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Keywords: bioeconomy; biorefineries; biorefinery technology; technological innovation systems

JEL: L73; O33; Q23; Q55

Technological innovation systems for biorefineries - A review of the literature

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JEL codes: L73, O33, Q23, Q55

1. Introduction

Biorefining and biorefineries are concepts that attract increasing attention from industrial actors, policy makers and academic researchers alike, largely considered as an integral part of a future sustainable bioeconomy[1] – as argued globally by the OECD,[2] the IEA,[3] and the World Economic Forum.[4] The concept of a bioeconomy can be understood as an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources, such as plant and animal sources.[1,5] Biorefineries are seen to be both the remedy for industry sectors struggling for survival in a changing, increasingly competitive global economy, such as the forestry sector,[6,7] as well as an important pathway to reduce the demand for fossil resources throughout the economy and thus address the global climate change challenge.[8] As demand and competition for limited biomass resources increase rapidly, biorefineries can be an important part of an efficient use of resources and raw materials.[9]

The research literature is reporting an ever increasing number of biorefining processes and technologies, using different biomass feedstocks for the production of a wide range of products. Beyond fuels, which were among the first biorefinery products to be produced and marketed on a large scale, many other biorefinery product categories have been identified, e.g. platform chemicals,[10] plastics[11], and other materials.[12] Despite the apparent interest in biorefining shared between high-level decision-makers and the research community, the deployment of biorefinery technologies in full industrial scale has been slow with most of the biorefinery projects in Europe and North America being pilot, demonstration or semi-commercial plants,[13] leading to calls for increased policy support for biorefineries to help cross the 'valley of death' towards greater commercial usage.[14,15] Albeit that such development and experimental verification of new technologies in demo- and production-scale facilities have helped to overcome important constraints,[16,17] other barriers for the widespread adoption of innovative biorefinery technologies continue to exist. Understanding these barriers, and how they can be overcome, is thus an important task to support the development of biorefinery technologies.

How the processes of diffusion and adoption of new technologies evolve have been key topics in innovation research,[18–21] which has shown that these processes depend not only on technological breakthroughs, but also on many other types of factors, e.g. cognitive and social lock-in to well-known solutions as well as poor alignment of new innovations to fit within existing regulatory schemes. The interplay of scientific, technological, economic and political dimensions is stressed in research on innovation systems – a concept describing all the actors, networks and institutions involved in developing, adopting and diffusing innovations.[22] Innovation systems for renewable energy technologies has become a key research area and it has been shown that the slow adoption of these technological innovations depend on complex innovation system failures.[23] Overcoming these failures requires policies and efforts in many different areas.[24,25] Research on technological innovation systems (TIS) has shown that several key processes, or functions, must be fulfilled to enable the emergence of new technologies. It is therefore relevant to ask the question how the extensive research on biorefineries has contributed to developing knowledge and enriched understanding of these functions and its implications in terms of policy and governance.

The purpose of this paper is thus to review the research on biorefinery technology innovation, with the aim to synthesize current knowledge about how biorefinery technologies are being developed, deployed, and diffused, and to identify actors, networks and institutions relevant for these processes. The review is limited to biorefinery development in North America and Europe, as these regions are among the most active in the development of biorefineries. Further, aiming to contribute to the understanding of how the emergence of biorefineries affects industrial development the review focuses on forest biorefineries. This focus is due to the fact that this is one of the sectors which is often in the spotlight in the discussion about deploying and integrating biorefinery technologies into current industries, as well as it is a sector in which firms have s put significant efforts into researching different possible applied biorefinery configurations.[26] Although biorefining is not a single technology but rather an umbrella concept for a range of different technologies and processes we argue that the TIS perspective can provide valuable insights into the development of biorefineries from a systemic perspective as the challenges facing renewable energy technologies are very similar.[23]

The literature reviewed was identified through academic databases. Relevant publications from 1995-2014 were initially identified in the SCOPUS database with the search string "biorefin* AND innovati*" in the title, abstract, or keywords. Publications related to the study of innovation processes for biorefinery technologies were included while publications strictly reporting technological experimentation were excluded. The material was subsequently expanded by snowball sampling, using the references in the identified publications. In the end 52 publications were included in the review. In addition, the authors of this paper bring together multi-disciplinary backgrounds and perspectives, including engineering, economics, geography and politics. The literature was therefore interpreted through various lenses.

