Quantifying Directionality and Innovation Output in Sweden's Transition to a Forest-Based Bioeconomy

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The transition to a bioeconomy is high on the agenda for research, industry and policy. Like other sustainability transition, the bioeconomy transition is characterized by contestation over desired outcomes and transition pathways. While shared visions are seen as pivotal in guiding transitions, the bioeconomy discourse is marked by the contention of three competing visions. The Swedish forest-based bioeconomy is well established as a case study in this arena. Yet, knowledge about innovation produced across the entire system is scarce. The use of detailed innovation data from a Swedish literature-based innovation output database, SWINNO, allows to capture the actual innovation output of the Swedish forest-based bioeconomy innovation system. Qualitative coding of the source material links innovation from 1970 to 2021 with visions of a bioresource, biotechnology and / or bioecology bioeconomy. Findings reveal a decrease in the innovation output of the forest-based bioeconomy relative to Sweden's overall commercialized innovation. Notably, innovations associated with a bioresource vision surged during the energy crises of the 1970s, pre-dating their formalization in strategy documents, suggesting a significant role for path-dependency in shaping shared visions. Concurrently, the presence of innovations aligning with multiple visions indicates an open opportunity space for future development across various directions. This research underscores the dynamic interplay between historical contexts, shared visions, and innovation trajectories within the bioeconomy transition, and questions the extent to which visions can provide novel directionality to transitions.

1 Introduction

At the heart of sustainability transitions lies the question how societal functions can be fulfilled within ecological boundaries (Köhler et al., 2019). Societal functions are provided through socio-technical systems, which consist of the interplay between the production, distribution, and use of technology (Geels, 2004). Transitions are complex, long-term processes of shifts between different systems, involving diverse actors who have to chose between multiple, open-ended pathways, uncertain of their technological, social and political success (Köhler et al., 2019). Further, success in the outcome and chosen pathway of sustainability transitions is contested based on the values, norms, and goals of different actors and social groups. Hence, innovation cannot be seen as a scalar, but must rather be understood as a vector, as possessing and providing direction to change rather than being simply progress forward (Stirling, 2011). Andersson et al. (2021) term these two properties *positive* and *normative* directionality, respectively. Positive directionality of innovation arises from the fact that technological change is path-dependent (Arthur, 1989; David, 1985), while normative directionality is rooted in the assumption that without public policy, private actors lack intrinsic incentives to pursue sustainability (Köhler et al., 2019).

A sustainability transition which has been gaining relevance for researchers, policy makers, and producers alike is the bioeconomy. Broadly speaking, it aims to radically shift economic systems from relying on fossil fuels for energy and material resource, to an economic system built on biobased materials (Bennich et al., 2018), circular and renewable value chains (D'Amato et al., 2017) and higher environmental integrity through innovation (Bugge et al., 2016). As one of the main sources for biomass in a bioeconomy (Priefer et al., 2017), forests have become a key arena for the bioeconomy transition, highlighting trade-offs between material provision, carbon storage and biodiversity (Högbom et al., 2021). Underneath the umbrella term "bioeconomy", the concept and viable transition pathways are heavily contested (Allain et al., 2022). Three different visions of a bioeconomy compete in discourse to provide normative directionality of the transition: the first vision centers on the provision of biomass and renewable resources, the second on the scientific development and application of biotechnology, while the third emphasizes ecological considerations(Bugge et al., 2016; Vivien et al., 2019). Although the discourse is well understood in terms of content (e.g., Bugge et al., 2016; Vivien et al., 2019) its narratives (Bauer, 2018), and actors (Holmgren et al., 2022), the material effects of this transition, however, remain important research topics (Fischer et al., 2020). How many innovations are commercialized in this new economy, especially considering the central role of innovation in bioeconomy discourse? And what does commercialized innovation suggest for the positive directionality of the bioeconomy transition?

To unpack the plurality of possible socio-technical development paths, requires high data quality when measuring innovation. Although progress towards monitoring the bioeconomy transition has been made (Jander et al., 2020; Jander & Grundmann, 2019), assessing directionality is limited by a lack of innovation output measures (Wydra, 2020). In this paper, I use SWINNO, a literature-based innovation output database capturing all significant commercialized innovation in Sweden (Sjöö et al., 2014), to analyze the innovation output of the Swedish forest-based bioeconomy. I develop and apply a classification scheme to identify which bioeconomy vision an innovation produced or used in forestry or the downstream value chain aligns with.

Results show that Swedish bioeconomy innovation output has declined over the last 50 years. Of the three different visions the bioresource vision is the most pronounced, in line with expectations from discourse analysis and the Swedish bioeconomy strategy. However, the strategy should not be seen as visionary, as the innovation system had been producing bioeconomy innovation and even bioresource aligned innovation from the 1970s onwards. This points to a strong interconnection between path-dependence and the creation of directionality in the policy space.

2 Directionality and Visions of Bioeconomy

Previous literature has investigated directionality of socio-technical systems and emphasized the importance of generating shared visions as tools to provide normative directionality. Three distinct visions of desirable transition pathways and outcomes compete for normative directionality of the bioeconomy transition. This section introduces key concepts from this literature.

2.1 Directionality

Technology does not change randomly. Instead, technological change is contingent and influences technological change at previous or later points in time. It is path-dependent, meaning events at one point in time affect later events, which may even lead to suboptimal outcomes (David, 1985). Path-dependency arises due to positive feedback effects, such as increasing returns (Arthur, 1989), or through extension of possibilities adjacent to exiting technology (Kauffman, 2000). Instead of more or less progress, each innovation implies a new direction for socio-technical systems (Stirling, 2011). Andersson et al. (2021) term this quality of innovation possessing direction *positive* directionality.

As innovation policy took a normative turn under which innovation is needed to solve grand societal challenges (Schot & Steinmueller, 2018), the question of how to steer innovation into desired directions became a central issue in innovation research (Köhler et al., 2019). Innovation policy now ought to promote the desired vector of societal development, instead of focusing on providing the right amount of progress (Schot & Steinmueller, 2018), lending innovation *normative* directionality (Andersson et al., 2021). As innovation systems are embedded in a spatial and temporal context, not all potentially desired pathways are available or feasible. Instead, socio-technical systems are constrained by path-dependency (Bergek et al., 2015; Kemp et al., 2022; Stirling, 2011), sometimes to the point of being locked-in to specific system states (Unruh, 2000).

