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The systemic challenge of the bioeconomy

A policy framework for transitioning towards a sustainable carbon cycle economy

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The bioeconomy is a political construct to address major societal challenges, such as food and energy security and climate resilience. What is less understood, however, is how bio-based value production chains can and must evolve in practice to achieve these goals. Policies face the challenge of balancing supply- and demand-side measures across diverse sectors, involving industrial manufacturing, agriculture, forestry, marine resources and waste management. Here, we demonstrate the importance of a systemic approach in policy development for transitions towards a bioeconomy.

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The bioeconomy and transition policies

A political obscurity just a mere decade ago, the concept of a bioeconomy has become increasingly popular: around 50 nations—including all of the G7 nations—either have a national bioeconomy strategy or policies consistent with the development of a bioeconomy. The main drivers behind the concept are concerns about climate change, reduced biodiversity, resource depletion, food and clean water security and energy supply. While these challenges require different solutions, they all share the need for a transition from fossil resources to a more sustainable societal carbon cycle.

Although the bioeconomy has attracted political attention, its actual deployment has been slow (Vainio *et al*, 2019). While previous transitions, such as wood to coal and coal to oil took several decades, they took place in the absence of the time constraints that rapid climate change is imposing. The urgency of the bioeconomy transition is thus calling for acute and decisive policy measures.

Surprisingly, there is still a lack of consensus regarding how the bioeconomy concept is understood, its scope as well as its main drivers. There are at least three main narratives (Bracco *et al*, 2018), one that focuses on replacing fossil carbon, another one driven by biotechnology and a third that seeks to optimise the use of available biomass in an ecologically sustainable manner. In this paper, we discuss policies relevant for all three interpretations. Nonetheless, the concept of the bioeconomy is increasingly integrated in the broader perspective of a renewable carbon strategy (Carus, 2018), which integrates biomass production with industrial carbon recycling.

The purpose of this paper is to propose a practical framework for policy makers, based on experience gathered over a 2-year period and six international workshops (OECD, 2019). In particular, we describe two case studies from Norway: although different in character, they are both supported by a similar mix of supply- and demand-side measures. Moreover, both bear the hallmarks of a circular (bio)economy, in which full and optimal use is achieved by converting all side streams into co-products and keeping materials in circulation as long as possible.

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Policies to support a bioeconomy can be examined in the context of transition management, a concept relating to governance of societally driven transitions. Consequently, transition theory can provide guidance for policy makers. It typically calls for massive and coordinated policy efforts and whole-government involvement to cover a multitude of policy areas: innovation, resources and land usage, carbon policy, industry policy, taxation, waste management and others.

The key principles of transition management are the following (Loorbach, 2007): to widen participation by taking a multi-actor approach; to take a long-term view on policy while responding to short-term objectives; experimentation to identify a successful pathway to a particular objective; and "systems thinking" to address multi-stakeholder societal challenges. When transition management is used as a frame for innovation policy, societal challenges can be transformed into opportunities for scientific and technological progress. The bioeconomy, understood as

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"the replacement of fossil resources with renewable carbon without compromising food security and biodiversity", fits very well with the principles of innovation-dependent transition management.

Systemic considerations in policy development

The aforementioned workshops have raised two main concerns that call for systems thinking in bioeconomy policies. First, progress appears to be slowing down in value chains characterised by an interdependency between multiple stakeholders. This could be described as a "systemic business risk", which discourages investments. Second, without an holistic approach and understanding of the complex interactions of value chains in the societal carbon cycle, policies may fail to balance unavoidable trade-offs between different sustainability objectives.

A value chain can be defined as "a set of interlinked activities that deliver products/services by adding value to bulk material (feedstock)" (Lokesh *et al*, 2018). In the emerging bioeconomy, a value chain would typically comprise a cascading series of manufacturing processes from biomass production, pre-treatment and conversion, through to the manufacture and marketing of bio-based products. Typically, many of these individual processing and manufacturing steps are all new and untried, and various public and private actors need to work together to make the chain work. The value chain is only as strong as its weakest link, and a single failure in the value chain might have the overall effect that the system will not work technically, logistically or financially. In other words, if policy simply acts on individual parts of a complex industrial system, there is a substantial risk of wasted resources and efforts. This underscores the need for coordination of different policies along value chains, as well as across disciplines and sectors.

