Technological innovation systems for biorefineries - A review of the literature

Fredric Bauer

Department of Chemical Engineering, Lund University, P.O. Box 124, 22100 Lund, Sweden

Lars Coenen

Melbourne Sustainable Society Institute, Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville VIC 3010, Australia

Centre for Innovation, Research and Competence in the Learning Economy (CIRCLE), Lund University, P.O. Box 117, 22100 Lund, Sweden

Teis Hansen

Department of Human Geography, Lund University, Sölvegatan 10, 22362 Lund, Sweden

Centre for Innovation, Research and Competence in the Learning Economy (CIRCLE), Lund University, P.O. Box 117, 22100 Lund, Sweden

Nordic Institute for Studies in Innovation, Research and Education (NIFU), P.O. Box 5183 Majorstuen, 0302 Oslo, Norway

Kes McCormick

International Institute for Industrial Environmental Economics (IIIEE) at Lund University, P.O. Box 196, 22100, Lund, Sweden

Yuliya Voytenko Palgan

International Institute for Industrial Environmental Economics (IIIEE) at Lund University, P.O. Box 196, 22100, Lund, Sweden

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Abstract: 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. Biorefineries are considered an integral part of the development towards a future sustainable bioeconomy. The purpose of this literature review is 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. A number of key findings can be obtained from the literature. First, investing more resources in R&D will not help to enable biorefineries to cross the ‘valley of death’ towards greater commercial investments. Second, while the importance and need for entrepreneurship and the engagement of small and medium-sized enterprises (SMEs) is generally acknowledged, there is no agreement how to facilitate conditions for entrepreneurs and SMEs to enter into the field of biorefineries. Third, visions for biorefinery technologies and products have focused very much on biofuels and bioenergy with legislation and regulation playing an instrumental role in creating a market for these products. But there is a clear need to incentivize non-energy products to encourage investments in biorefineries. Finally, policy support for biorefinery developments and products is heavily intertwined with wider discussions around legitimacy and social acceptance. The paper concludes by outlining current knowledge gaps.

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 bioeconomy¹ – 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 plastics¹¹, 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 infamous ‘valley of death’ – the phase between successful demonstration and market introduction which many technologies have had a hard time bridging due to a lack of

1 institutional support¹⁴ – towards greater commercial usage.^{15,16} Albeit that such development
2 and experimental verification of new technologies in demo- and production-scale facilities
3 have helped to overcome important technical constraints,^{17,18} other barriers, mainly of socio-
4 political and economic nature,¹⁹ for the widespread adoption of innovative biorefinery
5 technologies continue to exist. Understanding these barriers, and how they can be overcome,
6 is thus an important task to support the development of biorefinery technologies.

7
8 How the processes of diffusion and adoption of new technologies evolve have been key topics
9 in innovation research,^{20–23} which has shown that these processes depend not only on
10 technological breakthroughs, but also on many other types of factors, e.g. cognitive and social
11 lock-in to well-known solutions as well as poor alignment of new innovations to fit within
12 existing regulatory schemes. The interplay of scientific, technological, economic and political
13 dimensions is stressed in research on innovation systems – a concept describing all the actors,
14 networks and institutions involved in developing, adopting and diffusing innovations.²⁴
15 Innovation systems for renewable energy technologies has become a key research area and it
16 has been shown that the slow adoption of these technological innovations depend on complex
17 innovation system failures such as insufficient market demand, fragmented innovation
18 networks or lack of entrepreneurial experimentation.¹⁴ Overcoming these failures requires
19 policies and efforts in many different areas.^{25,26} Research on technological innovation systems
20 (TIS) has shown that several key processes, or functions, must be fulfilled to enable the
21 emergence of new technologies. It is therefore relevant to ask the question how the extensive
22 research on biorefineries has contributed to developing knowledge and enriched
23 understanding of these functions and its implications in terms of policy and governance.

1 The purpose of this paper is thus to review the research on biorefinery technology innovation,
2 with the aim to synthesize current knowledge about how biorefinery technologies are being
3 developed, deployed, and diffused, and to identify categories of actors, networks and
4 institutions relevant for these processes. This also allows the identification of current
5 knowledge gaps, which future research should address. The review is limited to biorefinery
6 development in North America and Europe, as these regions have been among the most active
7 in the development of biorefineries and analyzed in the research literature. Further, aiming to
8 contribute to the understanding of how the emergence of biorefineries affects industrial
9 development the review focuses on forest biorefineries. In this paper we use a definition of a
10 forest biorefinery which positions it as an analogy to a petroleum refinery that processes
11 forestry biomass into a wide range of fuels, products and chemicals. Such a broad definition is
12 motivated by the purpose of this paper as it allows us to capture data from major literature
13 sources that discuss the diffusion of forestry biorefineries including those sources that use
14 narrower definitions (see Section 3.2). The focus on forestry sector is due to the fact that it is
15 one of the sectors which is often in the spotlight in the discussion about deploying and
16 integrating biorefinery technologies into current industries, as well as it is a sector in which
17 firms have put significant efforts into researching different possible applied biorefinery
18 configurations.²⁷

19
20 The literature reviewed was identified through academic databases. Relevant publications
21 from 1995-2014 were initially identified in the SCOPUS database with the search string
22 “biorefin* AND innovati*” in the title, abstract, or keywords. Publications related to the study
23 of innovation processes for biorefinery technologies were included while publications strictly
24 reporting technological experimentation were excluded. The material was subsequently
25 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 social, environmental and political science. The literature was therefore interpreted through various lenses.