Dealing with the question of how to provide and exercise normative transition directionality Weber and Rohracher (2012) synthesize policy insights from innovation systems and multilevel perspective research into a failures framework. Therein, directionality failure is understood as the failure to provide direction to the process of search and unclear or missing setting of collective priorities. They caution that it should not be confused with shortsighted or flawed anticipation of market developments, as this myopia lacks a view on the direction of change. To overcome this failure, that is, to provide directionality, they argue, external requirements need to be internalized by the innovation system in a interpretive process of negotiation between different system actors. Reaching this collective understanding of direction, Weber and Rohracher (2012, p. 1042) write, is in practice, "… achieved by establishing shared future visions".

In the two central research streams of sustainability transitions, the innovation systems and the multilevel perspective literature, the importance of visions is highlighted. Hekkert et al. (2007) provide a framework of intervention in innovation on a systemic level, which highlights the importance of guidance of search as one of seven functions innovation system must provide. They explain guidance of search as, “those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users” (Hekkert et al., 2007, p. 423). Changing preferences in society, decides which direction of technological development is most promising through market and government influence and, “.. an interactive and cumulative process of exchanging ideas between technology producers, technology users, and many other actors” (Hekkert et al., 2007, p. 423). Bauer et al. (2017) adapts the innovation system functions to the specific case of biorefineries in Sweden and define the influence on the direction of search as “the incentives and/or pressures for organizations to enter the technological field. These may come in the form of visions, expectations of growth potential, regulation, policy targets, standards, articulation of demand from leading customers, crises in current business, etc.” (p. 4). Using the multi-level perspective, Yang et al. (2022) too highlight the importance of visions in directionality over transformations, stressing the importance of shared visions between niche and regime actors. Similarly, Bolton et al. (2019) illustrate how visions and pragmatic change combined in the development and evolution of a highly integrated European electricity system.

Rotmans et al. (2001) even go so far to argue that transition management is based on appealing and imaginative long-term visions and Loorbach (2010) argues that shared visions need to be developed and disseminated between transition stakeholders. But, as Bolton et al. (2019) show, visions alone are insufficient to provide directionality. In addition to being appealing, visions must also be specific and actors need to buy into them (Grillitsch et al., 2019). In summary, visions can be seen as shared imaginaries, mental models and aspirations of desired transitions which are expressed through narratives in discourse between actors (Bauer, 2018; Holmgren et al., 2022).

However, one transition can be characterized by multiple, competing visions, as is illustrated by the transition to a bioeconomy. The next section sharpens the conceptual understanding of what is meant with a bioeconomy and introduces the three visions.

2.2 Clarification of Bioeconomy Concept

Although the bioeconomy has gained importance as a research, policy and industry focus, it remains unclear what exactly it entails. At a high level, the bioeconomy refers to an economy in which raw materials for energy and production processes are provided from biological instead of fossil sources (Bugge et al., 2016). Hopes of increased resource efficiency and renewability as well as promised economic growth especially in regions rich in biological resources abound (El-Chichakli et al., 2016). However, a such a profound change to economic systems will not be possible without balancing significant tradeoffs between the needs and desires of different human and non-human stakeholders (Dieken et al., 2021). Högbom et al. (2021) summarize these tradeoffs as a trilemma between forests ability to provide sufficent wood to replace fossil based materials, carbon sequestration and storage, and the delivery of other eco-system services such as forest biodiversity. Resolving these tradeoffs is challenging, as goal conflicts between different development pathways make simulatneous progress on social, ecological and economic goals difficult (Bennich et al., 2021).

As one of the leading forestry nations in the world, Sweden sees substantial economic and political potential in advancing the bioeconomy . In a report commissioned by the Swedish Government, Formas (2012) lays out the plan for a Swedish bioeconomy based on two central pillars. It is to be an economy based on,

> [a] sustainable production of biomass to enable increased use within a number of different sectors of society. The objective is to reduce climate effects and the use of fossil-based raw materials.

With,

> [a]n increased added value for biomass materials, concomitant with a reduction in energy consumption and recovery of nutrients and energy as additional end products. The objective is to optimize the value and contribution of ecosystem services to the economy. (p. 9).

While the official Swedish bioeconomy strategy is still under development, the content of the quotes above echos across policy documents and the national forest program (Fischer et al., 2020). These pillars reflect the two most influential visions of the bioeconomy concept. Notions of a biotechnology and bio-resource oriented bioeconomy are widespread, dominate discourse at various levels (Dieken et al., 2021) and form the main industrial visions (Befort, 2020). A third vision, centered around ecology and an economy compatible with the biosphere acts as a counter point.

2.2.1 Bioeconomic Visions

The application of biotechnology to promote economic growth and provide jobs lends the biotechnology vision its name (Bugge et al., 2016). Biotechnology is the application of cellular and / or molecular biological agents in the production or processing of materials in a scientific and engineering informed manner (Yeung et al., 2019). Science driven innovation features prominently in this vision, with collaborations between research institutions in academia and industry taking on an important role (Bugge et al., 2016). Vivien et al. (2019) present a review of the concept showing that the focus on science as an absolute motor of change also shaped policy recommendations, driven especially by the OECD, towards increasing the speed and diffusion of innovation through partnerships between new start-ups and establish pharmaceutical companies. As a policy narrative this vision was particularly potent and widespread at the turn of the 21st century. According to Vivien et al. (2019), the intellectual heritage of Schumpeter and Kontradieff play an important role in this vision. Technological breakthroughs are poised to solve economic and ecological challenges, for example through genetic engineering. Consequently, this vision has a weak sustainability notion, viewing sustainability challenges as temporary, and nature as substitutable given sufficient research and knowledge creation (Vivien et al., 2019).

