste generation (Philp & Winickoff, 2018).

The criticisms of substitution and decoupling are either due to their implications (e.g. land-use changes or intensification, see section 2.3) or because they are considered fallacious. Sections 2.2.1 and 2.2.2 focus on the latter, which echoes the core principles of the bioeconomics paradigm.

2.2.1. Substitution

The hypothesis of substitution is a first challenge. As Asada et al. (2020) emphasize, the idea that the growth of the bioeconomic sector will be beneficial, especially in terms of lowering the dependence of our economies on fossil fuels, is hardly ever questioned. Indeed, their models, as well as historical data compiled in the field of social ecology (Krausmann et al., 2009), do not provide confirmation of bio-based energies replacing fossil fuels. We try here to provide explanations to this absence of substitution at the global scale, based on bioeconomics and ecological economics research.

First, in terms of thermodynamics, any material conversion requires funds (Couix, 2020; Georgescu-Roegen, 1971). Currently, many of these funds are manufactured, and hence depend on fossil fuels and raw materials to build and maintain them. A lasting demand for these resources is unavoidable in the context of developing a bioeconomy (e.g. developing biogas value chains requires to use non-renewable and polluting materials, to build production units, ensure transportation etc.). Having said that, partial substitution, as opposed to perfect substitution, could still be achieved. However, rebound effects (Alcott, 2005) constitute another limitation of substitution. Zink and Geyer (2017) explored the case of substitution of primary products with secondary products. They named 'circular economy rebound' cases when circular economy activities provoke a raise in product consumption, and hence undermine the theoretical benefits of these activities on resource use and the environment. Indeed, the authors point out that the use of secondary products does not guarantee a decrease in primary production as if it was a communicating vessels situation. Logistic chains and the market structure are not necessarily suited for this substitution (Zink & Geyer, 2017). Similarly, we can expect biofuel and biomaterial consumption to grow substantially, but by satisfying the overall growth in demand through new distinct markets and supply chains, and not by superseding fossil fuels, plastics and minerals. The consequence would be of two markets growing independently, with their environmental costs added to one another. Thus, substitution appears at least a questionable hypothesis, which deserves more investigation.

2.2.2. Decoupling

Modelling and empirical data provide evidence that decoupling (in terms of material resource use and carbon emissions from GDP) is not occurring in the long run on a global scale (Hickel & Kallis, 2020; Ward et al., 2016a). First, pollution and resource depletion transfers across space explain this absence (see 2.3) ; second, the relationship between efficiency and lower consumptions of energy and materials is questionable. Indeed, rebound effects apply to the decoupling hypothesis as well. These effects were initially described for productivity gains in the development of steam engines in the second half of the 19^{th} century (Alcott, 2005). Because machines were more productive, they became more economical, which favoured their spread and resulted in increased consumption of coal (Jevons' paradox). Indirect pathways are also possible when the energy difference between the old and the new technology is reinvested in the production of bigger, more powerful or more numerous artefacts. As in the case of steam engines, productivity gains should also take place within biorefineries (Levidow, 2015a), possibly leading to an unexpected boom of demand for input materials. If we consider that increased exploitation of natural resources - even when they fall into the category of renewable resources – can undermine ecosystem functioning (Navare, Muys, Vrancken, & Van Acker, 2021), then bioeconomy and circularity do not allow economic growth, independently from pressuring the environment and ecological renewability. Decoupling might therefore apply at the level of resource stocks, but not at the level of biological renewability.

Another argument against decoupling is – once again - that of thermodynamics. The bioeconomics paradigm observes any productive process (Georgescu-Roegen, 1971; Mayumi, 2009) as a chain of material and energy transformations to generate usable products and services for humans (Georgescu-Roegen, 1971; Mayumi, 2009). These transformations require low-entropy energy input and produce high-entropy energy output, in the form of heat, for instance. This dissipation of energy (often accompanied by the production of polluting emissions) is unavoidable. At the same time, the development of human societies has rested upon the production and use of exosomatic tools (Bobulescu, 2015; Georgescu-Roegen, 1971), from two-sided rocks to computers, which multiply the possibilities for doing and knowing of our species in comparison to endosomatic tools (e.g. our arms, brain and legs). Hence, the historical development of humanity is bound up with an increase in energy density and power intensity (Smil, 2008).

Drawing on the works of Georgescu-Roegen, Giampietro (2019) interprets the Industrial Revolution as a rupture, in which previously circular production processes based on natural processes became linear. This linearization relies on the depletion of fossil fuels on the one hand, and the accumulation of waste and pollution on the other, i.e. an escape from the low functioning rate of living systems. This makes possible much more rapid exosomatic-led development ('growth'), but in parallel the environmental impact of this continuous destocking process makes the quest for GDP biophysically unsustainable. He concludes: *“a massive increase in the weight of biological processes in the economy will slow down the pace of growth of the contemporary economy*” (Giampietro, 2019, p. 154). So, rebound effects show that efficiency does not prevent increases in resource consumption and polluting emissions; and thermodynamics shows that relying on natural processes involves degrowth. Both seriously undermine the possibility of decoupling, at least of a decoupling based on efficient productive systems and wide use of biological processes.