2. A technological innovation systems perspective on biorefineries

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.²⁴ 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, individual entrepreneurs and users – 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 TIS framework has been used to analyze the emergence of a multitude of technological innovations, and usually focuses on the development of a single technology. 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.¹⁴ The performance of a TIS is usually

assessed through a set of associated system functions or key processes.^{28–30} 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,³¹ biomass gasification in the Netherlands,³² agro-bioenergy in Ukraine³³ as well as in Sweden and Denmark.³⁴ 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.^{26,35} In this paper we use the functions as described by Bergek et al.,^{30,36} but do not include “development of positive external economies” as a separate function as this largely overlaps with the other functions.³⁷ The six functions used in this paper are introduced in Table 1. These functions are primarily used as a structuring device to order findings from various studies and should, thus, not be seen as an explanatory framework.

TABLE 1

3. The field of biorefinery research

3.1. A multidisciplinary and growing field

Although the first identified use of the term biorefining is from 1981³⁸ 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

3.2. 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”.³⁸ 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.³⁹ Later publications have left

the strict focus on the three-step process described by Levy et al. and propose more general conceptualizations of biorefining and biorefineries. A list of examples of definitions found in the literature is shown below in Table 2.

TABLE 2

Table 2 shows that the definitions differ widely as some of them view biorefineries as larger production systems that incorporate different firms and factories which may be geographically dispersed and operate throughout the entire value chain from raw material to consumer goods, whereas other definitions focus on the factory which utilizes an undefined set of processing technologies to produce certain products from biomass. 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. Finally, some definitions focus on biorefining as a knowledge concept, a new set of strategies and logics aiming to intensify the use of biomass resources. Common to most of the shown definitions is the emphasis on a multiplicity of products being produced by biorefining, indicating a need for parallel processes, as well as the need for biorefineries to not only produce fuel products but also materials or chemicals of higher complexity and value.

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.^{47,48} Later efforts focused on more refined categorizations based on either the feedstocks or the platform technologies used,^{46,49} 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 as well as the readiness of markets for these technologies and technology acceptance among the users.

4. 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

4.1. 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,^{27,50} 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.⁴¹ While biorefinery related research and development is a primary task for universities, research institutes and industry,

1 the public actors and civil society have been shown to play important roles primarily via
2 building understanding, support and acceptance for the biorefineries.¹⁹

3
4 The importance of collaboration in *networks* – within and across industry sectors and
5 including both public and private actors – is frequently stressed for the development of
6 biorefineries¹ as means to access the necessary capital for new large-scale investments,
7 combine complementary forms of knowledge, change regional institutions, and establish
8 control over delivery chains.^{51,52} In many policy initiatives, triple helix approaches to
9 biorefinery technology innovation have thus been suggested and implemented.⁵³ However,
10 evidence highlights that establishing new partnerships is often a challenging task, in particular
11 between forestry firms and potential partners from other industries such as chemicals or
12 energy, which find it difficult to agree on the distribution of value added between them.⁵⁴
13 Consequently, such joint ventures rarely materialize.^{51,52}

14
15 In terms of the *formal institutions* guiding the behavior of actors in the biorefinery TIS, many
16 are related to specific product groups. Policy initiatives regarding biofuels such as EU
17 directives on renewable energy and fuel quality, and US renewable fuel standards have played
18 an important role in developing the sector. In contrast, many higher value added product
19 groups such as biochemicals are considered by fewer policies for diffusion support, although
20 institutional support in terms of research is significant. Many product categories are also
21 defined by strict industrial standards and quality requirements, which decreases the
22 possibilities for experimentation.⁵⁵ *Informal institutions*, such as values, norms and practices
23 within the industries are usually strongly aligned within sectors and organizational structures.
24 Changing these institutions in favor for biorefineries thus requires an ability to sense and act

upon “weak signals”⁵⁶ or a more radical regime destabilization.⁵⁷ It has also been shown that changes in local institutional settings can be important for supporting biorefineries.⁵⁸

4.2. 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 fields has been important, creating overlaps which in the context of large manufacturing industries may not have been well explored, e.g. integrating knowledge of energy markets or composite materials with traditional wood products manufacturing processes.

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,^{10,59} as well as which chemicals and products can be substituted,⁶⁰ and the general outline of how different types of biorefineries could work is rather well understood.^{17,61} 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.³⁹ This concerns for example difficulties to integrate new material and energy flows in existing plants,⁵⁷ or to integrate biorefineries with larger, external systems.⁶² 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.¹⁹

1
2 The internal R&D investments of forestry and pulp and paper industry companies are
3 reportedly low,⁶³ leading to a low rate of innovations being developed and diffused from
4 within the sector, although the significance of R&D is understood to be increasing greatly
5 within the forest industry.⁶⁴ Sectoral research institutes driving R&D in the industry may have
6 contributed to other actors having neglected R&D and new possible technologies for a long
7 time.⁵⁵ One reason presented for this is that technologies are anyway supplied by special
8 suppliers, who provide all competitors with all technologies instantly, so it is of little use to
9 invest in in-house R&D. There is also a lack of strategies for innovation, education and skill
10 development within forest industry companies,^{63,65} which decreases the contribution these
11 companies can make to set the agenda for and actively participate in the development of
12 biorefinery technologies. Especially new biotechnological processes or pathways may be
13 ignored by the pulp and paper industry as the sector is traditionally not linked to the
14 biotechnology research community, and originates from a very different form of science.⁵⁵ On
15 the other hand the limited internal R&D may lead to cost- and risk-sharing if technology
16 providers can distribute the R&D costs and risks to several users, and it may also support the
17 formation of vertical R&D networks.⁶⁶