1.1. Approach: Technological innovation systems

Innovation system research has refuted the view of innovation as a simple, linear process in which fundamental research is followed by technical research and subsequently market deployment and diffusion.[22] Instead, it aims to describe the actors, institutions, and their networks involved in developing, adopting and using new technologies. Relevant *actors* include firms throughout the value chain, as well as universities, government bodies, industry associations, NGOs, and individual entrepreneurs – all of whom are engaged in activities related to the technology in focus. Actors develop *networks* through trade, cooperation, lobbying, and other forms of interactions that form links, which allow for exchange of knowledge, beliefs, and visions. *Institutions* are the regulations, norms, and routines that control and guide the behavior of the actors and their interactions, and can be both highly formalized, e.g. laws and regulations, as well as informal in character, e.g. norms and rules of thumb.

The performance of a TIS is usually assessed through a set of associated system functions or key processes.[27–29] The functional approach has been used to analyze and describe the drivers and barriers for deployment and diffusion of renewable energy technologies in different contexts – e.g. biogas in Switzerland,[30] biomass gasification in the Netherlands,[31] and agro-bioenergy in Ukraine.[32] It has also provided relevant advice to policy makers regarding the performance of the innovation system, as well as clear rationales for intervention based on the notion of system failures for transformative change.[25,33] In this paper we use the functions as described by Bergek et al.,[29,34] but do not include "development of positive external economies" as a separate function as this largely overlaps with the other functions.[35] The six functions used in this paper are introduced in Table 1.

Table 1. The TIS functions as used in the present paper, adapted from Bergek et al.[34]

Function	… is the process of strengthening …
(1) Knowledge development and diffusion	… the breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the system
(2) Entrepreneurial experimentation	… the testing of new technologies, applications and markets whereby new opportunities and ventures are created and a learning process is unfolded.
(3) Influence on the direction of search	… 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.
(4) Resource mobilization	… the extent to which actors within the TIS are able to mobilize human and financial capital as well as complementary assets such as network infrastructure.
(5) Market formation	… the factors driving market formation. These include the articulation of demand from customers, institutional change, changes in price/performance. Market formation often runs through various stages, i.e. "nursing" or niche markets, e.g. in the form of demonstration projects, bridging markets and eventually mass markets.
(6) Legitimation	… the social acceptance and compliance with relevant institutions. Legitimacy is not given, but is formed through conscious actions by organizations and individuals.

2. Key findings

2.1. The growing field of biorefinery research

Although the first identified use of the term biorefining is from 1981[36] it was not until recently that the concept became popular in the literature. The growing interest in biorefineries as a research topic is evident from the increasing number of publications (total 4098) on the topic during the last twenty years, and especially during the last decade, which is shown in Figure 1. The vast majority of biorefinery related publications seem to be concerned with the development of biorefinery technologies and processes. Biorefinery related publications categorized as "social sciences", "economics, econometrics and finance", or "business, management and accounting" constitute only 166 (4.1 %) of the publications. In only a small number of publications (177) are biorefineries explicitly related to innovation, with a slowly increasing trend also for these publications over the last ten years. The search focused on publications researching biorefineries and not all different, possible biorefinery technologies, such as ethanol fermentation, in which case the number of publications would probably increase significantly.