2.3. The bioeconomy transition generates new sustainability problems

While a bioeconomy transition attempts to solve fossil fuel dependency and waste production through substitution and more circularity, some critiques argue that although the expected advantages are valuable, they are bound to have countereffects elsewhere that are potentially more detrimental to the environment. This strand of criticism is certainly the best known and the least bioeconomics-centred; its main arguments are outlined below.

First, biomass has a lower energy potential than fossil fuels. Although plant biomass is best valorised, in energetic terms, through direct burning (Ioelovich, 2015), its net calorific values are still in this case two to three times lower than that of hydrocarbons (forestresearch.gov.uk). The energy return on investment of bioenergy (bioethanol or biodiesel) is an order of magnitude less than that of oil and gas (biofuels are around 20 times less efficient: Hall, Lambert, & Balogh, 2014). For these reasons, turning to biomass and biofuel requires access to large quantities of raw materials. Without neglecting the potential of exploiting by-products and waste, major biomass extraction from crops and forests appears necessary. Based on this observation, only two options would allow the decarbonization of the production processes of our energy-demanding economies: exploiting more land for biomass and bioenergy provision or intensifying land use. The impacts would vary depending on the previous land type (e.g. ‘marginal’ land, biodiversity-rich habitats, food or feed crops), and the farming/forestry choices made. Each of these pathways has specific weaknesses, which Lewandowski (2015) has extensively reviewed. Often they generate new environmental problems (e.g. biodiversity loss and ecosystem simplification, weakening of food- or feed-production capacity, soil and water degradation, greenhouse gas emissions), as well as social problems (e.g. low revenue for farmers, increased power asymmetry within global markets) (Lewandowski, 2015).

Worse still, geographical transfers (from one place to another) compound the displacement of problems (from one sustainability issue to another). This geographical transfer occurs mainly due to land-use spillover, i.e. “processes by which land use changes or direct interventions in land use (e.g. policy, program, new technologies) in one place have impacts on land use in another place” (Meyfroidt et al., 2020, p. 15). Such spillovers can allow countries implementing a bioeconomy transition to claim good environmental performance while externalizing their environmental costs elsewhere. This type of transfer has allowed, for instance, Western countries to profess successful decoupling trends (see section 2.3) that are now being demystified by indicators that integrate imports and novel flow-modelling methods (Bruckner et al., 2019; Hickel & Kallis, 2020). As an illustration, EU non-food bio-products embody almost as much land area outside as inside its own territory. (14.6 Mha of EU cropland vs 13.6 Mha of extra-European cropland: Bruckner et al., 2019). In contrast, more than half of Indonesia’s non-food cropland ‘flees’ the country as biofuels and textiles processed and consumed in other countries (estimates from the LANDFLOW-EXIOBASE model, Bruckner et al., 2019).

A second expectation of bioeconomy policies is to solve, or at least reduce, the waste burden of our consumption levels via cleaner production processes and the development and spread of recycling and circular economic solutions. There is evidence that the ideal of the circular economy is far from taking precedence over linear processes, and that on a global scale, we continue to follow cumulative trends in terms of waste and materials (Haas, Krausmann, Wiedenhofer, & Heinz, 2015; Haas et al., 2020). Moreover, even if circularity was able to overcome the challenge of its deployment and rebound effects (see section 2.2), effectively reducing the accumulation of waste and resource extraction, detrimental side effects would still be possible.

A case study that foreshadows the challenges of a 'circular bioeconomy' is that of biogas in Germany, where since 2000 it has expanded at a rapid rate through public incentives and subsidies. One side effect reported by Hennig and Latacz-Lohmann (2017) has been price inflation in farmland rent where biogas units had been set up, while Lajdova et al. (2016) noted competition with feed plants for animals. In France, where biogas expanded later than in Germany and limitations have been set for energy crops, most anaerobic digestion units are supplied with manure and intermediate crops, which could theoretically alleviate some of these drawbacks. Nevertheless, the transformation of the agricultural biomass value chains results in winners and losers. Among the latter can be ecological funds, such as soil when it loses natural organic replenishment, and environmentally friendly agricultural practices such as organic farming when the supply of neighbouring manure is diverted towards digestion units (Marty, Dermine-Brullot, Madelrieux, Fleuet, & Lescoat, 2021). More complex indirect effects of diverting biomass flow can also cause sustainability problems. For instance, while introducing alfalfa in crop rotations had been one of the few agroecology successes in the Aube area of France, this practice was undermined by the development of digestion units, which compete – in terms of input flows – with the dehydration units necessary to cost-effective alfalfa production (Marty et al., 2021). These examples show that even if there were fewer limitations to decoupling and substitution, a new wave of sustainability problems, perhaps worse, might have to be faced.

Most of the critiques mentioned take an academic, discursive perspective, and, with few exceptions, without paying much attention to innovations that emerge in the real economy. While such macroscale debate is fundamental, we also consider that another question deserves attention: the bundle of local initiatives that represent potential innovations shaping the emergence of a new, as yet undefined, bioeconomic regime.

It is even possible that the macroscale, theoretical critique of the bioeconomy might be deleterious to the bioeconomics ideal. This approach surely boosted the revival of the bioeconomics paradigm but refrained its spread and development through support for local innovations. The next section highlights some insights and research fronts that a bioeconomics perspective could provide, following the call of Béfort et al. (2020) to downscale and operationalize both societal debate and research.