18 19 4.3. Function 2: entrepreneurial experimentation

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

1
2 Although there is indeed very much R&D on biorefinery processes, designs and
3 configurations, most of this work seems to be carried out to develop knowledge.
4 Experimentation by entrepreneurs seems almost absent. One of the barriers towards
5 entrepreneurial experimentation is the large investments needed to fully test the viability and
6 feasibility of different biorefinery concepts and designs, which is closely related to the
7 mobilization of resources. Cases of entrepreneurial biorefinery experiments have been
8 described, in which pulp mills have been redesigned for new major products. Even though the
9 new product is intended for textiles and not for papermaking, it is however still cellulose
10 fibers from wood.^{67,68} Other reports highlight that the will for entrepreneurial experimentation
11 is very limited when the stakes and investment costs are as high as for converting pulp mills
12 into biorefineries.⁶⁹ Further, the struggle for control within companies has also been pointed
13 out to be one of the factors limiting the possibilities for biorefinery investments by large
14 incumbent firms – it is difficult for biorefinery departments within companies to convince the
15 management about the possible benefits from biorefinery investments, when competing
16 investments in improvements of existing technologies can present return-on-investment
17 calculations that are characterized by much lower uncertainty.⁷⁰ This uncertainty can be
18 handled in different ways, e.g. by measures such as formal risk modelling⁷¹ or supply-chain
19 scenario-based planning,⁷² but risk aversion is likely to remain an important weakness of
20 incumbent firms.

21
22 SMEs are reportedly participating in the development of biorefineries. Established forest
23 biorefinery consortia and clusters offer opportunities for small companies to enter new larger
24 markets. Although small firms are unlikely to be capable of investing in biorefineries due to
25 the scale of investment needed,⁵⁰ opportunities for SMEs are likely to occur in different parts

1 of biorefinery value chains, e.g. in raw material acquisition, consultancy, and technology
2 development.⁴³ SMEs with specialized knowledge and competences about parts of the value
3 chain thus reportedly have good chances of contributing to the development of biorefineries
4 through partnerships, networks, and cooperation with larger firms which can lead the
5 investments. At the same time the characteristics of the relations between large industry firms
6 and the SMEs are largely unknown,⁴¹ making it difficult to assess how these opportunities are
7 being exploited by SMEs.

8 9 4.4. Function 3: influence on the direction of search

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

16
17 Visions for biorefinery technologies and products have focused very much on biofuels and
18 bioenergy in the EU. Specific fuel products were early identified in European Union
19 directives on renewable energy and fuel qualities, pushing the development towards specific
20 fuel products, while no targets were set for chemicals, materials or other products from
21 biorefineries.¹⁹ The biofuel focus in EU policy is mirrored in interests of forest industry
22 actors, who were mainly considering fuel products when discussing possible products from
23 forest biorefineries.^{50,64} European policy makers perceive national and international
24 regulations as being drivers rather than barriers for biorefinery systems, but also acknowledge
25 that deficiencies exist in the strategies for how to promote the development of the industry.⁷³

1 Examples of such deficiencies include absence of EU policies that would target biorefineries
2 as a whole; lack of long term (beyond 2020), stable and consistent strategies by the
3 governments at various levels; and lack of ambitious targets for biofuels and bioproducts in
4 countries that have already achieved EU targets (e.g. Sweden).¹⁹

5
6 The USA did however in their efforts regarding biomass based technologies identify targets
7 for both biofuels and bioproducts in a vision up to 2030. This vision called explicitly for more
8 research in three key areas – biomass characteristics, biomass production, and biomass
9 conversion and processing – as well as emphasized the need to create regulations and a
10 market environment for biobased products.⁶¹ Governmental visions and targets have thus
11 aimed to influence the R&D on biorefineries, seemingly with a focus on biofuels rather than
12 bioproducts. Two important reports focusing attention of many biorefinery researchers to
13 specific outputs were prepared for the US DOE, a work that started already in 2004,^{59,74} but
14 has been revisited since due to the rapid knowledge development.¹⁰

15
16 It is interesting to note the discrepancy between the emphasis on non-fuel products in the
17 definitions of biorefineries, as shown in Table 2, and the strong focus on fuel products in
18 governmental policies. These policies have thus in a way directed the search away from
19 biorefineries towards simpler biofuel technologies and facilities. Long-term stability in the
20 use of specific policy instruments is crucial in sectors where new operations represent a high
21 risk investment such as biorefineries. If any long-term political targets are absent,
22 entrepreneurs face economic risks linked to high investment costs and project financing. The
23 later are amplified by low oil price, uncertainties around biomass price and feedstock
24 accessibility, as well as uncertainties of cognitive nature, e.g. no clear distinction between first
25 and second generation biofuels in the plans and policies contributes to "bad" reputation of

1 certain biomass feedstocks and biofuels.¹⁹ However, as already mentioned, there are no
2 policies that would directly target biorefineries in the EU, and any long-term targets, i.e.
3 beyond 2020, for the sector development are absent, which hinders the direction of search¹⁹
4 and still causes worries about actual support for biorefineries not only focusing on fuel
5 products.¹⁶ It thus seems that there is yet no shared understanding on which directions the
6 continued development of biorefinery technologies should take and thus the guidance remains
7 weak.