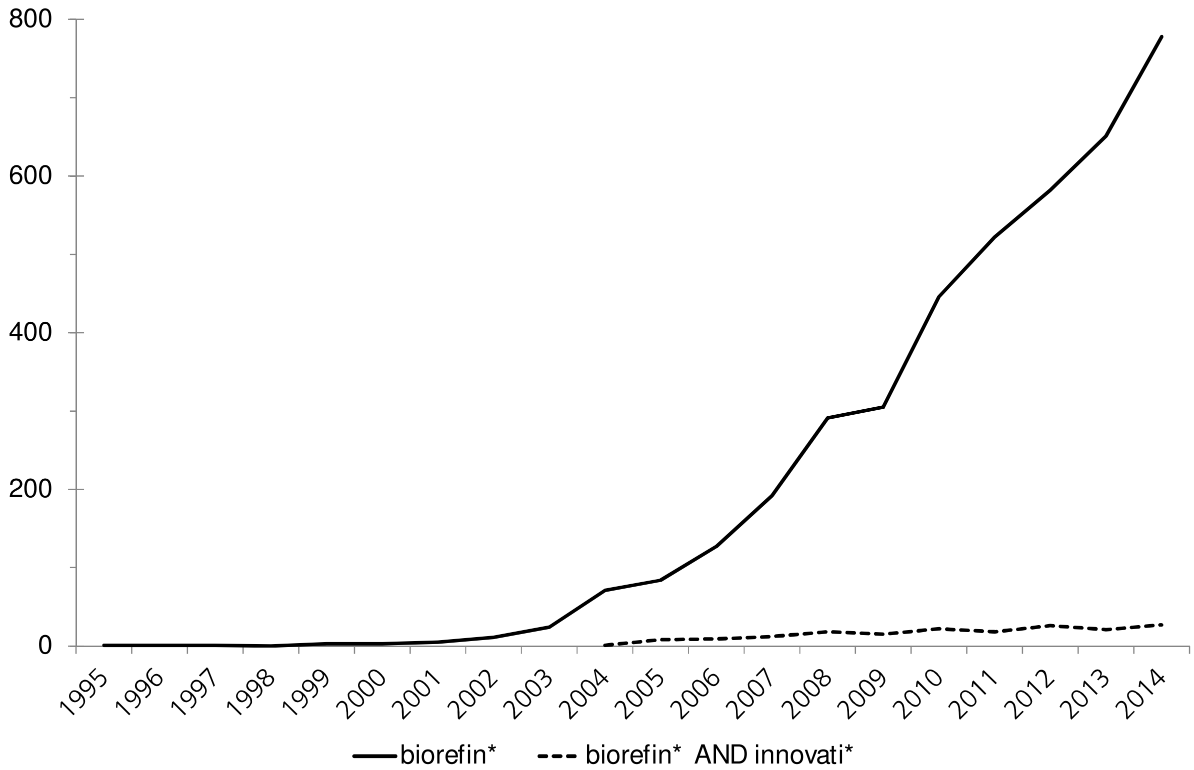

Figure 1. Number of biorefinery related publications per year indexed in SCOPUS from 1995 to 2014. Biorefinery related publications were identified as publications indexed with "biorefin*" and a subset with "biorefin* AND innovati*" in title, abstract, or keywords, yielding a total of 4098 publications and a subset of 177 publications.

2.2. Defining biorefinery technology

Although the biorefinery concept is not unambiguously defined, the common ground for the different definitions found in the research literature is that biorefining is about processing of biomass to a range of different products. The fact that there is no common definition for the concept could reflect that the field has emerged from and within different research traditions, which emphasize different characteristics of the concept.

The first identified use of the terms biorefinery and biorefining described a specific three-step process combining the fermentation of biomass to organic acids and subsequent electrolysis of those acids to produce a range of liquid fuels or chemicals, similar to the products of a petroleum refinery: "in the petroleum refining industry, it is usually desirable to produce from crude oil an optimal mixture of industrial organic chemicals and fuels, a concept known as coproduction. The biorefining process reviewed appears to be adaptable to this same concept of coproduction using biomass as a feedstock".[36] The comparison with the petroleum refinery is common in many later definitions, which emphasize the range of products a biorefinery should produce. This analogy has however also been questioned, due to the more direct competition for the fractions of biomass for different purposes.[37]

Later publications have left the strict focus on the three-step process described by Levy et al. and propose a more general conceptualization of biorefining. A list of examples of definitions found in the literature is shown below in Table 2. The table shows that the definitions differ widely as some of the definitions view the biorefinery as the facility or factory which uses biomass to produce certain products, whereas other definitions view biorefineries as systems that incorporate firms and factories throughout the value chain, and finally some definitions focus on biorefining as a conceptual process of intensifying the use of renewable resources or the transfer of specific knowledge. Further, among the factory-based definitions, some view the biorefinery as an add-on to existing facilities adapted for certain feedstocks, such as pulp and/or paper mills, whereas others include all options of biomass processing

Table 2. Examples of definitions of biorefineries.

