Towards a sustainable innovation system for the German wood-based bioeconomy: Implications for policy design

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Abstract

In recent years, the EU and several of its member states have adopted strategies in support of a renewable resource-based bioeconomy. It is promoted as a promising means of making economic processes and products more sustainable, with expected contributions to a range of policy aims. However, by increasing the demand for bio-based resources, bioeconomy concepts also impose additional pressures on ecosystems. In limiting these pressures, innovations regarding the use of biogenic and non-biogenic renewable resources play an important role. A well-developed innovation system for the bioeconomy must enable immature renewable resource-based technologies to progress down the learning curve, to eventually reach competitiveness with fossil resource substitutes; second, innovation efforts need to be steered towards bioeconomy pathways with favourable environmental characteristics; third, innovations need to be socially acceptable. Focussing on the case of the German wood-based bioeconomy, this contribution examines the role that policies can play in shaping such an innovation system. First, we review what policy contributions are considered as key for strengthening transition-oriented innovation systems in the innovation economics and innovation systems literature. We then apply these insights to the analysis of the case study's innovation system, to identify systemic weaknesses and discuss policy implications. Notably, the transition towards a bioeconomy is characterised by a high degree of uncertainty and complexity, making the design of demand-pull policies particularly challenging. We conclude with policy recommendations for strengthening a sustainability-oriented innovation system for the German wood-based bioeconomy.

Keywords: Bioeconomy; Germany; innovation systems; path transition; policy; wood

1 Introduction

In recent years, the promotion of a renewable resource-based bioeconomy has garnered much political support, both within the European Union and internationally (EC, 2012; OECD, 2009; see Staffas et al., 2013 for an overview). The bioeconomy is expected to contribute to diverse policy aims such as climate change mitigation, environmental protection, energy security, technological progress, growth, employment, and rural value creation (ibid.). However, an increasing demand for bio-based renewable resources also implies additional pressures on ecosystems such as forests and agricultural land, potentially beyond sustainable planetary boundaries (Ingrao et al., 2016), and gives rise to resource use conflicts.

To contribute to a greater sustainability of economic activities, the bioeconomy concept has to deliver more than a mere substitution of fossil resources for bio-based ones. Rather, it needs to encompass a wider path transition from the current, fossil resource-dominated “throughput economy” towards a circular flow economy based on biogenic and non-biogenic renewable resources, with sustainability as a core principle (cf. Albrecht et al., 2012; Staffas et al., 2013; Pannicke et al., 2015). In this line, this Special Volume emphasises the need for envisioning, designing, testing and implementing the bioeconomy transition “to ensure sustainable production, distribution and consumption of biomass for food, feed, fibre, energy and chemical feedstock to manufacture products, currently made from fossil energy sources” (Ingrao et al., 2016, p. 5).

In ensuring the sustainability of a bioeconomy transition, innovation plays an important role (Carus et al., 2014a; German Bioeconomy Council, 2010; Hellsmark et al., 2016a; Van Lancker et al., 2016). To become economically sustainable, immature renewable resource-based technologies – e.g. for the production of innovative bio-materials or bio-chemicals – have to progress down the learning curve, to eventually reach competitiveness with fossil resource-based options (given fair competitive framework conditions). For ensuring environmental sustainability, innovations which decrease impacts of renewable resource use on ecosystems are of central importance. The implementation of a circular flow economy requires novel technological, organisational and product solutions, e.g. with regard to cascading use concepts, to improve resource efficiency and close material flows (Carus et al., 2014a; German Bioeconomy Council, 2010; Ghisellini et al., 2016). This necessitates innovations on the supply side of technologies and products, but also adjustments on the user side, e.g. with regard to consumption and waste generation patterns.

This raises the question, under what conditions innovations may emerge and thrive which are conducive to a path transition towards a sustainable bioeconomy. In the absence of policy interventions, technology and product markets are unlikely to produce adequate incentives, because environmental externalities (Lahl, 2014) interact with externalities associated with knowledge production and learning which prevent investors from appropriating the whole benefits of investments in innovation (Fischer and Newell, 2008; Jaffe et al., 2005). Moreover, incumbent fossil resource-based technologies benefit from past learning effects, increasing returns and network externalities, all of which interact with the specialised nature of investments to create a technological path dependency (Arthur, 1989). This is reinforced by a co-evolutionary development of fossil resource-based infrastructures, interdependent industries, consumption patterns, and private and public institutions, resulting in a "carbon lock-in" which can be difficult to overcome (Unruh, 2000).

For designing appropriate policies, the innovation economics and innovation systems literature offers important insights. The latter in particular emphasises that a comprehensive and well-coordinated policy mix is required to support a well-developed innovation system, which is in turn supportive of a socio-technical path change (Edquist, 2001; Foxon et al., 2005; Gallagher et al., 2012; Borrás and Edquist, 2013). To date, research on the relationship between innovation systems, sustainability transitions and policies shows a focus on energy system transitions (e.g. Gallagher et al., 2012; Foxon et al., 2005; Jacobsson and Bergek, 2004; Markard et al., 2012). The purpose of this paper is to review literature findings on the role of policies in strengthening transition-oriented innovation systems, and apply these to develop recommendations for bioeconomy policy design. Given the wide scope of the bioeconomy concept and the context-dependency of policy recommendations, we focus on a case study of the German wood-based bioeconomy, which constitutes a subsystem of the overall bioeconomy. In recent years, interest in wood-based bioeconomy production pathways has grown, because unlike with energy crops, they do not directly compete with food production (Ollikainen, 2014; Carus and Dammer, 2013). The German case study is of interest because the government has published several strategies and action plans supporting the bioeconomy (e.g. BMEL, 2014; BMBF, 2011; BMELV, 2009); however, the lock-in into fossil resources is still quite pronounced in the material sectors, even as the energy transition is progressing (cf. Zinke et al., 2016). While there are countries where wood-based bioeconomy applications are already more established – e.g. Scandinavian countries with regard to wood-based construction (Schauerte, 2010; Hurmekoski, 2016) and bio-based chemicals (Piotrowski et al., 2016) –, the German case can provide interesting insights regarding the design of policies to overcome this lock-in.

Section 2 provides a brief introduction to the concept of "innovation systems" and discusses its applicability to the bioeconomy context. Section 3 conducts a literature review of recommendations regarding the role policies should play in supporting innovation systems, and discusses central challenges of policy design. Section 4 transfers insights to a case study analysis of the German wood-based bioeconomy, to identify policy-related systemic weaknesses and develop policy recommendations. Section 5 concludes with an outlook on the role of policies in shaping the wider bioeconomy innovation system.

2 Applying the Innovation Systems Approach to the Bioeconomy Transition

2.1 Innovation Systems and Sustainability Transitions

For formulating policy recommendations, the innovation systems perspective has grown in influence in recent years (Steinmueller, 2010; Weber and Rohracher, 2012). On a general level, a system of innovation can be defined as "all important economic, social, political, organizational, and other factors that influence the development, diffusion, and use of innovations" (Edquist, 1997/2005, p. 14). "Innovation" is understood broadly here, and can encompass technological or organisational process innovations, as well as product innovations related to goods and services (Edquist, 1997/2005). Also, it encompasses all three stages of Schumpeter's "trilogy" of invention (the generation of new ideas), innovation (the development of new ideas into processes and products) and diffusion (spread of new processes and products across potential markets) (Stoneman, 1995). As a research field, the innovation systems approach provides a heuristic for integrating insights from various theories which seek to understand processes of innovation and technological change (Hekkert et al., 2007; Edquist, 1997/2005). The approach is rooted in institutional theory and institutional economics, in that formal (e.g. legal framework) and informal (e.g. customs, norms) institutions as the "rules of the game" (North, 1990) play a central role in shaping the incentives that actors face (Edquist, 1997/2005). Besides institutions, actors (e.g. firms, universities, governmental and non-governmental organisations, intermediaries), networks between actors, and different types of infrastructure (i.e. physical, financial, knowledge-related) form central structural elements of innovation systems (Carlsson and Stankiewicz, 1991; Wieczorek and Hekkert, 2012; Markard et al., 2015).