8 9 4.5. Function 4: resource mobilization

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

15
16 The mobilization of resources is seen as one of the major problems for the development of
17 forest biorefineries, and as discussed above the scale of resources needed is identified as a
18 significant barrier for new firms and SMEs. The earlier discussed absence of political targets
19 beyond 2020 for advanced biofuels and biorefinery products in the EU creates low certainty
20 for investments and project financing, which significantly constrains the development of
21 biorefinery technologies.¹⁹ The forestry and pulp and paper industries in Europe and North
22 America are no longer strong and profitable enough to be able to mobilize the financial
23 resources needed for full-scale deployment of biorefineries. Thus partnering will be needed –
24 although not only for this reason – to deploy forest biorefineries, but it seems that there is also
25 a hesitancy to engage in partnerships with actors from the energy industry as it is believed that

1 it will be difficult to create partnerships which manages to distribute costs and potential
2 profits fairly.^{50,54} The importance to choose partners and create strategic partnerships has also
3 been stressed as a way of transforming companies from the forestry and pulp and paper
4 industries to biorefinery companies.⁵² In the search for partners it is then important to
5 acknowledge that different partners may be needed for different phases of biorefinery
6 development and deployment – initially for R&D, and later for product distribution and
7 marketing. Forest industry firms have experience of large investments and assessing risks for
8 long periods of time, which may enable these firms to take a lead role in proposing and
9 planning biorefinery investments together with SMEs and other firms which lack the same
10 capabilities.

11
12 Regarding human and organizational resources forest industry firms have hitherto been
13 focused on conventional technologies and economies of scale that have been dominating the
14 industry. The firms will thus have to complement and develop these into more dynamic
15 capabilities for innovation to manage the transition into a biorefinery sector with economies
16 of scope^{56,65} as well as utilizing unknown knowledge bases⁵⁵ to support new development
17 blocks of integrated process and product technologies.⁶⁶ Forest industry firms may however
18 have a better position to develop the needed capabilities than new entrants or firms from other
19 sectors.⁵⁰ Mobilizing and developing the needed capabilities and human resources does
20 however require new strategies for these purposes, something that is reportedly missing.^{63,65}

21
22 A further challenge is to handle the needed material resources. Collecting, transporting and
23 utilizing existing wood biomass resources are capabilities that are already well developed in
24 forest industry companies.⁵⁰ These firms also have infrastructure in place to manage raw

1 materials from the forest,⁷⁵ a type of raw materials that firms and infrastructures in other
2 industries, e.g. chemicals and energy, are not well adapted to handle.

4 4.6. Function 5: market formation

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

15 Markets for biofuels have been prioritized by policy makers and supported through e.g. tax
16 schemes and mandatory blending requirements in standard fuel products.⁷⁶ Clear targets for
17 production and use of biofuel products supported the creation of markets for these products.
18 By specifying market penetration requirements for both bioenergy and biofuels the market
19 was formed and fostered to grow, while no similar targets were set for biobased chemicals.⁴⁶

21 Although bulk chemicals have been argued to be a promising market for biorefinery
22 products,^{77,78} limited support within the chemical industry speak against this potential.⁴¹
23 Important platform chemicals, similar to the ones currently used as building blocks for most
24 of all petrochemical products, have been identified, but the global markets for most of these
25 are reportedly rather small – with the exception of fuel components. Also polymers and

1 plastics have been pointed out as important categories for biorefinery products. Some
2 products have been able to form special niches on the market where they have successfully
3 directly substituted traditional plastics and grow rapidly, but the general breakthrough remains
4 distant.^{11,12}

6 4.7. Function 6: legitimization

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

13 Factors that are contributing to the legitimacy of biorefineries are their possible ability to
14 support regional development and reindustrialization as well as the promise of reducing the
15 dependence on fossil resources in the modern economy.¹⁸ There are however also a number of
16 challenges for the legitimacy of biorefineries. Among them are the still high costs and
17 perceived low maturity of many of the technologies, discredited reputation of certain biomass
18 feedstocks and biofuels, and uncertainty regarding future sustainability requirements. This
19 creates mixed messages and heterogeneous public perceptions of bio-based products and
20 bioenergy.¹⁹

22 Surveys among European industrial actors show that biorefining is viewed to be a promising
23 concept. However, the interest differs across industrial sectors, with the chemical sector being
24 significantly less positive than other sectors, which could be detrimental to the development
25 of new chemical processes for biorefineries.⁴¹ 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.⁷⁹ 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.^{50,56} 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.⁷³

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.⁷³ 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.

5. Knowledge gaps and calls for future research

Although this review has shown that research on biorefinery innovation has made many important contributions, there are still significant gaps in the literature that future research needs to consider. It is clear that much knowledge has been developed around biorefineries, in

1 terms of technologies and processes, but an understanding of the determinants of how this
2 knowledge is absorbed and utilized in firms, e.g. within the forestry and pulp and paper
3 sectors, is still missing. Analyzing how absorptive capacity and organizational learning is
4 being constructed and developed within these firms would contribute to this end. As for
5 entrepreneurial experimentation, it is explicitly acknowledged in parts of the literature that
6 although the existence of entrepreneurs and SMEs in the field is known, their actual activities
7 and contributions to the field are not. An improved understanding of the conditions and
8 challenges for experimenting in different parts of the value chain and with different types of
9 products would be a valuable contribution. This pertains both to entrepreneurs wanting to
10 establish partnerships with incumbent industry firms and intrapreneurs aiming to diversify
11 current business models of existing firms. The relevance of organizational trust and networks
12 have been highlighted in research on partnerships for biorefineries, but not systematically
13 analysed. Case studies of successful as well as unsuccessful cases could provide valuable
14 information for this aspect.

16 Although it is clear that the interest for biofuels has been spurred by the focus of policies on
17 these products, it remains unknown to what degree different types of policy instruments have
18 contributed to this. Understanding the different roles of policy strategies, instruments, and
19 mixes in the biorefinery area is therefore an important task for future research. This includes
20 traditional research and supply side oriented policies, and, notably, different types of demand
21 side oriented policies which have currently not been well investigated in this area. The roles
22 of consumer preferences and pressure for process industries disconnected from end
23 consumers are also relevant, and hitherto neglected, topics of research. These issues are also
24 relevant for understanding how resources – both financial and human resources – are
25 mobilized in firms and organizations; strategies for prioritizing between incremental process

1 innovation along well-known technological trajectories as opposed to diverging trajectories
2 which may lead farther away from traditional processes but closer to multi-product
3 biorefineries based on new technologies.

