Innovation for biorefineries – Networks, narratives, and new institutions for the transition to a bioeconomy

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Innovation for biorefineries

Networks, narratives, and new institutions for the transition to a bioeconomy

Fredric Bauer

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Abstract

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The thesis poses three research questions: i) what are the systemic characteristics of innovation for biorefineries? ii) how do collaborations and networks shape innovation for biorefineries? and iii) in what ways are expectations and institutions shaping pathways of innovation for biorefineries? These questions are answered with a mixed methods approach.

Reorienting the socio-technical system for production and utilisation of chemicals, fuels, and materials towards a bioeconomy requires the overcoming of significant technological and institutional barriers. Though collaborations on innovation for biorefineries are needed to combine knowledge about technologies, materials, and markets they are costly and difficult. Expectations on biorefineries in the bioeconomy are divergent and conflictual. Acknowledging and resolving these conflicts is thus key to build effective and stable partnerships, which has proven to be difficult in the biorefinery field. Further, actors meet barriers to local transformative innovation in the global institutional context in which they are embedded. The thesis shows that transition initiatives are shaped by and dependent on institutional structures on multiple scales, but that opportunities exist for actors to build new networks which can enable the transition to a bioeconomy.

Keywords

bioeconomy; biorefineries; innovation; socio-technical transitions

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Knowledge is power, France is bacon.

Abstract

The transition to a bioeconomy is dependent on transformative changes to technologies, organisations, and institutions, which jointly can be described as a socio-technical change. The thesis contributes to the understanding of how the transition is shaped by expectations on and collaborations for innovation for biorefineries, which can produce chemicals, fuels, and materials needed in a bioeconomy.

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Reorienting the socio-technical system for production and utilisation of chemicals, fuels, and materials towards a bioeconomy requires the overcoming of significant technological and institutional barriers. Though collaborations on innovation for biorefineries are needed to combine knowledge about technologies, materials, and markets they are costly and difficult. Expectations on biorefineries in the bioeconomy are divergent and conflictual. Acknowledging and resolving these conflicts is thus key to build effective and stable partnerships, which has proven to be difficult in the biorefinery field. Further, actors meet barriers to local transformative innovation in the global institutional context in which they are embedded. The thesis shows that transition initiatives are shaped by and dependent on institutional structures on multiple scales, but that opportunities exist for actors to build new networks which can enable the transition to a bioeconomy.

Sammanfattning

I omställningen till en mer hållbar bioekonomi har mycket fokus legat på utvecklingen av biobränslen. När det gäller innovation och utveckling av kemikalier och andra produkter släpar utvecklingen efter av flera orsaker, vilket visas i denna avhandling.

Forskningen visar att det nuvarande systemet är inlåst i ett fossilberoende av flera olika orsaker, både tekniska, organisatoriska och materiella. Trots att det har funnits ett intresse från olika industrisektorer – som skog, energi och kemi – är samarbeten svåra, särskilt när det gäller faktiska investeringar. Förklaringen till detta ligger delvis i aktörers olika visioner av vad bioraffinaderier är och vilken roll de ska spela i en bioekonomi.

Utvecklingen till en hållbar bioekonomi kräver en omställning av många olika delar av samhället. Det gäller även produktionen av kemikalier och material som idag är beroende av fossila resurser. En möjlighet är att utveckla bioraffinaderier för att producera dessa produkter från bioråvaror.

För att kunna göra omställningen krävs omfattande teknisk innovation, men också förändringar av affärsmodeller, standarder, och regleringar. Sammantaget kan det beskrivas som en socio-teknisk förändring. Avhandlingen har undersökt villkor, utmaningar och möjligheter för just denna typ av socio-teknisk förändring i Sverige. Slutsatsen blir att även om många lovande initiativ har tagits så finns viktiga utmaningar kvar. Dessa utmaningar handlar om svårigheter att samarbeta och konflikter mellan olika visioner för utvecklingen på lokal och global nivå.