For studying particular technology fields, where relevant elements of the innovation system may transcend national, regional and sectoral boundaries, the technological innovation systems (TIS) approach provides an appropriate analytical framework (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Markard and Truffer, 2008). For the bioeconomy context, applications of the framework which focus on the contribution of TIS to socio-technical transitions towards greater sustainability are of particular interest (e.g. Jacobsson and Bergek, 2011; Markard et al., 2012; for the example of the energy transition, see e.g. Jacobsson and Bergek, 2004; Gallagher et al., 2012; Negro et al., 2012). In this paper, we use the term "sustainable innovation system" to indicate that bioeconomy TIS should contribute to such a transition, building on Foxon and Pearson (2008)'s definition of "sustainable innovation" as "innovation towards more sustainable technological and institutional systems and processes" (p. S148). At the same time, the transition perspective implies that the interaction of TIS and incumbent socio-technical regimes has to be taken into account (Markard and Truffer, 2008; Weber and Rohracher, 2012; Markard et al., 2015; Kivimaa and Kern, 2016). Regimes are stabilised by a set of established practices, routines and rules (Bosman et al., 2014; Geels, 2002), and often defined around societal needs, such as energy, mobility or food (Weber and Rohracher, 2012). Over time, the competition and complementary interaction of technological innovation systems may lead to change at the regime level (cf. Hekkert et al., 2007; Markard and Truffer, 2008).

However, within individual TIS as well as in the interaction between multiple TIS, problems can arise which hinder the development of sustainable innovation systems. The "functions of innovation systems" approach provides a basis for identifying such problems (see Hekkert et al., 2007; Bergek et al., 2008a; Hekkert and Negro, 2009). Here, the focus is on analysing how well a number of generic processes or functions which contribute to an innovation system's overall function (i.e. developing, diffusing and using innovation) are fulfilled. Meta-studies (Hekkert et al., 2007; Bergek et al., 2008a) identify the following functions as central:

- Entrepreneurial activities
- Knowledge development
- Knowledge diffusion through networks
- Guidance of search processes
- Market formation
- Resource mobilisation
- Creation of legitimacy

Furthermore, Bergek et al. (2008a, 2008b) highlight the importance of positive externalities that flow between complementary TIS (e.g. knowledge or legitimacy spillovers). If the development of one or several functions is blocked, systemic weaknesses may arise; the relevance of individual functions depends on the phase of a TIS' development as well as on interactions between functions (Hekkert et al., 2007; Bergek et al., 2008a). Causes of systemic weaknesses can be related to characteristics of a TIS' structural elements which influence how functions are performed, but they can also be exogenous to the TIS, as in the case of factors affecting the stability of relevant incumbent socio-technical regimes (Bergek et al., 2008a; Jacobsson and Bergek, 2011). For policy recommendations, an important question is therefore how the functions of sustainable innovation systems can be strengthened by addressing the causes of systemic weaknesses (also termed blocking mechanisms, see Bergek et al., 2008a; Jacobsson and Bergek, 2011).

2.2 *Application of the TIS Framework to the Bioeconomy Context*

In delineating a relevant innovation system for the bioeconomy, the diffuse nature of the "bioeconomy" concept is problematic – its definition is unclear and still under discussion (e.g. Staffas et al., 2013). The European Commission (EC, 2012, p. 9) understands bioeconomy as the knowledge-based "production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy". Other definitions emphasise the importance of services, including ecosystem services (Näyhä et al., 2015). The EC's product-centred definition, which we apply in this paper, already indicates the breadth of the bioeconomy concept – it encompasses a wide range of technologies and products with transregional value chains, which span and often integrate sectors such as agriculture, forestry, fisheries, food production, energy, biotechnology, chemical and pharmaceutical industries, or textile and paper production (German Bioeconomy Council, 2010). Moreover, relevant technologies and products are located at different stages of the innovation process. On the one hand, the innovation system has to encompass renewable resource-based products and processes in the diffusion stage, e.g. the use of wood as a building material (Wang et al., 2014) or wood-based heating applications (Thomson and Liddell, 2015). These may be based on comparatively mature technologies, but diffusion and associated economies of scale, incremental innovations and learning effects can be lower than socially desirable because competition with fossil resource-based incumbent technologies is distorted by insufficiently internalised externalities and path dependencies. On the other hand, the system also has to include technologies in invention and innovation stages, such as the bio-based production of chemicals, materials and energy in biorefineries (Cherubini, 2010) – some of these technologies may yield substitutes for fossil resource-based processes and products, while others may lead to new products.

As with any innovation system, the appropriate delineation of a bioeconomy TIS depends on the specific aspect of the bioeconomy that one wants to study (cf. Carlsson et al., 2002). However, there is a strong interdependency of established and innovative bioeconomy pathways, in that many of them compete for the same biomass and land resources. Also, innovative pathways with very different end-use applications may compete for the same financial resources, particularly in the form of public R&D support, or human capital. This strongly argues for a system delineation that takes interactions between technologies into account. At the same time, the role of incumbent regimes and associated technologies needs to be included in the analysis, given the relevance of path dependencies and other market failures which distort competition in their favour. Importantly, this approach allows for an analysis of institutions which enact selective pressure across various TIS, or support TIS indirectly by promoting a phase-out of the dominant socio-technical regime. Reversely, it is possible to study how actors of different TIS and dominant regimes interact to influence institutional change. **Figure 1** undertakes an exemplary application to the bioeconomy context. Here, the focus is on the two bioeconomy TIS bio-based chemicals and wood-based building, which may compete for resources such as wood or R&D funding, but also show complementarities (e.g. use of bio-based varnishes and glues in wood-based building materials). Also, a cascading use of biomass resources between TIS is possible, e.g. by using waste and residuals from wood-based building in biorefinery processes (Lesar et al., 2016). Further complementarities and competitions arise with bioenergy-related TIS. Moreover, the focal TIS interact with established materials, chemicals and energy provision regimes which are to date dominated by fossil resource-based technologies.

3 Review of Key Policy Contributions towards Strengthening Transition-oriented Innovation Systems

In the TIS perspective, systemic weaknesses act as the rationale for policy interventions (Hekkert et al., 2007, see 2.1). If multiple problems relating to actors, institutions (including markets), networks and infrastructures interact, a coordinated mix of policy instruments is required to support the innovation system's functions (e.g. Lehmann, 2012; Wieczorek and Hekkert, 2012; Rogge and Reichardt, 2016; Reichardt et al., 2016). In a policy mix, interactions between instruments are of central importance – instruments may have synergies, but also block and counteract each other (ibid.). Besides the consistency of instruments, policy strategies and aims, policy coherence, credibility and comprehensiveness represent characteristics which affect the performance of policy mixes (Rogge and Reichardt, 2016; Howlett and Rayner, 2007).

For formulating policy recommendations, it is moreover important to acknowledge the path dependence of institutional change and internal dynamics of policy processes (North, 1990; Howlett and Rayner, 2007). Rather than attempting to identify optimal states, this implies an evolutionary approach which starts from the existing policy mix and compares feasible alternatives for its further development (cf. Edquist, 2001).

The following section briefly reviews the different functions that need to work in an innovation system, and the role of policies in strengthening these functions (and, respectively, the structural elements that perform them). The focus is on identifying what avenues of action are considered as key in the literature, and reviewing general recommendations regarding the choice and design of policy mix elements. While some examples of specific instruments are given, providing a comprehensive inventory of instrument options is not the aim of the section, as concrete instrument choices will be strongly context-dependent (for more extensive overviews of instrument examples, see Wieczorek and Hekkert, 2012; Rogge and Reichardt, 2016). Tab. 1 summarises the key policy contributions identified for each function.