4
5 Markets for biofuels have been created and consolidated with a range of policy instruments,
6 but the conditions for other types of biorefinery products are not as well known. As both the
7 marketing strategies as well as consumer behavior for higher value products, e.g. advanced
8 materials, are likely to be different, establishing and nurturing niche markets for such
9 products will require other kinds of instruments. Research on how to regulate and support
10 these other types of markets is seemingly not well connected to the area of biorefineries,
11 although it is highly relevant, and even likely to be a key problem to solve. At the same time,
12 it should be noted that issues related to regulation for biorefinery products are heavily
13 intertwined with wider discussions around legitimacy and social acceptance. This has already
14 been documented in the case of biofuels and bioenergy. Questions around legitimacy and
15 social acceptance are deeply political and, some would say, politicized and would require
16 greater attention for how societal discourses around biorefineries are shaped by and shaping
17 its further development. Further research on how these visions and discourses are formed and
18 negotiated by different interests and actors to shape the material outcome of biorefinery
19 innovation processes would be valuable to provide insights on the very different futures that
20 biorefineries may shape.

21
22 Finally, it is important to improve the understanding of the importance of contextual factors
23 on the biorefinery TIS. Examples of contextual factors of potential importance are natural
24 resource availability, characteristics of visions and policies, and differences in consumption
25 practices. While several conceptual papers have outlined the importance of this analytical

perspective,^{80–82} empirical contributions on the influence of context on TIS development are still missing, also in the field of biorefining. Of particular interest would be a comparison between responses of the forestry industry in Scandinavia and North American to opportunities offered by biorefining, given differences in varieties of capitalism, which have been found to have an important influence on the character of sustainability transition processes.⁸³

6. Conclusions and outlook

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 the implementation of 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

1 vested interests and path-dependence and a relatively marginal interest to experiment with
2 cross-industry partnerships, new business models and creation of new value chains. This
3 process of lock-in is further corroborated by the way in which existing institutions, both
4 formal and informal, are more conducive to low value added products from biorefineries,
5 notably fuels, heat and energy, creating barriers to establish (and experiment with) new, more
6 radical development pathways for biorefineries that encompass a greater variety of products
7 and industries. This is particularly interesting to note since the conceptualization of
8 biorefining has, already from the start, emphasized the need for products of higher value.

9
10 When specifying the factors that drive and inhibit the development and diffusion of
11 biorefineries, a number of critical and important observations can be made. As internal R&D
12 investments of incumbent industry companies are reportedly low, and a lot of research instead
13 is left to sectoral research institutes, there is little absorptive capacity in industry to actually
14 exploit new knowledge on biorefineries. This lack of absorptive capacity should be
15 understood in both cognitive terms but also in terms of a lack of capacity for entrepreneurial
16 experimentation to develop new value propositions and business models. While the
17 significance and need for entrepreneurship, as well as the importance of SMEs is generally
18 acknowledged, there is no agreement on how to facilitate conditions for entrepreneurs and
19 SMEs to enter into the field of biorefineries.

20
21 Visions for biorefinery technologies and products have focused very much on biofuels and
22 bioenergy, which can be seen of course in light of current attention for climate change
23 mitigation. Similarly, legislation and regulation has been instrumental in creating a market for
24 these products. Here we find a very illustrative example of how policy-making has made a
25 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.

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8. References

1. McCormick K and Kautto N, The Bioeconomy in Europe: An Overview. *Sustainability* **5**: 2589–2608 (2013).
2. OECD, *The Bioeconomy to 2030: Designing a Policy Agenda*. OECD Publishing, (2009).
3. de Jong E, Higson A, Walsh P and Wellisch M, *Bio-based Chemicals - Value Added Products from Biorefineries*. IEA Bioenergy - Task 42 Biorefinery, (2012).
4. World Economic Forum, *The Future of Industrial Biorefineries*. World Economic Forum, (2010).
5. de Besi M and McCormick K, Towards a Bioeconomy in Europe: National, Regional and Industrial Strategies. *Sustainability* **7**: 10461–10478 (2015).
6. Ollikainen M, Forestry in bioeconomy - smart green growth for the humankind. *Scand J For Res* **7581**: 37–41 (2014).
7. Kleinschmit D, Lindstad BH, Thorsen BJ, Toppinen A, Roos A and Baardsen S, Shades of green: a social scientific view on bioeconomy in the forest sector. *Scand J For Res* **7581**: 1–31 (2014).
8. Kircher M, The transition to a bio-economy: emerging from the oil age. *Biofuels, Bioprod Biorefining* **6**: 369–375 (2012).