Den offentliga sektorn i Sverige har stöttat utvecklingen, men svenska aktörers möjligheter begränsas av globala marknader och strukturer. Det gör det svårt att satsa på de nya former av teknikutveckling och innovation som krävs för en omställning. Det behövs ett fortsatt stöd för teknisk innovation av produkter och processer. Men det finns också ett behov av att skapa modeller för nya värdekedjor som bryter de traditionella mönstren i systemet och som kan forma den nya bioekonomin.

Produktionen av bränslen, kemikalier och material är idag baserad på fossila resurser som olja och naturgas. I flera steg och av flera olika företag processas dessa råvaror till allt mer komplexa produkter som slutligen säljs till användare och konsumenter över hela världen. Under det senaste århundradet har processteknik, tillämpningar, organisationer och regleringar utvecklats till ett komplext socio-tekniskt system, som är anpassat för användningen av fossila resurser. Detta system möter idag stora utmaningar för en omställning till att istället baseras på förnybara, biobaserade råvaror.

Hur ser villkoren ut för att skapa innovationer för bioraffinaderier? Hur formar samarbeten och nätverk mellan aktörer innovation för bioraffinaderier? På vilka sätt skapar förväntningar och institutioner möjligheter för innovation för bioraffinaderier? Dessa frågor har varit grunden för forskningen som presenteras i avhandlingen och svaren är relevanta för både företags strategiska arbete och utformningen av politik för att stödja omställningen till en bioekonomi. I forskningen har flera olika metoder använts: social nätverksanalys för att studera samarbeten, Q-metodik för att undersöka visioner och narrativ, samt en fallstudie.

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Writing a thesis is in many ways a dreadfully lonesome task and yet at the same time so many have been involved in the work presented on the following pages. Many are those who have inspired me, shared their knowledge, and contributed with ideas in different ways. I cannot here express my gratitude to everyone who deserves it, but some must be mentioned.

Firstly, of course, I must thank my supervisors: Christian who showed me the ropes of academic research and allowed me to follow a route none of us knew where it would lead when we first sat down to discuss a PhD project aiming to research the process of reorienting the chemical industry; Pål who pushed me in the direction of innovation and transition studies and took the time to sit down for interesting discussions; Lars who welcomed me to CIRCLE, introduced me to transition studies, and helped me find my way in the field.

A sincere thank you to my co-authors, without whom the work presented in the papers appended to this thesis would not have been possible.

Thanks also to Lea, for being an inspiring colleague and a wonderful friend, always up for a rant about the follies of academia, Helena, for being a great reader whenever I needed one and for sharing laughs as well as tears, Laura, for being a supporting office mate, always listening to my frustrations about the most ridiculous things, and my colleagues both at the Department of Chemical Engineering and at CIRCLE.

A careful study of the following pages will, if conducted using both lemon juice and X-rays, undoubtedly lead to the finding of a few flaws and mistakes. I did my best.

List of included publications

This thesis is based on the following publications, which are appended to the thesis and will be referred to by the roman numerals.

I. **Bauer, Fredric**, Lars Coenen, Teis Hansen, Kes McCormick, and Yuliya Voytenko Palgan. 2017. "Technological innovation systems for biorefineries – A review of the literature." *Biofuels, Bioproducts and Biorefining* 11 (3): 534-548. doi: 10.1002/bbb.1767

II. **Bauer, Fredric**, Teis Hansen, and Hans Hellsmark. 2018. "Innovation in the bioeconomy – Dynamics of biorefinery innovation networks." *Technology Analysis & Strategic Management* In press. doi: 10.1080/09537325.2018.1425386

III. **Bauer, Fredric**. "Narratives of biorefinery innovation for the bioeconomy – Conflict, consensus, or confusion?" *Environmental Innovation and Societal Transitions* In press. doi: 10.1016/j.eist.2018.01.005

IV. **Bauer, Fredric**, and Lea Fuenfschilling. "Local initiatives and global regimes – Multi-scalar transition dynamics in the chemical industry." *Submitted*.