Replacing fossil resources with fresh biomass will put a huge pressure on agriculture and forestry. Shortage of arable land, water and fertilisers have already led to conflicts between different sustainability goals related to, for instance, food, energy and biodiversity and major concerns about associated land use change and deforestation. One would expect policies to prioritise the use of renewable carbon in those value chains where no alternatives are available, e.g. food, chemistry and materials. In practice, however, public policy attention has mainly focused on bioenergy, despite the fact that biomass conversion to fuels typically has a poor energy efficiency. Moreover, there are concerns that liquid biofuels may slow investments into more efficient alternatives such as electrification or hydrogen. These points underscore the need for balanced policies.

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The overall intention of policies to stimulate the conversion of waste streams is promoting a cyclic or cascading resource utilisation. However, given the fact that the carbon cycle is fundamentally an energy cycle, it is important to avoid policies for local recycling of carbon that do not make sense from an overall energy perspective and which may in fact increase energy consumption within a larger system. Most industry processes are validated by calculating the mass and energy balances, and there is a need to put bioeconomy policies to a similar test at the systemic level.

Temporal aspects in policy development

Bioeconomy strategies implicate a wide range of specific supply- and demand-side policies and their interactions with general macroeconomic policies, such as carbon quotas and carbon tax. Thus, a starting point to design a framework for innovation policy should consider the synergies and tensions emerging from a mixture of supply- and demand-side instruments.

Typical supply-side measures focus on education, public research financing and public–private partnerships to share the cost for process verification and scale up infrastructure. Supply-side measures may also include regulations for feedstock utilisation or improved logistics. However, faced with an undeveloped market and strong competition from highly efficient petrochemical supply chains enjoying economies-of-scale and fully amortised production plants, the private sector may still be unwilling to shoulder the risk of first-of-kind commercial operations. Hence, public market stimulation should also be prioritized in a coherent policy mix (OECD, 2011).

Examples of direct market intervention include mandated production or blend requirements of biofuels, for example, or bans on specific feedstocks, production methods or product categories, such as single-use, non-biodegradable plastic bags. Softer market stimulation typically involves different tax regimes for preferred/certified and undesired products, augmented by public awareness campaigns. An excellent example of a public demand-side intervention is public procurement—direct purchase of goods and services by the government—which sends strong signals to the market. In OECD member states, public procurement accounts for around 29% of total government expenditures and it has a significant effect on trade flows.

A policy mix, however, does not imply a temporal strategy and a progression path for policy makers; that is, it is not a sequence of measures or a recipe for policy implementation. Figure 1 shows a refined approach by describing specific and general measures in a sequence from idea to market. This four-step matrix is developed from previous work with the Norwegian national bioeconomy strategy (The Ministry of Trade, Industry and Fisheries (Norway), 2016), to stimulate the interplay between different ministries and research and innovation agencies. It may give a broader idea of how to construct a strategy that will connect and coordinate supply- and demand-side drivers to achieve a stronger and more robust effect on the economic system. For demand-side policies, temporal aspects, such as the duration of market intervention, are particularly important: too long can lead to market distortion and too short may not have the desired effect.

Value chain policies—two specific cases from Norway

There can be no single policy recommendation owing to regional, national or international perspectives, combined with a complex web of biomass types, conversion technologies and product opportunities. However, despite their differences, recent case studies have identified some

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commonalities and reference points for general policies in bioeconomy value chains (OECD, 2019). We are illustrating this using the following two cases from Norway.

Norway has several significant point sources of carbon waste gases, such as CO and CO_2, from metals and fertilisers production. The national oil and gas production is also generating concentrated CO_2 emissions. Moreover, Norway has an ample supply of hydropower for the generation of “green” hydrogen via water electrolysis. Fermentation by microorganisms can convert carbon waste gases using hydrogen as energy source to food and feed ingredients, chemicals, polymers and biofuels. In this Norwegian case, the aim is to replace soy protein in fish feed with protein from so-called knallgas bacteria; the main sustainability benefit is a reduced pressure on land use and biodiversity.

This case is a good illustration of the systemic challenge. It requires cross-sectoral cooperation, verification of sustainability at a systemic level and coordinated innovation. While Norway may have the feedstock gases and technical expertise related to CO_2 capture, hydrogen production and feed development, the Norwegian innovation ecosystem still needs technology providers related to the gas fermentation process. The lack of a key enabling technology is a typical problem for small countries with a limited R&D capacity.

Analysis of the Norwegian gas fermentation opportunity identified the need for several families of policy instruments, illustrating the interplay of supply- and demand-side policies (Fig 2). This includes penalties for industrial CO_2 emissions and the availability of renewable power for hydrogen production; stimulating multi-stakeholder dialogue to clarify the technical and economic robustness of the complete value chain; policies to attract international technology providers and investments; policies to reduce technology risk by offering publicly funded scale-up facilities; stakeholder-neutral assessment to verify the sustainability benefits; and demand-side policies to discourage the use of soy protein in feed.