Definition
Biorefining is the sustainable processing of biomass into a spectrum of marketable bio-based products (food/feed ingredients, chemicals, materials) and bioenergy (biofuels, power and/or heat) [3]
Biorefinery is an overall concept of a processing plant where biomass feedstocks are converted and extracted into a spectrum of valuable products. Based on the petrochemical refinery [38]
A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. The biorefinery concept is analogous to today's petroleum refineries, which produce multiple fuels and products from petroleum [39]
Biorefining intensifies the uses of biomass for building platform molecules [40]
A forest biorefinery is ... a multi-product factory that integrates biomass conversion processes and equipment to produce fuels and chemicals from wood-based biomass [41]
[The biorefinery is] an integrated system of bio-based firms, able to produce a wide range of goods from biomass raw materials (chemicals, bio-fuels, food and feed ingredients, biomaterials, including fibres and power) using a variety of technologies, maximising the value of the biomass [42]
Biorefining is the transfer of the efficiency and logic of fossil-based chemistry and substantial converting industry as well as energy production onto the biomass industry [43]
Biorefinery systems [are systems] in which biomass can be utilized entirely by conversion through multiple processes into a number of valuable products [44]

How to categorize different types of biorefineries into subdivisions is another question which has not yet been answered with any consensus. As the biorefinery concept spread and evolved the need to understand the differences became apparent leading to a discussion about different generations of biorefineries.[45,46] Later efforts focused on more refined categorizations based on either the feedstocks or the platform technologies used,[47,43] however none of these categorization efforts do hitherto seem to have been universally accepted. The biorefinery discourse in the research literature is thus clearly lacking a definition which all actors agree upon, which increases the difficulty to discuss general aspects of biorefinery innovation, e.g. policy instruments needed to facilitate the development and diffusion of biorefinery technologies.

3. The emerging biorefinery innovation system

Table 3 introduces and briefly summarizes the publications reviewed in the paper, and positions the literature in relation to the different structural and functional aspects of the biorefinery technology innovation system.

Table 3. Overview of the main findings relating to the TIS structure and functions.

Themes	Publications	Key insights
System structure: Actors, networks, institutions	Chambost et al., 2009; Janssen et al., 2008; Karltorp and Sandén, 2012; Laestadius, 2000; Lundberg, 2013; McCormick and Kautto, 2013; Menrad et al., 2009; Novotny and Nuur, 2013; Näyhä and Pesonen, 2014; Pätäri et al., 2011; Stuart, 2006; Voytenko and McCormick, n.d.;Näyhä and Pesonen, 2012	Actors from different industrial sectors engage with biorefinery innovation, although hesitantly Networks are important but difficult to develop into business partnerships
Function 1: Knowledge development and diffusion	Bennett and Pearson, 2009; Björkdahl and Börjesson, 2011; Bozell, 2008; Cherubini and Strømman, 2011; Ekman et al., 2013; Hansen, 2010; Kamm et al., 2006; Karltorp and Sandén, 2012; Laestadius, 2000; Novotny and Laestadius, 2014; Werpy et al., 2004; Voytenko and McCormick, n.d.;Bozell and Petersen, 2010	Academic research on biorefinery technologies dominates Forest industry firms find it difficult to lead development and diffusion of innovations
Function 2: Entrepreneurial experimentation	Dansereau et al., 2014; Hansen and Coenen, 2015; Hytönen and Stuart, 2010; Kivimaa and Kautto, 2010; Menrad et al., 2009; Näyhä and Pesonen, 2012;Cooke, 2011; Cooke 2012	Experimentation is rare due to high costs and vested interests SMEs in the area exist, but their activities are unknown
Function 3:	Bozell and Petersen, 2010; Holladay et	National policies have

Influence on the direction of search	al., 2007; Kamm et al., 2006; Näyhä and Pesonen, 2012; Peck et al., 2009; Pätäri, 2010; Schieb and Philp, 2014; Werpy et al., 2004;Voytenko and McCormick, n.d.	focused on biofuels, skewing biorefineries towards fuel production technologies
Function 4: Resource mobilization	Björkdahl and Börjesson, 2011; Chambost et al., 2009; Hansen, 2010; Laestadius, 2000; Novotny and Laestadius, 2014; Näyhä and Pesonen, 2012; Näyhä and Pesonen, 2014; Pätäri et al., 2011; Söderholm and Lundmark, 2009; Voytenko and McCormick, n.d.	Mobilization of financial resources is a large barrier for firms Lack of capabilities and strategies for biorefineries in firms Raw material resources are an important constraint
Function 5: Market formation	de Jong et al., 2012b; Dornburg et al., 2008; Kamm et al., 2012; Menrad et al., 2009; Shen et al., 2010; van Haveren et al., 2008; McCormick et al., 2012	Successful formation of markets for biofuels due to quotas and strict policies Other product categories still struggle to establish market niches
Function 6: Legitimation	Menrad et al., 2009; Näyhä and Pesonen, 2012; Ottosson, 2011; Peck et al., 2009; Pätäri et al., 2011; Voytenko and McCormick, n.d.; Wellisch et al., 2010	Biorefineries have legitimacy among policymakers globally Several concerns among consumers and NGOs remain

3.1. The structure of the innovation system: actors, networks, and institutions

Before reviewing work on the biorefinery TIS functions presented in Table 1, we first briefly consider the extent to which the structural components of the innovation system (the actors, networks and institutions) are present in the biorefinery TIS.