In more recent years, visions of a bio-resource bioeconomy have taken over as the leading narrative (Allain et al., 2022). Unlike the biotechnology vision, this conceptualization does not only focus on economic growth and job creation, but attempts to include ecological sustainability challenges (Bugge et al., 2016). Biological resources, not technologies, form the basis of a new economy. In essence, there are two ways in which bio-resources are poised to replace fossil resources: as substitution, e.g., biofuels replacing fossil fuels, and as high value added products, e.g., cross-laminated timber used as an alternative to concrete in construction (Vivien et al., 2019). To substitute fossil resources requires significant efforts in innovation. In contrast to the biotechnology vision, however, innovation is not confined to scientific advances from a narrow biochemical and pharmaceutical field. Instead, new and old actors are required to collaborate between and beyond established sectors (Bugge et al., 2016). Although sustainability plays a more important role in this vision of the bioeconomy, this vision is also considered an example of weak sustainability (D'Amato et al., 2017; Vivien et al., 2019). The reason is the focus of substitution and high biomass demands. The consumption of raw materials may even increase, not only for bio-based, but also for fossil-based resources (Asada et al., 2020).

An ecology focused counter-vision exists, which Bugge et al. (2016) term the bioecology vision, while ecological economists preferentially use the term bioeconomics (Allain et al., 2022; Vivien et al., 2019). Unlike the previous two visions, the bioecology vision builds on strong sustainability assumptions and emphasizes the need to develop an alternative economic system which respects the limits of the biosphere. Normative change towards material sobriety and degrowth to protect and restore ecosystems and biodiversity take precedent over technological and economic ambitions (Bugge et al., 2016; Vivien et al., 2019).

Development of the Term Bioeconomy

Analysis of the bioeconomy discourse, highlights that the visions have emerged at different times and with different actors at their centers (Bugge et al., 2016; Vivien et al., 2019). And while the two hitherto mentioned visions dominate contemporary discourse towards a forest based bioeconomy (Bauer, 2018; Holmgren et al., 2022), the bioeconomics concept itself was introduced in the 1920s in a work on fishery by the Russian biologist Baranoff (Vivien et al., 2019). Later, in 1975 ecological economist Georgescu-Roegen (1975) used the term to argue for an economy which minimizes its material and energy throughput to respect biological, physical and geochemical limits. Vivien et al. (2019) argue that the term biotechnology gradually emerged between 1990 and 2000, in the wake of enthusiasm about biotechnological advances, such as the discovery of DNA. It gained popularity and international importance when the OECD began increasingly supporting and reshaping its meaning at the turn of the millennium (Vivien et al., 2019). According to them, the last concept to enter the discourse was the bioresource oriented bioeconomy. While biomass has been used throughout history in various ways, the renewed interest with the intention to replace fossil inputs, for example in European Commission communication since 2010. However, Vivien et al. (2019) point to the long history of biorefinery as a core aspect of this vision, which was discussed as early as the 1930s. Hence, while the organization of the discourse into the labels biotechnology, bioecology and bioresource vision is a recent development, the underlying concepts have a richer history. Over time these visions have not only coexisted, but also influenced each other by borrowing from, contributing to, and distancing themselves from the other visions of a bioeconomy (Allain et al., 2022). And although the exact role played by forests in a bioeconomy transition depends on the desired vision (Kleinschmit et al., 2014), there is no doubt that the Swedish vision places high demands on forests as primary providers of the required biomass. Or, as Beland Lindahl et al. (2015) call it a forest sector that operates under a "more of everything" paradigm. Whether in the strategy formulated in Formas (2012), in Sweden's national forest program (Fischer et al., 2020), or in public discourse, a small, well-connected group of actors center the bio-resource vision as legitimate and desirable (Holmgren et al., 2022).

Common ground in ambitions to realize a bioeconomy is the need for diverse types of social, technological and organizational innovation (El-Chichakli et al., 2016). According to Jankovský et al. (2021) there are four types of innovation crucial for a forest-based bioeconomy: (i) substitute products, (ii) new (bio-based) processes, (iii) new (bio-based) products, (iv) new behavior. The need for innovation also features large in Swedish bioeconomy discourse and narratives therein (Bauer et al., 2017; Bennich et al., 2021), as, "[t]echnological innovation is key to a greener future" (Holmgren et al., 2022, p. 42). In a survey study sent to private organizations that received EU funding, Lovrić et al. (2020) find that the main type of European forest-based bioeconomy innovations are aimed at production processes, followed by goods and services, then business models.

In summary, despite – or perhaps because of – bioeconomy lacking a strong definition, the term is used to refer to different concepts, with different aims and objectives, foci, normative assumptions and hence implications for society and environment (Bugge et al., 2016). The summarized visions express themselves as narratives, actor coalitions and discourse artefacts in attempts to provide normative directionality to the transition. This normative directionality is expected to translate into positive directionality of technological change through innovation.

3 Data and Methods

Operationalizing directionality suffers from frequent lack of differentiation of positive and normative directionality, in addition to inherent issues in the measurement of innovation. Notable exceptions are the work on socio-technical system morphology by Andersson et al. (2021), who identify changes in the configuration of three different renewable energy systems, and by Yang et al. (2022) who use interviews and secondary source analysis to understand changes to insitutions in solar photovoltaic production in two Chinese provinces. However, both studies deal more with the aggregate effects of directionality on socio-technical systems rather than with positive directionality of innovation directly.

Normative directionality can and has been assessed through analysis of discourse [@] and narratives

(Bauer, 2018), visions and aims expressed in strategy documents (Parks, 2022), and R&D expenditure (Cappellano et al., 2022; Wydra, 2020). Where positive directionality of technological change has been assessed, scientific publications (Jankovský et al., 2021; Wydra, 2020), and more often, patents are used (e.g., Aghion et al., 2016; Moscona & Sastry, 2022; Popp, 2005). Such data, however, suffer from limitations when attempting to assess the directionality of socio-technical systems. While measures of normative directionality are equipped to identify the desired direction by different actors, visions need to first be accepted by innovators and reformulated into search. R&D funding can help in this task, but data on R&D funding is often too broad, targeting entire sectors or specific industries (Popp, 2005). While patents are more granular and a closer proxy of technological change, they suffer from well documented measurement errors (Popp, 2005); not all innovations are patented, and not all patents become innovations (Arundel & Kabla, 1998).

Literature-based innovation output measures remedy these issues, by capturing commercialized innovations (van der Panne, 2007). Applying this method to editor-reviewed articles published in 15 independent trade journals covering technological developments for general and highly specialized audiences, the SWINNO database contains 4972 innovations commercialized by Swedish companies between 1970 and 2021 (Sjöö et al., 2014). Since this method relies on the judgment of editiors and journalists, it can be described as significant innovations, omitting small reconfigurations of exisiting products and processes. The SWINNO database has significant benefits compared to other innovation measures. For one, it ensures that actual innovation, meaning commercialized products and processes, and thus that its positive directionality is captured. Second, because the source articles are preserved, it provides a rich source of data, frequently providing insights into the aims, motivations, advantages and challenges of the covered innovation, in addition to descriptions of what the innovation consists of, which allows to assess and quantify the direction of technological change.