3. From a conceptual critique towards operational research fronts

Today, many EU member states have translated European bioeconomy policy into national policy, with regional governments the new level for implementing bioeconomy measures. In France at least, this process is largely top-down. A recent report from the French Ministry of Agriculture (CGAAER, 2019) calls for a more consistent and integrated vision of the bioeconomy at a regional level and promotes the creation of a specific governance body supervised by government agencies. At the same time, a number of specific local and/or bottom-up strategies have been developed according to local conditions and participating stakeholders – these include initiatives such as contracts for the ecological transition, local food projects, zero net energy territories, etc. These do not necessarily fit into the mould of the EU and national bioeconomy strategy, although they are expected to be consistent with it.

Like many national strategies, French bioeconomy strategy promotes economic development based on the production, transformation and commercialization of bio-based products, lying in the mainstream of a bioeconomy transition. However, the French strategy also makes references to a bioeconomics transition. It states (though mainly in a context that justifies the development of the bioeconomy) an obligation of: the preservation of natural resources and functions, sustainability for present and future generations, and respect for planetary boundaries. These ambiguities offer an opportunity to address a wide scope of issues.

The malleability in the political use of the term 'bioeconomy' further increases when we turn to local initiatives and collective action in France. Plans to relocalize agri-food systems or to foster 'energy sobriety' (reducing or avoiding energy consumption) echo a bioeconomics transition. At the local scale, initiatives tend to be heterogeneous and weakly coordinated, with a vaguely defined overarching direction that develops as they unfold. Nonetheless, these initiatives get more bioeconomy research support, since this gets more publicity and national funding. The result is that somehow, the asymmetry of the 'bioeconomy vs bioeconomics' debate translates into research support being provided to collective action. Thus, identifying research fronts might help to make this debate more symmetrical, enriching it and producing more connections between local initiatives and bioeconomics insights. These research fronts are listed in Table 2, alongside the critiques they intend to address.

[Tab 2 here]

Below we discuss these research fronts grouped by three major topics: understanding bioeconomic systems, the operationalization of insights from bioeconomics research, and the handling of transitional dynamics.

3.1. Research front type 1: Exploring and understanding 'bioeconomic systems'

3.1.1. Systemic lock-ins and levers of change

Most representations of bioeconomic systems have a 'cradle-to-grave' logic emphasizing the efficiency of transformation processes (e.g. lifecycle assessments). They offer a value-chain approach to bioeconomic transitions, but neglect the ecological challenges posed by biomass production, especially agricultural biomass (Raghu, Spencer, Davis, & Wiedenmann, 2011; van der Werf, Knudsen, & Cederberg, 2020). As a result of this shortcoming, the use of 'marginal' lands and intensification processes (e.g. Clark & Tilman, 2017) become one-size-fits-all solutions for bioeconomy strategies. New frameworks aiming to better integrate the multiple effects of agricultural practices, spatial differences, and ecological dimensions are emerging (Nitschelm, Aubin, Corson, Viaud, & Walter, 2016; Raghu et al., 2011; van der Werf et al., 2020; Wohlfahrt et al., 2019);

these help to form a broader understanding of 'bioeconomic systems' as socio-ecological systems anchored in territories, and not mere above-ground value chains. Another blind spot in most bioeconomic system representations is value-chain interactions, which add to the complexity of characterizing and directing changes. Accounting for bioeconomic value-chain networks (Lewandowski, 2015) – exceeding the sole agri-food sector and its stakeholders – or modelling interactions between the production, use and recycling nexus of biomass value chains within a specific territory (Wohlfahrt et al., 2019) are promising research directions to overcome this gap.

If a better understanding of bioeconomic *systems* is required to take into account production practices, their ecological effects and anchorage in the local area, an understanding of the bioeconomic *transition* does not require the exact same lens. Many lock-ins situations, when new pathways are difficult to introduce even when environmental performance is acknowledged, are linked to value chains and socio-technical regimes. For instance, due to several self-reinforcing mechanisms – including economies of scale, network externalities, increasing returns of information, or institutional support (Magrini et al., 2019), the extension of crop diversification faces difficulties in France, although its agronomic and environmental performance exceeds that of cash crops (Meynard et al., 2018; Magrini et al., 2019). The analysis of agricultural models by Plumecocq et al. (2018) exemplifies the entanglement between farming practices, farmers' value systems, as well as commercialization and distribution options. Farming systems based on the use of exogenous inputs (whether chemical or organic) generally contribute to globalized commodity-based food systems valuing food security and efficiency. In contrast, biodiversity-based farming systems, drawing on ecosystem services as inputs for their crops, are more often included in local food production and distribution systems (Morel, Revoyron, Cristobal, & Baret, 2020; Plumecocq et al., 2018). Such coevolution can be an advantage, as it could be expected that changes in the configuration of value chains and R&D investment might drive more ecological farming practices and mindsets.