3.1 Entrepreneurial Activities

By undertaking risky experiments, entrepreneurs play an important role in reducing the many uncertainties involved with new technologies and their application (Hekkert et al., 2007; Bergek et al., 2008a). Given that payoffs of investments in technology development are often distant and risks are high, incentives for sustainability-enhancing entrepreneurial experiments depend crucially on the long-term stability and credibility of policy incentives (Gallagher et al., 2012; Nemet, 2010; Bosetti and Victor, 2011; Palgan and McCormick, 2016). But also general institutional and infrastructural framework conditions such as the existence of an entrepreneurial culture (Rossberger and Krause, 2013) or access to risk capital are important. Policies play a vital role in fostering an environment that is conducive to entrepreneurship – examples are the protection of commercial freedom and property rights (including intellectual property), capital market policies or supportive labour, taxation and competition policies (Minniti, 2008).

3.2 Knowledge Development

This function applies to different types of knowledge, e.g. scientific, technological, market or logistical knowledge, and sources of knowledge development, e.g. learning by doing or learning by searching (Hekkert et al., 2007; Bergek et al., 2008a). Public organisations such as research institutes and universities support knowledge development as well as knowledge diffusion (Jaffe, 1989; Mansfield and Lee, 1996). As a technology-push policy, public R&D support is crucial, given the high risks of investments in knowledge development, but also the difficulties that private firms face when attempting to appropriate the returns of R&D investments (Popp et al., 2010; Senker, 1996). Also, innovation policy can support the transfer of basic knowledge to different technological and societal applications (Popp et al., 2010), or attempt to stimulate learning curve effects by supporting diffusion processes (Jaffe et al., 2005). However, cost reductions and the success of innovations are never guaranteed, and policy makers should be prepared to accept failures (Gallagher et al., 2012). Especially in the presence of lock-in effects, policies have a role to play in incentivising experimentation and variety (Gallagher et al., 2012), to encourage the development of knowledge even if it is not compatible with the dominant socio-technical regime. At the same time, if policies are volatile and clear signals for a guidance of search processes are missing, this can lead to an accelerated depreciation and loss of knowledge, because avenues of search are abandoned when incentives change (Gallagher et al., 2012; Åstrand and Neij, 2006). Among institutional framework conditions, intellectual property rights are vital in setting incentives for knowledge development, although trade-offs with knowledge diffusion may arise (Popp et al., 2010; Foxon et al., 2005).

3.3 Knowledge Diffusion through Networks

In facilitating the exchange of information, networks of various actors (including researchers, producers and consumers) play a crucial role (Hekkert et al., 2007; Gallagher et al., 2012; Carlsson and Stankiewicz, 1991). They support the diffusion of R&D knowledge, but also knowledge from learning by doing, thereby reducing uncertainty about new technologies for consumers as well as companies (Popp et al., 2010). Policy makers can support feedback processes in networks; examples are government-funded test centres or publicly supported clusters (Gallagher et al., 2012). Clusters in particular are seen as drivers of innovation by creating innovative milieus and supporting “knowledge regions” (Audretsch and Feldman, 1996). Moreover, support for pilot and demonstration plants (in the form of R&D and investment support, but also deployment support) can stimulate knowledge diffusion and network formation processes (Hellsmark et al., 2016b).

3.4 Guidance of Search Processes

In the context of a transition towards greater sustainability, policies play a particularly important role in guiding the direction of technical and social innovations, to break the lock-in into dominant socio-technical regimes (Markard et al., 2012; Alkemade et al., 2011; Weber, 2005). Crucially, guidance of search processes is not about picking winners and replacing the market outcome by policy decisions (Gallagher et al., 2012). Indeed, the theory of economic policy warns against overestimating the central steering knowledge of policy makers, and emphasises that room should be provided for decentralised experimentation and the use of dispersed knowledge (Hayek, 1945/2005; Wegner, 1996). In effect, it is not possible to foresee the outcome of processes of innovation and socio-technological change, but their direction can be influenced by the design of framework conditions (Hayek, 1968/2002). Policies therefore have the task of creating collective expectations which reduce uncertainty for investors and entrepreneurs, and implementing a selection environment which aligns decentralised technology choices and search processes with societal aims (Gallagher et al., 2012; Bergek et al., 2008a; Hekkert et al., 2007; Lente, 1993). In achieving this, the credibility and stability of transition policies is of central importance: frequent and rapid shifts of policies would make actors disinclined to undertake investments whose payoff depends on the realisation of a path transition (Eucken, 1952/1990; Foxon et al., 2005; Hekkert and Negro, 2009; Bosetti and Victor, 2011). At the same time, especially in policy contexts characterised by high uncertainty and complexity, maintaining flexibility to adjust policies and incorporate learning is an important requirement (Gallagher et al., 2012; Jacobsson and Bergek, 2004). Balancing policy stability and adaptability therefore becomes a central challenge of transition policy design. An example for such a balancing attempt is the German Renewable Energy Sources Act’s approach to protect operative renewable energy plants from changes such as remuneration cuts (cf. Purkus 2016, pp. 322f.). To keep costs of steering errors in check, regular adjustments of support conditions for new plants are required. This translates into uncertainty for project and technology developers, but once plants are operational, planning security is high.

3.5 Market Formation

Depending on the state of the innovation system, different phases of market formation may prove relevant. Temporary niche markets act as protected learning spaces, to allow for knowledge development and diffusion, and the formation of expectations through success stories (Hekkert et al., 2007; Schot et al., 1994; Kemp et al., 1998). Eventually, an upscaling to bridging markets is necessary to allow for economies of scale to develop (Gallagher et al., 2012). A transition to commercial maturity and mass markets, finally, may take decades (Bergek et al., 2008a). In each stage of market formation, policies can play a role in supporting market demand for technologies that are considered beneficial from a societal perspective (Gallagher et al., 2012; Hekkert et al., 2007), or discouraging the use of, for instance, environmentally harmful technologies (Wegner, 1996). Examples of niche support policies are direct demand-pull measures for selected technologies, such as public procurement (Edquist and Zabala-Iturriagagoitiaa, 2012) or small-scale deployment support. On a larger scale, technology-specific deployment support can also be employed to create bridging markets, as demonstrated by renewable energy support policies in some EU member states (Jacobsson and Bergek, 2011; see Strunz et al., 2015 for an overview). Moreover, market formation (including eventual mass markets) is influenced by indirect demand-pull measures which discourage the use of substitute products and processes. Environmental taxes or permit schemes which increase the costs of fossil resource use are examples, but also command and control measures aimed at phasing out certain technologies (Kivimaa and Kern, 2016). Simultaneously, policies interact with consumer demand and private governance initiatives in support of niche markets, such as voluntary certification schemes or technical standardisation efforts (Bergek et al., 2008a; Gallagher et al., 2012). Apart from demand-pull policies, consumer demand can be affected by awareness rising and other information diffusion policies which educate potential adopters about potential benefits of innovative products (Steinmueller, 2010).

3.6 Resource Mobilisation

This function refers to the mobilisation of diverse resources which serve as inputs to an innovation system's activities, such as financial capital, human capital, and complementary assets (e.g. complementary infrastructures, products or services) (Bergek et al., 2008a; Hekkert et al., 2007). For bioeconomy innovation systems in particular, it is of high relevance whether a sufficient supply of biomass can be mobilised (cf. Hekkert and Negro, 2009). Along all these dimensions, policies can attempt to mitigate bottlenecks and reduce the costs of inputs required in innovation processes (Steinmueller, 2010). Besides public R&D

support, relevant measures include education and training policies aimed at enhancing the supply of skilled workers, trade policies facilitating the import of complementary assets, or policies supporting access to capital in financial markets, where innovative projects which are not part of the dominant socio-technical regime may be disadvantaged due to perceived higher risks (cf. Steinmueller, 2010; Stoneman and Battisti, 2010; Gallagher et al., 2012). Furthermore, the allocation of resources among competing TIS is influenced by demand-pull policy measures in support of selected technologies – this emphasises the importance of coordinating policy measures across TIS.