To capture the forest-based bioeconomy the database was searched for innovation associated with core forest sectors and keywords describing forest products which may be used in sectors along the bioeconomy value chain based on Wolfslehner et al. (2016). The list of keywords and sectors is presented in the appendix (Section 7.1), additionally reproducible code to generate the figures and tables in this paper can be found at `github.com/pjkreutzer/swinno-bioeconomy-directionality`.

3.1 Classification Methodology

I carefully read the source articles of innovations identified in the database and tagged their associated unique identifiers with two types of labels. The first label is the main interest of this study: the bioeconomy vision an innovation can be associated with. The second label provides a deeper understanding if and how the innovation reduces environmental impacts; not all bioeconomy innovations need to be sustainability oriented innovation (Bröring et al., 2020).

3.1.1 Bioeconomy Visions

Based on the analyses of competing bioeconomy visions in Bugge et al. (2016) and Vivien et al. (2019), I developed and applied a matrix of characterstics for each vision. While the criteria for the bioresource and bioecology vision are entirely based on the two previous publications, the biotechnology criteria are additionally based on a literature review of Yeung et al. (2019), concerning biotechnology publications.

Reading the source texts of innovations identified from SWINNO, I classified an innovation as being *aligned* with a vision if it fulfills at least one criteria in the matrix. An innovation can align with multiple visions, for example, where biomass is converted and upgraded (bioresource vision) by application of biotechnology (biotechnology vision). Or the value chain decommodifying introduction of new production lines by a family-business which use wood from their own forests to produce houses with high territorial identity (*Svensk trävaru- & pappersmassetidning*, 1976:7, pp. 539,541,544), that aligns with the bioresource and bioecology vision. Lastly, there is also the possibility that an innovation cannot be placed into at least one of the visions. This is the case for innovation which brings general technological improvements, purely advances economic performance, or relates to a general purpose technology such as appliance of computers. These innovations are labeled as Vision Neutral, which does not imply that the innovation is not used, or originates in the forest based bioeconomy as defined above. An illustrative example of such an innovation are improved work boots (*Sågverken*, 1974:2, p. 121), which promote safety of forest workers but do not correspond with any of the criteria in Table 1.

Table 1: Decision matrix used to classify innovation.

Corresponding Vision	Source article explicitly mentions that innovation:
Biotechnology	Develops new, or modifies existing, organism, biological system, or process
	Uses cellular or molecular process to solve problem or in production process
	Applies biological agent in scientific or engineering based principle to produce product or service
	Based on molecular biology, biochemistry, cell biology, embryology, genetics or microbiology research
	Provides method for research in the above areas
Bioresource	Biomass used to substitute other input
	Refines biomass through mechanical, chemical or other process
	Converts and upgrades bioresource
	Optimises land use
	Includes degraded land in production of biofuels
	Intensifies use of biomass, including from waste

Corresponding Vision	Source article explicitly mentions that innovation:
Bioecology	Prioritizes biodiversity, conservation, ecosystem or soil health
	Integrates production systems
	Develops high quality product with territorial identity
	Reuses or recycles waste
	States compatibility with biosphere as motivation or aim
	States need for social or ecological counter-expertise relative to other socio-technical innovations
	Promotes or uses a circular production mode
	Promotes or uses a self-sustained production mode

3.1.2 Eco-Innovation Types

The focus of this paper is understanding what bioeconomy visions dominate the Swedish innovation system's output. However, in order to gain a deeper understanding of the nature of innovation within each bioeconomy vision, I also tagged the innovation with labels of eco-innovation types. This classification uses eco-innovation types identified in a recent literature review by García-Granero et al. (2018). They review 104 publications and produce a list 30 key Eco-Innovation Performance Indicators of product, process, organizational and marketing innovation.

This initial list was tested on a subset of innovation in SWINNO and augmented with 15 categories. Because the list of eco-innovation types was relatively exhaustive from the beginning, few adjustments had to be made. These include: expanding the labeling for other sustainability criteria, such as human health and safety, and specific forest related aspects / tasks to gain a more detailed understanding of an innovations aim. For example, some innovations aim to protect harvested timber, either at harvest, during transport or storage. While Table 3 shows all new added labels, in the following text those that do not clearly represent an eco-innovation – following García-Granero et al. (2018) "…fewer adverse effects on the environment and more efficient use of resources" (p. 305) – were excluded. These excluded labels are Gen-manipulated plant, Increased plant yield, Gen-manipulated animal (incl new breed), Human Health and Safety, Automatization, Precision, and Biocide.

The decision process for labelling eco-innovation types was also based on the source texts for each innovation. Based on the information contained therein, I labeled the innovation with one or more categories. In case of uncertainty, I added the label uncertain. In case where the text does not mention any eco-innovation aspect, the innovation was labeled as not an eco-innovation. Where the source text only mentions that the innovation is less harmful to the environment, the label "Environmental-friendly technologies" was used.

4 Results

Querying the SWINNO database for forest based bioeconomy innovations initially yields 817 innovations. This number includes false positives. During classification, these false positives were removed from the dataset, resulting in 786 innovations which originate from, are used in, or make use of products derived from the forest.

4.1 Innovation Output of the Swedish Forest-Based Bioeconomy

In total, the forest-based bioeconomy produced 16% of innovation captured in the SWINNO database. While the total innovation output and bioeconomy innovations feature a period of high output from the 1970s to the 1990s, with a peak in 2008 for total output and 1976 for the bioeconomy, the economic downturn and industrial restructurization of the 1990s was accompanied with a decline in commercialized innovation. Unlike the other sectors and socio-technical systems, however, it appears that the bioeconomy was not able to recover to the same extent. Its percentage of total innovation declined by 18 percentage points from an all-time high of 32% in 1975 to 14% in 2021. Figure 1 illustrates this using the five year moving average for the number of innovations commercialized per year in the bioeconomy and in the entire dataset, including the bioeconomy. The decline in relative importance of bioeconomy innovations can be identified in the share of bioeconomy innovation of total innovation.