Co-authorship declarations

Three of the four appended publications were co-authored. My contributions to the the papers were as follows.

I. I conducted the main search for literature. I reviewed all identified publications and wrote a first draft of the paper. Co-authors added to the draft and we jointly edited and revised the manuscript.

II. I took part in designing the study, collecting the original material and constructing the database together with my co-authors. I was responsible for data analysis and wrote the manuscript together with the co-authors.

IV. I did the main part of research design and data collection. The authors took equal part in writing the manuscript.

Other publications

I have also contributed to the following peer-reviewed publications, which are not appended to the thesis.

1. Tallaksen, Joel, **Fredric Bauer**, Christian Hulteberg, Michael Reese, and Serina Ahlgren. 2015. "Nitrogen fertilizers manufactured using wind power: greenhouse gas and energy balance of community-scale ammonia production." *Journal of Cleaner Production* 107: 626-635. doi: 10.1016/j.jclepro.2015.05.130

2. Nilsson, Robert, **Fredric Bauer**, Sennai Mesfun, Christian Hulteberg, Joakim Lundgren, Sune Wännström, Ulrika Rova, and Kris Arvid Berglund. 2014. "Techno-economics of carbon preserving butanol production using a combined fermentative and catalytic approach." *Bioresource Technology* 161: 263-269. doi: 10.1016/j.biortech.2014.03.055

3. **Bauer, Fredric**, and Christian Hulteberg. 2014. "Isobutanol from glycerine – techno-economic evaluation of a new biofuel process." *Applied Energy* 122: 261-268. doi: 10.1016/j.apenergy.2014.02.037

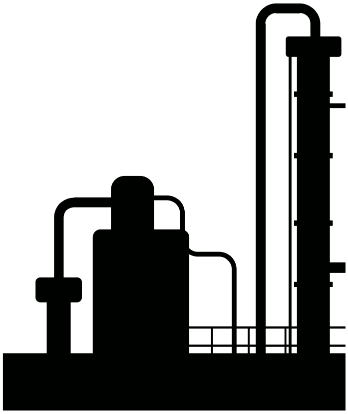
4. Tunå, Per, **Fredric Bauer,** Christian Hulteberg, and Laura Malek. 2014. "Regenerative reverse-flow reactor system for cracking of producer gas tars." *Biomass Conversion and Biorefinery* 4 (1): 43-51. doi: 10.1007/s13399-013-0088-0

5. **Bauer, Fredric**, Christian Hulteberg, Tobias Persson, and Daniel Tamm. 2013. "Biogas upgrading – technology overview, comparison and perspectives for the future." *Biofuels, Bioproducts and Biorefining* 7 (5): 499-511. doi: 10.1002/bbb.1423

6. **Bauer, Fredric** and Christian Hulteberg. 2013. "Is there a future in glycerine as a feedstock in the production of biofuels and biochemicals?" *Biofuels, Bioproducts and Biorefining*, 2013, 7 (1): 43-51. doi: 10.1002/bbb.1370

Contents

1 Introduction



This thesis consists of an introductory essay and four papers. The introductory essay gives an overview of the theoretical and empirical background of my work, contextualises it within the field of transition research, and presents a summary of the findings and conclusions. The four papers go further into the details of the different aspects of innovation for biorefineries that I chose to focus on – networks, narratives, and institutions – and how these aspects shape pathways for the transition to a bioeconomy in which biorefineries play an important role.