At the opposite extreme to value chains, consumption and diets are increasingly emphasized as key drivers to unlock a bieconomics transition (Priefer, Jörissen, & Frör, 2017). Many large-scale scenarios include the decreasing consumption of meat as a prerequisite for achieving global food sufficiency compatible with sustainable farming practices (see e.g. the 'Ten Years For Agroecology' report, Poux & Aubert, 2018) and land-use boundaries (Zanten et al., 2018). Yet these consumption-led transitions can serve as windows of opportunity for dominant actors, whose aim is not a profound change in their production modes. The well-documented case of the conventionalization of organic food is an alert that alternative pathways can be absorbed by the industrial regime, losing their transformative power (Buck, Getz, & Guthman, 1997; García, Guzmán, & Molina, 2018).

Although we are gaining insights into the nodes to unlock a bioeconomics transition, at least in the agri-food sector (for a review, see Table 2 in Morel, Revoyron, Cristobal, & Baret, 2020), this knowledge also emphasizes the need to invest more research effort in institutional and coordination issues. Aligning push and pull factors of change (in this case, push coming from socio-technical landscapes and pull from local niches) is for instance defined as key to scale up and maintain the diversification of crops (Magrini et al., 2018; Roesch-McNally et al., 2018). One conclusion derived from this has been to enlarge the type of stakeholders and the design process to what Meynard et al. (2017) call coupled innovation: collaborative 'open innovation' including various domains (such as genetic, technological, organizational, institutional) and designers (farmers, agronomists, food industries, consumers, the energy sector, etc.). Other scholars (Morel et al., 2020) have shown that some agroecological models stand 'outside' the dynamics of the agri-food regime: they rely on a reduced number of stakeholders and voluntary exclusion from commodity value chains in order to be economically viable. In this case, recommendations could favour institutional arrangements allowing peer-to-peer or horizontal diffusion instead of scaling up.

Overall, a better understanding of the resources that can unlock and secure shifting towards more sustainable economies in the long run is a major challenge. As with agroecology, a combination of material, cognitive, technical and socioeconomic resources are all factors favouring successful transitions (Moraine, Lumbroso, & Poux, 2018). Continuous efforts to track and document the diverse changes occurring within bioeconomic systems, as well as their determinants, are therefore critical.

3.1.2. Sustainability transfers and trade-offs

The need to adopt a systemic approach to bioeconomic transitions matters in order to identify where, in complex biomass value chains, the strategic levers for change occur, as well as to document sustainability transfers and trade-offs across time, space and sustainability goals. Competing claims on biomass and land use have become an issue of focused attention since the side effects of biofuels – which hardly contribute to global energy production – became visible (Bruckner et al., 2019; Lewandowski, 2015). The biofuel production experiment emphasizes the need to document potential trade-offs *ex-ante* rather than *ex-post* and reveal the blind spots that continue to compromise our understanding of the impacts of the bioeconomy.

Globalization counteracts many regional sustainability policies (e.g. ecotaxes) due to the bypass routes it creates (e.g. increases in imports from countries without ecotaxes). Interregional trade-flow accounting has started to encompass the consumption- and production-based human footprint and to demystify the decoupling thesis about material, water, carbon or biodiversity footprints (Zuindeau, 2007; Wiedmann, 2009; Hertwich & Peters, 2009, 2009; Peters, Minx, Weber, & Edenhofer, 2011; Hoekstra & Mekonnen, 2012). Tracking material and energy flows across distant regions also sheds light on the growing power asymmetry between world regions as well as between cities and their hinterland (Bahers, Tanguy, & Pincetl, 2020). Interregional flow accounting should therefore be essential when assessing the contribution and impacts of bioeconomic transitions in a context of globalization (Bruckner et al., 2019). Standardizing methods is, however, the key to foster adoption by international organizations (Brinkman, Wicke, Gerssen-Gondelach, van der Laan, & Faaij, 2015; Lewandowski, 2015).

Second, there is a need to develop prospective knowledge in order to put different bioeconomic transition options – e.g. based on bioeconomy or bioeconomics – in perspective. The development of spatially explicit land-use models is crucial (Schulze et al., 2015) to learn how supply and demand for biomass and land-use changes interact in different bioeconomic scenarios, and lead to competition between spaces for biodiversity protection, climate change mitigation, food security, and other sustainability goals (Kraxner et al., 2013; Bryan et al., 2015; Choi et al., 2019). These models show how increasing bio-based substitutes for unrenewable resources results in ecological feedback, geographical transfers and indirect land-use changes; they can also help target critical spatial hotspots (Seppelt et al., 2013) and point out when and where changes in living standards are the only resort to reduce the human ecological footprint (Bryan et al., 2015; Heck et al., 2018; Escobar & Britz, 2021).

Integrated or complex system modelling (Bazilian et al., 2011; Giampietro, 2003; Halog & Manik, 2011) are also key tools to deal with unintended or counterintuitive effects (e.g. rebound effects) (Lewandowski, 2015; Therond, Duru, Roger-Estrade, & Richard, 2017; Wohlfahrt et al., 2019). Integrated models combine cross-source knowledge about a given system; they are labelled ‘complex’ when they are able to represent emergent patterns (e.g. agent-based models, feedback loops). For example, Wohlfahrt et al. (2019) developed an integrated modelling framework to assess, in a systemic and ex-ante approach, the implementation of the bioeconomy at the level of a territory. The concept of the water-energy-food-environment nexus (Bazilian et al., 2011; Therond et al., 2017) could further inspire integrated models designed to observe trade-offs across sustainability domains. In the case of food consumption, for instance, ‘climate-friendly diets’ (vegan or vegetarian) were sometimes found to increase water use (Jarmul et al., 2020). Currently there is still little knowledge about the impacts on water resources and nutrient availability – and not only biomass availability – of competing bioeconomic transition options (Lewandowski, 2015; Rosegrant, Ringler, Zhu, Tokgoz, & Bhandary, 2013).