In terms of *actors*, forest industry companies are increasingly engaged with biorefinery innovation,[26,48] and universities and research institutes in countries such as Canada, Finland and Sweden have been very active in the field for decades. Companies from the sugar, starch and biofuel industry are also very active while, conversely, the chemical industry remains skeptical to committing resources to biorefinery activities.[44] While biorefinery related research and development is a primary task for universities, research institutes and industry, the public actors and civil society have been shown to play important roles primarily via building understanding, support and acceptance for the biorefineries.[49]

The importance of collaboration in *networks* – across industry sectors and including both public and private actors – is frequently stressed for the development of biorefineries[1] as means to access the necessary capital for new large-scale investments, combine complementary forms of knowledge, change regional institutions, and establish control over delivery chains.[50,51] In many policy initiatives, triple helix approaches to biorefinery technology innovation have thus been suggested and implemented.[52] However, evidence highlights that establishing new partnerships is often a challenging task, in particular between forestry firms and potential partners from other industries such as chemicals or energy, which find it difficult to agree on the distribution of value added between them.[53] Consequently, such joint ventures rarely materialize.[50,51]

In terms of the *formal institutions* guiding the behavior of actors in the biorefinery TIS, many are related to specific product groups. Policy initiatives regarding biofuels such as EU directives on renewable energy and fuel quality, and US renewable fuel standards have played an important role in developing the sector. In contrast, many higher value added product groups such as biochemicals are considered by fewer policies for diffusion support, although institutional support in terms of research is significant. Many product categories are also defined by strict industrial standards and quality requirements, which decreases the possibilities for experimentation.[54] *Informal institutions,* such as values, norms and practices within the industries are usually strongly aligned within sectors and organizational structures. Changing these institutions in favor for biorefineries thus requires an ability to sense and act upon "weak signals"[55] or a more radical regime destabilization.[56] It has also been shown that changes in local institutional settings can be important for supporting biorefineries.[57]

3.2. Function 1: knowledge development and diffusion

Fundamental for the development of all technological innovation is the development and diffusion of new knowledge. Different types of knowledge (e.g. scientific, technological, logistic, and design related knowledge) are all important. This is the traditional focus of R&D efforts and also for much of research and innovation policy, e.g. by supporting both academic and industrial research projects. For biorefineries not only the creation of new knowledge but also the combination of knowledge from different, earlier very separate fields, e.g. microbiology and process engineering, has been important.

The development of knowledge regarding the operation of biorefineries and their processes is extensive within mainly academic and public research. Important products from future biorefineries have been identified,[10,58] as well as which chemicals and products can be substituted,[59] and the general outline of how different types of biorefineries could work is rather well understood.[16,60] Several challenges regarding the implementation of biorefineries do however remain. Integration of biorefineries into existing technical systems is an important issue regardless of what kind of biorefinery is envisioned.[37] This concerns for example difficulties to integrate new material and energy flows in existing plants,[56] or to integrate biorefineries with larger, external systems.[61] Other potential challenges include a variety of technology choices in biorefineries that might create confusion, a lack of radical innovations, and a requirement that technology is able to accommodate different feedstocks.[49]

The internal R&D investments of forestry and pulp and paper industry companies are reportedly low,[62] leading to a low rate of innovations being developed and diffused from within the sector. Sectoral research institutes driving R&D in the industry may have contributed to other actors having neglected R&D and new possible technologies for a long time.[54] One reason presented for this is that technologies are anyway supplied by special suppliers, who provide all competitors with all technologies instantly, so it is of little use to invest in in-house R&D. There is also a lack of strategies for innovation, education and skill development within forest industry companies,[62,63] which decreases the contribution these companies can make to set the agenda for and actively participate in the development of biorefinery technologies. Especially new biotechnological processes or pathways may be ignored by the pulp and paper industry as the sector is traditionally not linked to the biotechnology research community, and originates from a very different form of science.[54] On the other hand the limited internal R&D may lead to cost- and risk-sharing if technology providers can distribute the R&D costs and risks to several users, and it may also support the formation of vertical R&D networks.[64]