3.7 Creation of Legitimacy

If a path transition is to overcome vested interests in incumbent socio-technical regimes, the legitimacy of technologies which form part of the new regime is of the utmost importance (Hekkert et al., 2007; Hekkert and Negro, 2009; Bergek et al., 2008b; Markard et al., 2016). Legitimacy refers to social acceptance, but also to how well technologies and their applications comply with relevant institutions (e.g. regulations, technical standards, social customs) (Bergek et al., 2008b). In effect, legitimacy plays an important role in functions such as market formation, resource mobilisation, or the forming of shared expectations which guide search processes (Bergek et al., 2008a). In creating legitimacy, advocacy coalitions play a crucial rule (Jacobsson and Lauber, 2006; Sabatier, 1988). Acting as lobbyists for institutional change in favour of innovative TIS, they counteract stabilising influences by incumbents and may create the political dynamics necessary to change the "rules of the game" and initiate a path change (cf. North, 1990). Policy makers can potentially act as mediators in social discourses and promote a debate about potential benefits and risks of new technologies (Weber, 2005), e.g. by organising stakeholder consultations. Furthermore, political entrepreneurs are required who are willing to interact with advocacy coalitions and offer transition-oriented policies. Specifically, regulatory legitimation can be created by adapting institutions to the needs of innovative technologies (Markard et al., 2016).

4 Case Study of the Innovation System for the German Wood-based Bioeconomy

In the following, the TIS framework outlined in Section 2 and insights regarding the role of policies in supporting a transition-oriented TIS (Section 3) are applied to the case of the German wood-based bioeconomy. The focus is on the question of how the performance, in terms of strengthening TIS functions, of the case study's policy mix could be improved. To do this, we discuss where the key policy contributions summarised in Table 1 are not fulfilled by the existing policy mix, contributing to systemic weaknesses (4.3). Based on this, we discuss where changes in the policy mix could resolve such weaknesses (4.4). To begin with, we briefly introduce the case study's context (4.1), and discuss policy-related systemic strengths (4.2). As the aim is to derive policy recommendations for the case study, however, the focus will be on the discussion of systemic weaknesses and options for overcoming them. Moreover, we focus on strengths and weaknesses that result from the current policy mix, rather than assessing the impact of all TIS elements (including actors, networks, infrastructures, informal institutions) in detail. For a more general assessment of innovation framework conditions for the wider German bioeconomy, see Zinke et al. (2016).

The case study was undertaken as part of the accompanying research to the BioEconomy Cluster supported by the German Federal Ministry of Education and Research. It is based on a review of scientific literature, policy and legal documents and publications by industry associations and NGOs, as well as discussions with cluster representatives and further stakeholders in workshops and cluster meetings. As part of the research project, we conducted an in-depth study of legal framework conditions for the wood-based bioeconomy in Germany (Ludwig et al., 2014), a scenario analysis (Hagemann et al., 2016) and a political economy analysis of bioeconomy policy making (Pannicke et al., 2015), generating insights that the TIS assessment can draw upon.

4.1 Status Quo of the German Wood-based Bioeconomy

The wood-based bioeconomy focusses on the material and energetic utilisation of lignin-containing plant parts (Ollikainen, 2014). These can stem from forests (e.g. round timber, pulpwood, forest residues), short rotation coppices (SRC) and landscape residues, but also from recycled wood, wood processing waste and by-products. In 2013, the economic sector "forestry and wood" generated a turnover of 177 billion € and employed ca. 1.1 million people, contributing 3.1% to the total turnover of the German economy and 2.9% to total employment (Becher, 2015). With that, it makes an important contribution to the wider bioeconomy in Germany, where biological resource use so far is dominated by food and wood product groups (Efken et al., 2016). Over the last two decades, the material and energetic use of wood has doubled; in 2010, it amounted to 135.4 million m^3, with energetic uses slightly surpassing material uses for the first time (Mantau, 2012). Energetic wood uses are dominated by heating applications, which can already be cost competitive to fossil fuel-based alternatives, followed by combustion in electricity and cogeneration plants (Mantau, 2012; FNR, 2014, pp. 767ff.).

Among material wood uses, well-established conventional applications dominate, e.g. saw mill products, timber and wood composite products, paper and pulp products (Bolte et al., 2016; FNR, 2014, p. 56). The supply and demand for innovative wood-based applications still remains low, although niche markets exist e.g. for structural wood applications in car manufacturing or the building sector, and the use of wood in biorefineries is currently tested in pilot and demonstration plants (Bolte et al., 2016; FNR, 2014; Zinke et al., 2016). Products are not always purely bio-based, but wood may be used as an admixture e.g. in wood-plastic composites and concrete. In the German construction sector, the average share of wood-based construction amounts to ca. 16%, compared to over 30% in Austria and Switzerland and over 80% in some Scandinavian countries (WBAE and WBW, 2016, p. 298). In the chemical industry, the share of renewable resources in organic raw material use increased slightly to 13% in recent years (FNR, 2014, p. 131; German Bioeconomy Council, 2015a). As yet, there is no comprehensive shift away from fossil resource use, with barriers to a more comprehensive use of renewable resources differing by sector. In the construction sector, examples for barriers are the cost competitiveness with materials such as steel and cement, the alignment of regulatory norms and established building practices with conventional construction materials, and high risk adversity concerning the use of innovative materials (Zinke et al., 2016; Hurmekoski, 2016). In the chemical industry, there are strong infrastructural path dependencies, and current price trends for oil and gas limit the interest in transitioning to renewable alternatives (German Bioeconomy Council, 2015a).

Moreover, for market formation, communicating the advantages of bio-based products is challenging, because product characteristics are similar to established fossil resource-based alternatives, but often costs are higher (Vandermeulen et al., 2012). The use of voluntary eco-labels or environmental product declarations provides starting points for niche markets; research indicates that bio-based products can in principle command "green" price premiums, but willingness to pay a premium varies significantly between product types, and tends to be lower for end consumers than for companies purchasing bio-based intermediate products for strategic reasons (Carus et al., 2014b). Also, the trust of consumers in sustainability advantages of bio-based products is an issue (Asveld et al., 2015; Meeusen et al., 2015). For instance, wood imports for co-combustion in the UK have sparked a contentious debate about sustainability risks (e.g. Coath and Pape, 2011).

As for political support, the German federal government has adopted dedicated research and policy strategies which promote bioeconomy applications, including wood-based ones, as alternatives to fossil resource use (BMEL, 2014; BMBF, 2011). Moreover, a number of sectoral strategies and research programmes support bioeconomy developments (see Hagemann et al., 2016 for an overview), and several "Länder" (federal states) have published bioeconomy strategies of their own. Relevant policy instruments which support innovation systems for energetic and material wood-based bioeconomy technologies are summarised in **Table 2**, alongside relevant private or public-private governance structures (e.g. voluntary norms and standards). They will be discussed in the following sections, alongside the assessment of their impacts on TIS functions and elements. Generally, instruments can be distinguished according to whether they strengthen the bioeconomy's resource base, promote bio-based processes and products, or aim to reduce fossil resource use. Also, the focus may be on conventional wood resources (e.g. forests) and comparatively well-established applications (e.g. construction timber, wood pellets), or on innovative wood resources (e.g. SRC) and applications (e.g. chemicals from gasification). Legal framework conditions such as forestry or agricultural law do not directly support the wood-based bioeconomy's innovation systems, but by providing sustainability safeguards they contribute to the guidance of search processes.

4.2 Evidence for Policy-related Systemic Strengths

So far, policy measures promoting the wood-based bioeconomy show a strong focus on support for R&D, pilot and demonstration projects, networks and knowledge exchange (see Tab. 2, cf. also Zinke et al., 2016; Deutscher Bundestag, 2016). The "National Research Strategy BioEconomy 2030" (BMBF, 2011) has a funding budget of 2.4 billion € for the period 2011-2016 (BMEL, 2014) and is currently being further developed. Among supported projects are a number of lignocellulose-based biorefinery pilot and demonstration plants, although an upscaling to commercial scales has yet to take place (Federal Government, 2012). As networks, bioeconomy industry clusters are considered to be well developed (Lichtenberg et al., 2015). Examples of publicly supported clusters are the "Forestry and Wood Cluster Bavaria" which focusses on wood value chains and topics such as logistics, timber mobilisation and green building, or the "BioEconomy Cluster", with a focus on innovative material and energetic uses of non-food biomass. Also, several publicly funded universities and research institutes engage in bioeconomy-focused education and research activities, including interdisciplinary knowledge clusters such as the "ScienceCampus Halle – Plant-Based Bioeconomy" or the "Bioeconomy Science Center (BioSC)". On the policy level, knowledge exchange is promoted through the German Bioeconomy Council, a prominent expert panel providing government advice; moreover, an inter-ministerial working group has been established to improve coordination between bioeconomy-relevant policy fields (Deutscher Bundestag, 2016).