4.2 Visions of the Swedish Forest Bioeconomy Innovation System

For the following part, 37 innovations whose source text did not allow labeling without significant uncertainty are excluded. These innovations are planned to undergo a revision by subject matter experts at a later point.

Among the remaining 633 innovations, 351 (55% of all commercialized innovation) were not aligned with any vision. Next the bioresource vision was associated with 232 (37%), while 87 (14%) and 37 (6%) innovations were classified as bioecology vision and biotechnology vision, respectively. Note that the sum of all categories does not equal the total number of classified innovations, as one innovation can be associated with more than one bioeconomy vision. Figure 2 shows the count of innovation for each categorization per year. Output for the biotechnology and bioecology vision appears inconsistent, with years in which not a single commercialized innovation aligned with these visions. Additionally, due to the low number of innovations aligned with these visions no clear trends can be identified. In contrast, the two peaks of total innovation output of Figure 1 a, can be identified in the bioresource and vision neutral innovations. Unlike vision neutral innovation, bioresource innovation declined to under 4 commercialized innovations after 2010.

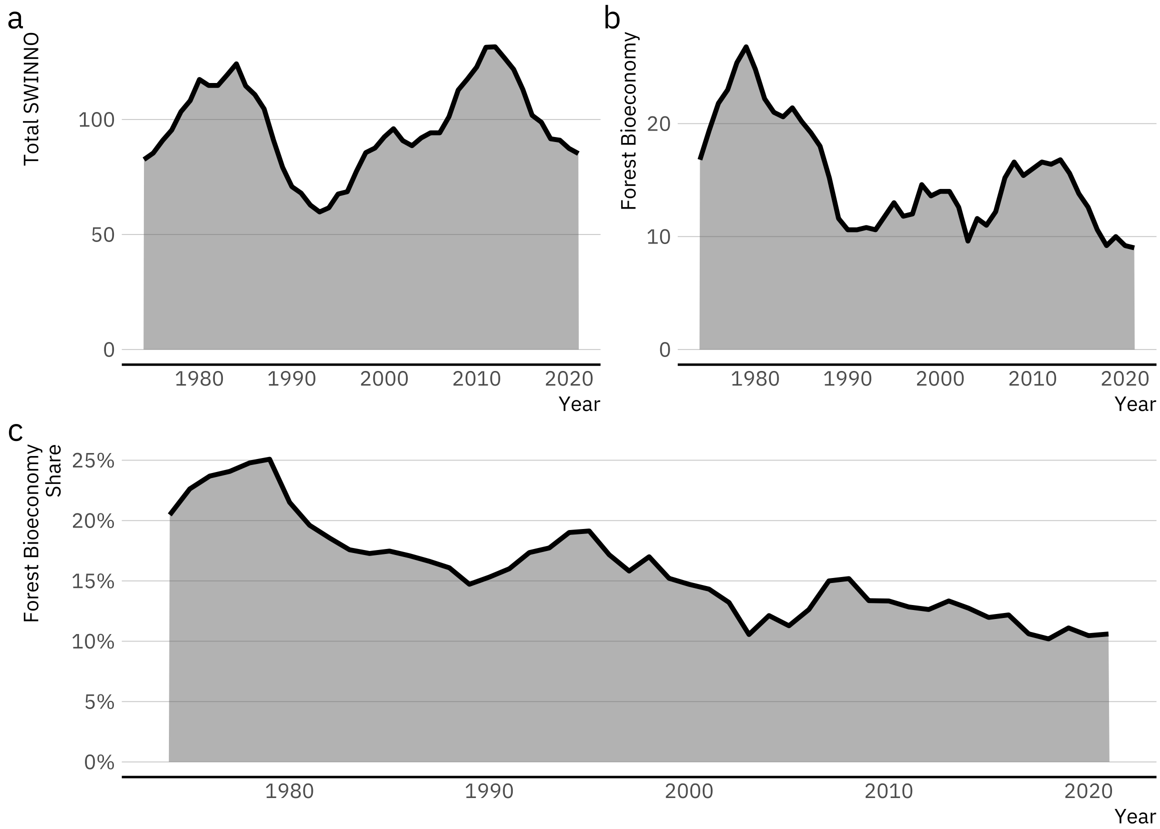

Figure 1: a. A total number of innovation registered in SWINNO database. b. Forest-based bioeconomy innovations registered in SWINNO database. c. Percentage of forest based bioeconomy innovations to total innovation registered in SWINNO database. Shown are the 5 year moving averages for each time series.

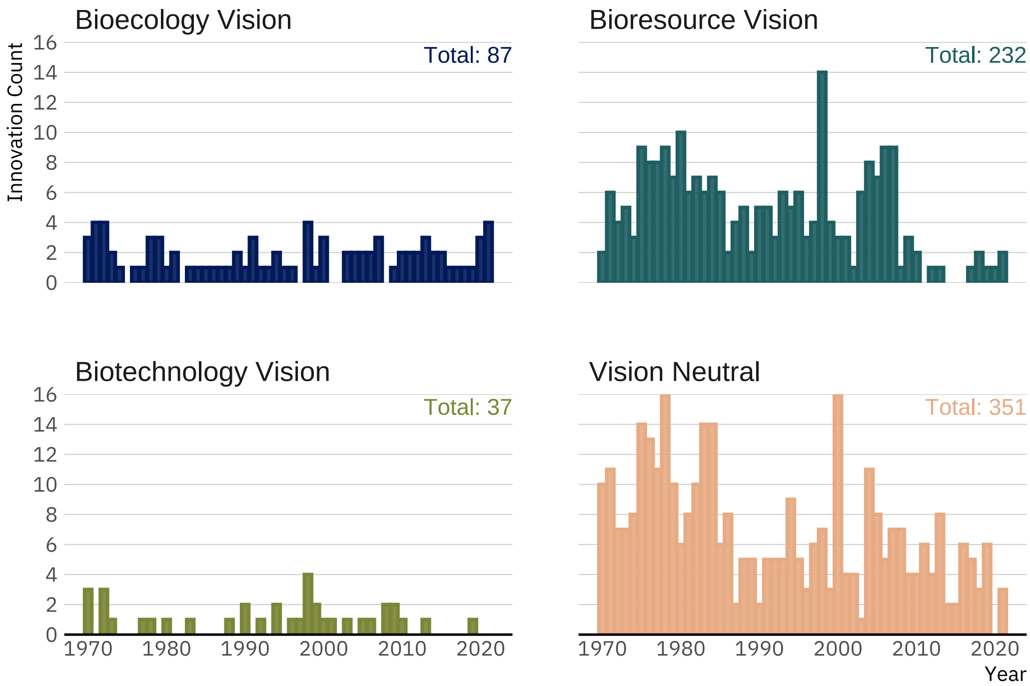

Figure 2: Counts of innovation classification by Bioeconomy Vision Category. Innovations can be classified into multiple visions simulatenously. The sum of all vision counts does not match the sum of all bioeconomy innovations.