9. Keegan D, Kretschmer B, Elbersen B and Panoutsou C, Cascading use: a systematic approach to biomass beyond the energy sector. *Biofuels, Bioprod Biorefining* **7**: 193–206 (2013).
10. Bozell JJ and Petersen GR, Technology development for the production of biobased products from biorefinery carbohydrates—the US Department of Energy’s ‘Top 10’ revisited. *Green Chem* **12**: 539–554 (2010).
11. Shen L, Worrell E and Patel MK, Present and future development in plastics from biomass. *Biofuels, Bioprod Biorefining* **4**: 25–40 (2010).
12. de Jong E, Higson A, Walsh P and Wellisch M, Product developments in the bio-based chemicals arena. *Biofuels, Bioprod Biorefining* **6**: 606–624 (2012).
13. Bacovsky D, Ludwiczek N, Ognissanto M and Wörgetter M, Status of Advanced Biofuels Demonstration Facilities in 2012. *IEA Bioenergy Task 39 Report* (2013).
14. Negro SO, Alkemade F and Hekkert MP, Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renew Sustain Energy Rev* **16**: 3836–3846 (2012).
15. Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, *et al.*, The path forward for biofuels and biomaterials. *Science* (80-) **311**: 484–489 (2006).
16. Schieb P-A and Philp JC, Biorefining policy needs to come of age. *Trends Biotechnol* **32**: 496–500 (2014).
17. Bozell JJ, Feedstocks for the Future - Biorefinery Production of Chemicals from Renewable Carbon. *CLEAN - Soil, Air, Water* **36**: 641–647 (2008).
18. Wellisch M, Jungmeier G, Karbowski A, Patel MK and Rogulska M, Biorefinery systems - potential contributors to sustainable innovation. *Biofuels, Bioprod Biorefining* **4**: 275–286 (2010).
19. Voytenko Palgan Y and McCormick K, Biorefineries in Sweden: Perspectives on the opportunities, challenges and future. *Biofuels, Bioprod Biorefining* **10**: 523–533 (2016).
20. Carlsson B and Stankiewicz R, On the nature, function and composition of technological systems. *J Evol Econ* **1**: 93–118 (1991).
21. Carlsson B and Jacobsson S, in *Systems of Innovation: Technologies, Institutions and Organizations* (ed. Edquist, C) 266–294 Pinter, (1997).
22. Jacobsson S and Bergek A, Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Ind Corp Chang* **13**: 815–849 (2004).
23. Geels FW, Hekkert MP and Jacobsson S, The dynamics of sustainable innovation journeys. *Technol Anal Strateg Manag* **20**: 521–536 (2008).
24. *Systems of Innovation: Technologies, Institutions and Organizations*. Pinter, (1997).
25. Foxon T and Pearson P, Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. *J Clean Prod* **16**: S148–S161 (2008).

26. Weber KM and Rohrer H, Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive ‘failures’ framework. *Res Policy* **41**: 1037–1047 (2012).
27. Stuart P, The forest biorefinery *Pulp Pap Canada* **107**: 13–16 (2006).
28. Hekkert MP and Negro SO, Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technol Forecast Soc Change* **76**: 584–594 (2009).
29. Hekkert MP, Suurs RAA, Negro SO, Kuhlmann S and Smits REHM, Functions of innovation systems: A new approach for analysing technological change. *Technol Forecast Soc Change* **74**: 413–432 (2007).
30. Bergek A, Jacobsson S, Carlsson B, Lindmark S and Rickne A, Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Res Policy* **37**: 407–429 (2008).
31. Markard J, Stadelmann M and Truffer B, Prospective analysis of technological innovation systems: Identifying technological and organizational development options for biogas in Switzerland. *Res Policy* **38**: 655–667 (2009).
32. Negro SO, Suurs RAA and Hekkert MP, The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. *Technol Forecast Soc Change* **75**: 57–77 (2008).
33. Voytenko Y, Pathways for agro-bioenergy transition in Ukraine. *Biofuels, Bioprod Biorefining* **6**: 124–134 (2012).
34. Voytenko Y and Peck P, Organisational frameworks for straw-based energy systems in Sweden and Denmark. *Biomass and Bioenergy* **38**: 34–48 (2012).
35. Klein Woolthuis R, Lankhuizen M and Gilsing V, A system failure framework for innovation policy design. *Technovation* **25**: 609–619 (2005).
36. Jacobsson S and Bergek A, Innovation system analyses and sustainability transitions: Contributions and suggestions for research. *Environ Innov Soc Transitions* **1**: 41–57 (2011).
37. Binz C, Truffer B and Coenen L, Path Creation as a Process of Resource Alignment and Anchoring: Industry Formation for On-Site Water Recycling in Beijing. *Econ Geogr* **92**: 172–200 (2016).
38. Levy PF, Sanderson JE, Kispert RG and Wise DL, Biorefining of biomass to liquid fuels and organic chemicals. *Enzyme Microb Technol* **3**: 207–215 (1981).
39. Bennett SJ and Pearson PJG, From petrochemical complexes to biorefineries? The past and prospective co-evolution of liquid fuels and chemicals production in the UK. *Chem Eng Res Des* **87**: 1120–1139 (2009).
40. U.S. Department of Energy - Office of Energy Efficiency and Renewable Energy, Biorefinery. *Energy, Environmental, and Economics (E3) Handbook* (1997). Available at: <http://infohouse.p2ric.org/ref/36/35057.htm>. (Accessed: 16th September 2015)