Presently, the main Norwegian strategy focuses on classic supply-side stimulation by providing scale-up and demonstration facilities. Demonstration is often seen as an essential stage in technology development, but one that is risky and unattractive to the private sector in the absence of market and policy certainty. Using public money to build demonstrator facilities is usually seen as a trigger for private investments, and in the Norwegian case, it also serves to attract international expertise on fermentation technologies.

The other exemplary case concerns enzymatic refining of fish residuals from aquaculture and fisheries. Farmed salmon is the second-largest industry sector in Norway producing 1.3 million tons of salmon, more than 50% of global salmon production. About half of the fish is sold as fillet and other direct consumer products, the rest is turned into relatively low-value intermediates such as fishmeal and fish oil for use in feed. In some conventional fisheries, resource utilisation is even less, as off-cuts from on-board processing are simply discharged into the sea.

There is a large potential thus to extract more value from marine fisheries and aquaculture, provided that the residuals are treated under the same high quality regimen as the fillet. Several Norwegian companies

FEEDSTOCK	TECHNOLOGY	INDUSTRIALISATION	MARKET
OBJECTIVES			
Stimulating availability of bio-resources	**Strengthen skills and technology base**	**Trigger investments in new manufacturing**	**Increased sustainability and value creation**
VALUE CHAIN SPECIFIC POLICIES			
Resource regulations and permits	Targeted R&D grant programmes	Public technology scale-up and pilot facilities	Product standards and norms
Transportation and logistics infrastructure	Specific education and training programmes	Financial support for first-of-kind (flagship) projects	Price subsidies and product tax policies
Feedstock specific trade regulations	Technology cluster and network support	Targeted government investments programmes	Product mandates and bans policies
GENERIC POLICIES			
Biomass sustainability assessment studies	Broad scope R&D grant programmes	Start-up and SME support	Sustainability labels and their communication
Governance and regulation efficiency	Tax incentives for applied R&D	Industry-oriented education programmes	Public awareness and acceptance campaigns
Waste management policies	Stimulate international partnerships	Techno-economic feasibility studies	Tax on CO_2 emissions
International trade agreements	Exchange programmes and apprenticeship	Private investment stimulating policies	Public procurement of bio-based products

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Figure 1. A bioeconomy innovation policy matrix.

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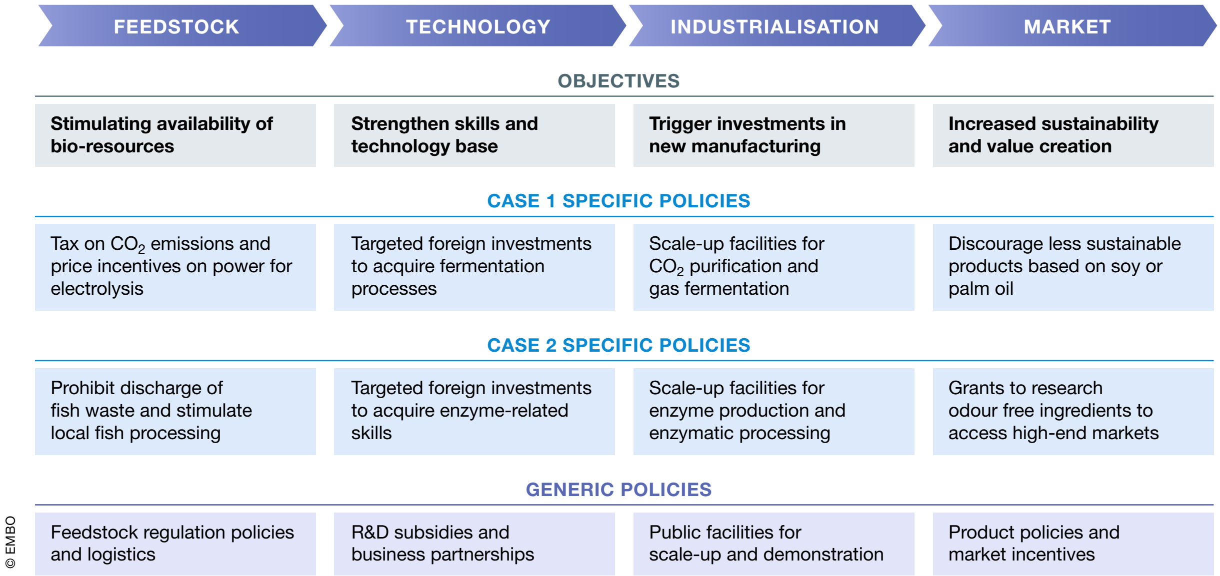