These measures strengthen knowledge development and knowledge diffusion functions in particular, but they also contribute to stimulating entrepreneurial activities, resource mobilisation, and potentially legitimacy creation. Moreover, the design of R&D funding programmes influences the direction of search. On a more general level, relevant institutional framework conditions such as intellectual property rights, labour productivity or infrastructure are well developed in Germany (EC, 2014). Encompassing a strong research landscape and an entrepreneurial culture of innovative and often internationally leading small and medium-sized enterprises (SMEs), the national innovation system is assessed as very effective (ibid.). However, the mobilisation of risk capital for innovations is seen as insufficient, caused in part by a lack of tax incentives and design properties of capital market regulation (Zinke et al., 2016).

4.3 Evidence for Policy-related Systemic Weaknesses

To focus our results on systemic weaknesses and identify priority areas of action, we assess where elements and characteristics of the policy mix interact to impair several functions at once. Broadly, three problem areas can be identified which imply that several of the key policy contributions identified in Section 3 are not fulfilled: the lack of (a) a credible, long-term transition policy mix; (b) an effective selection environment; and (c) an advocacy coalition in support of the TIS and comprehensive transition policies.

4.3.1 Lack of a credible, long-term transition policy mix

The literature review in Section 3 has shown the importance of providing credible, long-term policy signals for strengthening the functions of sustainability-oriented TIS (see Tab. 1). On the strategy level, long-term signals exist (see 4.1). Also, ambitious long-term targets for greenhouse gas emission reductions are in place: for 2050, a reduction of 80-95% compared to 1990 levels is envisioned (BMWi and BMU, 2010). To be credible, however, strategic aims need to be implemented by an effective policy mix which not only supports innovative technologies but increases pressure on incumbent ones as well, to promote a regime change (see 3.4 and 3.5). So far, indirect demand-pull instruments mainly focus on the energy sector, whereas the implementation of an effective decarbonisation policy which encompasses material sectors as well is lacking (cf. Rodi et al., 2011 for an overview). The European Emissions Trading System (EU ETS) and energy taxes are major examples of climate policy instruments aimed at increasing the relative prices of fossil resource use in the energy sector. However, the effectiveness of the EU ETS has been limited by low and volatile carbon certificate prices in recent years (Koch et al., 2014). Energy taxes which reflect the GHG emissions associated with energy carriers can provide effective incentives for investments in low carbon options (including bio-based ones, with the Swedish carbon tax as a positive example, see Andersen 2010; Börjesson et al., 2017). However, German energy tax rates are not well aligned with GHG emissions – tax rates for coal are comparatively low, for instance –, and the effectiveness in reducing GHG emissions has been limited (Andersen, 2010; Gawel and Purkus, 2015). In the materials sector, chemicals regulation and waste and recycling law could in principle set incentives for a reduction of fossil resource use (Ludwig et al., 2014). The chemicals regulation REACH promotes the substitution of substances which are harmful for human health or the environment in production processes (Köck, 2014). However, while this may incentivise innovation, it does not imply that bio-based substances are given preference over fossil resource-based ones. The German Waste Management Act's effectiveness in preventing waste and increasing the recycling of used wood is likewise limited, because the bindingness of recycling requirements depends on an assessment of "economic reasonableness", leaving significant scope for interpretation (Ludwig et al., 2014; Herrmann et al., 2012).

Besides indirect demand-pull measures, direct demand-pull instruments are required for supporting market formation (see 3.5); particularly given the weak demand-pull from markets for innovative wood applications (see 4.1). To complement technology-push policies at R&D and demonstration stages, an upscaling of technologies is required to develop economies of scale and learning effects. Especially for comparatively mature TIS, such as wood use in buildings, a successful market formation is critical; but also for emerging TIS, long-term expectations about market formation need to be in place.

However, Table 2 demonstrates that existing direct demand-pull policies focus on energetic wood uses. Especially effective in increasing energetic wood use have been feed-in tariffs and feed-in premiums in the electricity sector; and in the heating sector, mandatory minimum shares for the use of renewables in the heat supply of new buildings, in combination with loans and grants (cf. Purkus, 2016, pp. 221ff.). For material wood applications, small-scale publicly supported niches exist. For instance, the German Energy Saving Ordinance provides incentives to use wood in building construction, whereas procurement law promotes wood use, if wood sources can be verified as sustainable. However, the effectiveness of this measure is limited by the voluntary nature of provisions to include environmental or social aspects in public procurement, an alleged disproportional increase in the complicatedness of tendering processes, as well as information deficits (Ludwig et al., 2014).

In the absence of indirect demand-pull measures, it is extremely doubtable whether the combination of selective support for specific (but mostly energetic) wood uses and strong R&D support will be sufficient to give rise to collective expectations about a path transition. Furthermore, the erratic nature of direct demand-pull policies proves problematic. Examples are German and European biofuels policies and German bioelectricity deployment support under the Renewable Energy Sources Act, which both have been subject to frequent and significant changes in recent years (cf. Purkus, 2016, pp. 221ff.), leading to increased policy uncertainty on the side of market actors. Unclear and shifting political priorities are an important source of policy uncertainty (Purkus, 2016; Uyarra et al., 2016) – in this context, the multitude of (partly conflicting) aims which are commonly associated with the bioeconomy (see Section 1) and the lack of clarity as to their prioritisation prove a serious obstacle to the formation of a stable and consistent policy mix. Policy uncertainty is especially problematic for bioeconomy TIS, whose output is often not new products that meet or create new consumer demands, but innovative substitutes for existing, established fossil resource-based products and processes. Whether there will be a long-term market for bio-based options therefore depends crucially on the existence of a long-term oriented, consistent and consequent policy mix in support of a path transition.

In effect, the lack of effective, direct and indirect demand-pull instruments and the resulting lack of policy credibility directly weaken guidance of search, market formation and entrepreneurial activities functions (see Tab. 1). Indirectly, the lack of reliable, long-term expectations and investment signals also dampens incentives for knowledge development and knowledge diffusion, as well as resource mobilisation. Also, the legitimacy of bioeconomy TIS can be negatively affected, if they are not perceived as part of a wider sustainability transition with necessary changes in production, consumption and waste generation patterns, but as a mere substitution of fossil resources for bio-based ones with uncertain sustainability effects.

4.3.2 Lack of an effective selection environment

Hekkert et al. (2007) highlight the importance of the guidance of search processes function in triggering "virtuous cycles" in TIS development. Changes in the selection environment affect the direction of resource mobilisation, knowledge development and entrepreneurial activities; moreover, especially if path dependencies are present, policies which guide supply- and demand-side search processes can be an important prerequisite for eventual market formation (see 3.4). Here, the case study's policy mix shows a twofold problem: first, there is a lack of guidance to shift innovation efforts away from fossil resource-based technologies and initiate a long-term regime shift (see 4.3.1). Second, there is a lack of guidance to focus innovation efforts within bioeconomy innovation systems on options which are particularly sustainable with regard to environmental or social criteria. This, in turn, may negatively affect the legitimacy of the TIS and consumer trust.

The sustainability of domestic wood supply is safeguarded by the German National Forest Act as well as Federal Forest Acts, which are based on the principle of sustainable forest management and promote multi-functionality of forests. National- and EU-level trade law seek to safeguard timber imports against illegal logging, but ensuring the sustainability of wood imports, which are increasingly seen as necessary to meet future demand in Germany (cf. Mantau, 2012), still remains an issue. Resource streams of "used" wood are subject to waste and recycling law – however, effective incentives for cascade utilisation require a reform of recycling regulation and waste charges (Ludwig et al., 2014).