3.2. Research front type 2: Frameworks and proxies to operationalize insights from bioeconomics

Comparing the fitness of different scenarios to planetary boundaries (Rockström et al., 2009) should be a widely shared objective. Scholars investigating circular economy policies have stressed the importance of absolute measures of resource use and waste production as normative indicators, rather than ratios (e.g. the share of production coming from recycled or bio- resources) (Akenji, Bengtsson, Bleischwitz, Tukker, & Schandl, 2016; Haas et al., 2015, 2020). Bioeconomics-based frameworks can be of interest to this end. One example is the MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) framework, which introduces compatibility checks with internal constraints (e.g. demographic composition and human labour available) and external constraints (capacity of the biophysical system to ensure the production of resources and assimilation of waste over the long run) (Giampietro, Mayumi, & Bukkens, 2001; Giampietro, Mayumi, & Ramos-Martin, 2009). Recent developments in this framework have targeted imbalances between the internalization and externalization of resource/emission pressures, helping to highlight, for instance, the irreducible dependence of EU agriculture on ‘virtual’ flows of land and water, hence the impossibility of extending this model to other parts of the world (Renner, Cadillo-Benalcazar, Benini, & Giampietro, 2020).

Indicators reflecting that a society’s metabolism is consistent with human and biophysical limits should become the benchmark against which bioeconomic transition options are assessed. At the same time, as the associated methodologies are complex and data intensive, it would also be advisable to invest research efforts in developing proxies. For instance, a thermodynamics approach (e.g. each conversion of matter or energy dissipates energy) adopted by degrowth scholars (D’Alisa, Demaria, & Kallis, 2014) to look for proxies that assess the size of societal metabolism (e.g. number of links and value chains? Amount of heavily processed products in the average shopping basket? Pace of growth of material infrastructure?). Urban metabolism scientists have paved the way by comparing city configurations and lifestyle characteristics with material footprints (Lablonovski & Bognon, 2019; Kalmykova, Rosado, & Patrício, 2016).

A second research front regarding evaluative frameworks supporting a bioeconomics transition is to explore how socioeconomic performance is assessed. To change the course of growing human demand for materials, bioeconomic transitions should find alternatives to GDP – a self-reinforcing measure of material consumption (Ward et al., 2016b; Hickel & Kallis, 2020). Promising options lie in more comprehensive and multidimensional social welfare and human development indicators (Fleurbaey, 2009; Andreoni & Galmarini, 2014), and an approach of environmental and intergenerational ethics (Gough, 2015). It has been shown that the free pursuit of self-interest does not mechanistically lead to higher social benefit (Frank, 2011; Johnson, Price, & Van Vugt, 2013), hence individual-centred metrics (including well-being, happiness or capability) often have low social accuracy (Gough, 2015). Of these post-GDP metrics, human-scale systemic development methods (Cruz, Stahel, & Max-Neef, 2009) distinguish universal and irrevocable human needs (e.g. subsistence, protection, freedom, etc.) from need satisfiers, which are highly variable and dynamic across cultures, space and time. While considering the satisfaction of human needs as an imperative, the nature, impacts and distribution of need satisfiers could be questioned and acted upon in consequence. However, driven by solvency, markets continuously fulfil the material demand of the wealthiest, offering new satisfiers and positional goods (that provide status symbols in hierarchized societies), ultimately “at the expense of the environment” (Greenhalgh, 2005). A key research front for a bioeconomics transition is the quest for assessing, monitoring and promoting low-material but socially rich development pathways.

3.3. Research front type 3: Objectives and pathways for a bioeconomics transition

3.3.1. Exploring and debating the end purposes of bioeconomic transition initiatives

A research front with broad consensus among authors is to shed light on competing narratives about the bioeconomic transition (see Tab. 1) to enrich the debate and empower stakeholders. Efforts on this subject have produced quite clear accounts of the different imaginaries of the bioeconomy (technology or ecology intensive; based on a rationale of eco-efficiency or sufficiency, etc.) and their respective positions in arena (Bugge et al., 2016; Hausknost et al., 2017; Levidow et al., 2012; Meyer, 2017; Vivien et al., 2019). Yet there remains a lack of clarification about the final aims, underlying values and sustainability commitments of these different narratives. The positioning of agroecological models offered by Plumecocq et al. (2018) and Therond et al. (2017) could inspire analyses of bioeconomic models in terms of legitimizing principles, their relationship to strong vs weak sustainability, as well as to underlying conceptions of well-being (individual or social, related solely to material accumulation or more diverse human needs and capabilities). This exercise could apply to international and national strategies as well as to regional policy and local initiatives, as guiding frameworks and stakeholder discourse do not overlap (Bauer, 2018).