3.3. Function 2: entrepreneurial experimentation

Not only fundamental knowledge is important, but also the use of that knowledge by different actors for a wide range of experiments, of which many by default will fail, to reduce the uncertainty regarding the novel technologies. Entrepreneurial experimentation relates not only to activities by new firms but also includes for example incumbent firms experimenting with different varieties and applications of the new technology, or novel business models and marketing approaches for the new technologies.

Although there is indeed very much R&D on biorefinery processes, designs and configurations, most of this work seems to be carried out to develop knowledge. Experimentation by entrepreneurs seems almost absent. One of the barriers towards entrepreneurial experimentation is the large investments needed to fully test the viability and feasibility of different biorefinery concepts and designs, which is closely related to the mobilization of resources. Cases of entrepreneurial biorefinery experiments have been described, in which pulp mills have been redesigned for new major products. Even though the new product is intended for textiles and not for papermaking, it is however still cellulose fibres from wood.[65,66] Other reports highlight that the will for entrepreneurial experimentation is very limited when the stakes and investment costs are as high as for converting pulp mills into biorefineries.[67] Further, the struggle for control within companies has also been pointed out to be one of the factors limiting the possibilities for biorefinery investments – it is difficult for biorefinery departments within companies to convince the management about the possible benefits from biorefinery investments, when competing investments in improvements of existing technologies can present return-on-investment calculations that are characterized by much lower uncertainty.[68] This uncertainty , however, can be handled in different ways, e.g. through formal risk modelling[69] or supply-chain scenario-based planning.[70]

SMEs are reportedly participating in the development of biorefineries. Established forest biorefinery consortia and clusters offer opportunities for small companies to enter new larger markets.[48] At the same time the characteristics of the relations between large industry firms and the SMEs are not clear.[44]

3.4. Function 3: influence on the direction of search

Incentives and pressures which push and pull actors into a new technological field, as well as set the agenda within the field, are what constitute the influence on the direction of search. Such incentives and pressures can be of different kinds, e.g. regulations and policy, identification of new demands, visions and expectations, research outcomes as well as crises in traditional technological fields. The direction of search is thus closely related to the perceived opportunities for business related to the emerging technologies.

Visions for biorefinery technologies and products have focused very much on biofuels and bioenergy in the EU. Specific fuel products were early identified in European Union directives on renewable energy and fuel qualities which pushed the development towards specific fuel products. No targets were set for chemicals, materials or other products from biorefineries.[49] The biofuel focus in EU policy is mirrored in interests of forest industry actors, who were mainly considering fuel products when discussing possible products from forest biorefineries.[48,71] European policy makers perceive national and international regulations as being drivers rather than barriers for biorefinery systems, but also acknowledge that deficiencies exist in the strategies for how to promote the development of the industry.[72]

The USA did however in their efforts regarding biomass based technologies identify targets for both biofuels and bioproducts in a vision up to 2030. This vision called explicitly for more research in three key areas – biomass characteristics, biomass production, and biomass conversion and processing – as well as emphasized the need to create regulations and a market environment for biobased products.[60] Governmental visions and targets have thus aimed to influence the R&D on biorefineries, seemingly with a focus on biofuels rather than bioproducts. Two important reports focusing attention of many biorefinery researchers to specific outputs were prepared for the US DOE, a work that started already in 2004,[58,73] but has been revisited since due to the rapid knowledge development.[10]

Long-term stability in the use of specific policy instruments is crucial in sectors where new operations represent a high risk investment such as biorefineries. However, currently there are no policies that would directly target biorefineries in the EU, and any long-term targets, i.e. beyond 2020, for the sector development are absent, which hinders the direction of search[49] and still causes worries about actual support for biorefineries not only focusing on fuel products.[15] It thus seems that there is yet no shared understanding on which directions the continued development of biorefinery technologies should take and thus the guidance remains weak.

3.5. Function 4: resource mobilization

During the development of the TIS there will be a need for resources of different kinds. Financial resources such as seed and venture capital are needed for investments, human resources are needed for skilled tasks such as research and education, and material resources such as infrastructure and raw materials are necessary for the construction and operation of the technologies.