On the side of demand-pull measures, specific sustainability requirements for wood use are still an exception (see Tab. 2). Primarily, these apply to public procurement, and in principle, to biofuels produced from wood, although associated biomass to liquid technologies are still at the pilot and demonstration stage (Naumann et al., 2014). Impulses for the future introduction of more comprehensive sustainability criteria may come from the European level – in its recent proposal for a revised Renewable Energy Directive, the European Commission suggests an extension of sustainability certification requirements from biofuels and bioliquids to solid and gaseous biomass used in electricity and heating sectors (EC, 2016).

The example of the energy crop debate which in Germany is strongly influenced by sustainability concerns (e.g. WBGU, 2008) shows the importance of safeguarding the sustainability of wood-based supply chains from early on. If demand for energetic and material wood uses were to increase further, the current piecemeal implementation of sustainability requirements and incentives for cascading uses is likely to prove insufficient. Additional problems in the selection environment result from the limited coordination of policy instruments: between comparatively large-scale deployment support for energetic biomass uses and small-scale niche support for material uses (see 4.3.1), resource mobilisation is currently distorted in favour of energetic uses (see also Carus et al., 2015). In effect, search processes do not necessarily focus on achieving the highest environmental benefits with limited resources (e.g. in terms of GHG mitigation), but follow an incentive structure which has grown over time and been shaped strongly by the energy transition context.

4.3.3 Lack of broad advocacy coalitions

Policies promoting the wood-based bioeconomy will only emerge on political markets if they are supported by advocacy coalitions (see 3.7). In creating legitimacy and overcoming resistance by incumbent actors, the heterogeneity of the actors involved in the wood-based bioeconomy proves problematic, because forming consistent advocacy coalitions becomes challenging (cf. Pannicke et al., 2015). Business sector actors alone encompass conventional wood-based industries, consumer goods production, chemical industries and energy production, whereas among primary biomass producers, private and public forestry actors on domestic, EU and international levels and, in the case of SRC, agricultural actors are relevant (FNR, 2014). Also, entrepreneurs include both SMEs entering markets as challengers and larger, incumbent firms seeking diversification. The latter have little incentive to ask for policies which will impose burdens on the incumbent regime (cf. German Bioeconomy Council, 2015a for the example of chemical industries).

Also, compared to renewable energy TIS, there is less of a positively connoted public discourse that advocacy coalitions could form around. In the public but also scientific debate, there are numerous viewpoints as to whether and under what conditions the bioeconomy can contribute towards greater sustainability of economic activities (Pfau et al., 2014). On the European level, an industrial perspective which views the bioeconomy as a potential driver of growth is perceived as dominant, rather than an understanding of the bioeconomy as part of a sustainability transition (Schmid et al., 2012; Ramcilovik-Suominen and Pülzl, 2016). Given the complexity and ambiguity of the issue, environmental interest groups or the green party are less of a "natural ally" for bioeconomy entrepreneurs as was the case for challengers from renewable energy industries.

Besides sustainability concerns, the societal attitude towards technologies with high perceived uncertainties can also become an issue (cf. Wynne, 1983). For crop-based bioeconomy pathways in Germany, the prevalence of a critical attitude towards agricultural applications of genetically modified organisms (Lucht, 2015) proves very relevant. For wood, the use of genetically modified species is also being researched (Verwer et al., 2010).

Given the lack of broad and coherent advocacy coalitions and uncertainty about the social acceptance of bioeconomy technologies, policy makers have little incentive to push for a more comprehensive mix of policies in support of bioeconomy innovation systems and a wider regime transition (Pannicke et al., 2015). The creation of advocacy coalitions and legitimacy therefore becomes a crucial bottleneck in promoting bioeconomy innovation.

4.4 Implications for Policy Design

Policies in support of innovation systems for the German wood-based bioeconomy show clear evidence of what Weber and Rohracher (2012) describe as "transformative failure": strategies, technology-push policies such as R&D and demonstration support, network support as well as selective demand-pull measures are not sufficient to induce a path change, if clear commitments and policies directed at a gradual phase-out of the dominant regime are missing. By applying the literature review-based insights regarding the role of policies in strengthening TIS functions (Section 3) to the case study findings (4.1-4.3), the following key policy recommendations for addressing systemic weaknesses can be identified (see **Figure 2**).

4.4.1 Strategic commitment to a path transition as prerequisite for credible long-term policies

A central policy recommendation is to strengthen strategic commitment to a path transition away from the fossil resource-based throughput economy, as a basis for creating stable collective expectations. On the level of policy instruments, maintaining a certain flexibility to adapt to changing circumstances and new information is unavoidable. To reduce uncertainty for market actors, it is therefore all the more important to establish credible commitment on the level of strategies. Promoting an alignment of investments with political strategies requires a prioritisation of aims, especially if they conflict (e.g. growth rationale vs. environmental protection). A clear hierarchy of aims is also a prerequisite for a consistent policy mix.

In particular, strategies need to place a credible emphasis on sustainability, to guide search processes and create legitimacy. Greater clarity is needed as to what sustainability requirements bioeconomy TIS have to comply with. Moreover, the role of a wider renewable resource base and circular flow economy aspects needs to be further developed, given that a comprehensive regime shift cannot be based on biomass alone. To support a normative "shared vision" of a sustainable bioeconomy, a stronger integration of non-governmental organisations as societal interest groups in strategy building processes would be desirable (cf. BfN and NABU, 2016). By broadening the actor base and contributing to network building, this can potentially act as a systemic measure which strengthens several functions at once (Wieczorek and Hekkert, 2012).

Of course, strategic commitment has to be made credible by the adoption of adequate policy instruments (see 4.3.1) – decarbonisation and resource efficiency are established aims at the strategy level, and would, if consequently implemented, go a long way towards generating demand for bioeconomy technologies.

4.4.2 Consistent policy mix to support technology-push and demand-pull and create selection environment

To implement strategic commitment, a consistent mix of polices is required, encompassing (i) “classical” technology-push instruments, i.e. R&D and demonstration support; (ii) promotion of networks within and across complementary TIS; (iii) information and moral suasion instruments, to improve the transition’s legitimacy; (iv) technology-specific direct demand-pull instruments which create niche markets and experimentation opportunities for innovative technologies; and (v) technology-neutral indirect demand-pull instruments which help destabilise dominant, fossil resource-based regimes (Sandén and Azar, 2005; Jacobsson and Bergek, 2011; Gallagher et al., 2012; Kivimaa and Kern, 2016).

In the case study, technology-push instruments help to create variety at the R&D stage, but there is a need to strengthen instruments which pull innovations into markets and provide a selection environment for fossil resource-based and bio-based production and consumption processes alike. Insights from evolutionary economics and the theory of economic order indicate that a selection environment performs better if it applies pressure on options with undesirable characteristics, rather than enhancing the value of selected options (van den Bergh, 2007; Wegner, 1996). For the German wood-based bioeconomy, central starting points for “devaluating” options (Wegner, 1996) would be strengthening the EU ETS and complementary climate policy instruments for non-ETS energy sectors; extending emissions taxes or permit schemes to emissions-intensive material applications; and adjusting waste and recycling regulations, to increase incentives for circular flow economy concepts. All these measures are examples of an environmental structural policy, which incentivises search and innovation processes along a range of bio-based and non-bio-based options, in contrast to process policy measures which attempt to influence outcomes (cf. Wegner, 1996). In the case of bio-based options, it may be necessary to combine technology-neutral instruments with additional sustainability requirements, to complement the selection environment (e.g. by adopting certification schemes).