The underlying idea is that societal change, especially in values and in perceptions of human–nature relationships, is a vehicle for macrolevel change (or ‘landscape’ change in a multilevel perspective: Geels, 2011). There is therefore a need to connect local stakeholder discourse with scientific knowledge, institutions and societal models (Befort, 2020; Lewandowski, 2015; Wohlfahrt et al., 2019). To fill this gap, participatory methods could be helpful, such as quantitative storytelling (Saltelli & Giampietro, 2017), deliberative sustainability assessments (Allain, Plumecocq, & Leenhardt, 2020; Frame & O’Connor, 2011) or participatory scenario development (Bauwens, Hekkert, & Kirchherr, 2020). ‘Soft’ modelling methods, so called because they rely more on discourse than on computational ability, can also help pinpoint the consistency and contradictions of bioeconomic narratives (Bennich et al., 2021; Heimann, 2019). All these methods could contribute to overcoming the framing biases and restricted knowledge introduced by the rationale of a bioeconomy transition. They could foster people’s capacity to grasp the future bioeconomy traced by leading institutions, while helping them to build alternative futures. In parallel, it also seems necessary to downscale the bioeconomic models embedded in national and international strategies and question their fit with local trajectories (e.g. industrial transitions) and specificities (Béfort et al., 2020).

3.3.2. Policy issues raised by the transition process: coordination and temporality

Even once the values and end purposes of a bioeconomic model are made clear and assessed against biophysical limits and societal needs, the horizon remains blurry. It is also important to understand trajectories and processes of change in a context of ever-shifting targets and weakly-specified levers of change (production practices, consumption and lifestyles, size of value chains, etc.). Two governance factors of the transition process are especially important to emphasize: the coordination of stakeholders/activities and the management of transition temporalities.

Recent accounts of bioeconomic innovations highlight the numerous organizational obstacles and uncertainties that new value chains face: for example, those of biogas (Åkerman, Humalisto, & Pitzen, 2020; Marty et al., 2021). Likewise, innovative business models, such as product–service systems (PSS), which raised high expectations, have created partial disillusionment. The initial idea was that shared PSS (e.g. a bike-rental service) could substitute for individually owned goods, hence reducing overall material demand. However, the environmental gains from PSS have proven limited, except when they lead to more structural changes driven by 'functional results' (e.g. providing a comfortable working temperature with passive solar design, for example, rather than providing heating or air-conditioning equipment as an end) (Tukker, 2004). It has been shown that the implementation of ambitious PSS quickly faces socio-technical lock-ins, although proactive system governance, acting to push the demand, for example (Hannon, Foxon, & Gale, 2015), can help to remove these. Regulatory and normative policies are pointed out as necessary to embed the required changes into everyday behaviours and new societal values to secure long-term changes (Mont, 2004). Also, specific competences to coordinate people holding plural value and knowledge systems appear necessary to trigger any transition process: some advocate for the production of inspiring narratives while listening and learning from arising resistances (Kristof, 2020), others for value-articulating tools (Chamaret, O'Connor, & Douguet, 2009; Matos Castaño, van Amstel, Hartmann, & Dewulf, 2017). The governance factors and processes that could help to activate systemic changes remain a major research front.

Insights gained in the field of design (and co-design) for sustainability (Ceschin & Gaziulusoy, 2016) could help change the focus from product or even value-chain innovations to a multilevel perspective of system innovation (e.g. socio-technical regimes) and help define more inclusive and effective institutional arrangements (Mont, 2004). Such a conception of co-design is gaining popularity in the case of agroecology, for instance (see 3.1). A specific challenge, rarely tackled, is that of transient economic activities necessary in the transition stage to mitigate the effects of past and current economic systems (e.g. to remediate environmental damage), but expected to become useless or marginal in a less environmentally impactful economic system (Ruault et al., 2022). The management of transition temporalities also involves linking the dismantling of unsustainable activities with the development of other more sustainable activities when the transition from one to the other is impossible. As Rogge & Johnstone (2017) point out in a study on the energy transition in Germany, phase-out policies, by giving credibility to the political commitment to the ecological transition, can both encourage private investment in sustainability innovations and make room for the diffusion of competing alternatives.

Conclusion

Behind every innovation vaunted by bioeconomy strategies, one could denounce its side effects, counterproductive mechanisms and hidden agendas. However, this message alone is too simplistic and unbalanced: although a blatant lack of reflexivity characterizes bioeconomy discourse, bioeconomic policies are not a monolith of initiatives with the aim of fuelling capitalist growth and deaf to ecological and societal alerts. If criticism and deconstruction of the bioeconomy are not followed by an operational research agenda, this may unwittingly contribute to building a preference for the status quo. Experimenting with changes is needed – although caution must be taken not to create a cure worse than the disease or to employ soothing words that obscure the extent of the crisis. The ways to prevent this are reflexivity about innovations, collective debate about their final aims, and awareness about the trade-offs they produce.

The aim of this article is twofold: to reveal certain fallacies regarding the mainstream bioeconomy transition and to outline constructive research proposals to redirect the course of this transition. These proposals include coupled economic-biophysical models, absolute metrics of sustainability, renewed well-being frameworks, consideration for entire value chains and value-chain networks (including production practices and consumption modes), as well as pathways for developing low-material and socially rich innovations while phasing out the activities, knowledge, technologies and values that maintain and reinforce the current industrial regime. Many of the research fronts we focus on are already underway, within and outside bioeconomics scholarship, yet they lack coordination. For instance, accounting frameworks, indicators and proxies allow the critical analysis of the bioeconomic transition as a research object, but are weakly adapted to and little used within deliberative settings for defining socially and ecologically desirable transition narratives and pathways.