Figure 2. Commonalities as well as more specific policy needs for carbon gas fermentation (Case 1) and enzymatic refining of marine residuals (Case 2), respectively.

are now developing novel technologies for enzymatic biorefining of fish residuals to produce ingredients for health or sports drinks, cosmetics or pharmaceuticals. As with gas fermentation, the entire value chain needs to be developed *in toto* to be successful. The Norwegian industry has pioneered the design efficient reactors for continuous enzymatic processing, but the national innovation ecosystem is lacking an extensive enzyme toolbox provided by specialist companies. Tailor-making the enzyme mix to the specific substrates is key to high-end applications. Moreover, future customers need to be involved in the innovation process to specify the desired features of the resulting ingredients.

The relevant policy elements for marine co-products have many similarities to the CO_2 fermentation (Fig 2). Feedstock availability should be stimulated, for instance by prohibiting discharge of residuals at sea or by discouraging export of unprocessed fish. The innovation ecosystem should attract enabling technologies, such as enzyme design and production. Technology risk has been reduced by a publicly funded demonstration facility, offering open access, state-of-art equipment for scale-up of enzymatic processes. Moreover, the opportunity to produce test material at this facility is expected to stimulate collaboration with customers and potential end-users.

Aspects of policy integration and coordination

Here, we focus on systemic aspects of the bioeconomy transition. Systemic risk in value chains is often associated with political framework conditions related to feedstock and market that may discourage investments and slow development. We also point to another systemic barrier for the development of new value chains: the dependency of individual companies in a multi-actor supply chain on the performance of other parts of the chain. In other words, this is a risk beyond the control of the individual company and superimposed on more conventional feedstock, technology and market risk factors. In policy development, these findings call for coordinated public intervention along the entire value chain to enhance and ensure the efficacy of public investments.

With these perspectives in mind, cross-sectorial coordination is essential. The Norwegian bioeconomy strategy (The Ministry of Trade, Industry and Fisheries (Norway), 2016) was developed and signed by 10 different ministries, and the two case studies imply a number of government responsibilities within knowledge and innovation, industry, fisheries, energy and the environment. When international trade is involved, coordination has to take place at multi-national level, such as in the EU.

Another general challenge in policy development is to balance recommendations and vested interests from industry and NGOs. Governments will typically rely on their sector-specific agencies for technical expertise and advice. However, as argued above, the ubiquitous and transformative nature of the bioeconomy requires that established industry sectors leave their silo positions, also for their own benefit. The first Norwegian case study is a good example of new and perhaps surprising cross-sectoral opportunities, here leveraging cooperation between the metallurgical industry and producers of fish feed.

A possible instrument to coordinate ministries, agencies and industry sectors is independent advisory bodies with a broad mandate anchored for instance in a national bioeconomy strategy. Such advisory bodies can assist governments by monitoring progress and by compiling and presenting individual stakeholder views within the context of international trends. Arguably the most well-known example is the German Bioeconomy Council, the advisory body to the German Federal Government. A Norwegian example related to the first case study discussed above is Prosess21, comprising a number of expert committees appointed by

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the government to create a roadmap for making the Norwegian processing industry carbon neutral by 2050. While this is a transient advisory body, it involves all relevant agencies, research institutions and senior representation from major companies.

The bioeconomy involves numerous examples of technology convergence. While new breeding techniques may generate crops with higher yield and robustness, such innovations are increasingly combined with automation, robotics and precision farming. Synthetic biology may create novel enzymes, organisms and intermediates, which may require improved fermentation or product purification techniques. In the chemical sector, bio-based feedstocks are typically further processed in a conventional petrochemical refinery. The dependency on multiple technologies is a further illustration of the systemic business risk where a coordinated, interdisciplinary research policy is needed to support complete and robust value chains.

While biotechnology may enable but a single step in a multi-technology value chain, its importance is not only evident in the specific "biotechnology narrative" (Bracco *et al*, 2018) of the bioeconomy. It also serves a key role in the other narratives, that is replacing fossil carbon and improving utilisation of biomass (Hausknost *et al*, 2017). In the first Norwegian case study, fermentation of CO_2 could alternatively produce renewable chemicals and fuel, and in the second case, enzymes enable the production of high value co-products from fish waste material.