4.2.1 A Deeper Look at Innovations in Each Vision

Bioresource Vision

Although the bioresource vision claims the most aligned innovations, its most active period in terms of commercialized innovations was at the beginning of this study's time frame. 121 innovations were commercialized between 1970 and 1990. These can be grouped into two themes.

The first theme addressed environmental issues, especially greening the pulp and paper production process and has been extensively documented, for example by Bergquist and Söderholm (2011, 2015), and Bergquist & Söderholm (2018). The second innovation group was a response to the energy crisis resulting from oil export restrictions placed by OPEC countries in the 1970s (Bergquist & Söderholm, 2016). Once again a major player was the pulp and paper industry which commercialized numerous innovations to improve energy efficiency in drying (*Ny Teknik*, 1972:1, p. 4), reduce cool down of furnaces (*Kemisk Tidskrift*, 1976:9 pp. 96,99-100) and generate cheaper energy from waste, byproducts (*VVS*, 1980:7-8, p.69) and excess process heat (*Kemisk Tidskrift*, 1981:7, p. 82). The second major player was the forestry sector. A cluster of technologies such as forwarders, tree harvesters, wood driers and processors emerged in response to a wood shortage and soaring energy prices from the oil shocks in the 1970s (Taalbi, 2014). Key innovations in this technology cluster were the pendulum saw (*Sågverken*, 1977:2, pp. 97-101,125), which could be mounted on vehicles to mechanically fell entire trees at once (*Sågverken*, 1974:10, pp. 725-727), and vehicles that, despite being heavy, limited the damage to soft forest soil and importantly, the roots therein (e.g., *Sågverken*, 1974:10, p. 725-727; *Sågverken*, 1975:10, p. 731).

The second period of increased activity starting in 2000 focused more on upgrading of biomass into new products such as construction timber (e.g., *NTT* 2003:27, p. 11; *NTT*, 2003:8, p.6; *NTT* 2004:18, pp.16-17), various paper products (e.g., *Kemivärlden Biotech med Kemisk Tidskrift*, 2009:11, pp. 60-61; *SPCI Svensk Papperstidning*, 2005:7, pp.10-11), but also biobased alternatives to plastics (e.g., *SPCI Svensk Papperstidning*, 2018:4, pp. 28-33; *SPCI Svensk Papperstidning*, 2019:6, p.24; *Plastforum*,2019:5, p.31), or refined bio-fuel alternatives to fossil fuels, such as the LignoBoost Process (*SPCI Svensk Papperstidning*, 2006:7, pp. 14-16), or gassification of black liquour – a by-product of pulp digestion – for electricity generation (*Ny Teknik*, 1990:16, p.5) . A second theme is rationalization of production processes, especially through the application of computers and software (e.g., *NTT*, 2007:14, p. 13; *Automation*, 2021:1, p. 24).

Therefore, while the first period of high innovation output until the 1990s was characterized by attempts to modernize timber production, mainly through the mechanization of harvesting, and cleaning the pulp and paper process, the second period of active commercialization focused on finding new applications for biomass and improving the cost effectivness of exisiting processes. This is illustrated with innovations in forwarders – specialized machines to aid in the removal of timber from harvest sides before loading them onto transport – where of 9 innovations, 7 were commercialized before 1990. Moreover, the two innovations commercialized after focused on greening fuel consumption through hybrid engines (*Ny Teknik*, 2008:34, p. 24) and weight reduction (*Ny Teknik*, 2008:34, p. 24; *Automation*, 2012:40, p. 26). Meanwhile, earlier innovations focused on establishing the product category by solving issues of soil damage from use of heavy machinery (*Sågverken*,1975:10, p. 731; *Sågverken*, 1982:10, p. 77) as well as integrating forwarders with other technologies for planting (*Sågverken*, 1979:3, p. 237) and removing trees (*Ny Teknik*, 1976:43, p.20; *Sågverken*, 1975:12, pp. 905,907).

Biotechnology Vision

Only 37 innovations were aligned with the biotechnology vision. Of those, the majority focused on cleaning waste water from, for example, fibers (e.g., *Kemisk Tidskrift*, 1972:4, p. 19), or chemicals (e.g., *Ny Teknik*, 1970:4, p. 8), with applications mostly in the pulp and paper industry. Other innovation applied biomass derived from the forest in new products, such as new fibers (*Ny Teknik*, 1976:9, pp. 1,4-5), or applications of cellulose in heat isolation materials (*Ny Teknik*, 2002:9, p. 14). Innovations in this vision frequently overlapped with bioresource innovations, such as the above mentioned LignoBoost process.

Bioecology Vision

Recycling accounted for 64 unique innovations, or 74% of innovation associated with the bioecology vision. The majority of innovations in aligned with this vision due to some explicitly stated environmental aim within existing production methods. An example is an instrument that measures the extent to which a tree is decayed from the inside (*NTT*, 2006:2, p. 20). While such trees are of little economic value, they play a big role in biodiversity conservation if left standing. This innovation aims to identify these trees before they are felled and thus to protect it from being felled. Some innovations stood out as attempts to generate social or ecological counter expertise. For example, in 1971 *Sågverken* (3, p. 195), covered an innovation in wooden floors made from wide, red pine planks. Notable about this innovation was that it countered the trend of economic rationalization of the time, in favor of tight integration between production and forest ownership. Another example of regional timber being treated not as a commodity, but as a desirable high quality product is the Masonite sytem for pre-fabricated wooden house (*Svensk trävaru- & pappersmassetidning*, 1976:7, pp. 539,541,544). The specifc growing conditions of Northern Sweden are provided as a reason for denser wood, especially well suited for construction due to its strength properties and the "[t]otal integration makes the company feel optimistic: own forests, top-modern sawmill, board mill, newly built component factory are positive factors meaning advantages in all stages" (p. 544). Similiar decommodification of value chains in favor of local product could even be found in the paper industry, where fresh wood from within a 100km radius was found to produce better quality and reduce chemical and energy usage (*SPCI Svensk Papperstidning*, 2015:8, pp. 26-30).