The mobilization of resources is seen as one of the major problems for the development of forest biorefineries. The earlier discussed absence of political targets beyond 2020 for advanced biofuels and biorefinery products in the EU creates low certainty for investments and project financing, which significantly constrains the development of biorefinery technologies.[49] The forestry and pulp and paper industries in Europe and North America are no longer strong and profitable enough to be able to mobilize the financial resources needed for full-scale deployment of biorefineries. Thus partnering will be needed – although not only for this reason – to deploy forest biorefineries, but it seems that there is also a hesitancy to engage in partnerships with actors from the energy industry as it is believed that it will be difficult to create partnerships which manages to distribute costs and potential profits fairly.[48,53] The importance to choose partners and create strategic partnerships has also been stressed as a way of transforming companies from the forestry and pulp and paper industries to biorefinery companies.[51] In the search for partners it is then important to acknowledge that different partners may be needed for different phases of biorefinery development and deployment – initially for R&D, and later for product distribution and marketing.

Regarding human and organizational resources forest industry firms have hitherto been focused on conventional technologies and economies of scale that have been dominating the industry. The firms will thus have to complement and develop these into more dynamic capabilities for innovation to manage the transition into a biorefinery sector with economies of scope[55,63] as well as utilizing unknown knowledge bases[54] to support new development blocks of integrated process and product technologies.[64] Forest industry firms may however have a better position to develop the needed capabilities than new entrants or firms from other sectors.[48] Mobilizing and developing the needed capabilities and human resources does however require new strategies for these purposes, something that is reportedly missing.[62,63]

A further challenge is to handle the needed material resources. Collecting, transporting and utilizing existing wood biomass resources are capabilities that are already well developed in forest industry companies.[48] These firms also have infrastructure in place to manage raw materials from the forest,[74] a type of raw materials that firms and infrastructures in other industries, e.g. chemicals and energy, are not well adapted to handle.

3.6. Function 5: market formation

Markets are not naturally existing phenomena, but have to be formed by identifying and articulating demand as well as supply and designing and implementing its institutional and regulative underpinnings. Market places must be created, as well as standards for trade and support related to the technology. Markets often develop from niche markets with a limited number of actors present, via bridging markets when volumes grow, to mass markets when uncertainties regarding the technology are reduced. As markets are always related to specific products or services, it becomes crucial to establish exactly which products are in the focus of the analysis. Biorefinery products can be a very wide range of fuels, chemicals or other bioproducts intended for mass markets.

Markets for biofuels have been prioritized by policy makers and supported through e.g. tax schemes and mandatory blending requirements in standard fuel products.[75] Clear targets for production and use of biofuel products supported the creation of markets for these products. By specifying market penetration requirements for both bioenergy and biofuels the market was formed and fostered to grow, while no similar targets were set for biobased chemicals.[43]

Although bulk chemicals have been argued to be a promising market for biorefinery products,[76,77] limited support within the chemical industry speak against this potential.[44] Important platform chemicals, similar to the ones currently used as building blocks for most of all petrochemical products, have been identified, but the global markets for most of these are reportedly rather small – with the exception of fuel components. Also polymers and plastics have been pointed out as important categories for biorefinery products. Some products have been able to form special niches on the market where they have successfully directly substituted traditional plastics and grow rapidly, but the general breakthrough remains distant.[11,12]

3.7. Function 6: legitimation

Legitimation is the process of gaining social acceptance and support for the TIS among relevant surrounding actors and institutions, which is necessary for the mobilization of resources as well as for customers to articulate a demand. An important initial hurdle to overcome is to describe and gain acceptance for the challenge that the technology is intended to handle, as well as the reasons for it being a suitable answer to the question.