A recent OECD analysis of case studies and associated bioeconomy policies in 10 countries (OECD, 2019) noted a significant preponderance for supply-side policies. Unfortunately, feedstock or technology push alone may not be sufficient to drive the transition in those large-volume value chains that would have a significant effect on climate change mitigation. Petrochemistry has had decades to perfect its processes, and in the short term, it is very difficult for bio-based chemicals and materials to compete on price. One rather obvious measure to make the bioeconomy transition work economically would be to gradually shift fossil-fuel subsidies, the world's largest subsidies system, towards green products.

While market stimulation may be necessary to speed up the bioeconomy transition, credible sustainability criteria should be at the core of any market intervention. However, it remains difficult for governments to predict the efficiency of policies, as well as undesired side-effects, illustrated by the evolution of international agreements on carbon pricing and bioenergy incentives programmes [for instance, Japan's Feed-in Tariff (FIT), the European Renewable Energy Directive (RED1 and RED2) and the US Renewable Fuel Standard (RFS)]. Moreover, such criteria need to consider and balance trade-offs between different sustainability objectives, exemplified by the recent announcement of the European Commission's European Green Deal.

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Economic penalties in the form of a tax on carbon emissions appears as another obvious policy measure. As of 2019, there were 57 carbon pricing schemes either in practice or in development. This represents some 11 Gigatons of CO_2 equivalents or 20% of global emissions per annum, and the figure is steadily increasing (International Bank for Reconstruction and Development/The World Bank, 2019). There are essentially two methods for using revenues from these taxes to help grow the bioeconomy and carbon management more generally. In the first, revenues are added to the general budget of a government, and that government can choose to use these for climate-friendly purposes. Alternatively, the revenues can be earmarked for specific projects or purposes, rather than being added to the general budget. Both approaches have advantages: adding to the general budget minimises the cost for new administration, while earmarking is more direct, transparent and perhaps easier to gain public acceptance. In either case, the revenues should be spent within a broad set of sustainability policies acknowledging the importance of systems thinking.

The next phase: The bioeconomy in carbon management

One fundamental question is still not answered, however: Can the bioeconomy provide the quantities of biomass needed to supply all carbon-based value chains? The current annual consumption of fossil carbon as feedstock for chemicals, textiles, lubricants and polymers is significantly more than 1 billion tons—the polymer industry alone generates 350 million tons of products. In addition, there are some 360 million tons of aviation fuel, which is difficult to replace. The required volume of biomass would be substantially higher, as moisture and oxygen must be removed to make it suitable for the chemical industry.

This would not only increase the demand for natural resources, but also reinstate bioresources as primary strategic assets for international industry and trade. As with petroleum, biomass is not equally distributed, and thus likely to become a major cause of national rivalry. The potential for major economical shifts, driven by societal grand challenges, increases the urgency for harmonising transnational bioeconomy policies.

Should the bioeconomy turn out to be incapable of providing sufficient quantities of biomass or only with unacceptable trade-offs for other sustainability goals such as food security and biodiversity, then it needs to be supplemented by extensive carbon recycling, artificial photosynthesis and direct air capture or even continued use of fossil resources combined with CCS (carbon capture and storage). This again argues for coherent policies. We therefore subscribe to the recent proposal for expanding the bioeconomy to include all aspects of carbon management, that is the need for an international carbon strategy and policy framework (Carus, 2018).

Concluding remarks

For politicians, the fundamental justification for public intervention in the bioeconomy is increased sustainability. However, even with the best intentions to foster sustainability and resilience, it is entirely foreseeable that the increasing use of biomass for food, materials and chemicals, could lead to over-exploitation of natural resources and undesired consequences such as increased illegal logging, soil degradation, groundwater depletion, decreased biodiversity and international disputes.

Hence, it is of vital importance that bioeconomy policies have the desired outcome and effects. Consistent with transition theory, the policy discussion above

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underscores the importance of systems thinking, but also points to the need for experimentation. As a toolbox for transition management, we have provided a general policy matrix, attempting to incorporate the temporal aspects of value chain maturation (Fig 1) that can be generalised across many renewable carbon value chains (Fig 2).

A further aspect of managing the bioeconomy transition is credible criteria for those overarching sustainability goals that form a common core of the different narratives. Demand-side policies are particularly dependent on internationally agreed criteria in order to mitigate expected national rivalry. We would encourage increased efforts in policy harmonisation related to sustainability criteria and corresponding best practice methodologies to enable measuring of progress towards increased sustainability.

Disclaimer

The views expressed are those of the authors and not necessarily those of Innovation Norway or the OECD (or the governments of OECD member countries).

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