1.1 The bioeconomy transition challenge

It has by policymakers been laid upon researchers, scientists, inventors, and innovators to solve a group of grand challenges that face modern society (Cagnin, Amanatidou, and Keenan 2012; Kuhlmann and Rip 2014). As expressed in the Lund Declaration these challenges "must turn into sustainable solutions in areas such as global warming, tightening supplies of energy, water and food, ageing societies, public health, pandemics and security" (Lund Declaration 2009). In brief, research is expected to identify possibilities for and lead the implementation of new modes of social, technological and economic activity that are sustainable. Central to these challenges are issues related to food production, energy and resource efficiency, and climate change mitigation – issues which are all brought together in and possibly solved by the development of a bioeconomy (European Commission 2012; OECD 2009). The bioeconomy can be understood as an economy in which "the basic building blocks for materials, chemicals and energy are derived from renewable biological resources" (McCormick and Kautto 2013) and would necessitate a great increase in the supply of biomass and bioenergy from different sources for the production of biobased fuels, materials, pharmaceuticals, and other products (Scarlat et al. 2015).

The concept of the bioeconomy has become prominent in research over the past years, interesting researchers from different fields and backgrounds (Bugge, Hansen, and Klitkou 2016). Aiming to clarify what the bioeconomy is, or could be, contributions have analysed it as a concept of political economy (Birch and Tyfield 2013; Levidow, Birch, and Papaioannou 2013) and compared the different policy strategies for its realisation (de Besi and McCormick 2015; Staffas, Gustavsson, and McCormick 2013; Ollikainen 2014; Meyer 2017; Priefer, Jörissen, and Frör 2017). However, despite being promoted as a pathway towards a sustainable economic development, critics argue that the bioeconomy might itself be a threat to sustainability (Pfau et al. 2014), using sustainable development merely as a selling point while in fact focusing on industrial competitiveness and increased exploitation of natural resources (Ramcilovic-Suominen and Pülzl 2018; Kitchen and Marsden 2011). The bioeconomy necessitates new ways of organising many aspects of modern economies – energy systems, transportation systems and institutions of modern societies have all evolved in a context where fossil resources were abundant and extensively used to propel social, economic and technological development. Developing a bioeconomy is thus not simply about optimising technology through tweaks, updates, and fine-tuning – it requires far-reaching changes to *socio-technical systems*, which are comprised by actors (e.g. producers, consumers, and intermediaries) and their networks, institutions (e.g. regulations, standards, and norms), as well as technologies. Such multi-faceted changes to all elements of socio-technical systems can be described as *socio-technical transitions* (Geels et al. 2017).

Significant research efforts have been devoted to study the possibilities of transitions within the socio-technical systems for energy and transportation, which demand the main share of fossil resources for the production of heat, power and transportation fuels (see e.g. Geels, 2012; Jacobsson and Bergek, 2004; Markard and Truffer, 2006). However, also other systems and sectors are deeply entrenched in a dependency on fossil resources, a situation described as a 'carbon lock-in' (Unruh 2000; Unruh 2002), and face low-carbon transition challenges. The challenges for the energy-intensive process industries – such as the steel, cement and chemical industries – are noteworthy as their dependence on fossil resources is not only due to their energy intensity but also due to the fact that the fossil carbon is embedded in the products themselves (Åhman, Nilsson, and Johansson 2017). Although energy efficiency improvements are important for these sectors, the challenge is much wider in scope (Napp et al. 2014). These sectors share many characteristics regarding innovation patterns and structure as they are very capital intensive, dependent on economies of scale, and focused on incremental improvements of conventional technologies (Wesseling et al. 2017). The chemical industry produces many of the materials and other products to which modern societies have grown accustomed and is the largest industrial energy user, accounting for 28% of industrial final energy consumption (International Energy Agency 2017). Understanding and enabling a transition within the sector is therefore an important piece of the puzzle that a transition to the bioeconomy is.

The remainder of this first chapter outlines some of the challenges for a transition towards a bioeconomy, presents the aims of my research together with the research questions that have guided it, and gives a brief introduction to the appended papers. The second chapter presents a background on theories of innovation and socio-technical change and introduces the field of transition research. The third chapter presents the research process and introduces the methodological approaches used. The fourth chapter summarises and discusses the findings. Finally, conclusions and implications for future research are presented in the fifth chapter.