4.2.2 How many eco-innovations are there?

How does each vision contribute to lessening the environmental impact of the forest bioeconomy? While a quantitative assessment of technological impact on the environment comes with a host of challenges, the labelling of eco-innovations at least allowed a glimpse at what could be expected from each vision. Figure 3 shows the count of eco-innovation associated with each bioeconomy vision by type. As before, the total sum of all eco-innovation across all bioeconomy visions outnumbers the sum of innovations in the bioeconomy. A single innovation can be more than one eco-innovation type, for example, if it reduces the amount of raw material needed by recycling waste. Product and Process innovation were by far the most frequent across all visions. The bioresource vision was heavily associated with improving raw-material utilization, while the Bioecology Vision is most frequently associated with recycling. At least, this suggests that the definitions for each Vision and the classification scheme are in agreement.

A noteworthy feature of innovation lacking alignment to a bioeconomy vision was that this category has by far the most non-eco-innovations. The chi-squared test of independence revealed a statistically significant association between an innovation being aligned with a vision and it being an eco-innovation ($\chi^2 = 63.579$ df = 1, $p < 0.05$).

Table 2: Cross Table of Unique Innovations Classified as Vision Neutral And Eco-Innovation

	Non-Eco-Innovation	Eco-Innovation
Bioeconomy Vision	45	214
Vision Neutral	136	132

5 Discussion

The decline in innovations commercialized in the forest-based bioeconomy relative to all commercialized innovations suggests that Sweden's capacity to produce technological change towards a bioeconomy has diminished over the last 50 years. While innovation counts should be interpreted with caution, as the magnitude of technological change stemming from individual innovations can differ, it is surprising that a economic sector, which is expected to realize ambitious economic, social and ecological targets, is losing importance in relation to other Swedish innovations. While it appears that the crises in forestry and energy of the 1970s stimulated innovation directed towards economic rationalization of forestry, the bioeconomy could not benefit from similar stimulants when exploring conversion of biomass into new products after the financial crisis in 2008, and the shock to timber production after storm Gudrun in 2005.

As for the positive directionality of the Swedish transition to a forest-bioeconomy, the dominant vision appears to be successful in so far as it is the vision most innovations align with. That a majority of innovation appear neutral in regards to vision based directionality is not to say that these do not posess positive