However, while important for the creation of long-term expectations, indirect demand-pull measures will mainly be effective in supporting market formation for comparatively mature bioeconomy options, which can compete with other substitution options for fossil resources or technical efficiency improvements. Therefore, there is also a need for technology-specific direct demand-pull instruments, to bring new technologies into the market (Sandén and Azar, 2005; Jacobsson and Bergek, 2011; Gawel et al., 2017). By promoting learning curve effects for a portfolio of technologies, the dynamic costs of the path transition can be reduced compared to a technology-neutral approach which is cost-effective only in a static perspective. Also, technology-specific measures are necessary to address specific characteristics and functional failures of TIS (Jacobsson and Bergek, 2011), reduce technology-dependent risks of investments in innovative technologies, and reflect differences in the external costs and benefits of technologies (Gawel et al., 2017).

This leads to the question what form direct demand-pull instruments should take. In the case study, starting points for small-scale niche support would be improving green public procurement procedures; and strengthening information and labelling initiatives to improve awareness and acceptance for sustainable bio-based products on the side of consumers. Potentially, a stronger inclusion of consumers in networks could also contribute to improving social acceptance and help generating success stories which support collective expectations. Moreover, a closer integration of support for pilot and demonstration plants and demand-sided niche support could improve the economic attractiveness and success chances of demonstration projects, and facilitate the transition to commercial applications (cf. Hellsmark et al. 2016). At this stage, technology-specific niche support should be about variety creation rather than picking winners, but given limited resources, a degree of selection is necessary: to prioritise between technologies, compatibility with a sustainable path transition and a promising environmental balance are important criteria, besides the prospect of future competitiveness.

On the other hand, using large-scale deployment support for specific bioeconomy technologies to establish bridging markets, as practiced with renewable energies in the form of feed-in tariffs or quota requirements, does not seem promising. Major reasons for this lie in the complexity of bioeconomy innovation systems which cover a wide scope of heterogeneous bioeconomy technologies and interact with non-bio-based TIS; the high level of uncertainty not only about future commercial potentials of technologies, but also their environmental impacts, sustainable biomass availability and consumer acceptance; and the existence of many competing uses for wood and other biomass resources. Deployment support, or even fixed targets for certain bio-based materials or chemicals, for instance, would be likely to result in significant allocative distortions and adjustment needs that limit credibility – European and German policy debates about biofuels targets already serve as an example (cf. Purkus, 2016; WBGU, 2008). Moreover, when creating bridging markets with direct-demand pull instruments, costs of errors can be high. The uncertainty associated with impacts and development potentials of bioeconomy technologies reinforces the importance of allowing room for failures and learning, and small-scale niche support can accommodate this better than larger scale deployment support.

For example, in the construction sector, investment subsidies for wood-based buildings would be an option to increase the share of wood construction in Germany (cf. 4.1), similar to existing grants for renewable heating installations (see Tab. 2). However, if implemented on a significant scale, the sizable demand-pull for wood would distort resource competition with other wood-based TIS, and raise as yet unanswered questions about the sustainability of wood supply. Moreover, innovation efforts would be diverted from other options for lowering GHG emissions or reducing mineral resource-based waste in the construction sector. To support learning and upscaling, a more promising approach could be a combination of niche support and indirect-demand pull measures: using sustainably sourced wood in public construction projects could promote learning and skill development, provide impulses for entrepreneurs to specialise on wood-based building, and raise awareness among private project planners (cf. Schauerte, 2010 for examples in Scandinavian countries); while increasing the costs of cement through carbon pricing or the costs of non-cascadable waste through waste and recycling regulation would incentivise search processes for alternative construction options on a broader scale.

Another relevant aspect of policy mix design is the appropriate sequencing of policy measures. Depending on the stage of a TIS' development, different sets of functions prove particularly relevant (Hekkert et al., 2007; Bergek et al., 2008a; Suurs, 2009). For instance, Suurs (2009) distinguishes combinations of functions which support science and technology push, entrepreneurial, system building and market "motors" of sustainable innovation. For wood-based bioeconomy technologies which are comparatively close to commercial maturity, strengthening market formation through demand-pull measures is more of a priority than for technologies which are still at the R&D stage. In case of the latter, a first step could be to build on well-developed knowledge development and diffusion functions with measures which strengthen entrepreneurial activities, such as improving access to risk capital, establishing strategic commitment to a path transition and strengthening networks. As technologies pass to demonstration and diffusion stages, stimulating legitimacy creation and market formation gains in importance, to support system building and eventually market motors. Here, technology-specific niche support instruments may contribute to reducing the political transaction costs of reforming or introducing technology-neutral demand-pull instruments, if they succeed in strengthening advocacy coalitions (McCann, 2013; see 4.4.3). However, a central characteristic of the wood-based bioeconomy is that multiple TIS at different stages of development interact (see 2.2). When introducing demand-pull measures in support of a comparatively established TIS, such as wood-based building, policy makers need to take impacts on TIS at formative stages into account, e.g.

lignocellulose-based biorefinery concepts. For instance, if measures on behalf of the former result in significant price increases for wood resources, this impacts incentives for entrepreneurial activities and search processes in the latter. It is therefore of special importance to coordinate measures which guide search processes across interacting TIS, to promote the search for particularly sustainable and synergistic solutions at different stages of technology development (e.g. in the context of cascading use concepts).

4.4.3 Gradual strengthening of advocacy coalitions, to improve political feasibility of transition policies

The case study of the German wood-based bioeconomy illustrates a difficult problem of political economics – who demands transition policies which impose burdens on incumbent regimes, and associated producers and consumers? The success of energy transition efforts in the German electricity sector has relied heavily on technology-specific direct demand-pull instruments (i.e. feed-in tariffs, later feed-in premiums) to create bridging markets. They enabled technologies to move down the learning curve, while successfully stimulating advocacy coalitions through the creation of new rents, financed collectively by electricity consumers (Jacobsson and Lauber, 2006; Strunz et al., 2016). At the same time, deployment policies met with high voter support. In effect, the energy transition is characterised by a crowding out of "old" technologies by supported new ones, followed by a gradual adjustment of system framework conditions to meet the successful challengers' needs, rather than a "deselection" of fossil resource-based, environmentally harmful options (Gawel et al., 2014). As argued above, the use of deployment support to create bridging markets of any significant scale is a less promising option for bioeconomy technologies. This raises the question how advocacy coalitions can gain the necessary momentum to improve the legitimacy of bioeconomy innovation systems and increase policy demand for a regime change.

Besides enhancing legitimacy through a stronger strategic focus on sustainability, a gradual increase in the effectiveness of existing niche support and indirect demand-pull instruments may provide first steps for strengthening advocacy coalitions (Pannicke et al., 2015). In turn, these may support more comprehensive transition policies. This process is likely to be iterative and requires a long-term perspective. On the plus side, increasing policy stringency gradually allows room for policy learning and adjustments, which is a significant advantage compared to support strategies with greater short-term ambitions (cf. Dewatripont and Roland, 1995; Wei, 1997).

Importantly, advocacy coalitions can only succeed if they include sustainability-oriented consumers who also act as voters. To achieve a mutual reinforcement of policy demand and supply, as in the energy transition case, it is vital to strengthen consumer trust in innovative bioeconomy technologies. For business actors seeking to develop the bioeconomy as an opportunity, it is therefore highly recommendable to integrate sustainability at an early stage of supply chain development, and form coalitions with societal and user interest groups.

5 Outlook: The Role of Policies in Shaping Innovation Systems for a Sustainable Bioeconomy

The literature review and case study analysis both show that policies have an important role to play in supporting functioning bioeconomy innovation systems. Crucially, it is not sufficient to focus on innovation and technology support policies in a narrow sense – rather, these must be embedded in a wider transition strategy, and accompanied by a comprehensive process of institutional change.