41. Menrad K, Klein A and Kurka S, Interest of industrial actors in biorefinery concepts in Europe. *Biofuels, Bioprod Biorefining* **3**: 384–394 (2009).
42. National Renewable Energy Laboratory, What is a biorefinery? (2009). Available at: <http://www.nrel.gov/biomass/biorefinery.html>. (Accessed: 16th September 2015)
43. Hämäläinen S, Näyhä A and Pesonen H-L, Forest biorefineries – A business opportunity for the Finnish forest cluster. *J Clean Prod* **19**: 1884–1891 (2011).
44. Lopolito A, Morone P and Sisto R, Innovation niches and socio-technical transition: A case study of bio-refinery production. *Futures* **43**: 27–38 (2011).
45. Debref R, The Paradoxes of Environmental Innovations: The Case of Green Chemistry. *J Innov Econ* **9**: 83 (2012).
46. Kamm B, Gruber PR and Kamm M, in *Ullmann's Encyclopedia of Industrial Chemistry* 659–688 Wiley, (2012).
47. Hatti-Kaul R, Biorefineries- A Path to Sustainability? *Crop Sci* **50**: S-152-S-156 (2010).
48. Clark JH, Green chemistry for the second generation biorefinery - sustainable chemical manufacturing based on biomass. *J Chem Technol Biotechnol* **82**: 603–609 (2007).
49. Cherubini F, Jungmeier G, Wellisch M, Willke T, Skiadas I, van Ree R, *et al.*, Toward a common classification approach for biorefinery systems. *Biofuels, Bioprod Biorefining* **3**: 534–546 (2009).
50. Näyhä A and Pesonen H-L, Diffusion of forest biorefineries in Scandinavia and North America. *Technol Forecast Soc Change* **79**: 1111–1120 (2012).
51. Janssen M, Chambost V and Stuart PR, Successful partnerships for the forest biorefinery. *Ind Biotechnol* **4**: 352–362 (2008).
52. Chambost V, McNutt J and Stuart PR, Partnerships for successful enterprise transformation of forest industry companies implementing the forest biorefinery. *Pulp Pap Canada* **110**: 19–26 (2009).
53. Lundberg H, Triple Helix in practice: the key role of boundary spanners. *Eur J Innov Manag* **16**: 211–226 (2013).
54. Näyhä A and Pesonen H-L, Strategic change in the forest industry towards the biorefining business. *Technol Forecast Soc Change* **81**: 259–271 (2014).
55. Laestadius S, Biotechnology and the Potential for a Radical Shift of Technology in Forest Industry. *Technol Anal Strateg Manag* **12**: 193–212 (2000).
56. Pätäri S, Kyläheiko K and Sandström J, Opening up new strategic options in the pulp and paper industry: Case biorefineries. *For Policy Econ* **13**: 456–464 (2011).
57. Karltorp K and Sandén BA, Explaining regime destabilisation in the pulp and paper industry. *Environ Innov Soc Transitions* **2**: 66–81 (2012).
58. Novotny M and Nuur C, The transformation of pulp and paper industries: the role of local networks and institutions. *Int J Innov Reg Dev* **5**: 41 (2013).
59. Werpy TA, Petersen GR, Aden A, Bozell JJ, Holladay JE, White JF, *et al.*, *Top Value Added Chemicals From Biomass. Volume I: Results of Screening for Potential*

1 *Candidates from Sugars and Synthesis Gas*. United States Department of Energy,
2 (2004). doi:10.2172/926125

3 60. Cherubini F and Strømman AH, Chemicals from lignocellulosic biomass:
4 opportunities, perspectives, and potential of biorefinery systems. *Biofuels, Bioprod*
5 *Biorefining* **5**: 548–561 (2011).

6 61. Kamm B, Kamm M, Gruber PR and Kromus S, in *Biorefineries - Industrial Processes*
7 *and Products, Vol 1* (eds. Kamm, B, Gruber, PR and Kamm, M) **1**: 3–40 Wiley-VCH,
8 (2006).

9 62. Ekman A, Wallberg O, Joelsson E and Börjesson P, Possibilities for sustainable
10 biorefineries based on agricultural residues - A case study of potential straw-based
11 ethanol production in Sweden. *Appl Energy* **102**: 299–308 (2013).

12 63. Hansen EN, The role of innovation in the forest products industry. *J For* **108**: 348–353
13 (2010).

14 64. Pätäri S, Industry- and company-level factors influencing the development of the forest
15 energy business — insights from a Delphi Study. *Technol Forecast Soc Change* **77**:
16 94–109 (2010).

17 65. Björkdahl J and Börjesson S, Organizational climate and capabilities for innovation: a
18 study of nine forest-based Nordic manufacturing firms. *Scand J For Res* **26**: 488–500
19 (2011).

20 66. Novotny M and Laestadius S, Beyond papermaking: technology and market shifts for
21 wood-based biomass industries – management implications for large-scale industries.
22 *Technol Anal Strateg Manag* **26**: 875–891 (2014).

23 67. Cooke P, Transversality and Transition: Green Innovation and New Regional Path
24 Creation. *Eur Plan Stud* **20**: 817–834 (2012).

25 68. Cooke P, Transition regions: Regional–national eco-innovation systems and strategies.
26 *Prog Plann* **76**: 105–146 (2011).

27 69. Kivimaa P and Kautto P, Making or breaking environmental innovation?:
28 Technological change and innovation markets in the pulp and paper industry. *Manag*
29 *Res Rev* **33**: 289–305 (2010).

30 70. Hansen T and Coenen L, Unpacking resource mobilisation by incumbents for
31 biorefineries: the role of micro-level factors for technological innovation system
32 weaknesses. *Technol Anal Strateg Manag* **In press**: 1–14 (2016).

33 71. Hytönen E and Stuart PR, Biofuel production in an integrated forest biorefinery-
34 technology identification under uncertainty. *J Biobased Mater Bioenergy* **4**: 58–67
35 (2010).

36 72. Dansereau LP, El-Halwagi M, Chambost V and Stuart PR, Methodology for
37 biorefinery portfolio assessment using supply-chain fundamentals of bioproducts.
38 *Biofuels, Bioprod Biorefining* **8**: 716–727 (2014).

39 73. Peck P, Bennett SJ, Bissett-Amess R, Lenhart J and Mozaffarian H, Examining
40 understanding, acceptance, and support for the biorefinery concept among EU policy-
41 makers. *Biofuels, Bioprod Biorefining* **3**: 361–383 (2009).