There is an undeniably long and difficult road before research can effectively support a bioeconomic transition leading to a more sustainable society. And without wider institutional change, research has little, if any, transformative capacity. In this sense, the ball is in the court of politics. The power balance that favours soft transition options by focusing on instruments of the bioeconomy (biotechnologies, biorefineries, etc.) while blurring normative sustainability goals is the first obstacle to overcome. The development of the bioeconomy is seen as a central part of many current ecological transition policies (EU green deal, the US Green New Deal, Paris Agreement commitments), since it offers a seducing promise – yet to be realized - of employment, innovation, economic wealth, climate change mitigation and renewability. Instead of focusing on this global promise and its plausibility, we could turn our attention to local level experiments, through dedicated research settings. Innovation and change often come from the bottom, making it vital to support local initiatives while striving to frame and assess achievements and progress against ambitious standards at the macro and institutional levels within a strong sustainability perspective. This might be the case with agriculture: although alignment with national and international strategies is an undeniable driving force, many changes also incubate at farm level and spread through horizontal exchanges. While the negotiation of the national strategic plans for the CAP 2023-2027 is still underway at the end of 2021, the transformative power of bottom-up agroecological initiatives should not be overlooked.

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Selected references	Position of the authors / Aim of the work	Source material	Objects of the analysis *(What is depicted?)*	Analysis areas (*What is it contrasted with?)*	Resulting clusters
Levidow, Birch, & Papaioannou, 2012	To clarify the economic and techno-scientific paradigms underlying the EU discourse on the bioeconomy; to de-naturalize the dominant life-science vision of the bioeconomy	EU strategy documents and stakeholder interviews	**Visions of the bioeconomy** embedding a desirable reality, societal objectives and a strategy to reach it	• Economic and sociotechnical imaginaries • Paradigms of agri-food engineering, product quality and knowledge	• ***Life-science vision***: bioeconomy as a transition from a fossil fuel to a bioresource economy allowed by converging technologies and global value chains • ***Agroecology vision***: bioeconomy as a means for sustainable and equitable provision of food, fibre and energy, based on diversified low-input agricultural systems and short supply chains
Pfau, Hagens, Dankbaar, & Smits, 2014	To list the possible contributions of the bioeconomy to sustainability as well as its risks, and the conditions for a sustainable bioeconomy	Corpus of articles retrieved from a specific keyword request on five databases	The way scholars qualify the **link between the bioeconomy and sustainability**	• Contributions of the bioeconomy to sustainable development • Conditions under which these contributions are made possible • Problems that impede the achievement of sustainability	• ***Bioeconomy as inherently sustainable*** • ***Bioeconomy as beneficial for sustainability under certain conditions*** • ***Bioeconomy as a potential source of benefits and problems*** • ***Bioeconomy as a threat to sustainability***
Bugge, Hansen, & Klitkou, 2016	To explore the content of the term 'bioeconomy' in academic literature	Corpus of articles retrieved from a specific keyword request on the WoS Core Collection	The way scholars conceive of the bioeconomy (**'visions'** of the bioeconomy concept)	• Aims and objectives assigned to the bioeconomy • Value creation • Drivers and mediators of innovation • Spatial focus	• ***Biotechnology vision:*** bioeconomy as a means for growth and job creation, through the development, application and diffusion of biotechnology, taking place in innovation clusters • ***Bioresource vision:*** bioeconomy as a means of reconciling economic growth and sustainability through cross-sectoral innovation allowing the conversion and valorisation of biomass and waste • ***Bioecology vision:*** bioeconomy as a means for sustainability, requiring the enhancement of biodiversity conservation and ecosystem services, as well as localized food systems
Hausknost, Schriefl, Lauk, & Kalt, 2017	To define and explore a techno-political space for the bioeconomy; to highlight discrepancies between official documents, stakeholder discourse and biophysical constraints	Policy documents, stakeholder interviews and scenarios from biophysical modelling	**Societal master narratives:** the specific visions of societal development conveyed by different bioeconomic narratives and scenarios	• The technological dimension of bioeconomy narratives (from industrial biotech and agroecology) • The socio-economic goal assigned to the bioeconomic transition (from capitalist expansion to sufficiency)	• ***Sustainable capital:*** bioeconomy as a technology-led transition that sustains economic growth • ***Eco-growth:*** bioeconomy as the realization of the economic potential of agroecology and organic farming • ***Eco-retreat:*** bioeconomy as a systemic transition that decreases human activities, from