1.2 A historical perspective on the challenge for chemicals

The chemical industry as we know it today has its roots in the European industrial revolution of the 19th century, which was fuelled by the changing socio-technical system for textiles towards industrial production. In the search for new dyestuffs for textiles scientific exploration led to the discovery of new ones that were chemically synthesised from coal, which became an important part of the industrialisation process (Aftalion 2001). This created strong links between the chemical industry and the exploitation of coal, establishing a special relationship between chemicals and energy, constituted by material, economic and institutional interdependencies that still remain (Bennett 2007), although the use of raw materials for chemicals shifted during the 20th century from coal towards petroleum and natural gas (Diercks et al. 2008). The demand for petroleum and natural gas for feedstock purposes corresponds to about 7 % of global petroleum demand and 5.5 % of natural gas demand according to reported estimates. The demand for petroleum and natural gas for fuel and energy purposes in the chemical industry is estimated to be almost as large (Bennett 2012).

The development of the industry was shaped by important technological innovations such as the contact process for production of sulfuric acid (1831), the Haber-Bosch process for ammonia production (1905), and catalytic cracking of petroleum (1936) which all came to enable and focus the sector on large-scale production (Aftalion 2001). During the 20th century the sector developed from being a regionally based industry almost completely based on the use of coal into a global industry largely integrated with the petroleum industry. The post-war era saw the emergence of petrochemicals, which grew to become a very powerful part of the industry (Spitz 1988) – 92 % of chemical products are today reported to be produced from petroleum and natural gas (Bennett 2012). For decades the sector grew steadily, seeing no end to prosperity during the post-war era of high GDP growth and low energy costs. The chemical industry grew to become an important industrial sector in developed countries, being one of the largest manufacturing industries in western economies (Landau 1994; Arora, Landau, and Rosenberg 1999; Arora, Landau, and Rosenberg 1998). Although the chemical industry in Sweden is by international measures rather small, it is an important part of the domestic economy, being one of the four basic industries (together with forestry, mining, and steelmaking), accounting for almost 17% of Swedish exports (Mossberg 2016).

The production of basic chemicals is capital intensive as the construction of new plants of commercial scale is very expensive. This leads to economies of scale being very important for basic chemicals, some of which are produced in enormous quantities, e.g. sulfuric acid, ammonia and ethylene, and for which the feedstock constitutes the absolutely dominating part of total production costs (Boulamanti and Moya 2017). Marketa for many chemical products are therefore dominated by price competition and firms engage in cost leadership strategies (Albach et al. 1996; Ren 2009). Innovation is consequently to a large degree focused on process improvement, i.e. increasing productivity or decreasing costs of production through higher conversion rates and other efficiency improvements (Cesaroni et al. 2004), leading to plant sizes increasing with orders of magnitude during past decades (Lieberman 1987). This has resulted in mega-plants for basic chemicals, using equipment so large that the sheer size of it limits the construction of new plants (Fertilizer International 2011; Buffenoir, Aubry, and Hurstel 2004). As the production of chemicals is very energy intensive, process energy cost saving is one of the main drivers for process innovation (Ren 2009). Incremental process innovation efforts have resulted in a 27.1 % decrease in total fuel and power consumption in the European chemical industry (similar to EU total industry decrease which was 26.8 %), and a decrease in energy intensity of chemical production of 54.5 % from 1990 to 2009 (significantly larger than EU total industry decrease which was 35.8 %) (Cefic 2012).