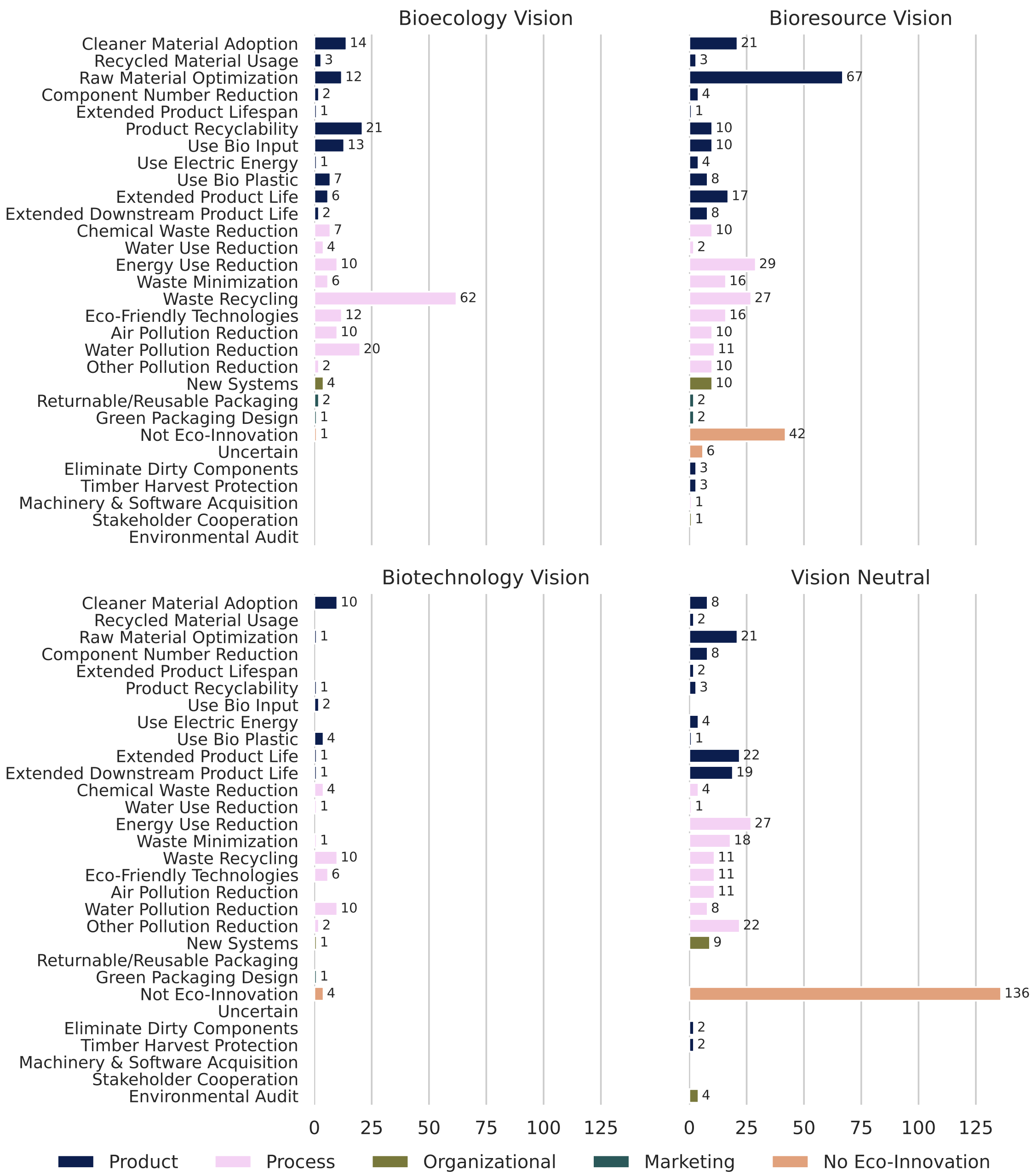

Figure 3: Count of Eco-Innovation Types by Bioeconomy Vision

directionality. These innovations should be regarded as general improvements to exisiting technology and hence are not neutral in regards to technological change, only in regards to not aligning with normatively directionality. The congruency between positive and normative directionality can be explained by a specific feature of Swedish socio-technical systems: a strong desire to create consensus (Beland Lindahl et al., 2015). Bergquist & Söderholm (2011) illuminate how strong collaboration networks between public and private actors shaped the greening of Sweden's pulp and paper industry between 1960 and 1980. The findings of this study support this view. Rather than providing directionality towards sustainability, preparations for a national forest strategy and the national forest program strongly align with the trajectories of technological change produced by the innovation system. While innovation systems literature highlights this as the mark of well implemented transition management, this consensus building also comes at a cost to transition paths. However, this consensus building comes at a cost, where dissenting views are marginalized (Fischer et al., 2020). Holmgren et al. (2022) show that industry interest dominate the transformation to a bioeconomy. Fischer et al. (2020) even go so far to liken it to consensus building through exclusion.

Looking at the direction embedded in commercialized innovations suggests are more nuanced picture. While the bioresource vision is the most pronounced out of the three visions for a bioeconomy, innovations can and do align with multiple visions at once. In addition, those innovations that align with any of the bioeconomy visions are more often eco-innovations than vision neutral technological change. However, it must be said that whether this generates positive environmental impact depends on a number of factors such as technological diffusion and possible rebound effects.

5.1 Limitations

In regards to the above, an important limitation is the use of innovation as a measure of socio-technical transitions. While the results of this study agree with the survey results of Lovrić et al. (2020) and capture the production of technological change, it does not directly capture its adoption and use. In addition literature-based innovation output measures have data limitations might result in a bias against non-commercialized innovation, especially for research into forest sector innovation where organizational innovations such as silviculture management can be important levers to improve, for example biodiversity or cultural ecosystem services. Such new processes, or new organizational approaches, will only be captured if they are sold to another company. Relevant product innovation which facilitates these plans, for example products related to the planting of trees, on the other hand, are captured. A likely consequence of this limitation is that the number of innovation related to the bioecology vision could be under counted, as this vision highlights "[c]ounter-expertise rather than concrete technical solutions" (Vivien et al., 2019, p. 194).

A second limitation arising from the data is the usage of innovation counts. While the literature-based innovation output captures significant innovation rather than mere reconfiguration, counting innovation thus captured can be misleading as to the impact of each individual innovation. Some technologies require few break-through innovations before meeting large market demand and diffusing quickly. Others might go through multiple rounds of more incremental improvements. Although literature-based innovation output measures assume editors at trade journales already discard incremental changes to include only important improvements, they cannot ex-ante anticipate which innovation will be most important in terms of impact (Kander et al., 2019). Therefore the decline in innovation output this paper identifies should not be taken to necessarily imply a decline in the importance of the commercialized innovation. Similarily, the positive directionality measured in this paper should be seen more as a the vector of change embedded in the transition to a bioeconomy, rather than a scalar of its progress.

6 Conclusion

In conclusion, the technological artefacts produced in the transition to a forest-based bioeconomy in Sweden show a clear directionality aligned with the bioresource vision, which is most favored by central actors and policy makers. At the same time, there is evidence that the innovation system has produced knowledge aligned with alternative transition pathways towards an ecological bioeconomy, such as decommodification of value chains as well as efforts to increase the circularity of the system and to reduce environmental pollution. The temporal distribution of innovation output aligns strongly with the Swedish tendency to produce consens oriented policy by aligning policy objectives with existing technolgical trajectories. While this approach is pragmatic and has produced good outcomes in the past, it is at least doubtful how radical a shift can be expected for the bioeconomy transition, considering that innovation output since the 1970s has not meaningfully explored alternatives to the intensification of biomass resource extraction.

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Kemisk tidskrift: svensk kemisk tidskrift, kemiteknik. (1969-1993). Stockholm: Ingenjörsförlaget.

Kemivärlden, Biotech, Kemisk tidskrift. (2005-2018) Stockholm : Mentor Communications

Ny teknik. (1970-2024). Stockholm: Teknisk tidskrifts förlag.

NTT såg & trä: Nordisk träteknik, Sågverken, Träindustrin. (2003-2024). Lidingö: Mentor Communi-

cations
Svensk papperstidning: medlemstidning för Svenska pappers- och cellulosaingeniörsföreningen - SPCI.(2003-2024). Stockholm: AB Svensk papperstidning.
Svensk trävaru- & pappersmassetidning. (1970-1990). Stockholm: AB Svensk trävarutidning.
Sågverken: tidskrift för sågverksindustri, trävaruhandel och skogsbruk. (1974 - 1998). Stockholm: Svensk trävarutidning.
VVS: tidskrift för värme-, ventilations- och sanitetsteknik : organ för Sven- ska värme- och sanitetstekniska föreningen. (1970-1982). Stockholm: VVS.

7 Appendix

7.1 Data Appendix

Table 3: List of Eco-Innovation Labels

Table 3

Code	Category
101	Use new cleaner material or new input with lower environmental impact
102	Use of recycled materials
103	Reduction / optimization of raw material use
104	Component number reduction
105	Elimination of dirty components

Using producer / user codes

Table 4: Key Sectors Used in Query

SNI Code	Description
02	Forestry and related services
20	Wood and wood product manufacturing except furniture
21	Pulp, paper and paper product manufacturing
36	Furniture manufacturing; other manufacturing

Table 5: Swedish Keywords used in Query: `WHERE description LIKE %keyword% OR ...`

Swedish	English
virke	timber
cellulos	cellulose
lignin	lignin
spån	chip
bark	bark
levulinsyra	levulinic acid
furfural	furfural
svarttjära	black tar
svartlut	black liquor
växtbas	plant-based
ved	wood
trä	timber
skog	forest
biobränsle	biofuel
biologiskt	biological
nedbrytbar	biodegradable
papper	paper
pappret	cardboard
karton	carton
lyocell	lyocell
tencel	Tencel (brand of lyocell)