Factors that are contributing to the legitimacy of biorefineries are their possible ability to support regional development and reindustrialization as well as the promise of reducing the dependence on fossil resources in the modern economy.[17] There are however also a number of challenges for the legitimacy of biorefineries. Among them are the still high costs and perceived low maturity of many of the technologies, discredited reputation of certain biomass feedstocks and biofuels, and uncertainty regarding future sustainability requirements. This creates mixed messages and heterogeneous public perceptions of bio-based products and bioenergy.[49]

Surveys among European industrial actors show that biorefining is viewed to be a promising concept. However, the interest differs across industrial sectors, with the chemical sector being significantly less positive than other sectors, which could be detrimental to the development of new chemical processes for biorefineries.[44] The forestry and pulp and paper industries are described as very conservative and more focused on protecting current business structures rather than exploring new possibilities by resisting change.[78] There is thus no consensus in how the industry should engage in the biorefinery business, but at the same time actors express that it is most probably necessary, or at least a good way of broadening the scope of current business.[48,55] Surveys among European policy-makers also show that although biorefineries are supported by policymakers, there are also threats and negative connotations to biorefineries. Perceived threats to the legitimacy of biorefineries are the use of GMO crops, food crop displacement, deforestation, and biodiversity losses. Further, the understanding of how policies and policy systems related to biorefinery development interact was reported to be flawed, pointing to the fact that policymakers have limited knowledge about how policies support or oppose biorefineries.[72]

Information and knowledge about biorefineries is reported to be mainly diffused by national governmental agencies and research institutes, followed by mass media and NGOs. The information from governmental agencies and research institutes is most highly regarded, and also most positive, whereas information from other actors is perceived as less reliable and more negative to biorefineries.[72] However, the fact that international agencies and organizations such as the IEA, OECD and WEF are actively partaking in discussions about the future of biorefineries clearly shows that it is an issue that has gained legitimacy among policymakers globally.

4. Conclusions and implications for future research

The purpose of this literature review has been to synthesize current knowledge about how biorefinery technologies are being developed, deployed, and diffused, and to identify actors and institutions relevant for these processes. Even though our first main insight partly follows from the adopted conceptual (innovation system) approach, it is nonetheless important to stress that there is a consensus in the reviewed literature that research and knowledge are necessary but certainly not sufficient to further biorefining. That is, simply investing more resources in R&D will not help to enable biorefineries to cross the "valley of death" towards greater commercial investments. This is however not to say that R&D on biorefineries is no longer needed. Especially knowledge on how to integrate biorefineries into existing technical systems remains critical for its further development. This is challenging as it often transcends the competences of single disciplines and sectors and requires inter-disciplinary and inter-sectoral partnerships to allow for more combinatorial and re-combinatorial modes of innovation.

At the same time, this literature review has revealed that establishment and maintenance of such partnerships has been difficult. This could partly be seen against a background where strategies and investments by actors in the forest industry are to a great extent guided by vested interests and path-dependence and a relatively marginal interest to experiment with cross-industry partnerships, new business models and creation of new value chains. This process of lock-in is further corroborated by the way in which existing institutions, both formal and informal, are more conducive to low value added products from biorefineries, notably fuels, heat and energy, creating barriers to establish (and experiment with) new, more radical development pathways for biorefineries that encompass a greater variety of products and industries.

When specifying the factors that drive and inhibit the development and diffusion of biorefineries, a number of critical and important observations can be made. As internal R&D investments of incumbent industry companies are reportedly low, and a lot of research instead is left to sectoral research institutes, there is little absorptive capacity in industry to actually exploit new knowledge on biorefineries. This lack of absorptive capacity should be understood in both cognitive terms but also in terms of a lack of capacity for entrepreneurial experimentation to develop new value propositions and business models. While the significance and need for entrepreneurship, as well as the importance of SMEs is generally acknowledged, there is no agreement on how to facilitate conditions for entrepreneurs and SMEs to enter into the field of biorefineries.

Visions for biorefinery technologies and products have focused very much on biofuels and bioenergy, which can be seen of course in light of current attention for climate change mitigation. Similarly, legislation and regulation has been instrumental in creating a market for these products. Here we find a very illustrative example of how policy-making has made a substantial contribution in providing conducive conditions for the adoption and diffusion of biorefineries, albeit with a relatively limited scope in terms of products. Whether and how, (climate) regulation and legislation could also provide a similar role for non-energy related products from biorefineries remains to be seen but would provide a highly relevant and important area of future research.

At the same time, it should be noted that issues related to regulation for biorefinery products are heavily intertwined with wider discussions around legitimacy and social acceptance. This has already been documented in the case of biofuels and bioenergy. Questions around legitimacy and social acceptance are deeply political and, some would say, politicized and would require greater attention for how societal discourses around biorefineries are shaped by and shaping its further development. Further research on how these visions and discourses are formed and negotiated by different interests and actors to shape the material outcome of biorefinery innovation processes would be valuable to provide insights on the very different futures that biorefineries may shape.

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