					production to consumption, within planetary boundaries • ***Planned transition:*** bioeconomy as a contraction of material consumption driven by states and achieved through the efficiency gains offered by biotechnology
Meyer, 2017	To draw attention to the overoptimistic promises of bioeconomy strategies	International and national (European, esp. German) policy documents	**Visions:** The political and operational content of bioeconomy strategies	• The foci of the strategies in different domains (technology, knowledge, economy, space) • Framing these in terms of the problem tackled, sustainability, land use, agricultural models and resource utilization	• ***Biotechnology-centred vision:*** life science and biotechnology drive innovation and improve economic competitiveness • ***Transformation-centred vision:*** biomass conversion and utilization allow transforming the economy from fossil-fuel dependent to bio-based • ***Ecology-centred vision:*** Agroecological engineering favours sustainable production of quality food, ecosystem services and nutrient cycling, and social innovation, such as local production/consumption networks, reduces biomass demand
(Bauer, 2018)	To disentangle the apparent consensus on the bioeconomic transition; to open up the diversity of different and conflictual discourses	Statements extracted from Swedish press articles, strategic documents and innovation projects	**Narratives** based on the clustering of statements (Q methodology applied to 20 individuals)	Q analysis resulting in three factors representing archetypal narratives, revealing three lines of debate: • Types of products stimulating the development of the bioeconomy (energy products vs new advanced products) • Politics of knowledge (spreading and applying current knowledge vs investing in the creation of new knowledge) • Governance (state intervention vs business-centred innovation)	• ***F1 'Let firms innovate at their own pace':*** Bioeconomy as business-led innovations, especially from the forest industry, ensuring growth and sustainability. • ***F2+ 'Energy is the key issue':*** Bioeconomy as driven by the challenge of global climate change, requiring state incentives and technology investments to substitute petroleum with bioproducts. • ***F2- 'The bioeconomy, an endless frontier':*** Simple substitution will not suffice to manage global problems; new knowledge and R&D is required, especially in the chemical industry. • ***F3 'A green intervention agenda':*** Bioeconomy through public policy interventions (research, objectives, policies targeting the demand for bioproducts, finance) to transform industrial and economic structures that the market alone cannot address.
Vivien, Nieddu, Befort, Debref, & Giampietro, 2019	To allow ecological economists to re-appropriate and enrich the bioeconomy debate	Documents (scientific publications and grey literature); stakeholder	**Narratives:** the formalization of stakeholder expectations, driving strategic resource allocation (production	• Nature/economy relationships • Socio-technical relationships • Sustainability model • Governance model	• ***Type I Bioeconomy:*** Human activity is reduced within the biological and physical limits of the biosphere and coevolves with ecological systems, while technology is regarded with prudence and put under democratic control.

		interviews; reports from participant observation at bioeconomy conferences	of strategic documents, funding of research programmes etc.). Narratives are seen as an entry point to stakeholder strategies.		• ***Type II Bioeconomy:*** Biotechnology fosters a new economic growth cycle, and living systems become the factories of the socioeconomic system. • ***Type III Bioeconomy:*** Biomass raw materials enter biorefineries, which spread and allow a transition towards less fossil-fuel-dependent and more circular economies.

Table 1 : Selected overview of classifications of bioeconomic narratives and visions

Critiques	Research fronts for constructive support
1. The bioeconomy transition as the continuation of the industrial regime - Risk of greenwashing in the absence of add-ons and unlocking mechanisms - Bioeconomy policies embed a logic of resource mining and nature commodification	Adopt a systemic vision of the bioeconomic transition that encompasses all material and energy conversions Identify locking/unlocking mechanisms for the different parts of the biomass value chain Investigate governance factors helping to implement and coordinate the activation of levers of change Build on existing knowledge and previous experiments with the agroecological transition and the effects of different coexisting models, especially concerning human–nature relationships Feed the debate by clarifying not only competing narratives, but also aims, underlying values, and the sustainability commitment of different bioeconomic transition models
2. The bioeconomy transition rests on fallacious hypotheses - Decoupling - Substitution	Build assessment tools that allow widening the scope and scale of our understanding of society's footprint on ecosystems and natural resources Develop sufficiency and sobriety analyses, relying on indicators and proxies of the scale/magnitude of material and energy flows and not on ratios and efficiency Develop and widen the use of multidimensional well-being and human needs assessments (not only based on material development) Develop complex system approaches to better envision counterintuitive effects, such as rebound effects
3. The bioeconomy transition generates new sustainability problems - Unsustainable agricultural and forestry practices - Land-use competition and spillovers - Destructuring of other ecologically friendly value chains and local arrangements	Develop nexus approaches that account for interactions between water, food, waste and energy systems in order to capture crises and vulnerability transfers Develop spatially explicit models, combining land-use and complex systems approaches in order to explore potential indirect land-use changes and conflicts Trace and document vulnerability and footprint transfers across space and time Identify trade-offs between overarching principles of bioeconomic models and strong sustainability models Design system-wide innovations with the help of new economic paradigms (e.g. functionality/access approach) and consider the temporality of transition pathways Produce contextualized analyses and representations that empower local stakeholders in conceiving and organizing a desirable bioeconomic transition

Types of research fronts

Type 1: Exploring and understanding bioeconomic systems
- 1.1– Lock-ins and levers of change
- 1.2- Sustainability transfers and trade-offs

Type 2: Frameworks and proxies to operationalize insights from bioeconomics

Type 3: Objectives and pathways for a bioeconomics transition
- 3.2– Policy issues raised by the transition process
- 3.1– Exploring and debating the end purposes of bioeconomic transition initiatives

Table 2: The bioeconomy vs bioeconmics debate in terms of critiques and research fronts