In generating concrete bioeconomy policy recommendations, the innovation systems approach proves helpful along two dimensions. First, it helps to structure the rather diffuse concept of a "bioeconomy", and analyse interactions between complementary and competing TIS as well as dominant fossil resource-based regimes. Moreover, it allows for a structured analysis of strengths and weaknesses of specific bioeconomy innovation systems. By applying TIS and innovation economics literature insights to the case of the wood-based bioeconomy in Germany, three key policy recommendations could be derived: (i) bioeconomy strategies require a greater emphasis on sustainability and the need for a path transition; (ii) niche support and indirect demand pull instruments should be strengthened, to complement well-developed support for R&D and demonstration; (iii) existing instruments should be gradually improved to stimulate advocacy coalitions including consumers and voters for more comprehensive transition policies. These findings prove relevant also for other countries seeking to promote the bioeconomy, given that from comparative assessments of national strategies and policies, the implementation of market formation support and sustainability considerations emerge as challenging areas of future policy development (Staffas et al., 2013; De Besi and McCormick, 2015; German Bioeconomy Council, 2015b).

In comparison to TIS research on energy transitions, meanwhile, the bioeconomy context involves even greater degrees of complexity and uncertainty. The wood-based bioeconomy alone illustrates the complex nature of the field with many heterogeneous pathways and value chains, and uncertainties about sustainable wood supply. This makes recommendations for demand-pull policies particularly challenging – not only can there be too little policy support, but the wrong kind of policies can lead to high distortions and costly errors. While technology-specific niche support is indispensable to bring technologies forward, the use of large-scale deployment support for creating bridging markets seems less promising, due to the high risk of steering errors. At the same time, political demand for more stringent indirect demand-pull measures (e.g. improved EU ETS and energy taxes, material climate policy) remains low. For further research, a closer look at the interplay between small-scale niche support and indirect demand-pull measures in supporting bioeconomy TIS functions may prove rewarding, as well as a focus on contributions of networks and public-private intermediaries (e.g. labelling organisations).

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Table 1. Overview of key policy contributions towards strengthening TIS functions

Function	Key policy contributions
Entrepreneurial activities	Create conducive institutional and infrastructural environment
	Provide long term-oriented and credible investment signals (e.g. via guidance of search, and market formation policies)
Knowledge development	Support build-up of knowledge and skill-base
	Reduce risks of private R&D and compensate for positive knowledge and learning externalities
	Support knowledge transfer and learning curve effects
	Incentivise experimentation and variety, to overcome path dependencies in knowledge development
	Provide intellectual property rights protection without overly restricting positive knowledge spillover effects
Knowledge diffusion through networks	Support knowledge exchange and feedback processes
	Support pilot and demonstration plants and formation of associated knowledge networks
Guidance of search processes	Guide direction of technical and social innovations, to overcome the lock-in into dominant socio-technical regimes, while leaving room for decentralised experimentation
	Create reliable collective expectations, to reduce uncertainty for investors and entrepreneurs
	Implement a selection environment which aligns decentralised technology choices and search processes with societal aims
Market formation	Implement and dynamically adapt a policy mix of direct and indirect demand-pull measures, in order to: - support niche, bridging and eventually mass market formation for technologies that are considered beneficial from a societal perspective; - discourage the use of unsustainable technologies.
Resource mobilisation	Mitigate bottlenecks and reduce costs of inputs
	Coordinate demand-pull policy measures to avoid creating policy-induced resource bottlenecks
Creation of legitimacy	Enhance social acceptance of transition-oriented TIS
	Offer transition-oriented policy proposals to strengthen advocacy coalitions in favour of a socio-technical regime change
	Align institutions with requirements of innovative TIS

Table 2. Policy instruments and further institutional framework conditions with major implications for the wood-based bioeconomy in Germany (based on Pannicke et al., 2015)

		Institutions supporting the bioeconomy resource base	**Institutions supporting bio-based processes and products**	**Institutions aimed at reducing fossil resource use**
Focus on conventional wood resources and applications	**Explicit sustainability focus**	- Forestry law - Trade law for imports - Financial support for afforestation (agri-environmental schemes and rural development funds)	- R&D and demonstration support - Support for research networks and clusters - Voluntary eco labels, Environmental Product Declarations - Procurement law	
	No explicit sustainability focus	- Networks of forestry businesses and forest owners	- Energy Saving Ordinance - Incentives for wood use in electricity production (feed-in tariffs/premiums) - Incentives for wood use in heating (minimum renewable energy shares, grants and low interest loans, reduced VAT on firewood)	- EU Emissions Trading System (electricity sector) - Energy taxes (electricity, heating, transport fuels) - Grants and loans for energy efficiency investments - Energy efficiency standards for products and buildings - Energy labelling - Waste and recycling law
Focus on innovative wood resources and applications	**Explicit sustainability focus**	- Agricultural law (for SRC) - R&D support - Financial support for SRC (agri-environmental schemes)	- R&D and demonstration support - Support for research networks and clusters - Incentives for biomass to liquid (biofuels quota, with mandatory sustainability certification)	
	No explicit sustainability focus	- Financial support for SRC (rural development funds) - Incentives for cascades (waste and recycling law)	- Norms and standards (e.g. Bio-based Content) - Incentives for wood gasification for electricity production (feed-in tariffs/ premiums)	- Chemicals regulation (REACH)

Fig. 1. Exemplary bioeconomy innovation systems and interactions with relevant socio-technical regimes (own illustration, based on Markard and Truffer, 2008, p. 612)

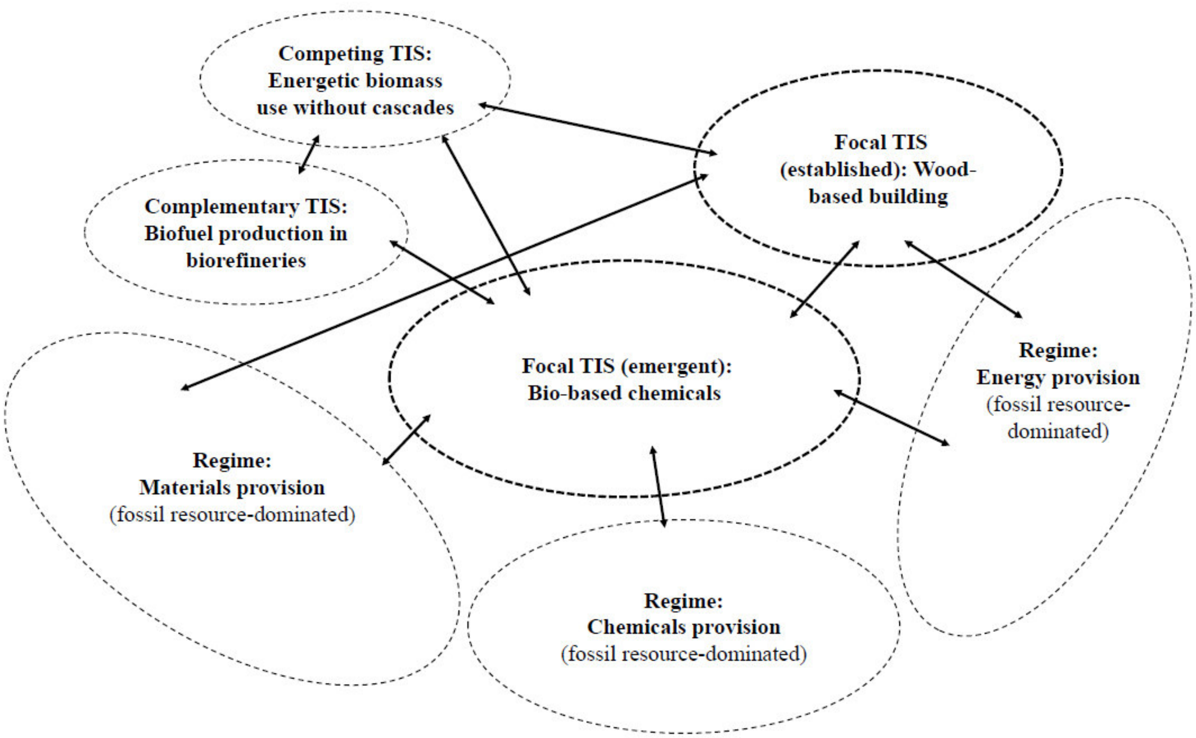

Fig. 2. Overview of policy-related systemic weaknesses and policy implications (own illustration, structure based on Bergek et al., 2008a, p. 422)