74. Holladay JE, White JF, Bozell JJ and Johnson D, *Top Value-Added Chemicals from Biomass. Volume II: Results of Screening for Potential Candidates from Biorefinery Lignin*. (2007). doi:10.2172/921839
75. Söderholm P and Lundmark R, The Development of Forest-based Biorefineries: Implications for Market Behavior and Policy. *For Prod J* **59**: 6–16 (2009).
76. McCormick K, Bomb C and Deurwaarder E, Governance of biofuels for transport in Europe: lessons from Sweden and the UK. *Biofuels* **3**: 293–305 (2012).
77. Dornburg V, Hermann BG and Patel MK, Scenario projections for future market potentials of biobased bulk chemicals. *Environ Sci Technol* **42**: 2261–7 (2008).
78. van Haveren J, Scott EL and Sanders J, Bulk chemicals from biomass. *Biofuels, Bioprod Biorefining* **2**: 41–57 (2008).
79. Ottosson M, Opposition and Adjustment to Industrial ‘Greening’: The Swedish Forest Industry’s (Re) Actions regarding Energy Transition - 1989-2009. Linköping University, (2011).
80. Bergek A, Hekkert M, Jacobsson S, Markard J, Sandén B and Truffer B, Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environ Innov Soc Transitions* **16**: 51–64 (2015).
81. Coenen L, Hansen T and Rekers J V., Innovation Policy for Grand Challenges. An Economic Geography Perspective. *Geogr Compass* **9**: 483–496 (2015).
82. Hansen T and Coenen L, The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environ Innov Soc Transitions* **17**: 92–109 (2015).
83. Stroud D, Fairbrother P, Evans C and Blake J, Skill development in the transition to a ‘green economy’: A ‘varieties of capitalism’ analysis. *Econ Labour Relations Rev* **25**: 10–27 (2014).

1 Table 1. The adapted TIS functions as used in the present paper.³⁶

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

1 Table 2. Examples of definitions of biorefineries.

Definition	Focus	Source
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 ⁴⁰	Factory	US DoE, 1997
Biorefinery systems [are systems] in which biomass can be utilized entirely by conversion through multiple processes into a number of valuable products ⁴¹	System	Menrad et al., 2009
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 ⁴²	Factory	NREL, 2009
A forest biorefinery is ... a multi-product factory that integrates biomass conversion processes and equipment to produce fuels and chemicals from wood-based biomass ⁴³	Factory	Hämäläinen et al., 2011
[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 ⁴⁴	System	Lopolito et al., 2011
Biorefining intensifies the uses of biomass for building platform molecules ⁴⁵	Knowledge	Debref, 2012
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	Factory	IEA Bioenergy, 2012

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 ⁴⁶	Knowledge	Kamm et al., 2012
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1 Table 3. Overview of the main findings relating to the TIS structure and functions.

Themes	Key insights	Publications
System structure: Actors, networks, institutions	Actors from different industrial sectors engage with biorefinery innovation, although hesitantly Networks are important but difficult to develop into business partnerships	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, 2010; Pätäri et al., 2011; Stuart, 2006; Voytenko Palgan and McCormick, 2016.;Näyhä and Pesonen, 2012
Function 1: Knowledge development and diffusion	Academic research on biorefinery technologies dominates Forest industry firms find it difficult to lead development and diffusion of innovations	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 Palgan and McCormick, 2016;Bozell and Petersen, 2010
Function 2: Entrepreneurial experimentation	Experimentation is rare due to high costs and vested interests Business opportunities for SMEs in the area exist, but their activities are unknown	Dansereau et al., 2014; Hansen and Coenen, 2016; Hytönen and Stuart, 2010; Hämäläinen et al., 2011; Kivimaa and Kautto, 2010; Menrad et al., 2009; Näyhä and Pesonen, 2012;Cooke, 2011; Cooke 2012
Function 3:	National policies have focused on	Bozell and Petersen, 2010; Holladay et al.,

Influence on the direction of search	biofuels, skewing biorefineries towards fuel production technologies	2007; Kamm et al., 2006; Näyhä and Pesonen, 2012; Peck et al., 2009; Pätäri, 2010; Schieb and Philp, 2014; Werpy et al., 2004; Voytenko Palgan and McCormick, 2016
Function 4: Resource mobilization	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	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 Palgan and McCormick, 2016
Function 5: Market formation	Successful formation of markets for biofuels due to quotas and strict policies Other product categories still struggle to establish market niches	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
Function 6: Legitimation	Biorefineries have legitimacy among policymakers globally Several concerns among consumers and NGOs remain	Menrad et al., 2009; Näyhä and Pesonen, 2012; Ottosson, 2011; Peck et al., 2009; Pätäri et al., 2011; Voytenko Palgan and McCormick, 2016; Wellisch et al., 2010

Fredric Bauer is a PhD candidate at Lund University researching innovation in the bioeconomy, in particular innovations for biorefineries.

Lars Coenen is City of Melbourne Chair in Resilient Cities at the University of Melbourne. His research interests converge around economic geography, eco-innovation and sustainability transitions. Empirically his research is centred on the biobased economy as well as sustainable urban transitions.

Teis Hansen is an Associate Senior Lecturer at Lund University and also a senior researcher at the Nordic Institute for Studies in Innovation, Research and Education. His current research focuses on the importance of spatial aspects of innovation processes for sustainability transitions.

Kes McCormick is an Associate Professor at Lund University. Broadly speaking, he works in the fields of sustainability and governance. Specifically, he focuses on the implementation of renewable energy technologies, sustainable urban transformation, and education for sustainability.

Yuliya Voytenko Palgan is an Assistant Professor at Lund University. She works in the areas of sustainability, urban governance, innovation, and sustainable consumption. Her work focuses on strategies for sustainability solutions in new economies: bioeconomy, sharing economy and circular economy.

Author

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Author/s:

Bauer, F;Coenen, L;Hansen, T;McCormick, K;Palgan, YV

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