The production and utilisation of chemicals, materials, and energy are socio-technical systems which have co-evolved for almost two centuries and have become institutionalised in modern societies. The notion that the production of chemicals and materials could – and should – break away from its reliance on fossil resources is however not a new one but has been around for quite some time. Already before petrochemistry reached its position as the dominating technological paradigm in the second half of the twentieth century it was argued that the future for chemicals and materials lies in advanced utilisation of wood (Glesinger 1949). During subsequent decades of recurring oil crises and increasing awareness of the environmental problems caused by the use of fossil resources the proposition to look to biomass as a future alternative for the production of chemicals and fuels was repeated time and again (e.g. by Sarkanen 1976; Lipinsky 1978; Lipinsky 1981; Swinnen and Tollens 1991; Wyman and Goodman 1993) – yet it seemingly had little effect on the industry. With the increasing intensity in the debate around climate change as a global challenge the issue has once again become a focal point for the discourse on the future development of the industry. A strong element in this discourse, and the topic of much research in recent years, is the idea of developing technologies, processes, and value chains that in novel ways could use biomass for the production of fuels, chemicals, and other material products in so called *biorefineries*.

At the same time as biorefineries open up pathways for a transition towards the bioeconomy, they do however also challenge the traditional knowledge, networks, and institutions in the current system. Given its strength, dependence on fossil resources, and knowledge it becomes clear that the sector has an important role to play in the bioeconomy transition. Questions do however remain regarding what possibilities the firms and other actors in this sector have to contribute, given that they are deeply embedded in global structures that must be dissolved to enable the transition to the bioeconomy.

1.3 Biorefineries as socio-technical configurations for the bioeconomy

The biorefinery has reached prominence as an organising concept for a group of technological configurations for the production of fuels, chemicals, and materials from biobased raw materials that could supply a bioeconomy with its needed building blocks (Bozell 2008). Although the concept emerged almost four decades ago (Levy et al. 1981) it did not gain traction until a few years into the new millennium, but is now prominent both in the scientific and political discourse (King and Hagan 2010). The idea of the biorefinery is an analogue to that of the petroleum refinery, which makes use of a complex feedstock, crude oil, to produce a range of valuable products such as fuels, solvents, and basic petrochemicals. Biobased feedstocks could thus potentially be used in a similar fashion to produce food, feed, fuels, and chemicals using a set of different separation and conversion processes – products that could either be new ones substituting those currently produced from petroleum, or identical ones that could be used directly in existing applications (Cherubini 2010). Depending on the local availability and intended products biorefineries could use different sources of raw materials, ranging from grass to agricultural crops, residues, wood, or algae and process them with different fractionation, conversion and separation technologies using thermal, chemical or biotechnological routes, or a combination thereof (Kamm, Gruber, and Kamm 2006; Cherubini et al. 2009). The biorefinery is thus neither a single technology, nor is it a specified set of technologies, but rather a concept for different possible configurations of processes, practices, and procedures.

Just as petroleum refineries and steam crackers today produce a set of platform petrochemicals – olefins (ethylene, propylene, and butenes), BTX aromatics (benzene, toluene, and xylene), and methanol – which are subsequently used to for more complex chemical products, biorefineries could produce other biobased platform chemicals. Several attempts have been made to identify groups of biorefinery products that would have the potential to be used as chemical building blocks in a bioeconomy, most notably by the US Department of Energy which came up with a list of ten candidates focused on alcohols, sugar alcohols, biohydrocarbons, furans, and organic acids (Bozell and Petersen 2010). Beyond such platform chemicals, biorefineries could also produce new biobased plastics and fibres (Philp, Ritchie, and Guy 2013), as well as other advanced materials which could substitute not only fossil carbon based ones but potentially also reduce the dependence on other finite resources through new applications of biogenic carbon materials (Arvidsson and Sandén 2017).

Requiring innovation in terms of process technologies, business models, and infrastructure alike, developing and launching biorefineries has been a slow process. This is similar to many other renewable energy technologies that have had to overcome significant barriers before diffusing more widely (Negro, Alkemade, and Hekkert 2012). Although having gained large support for research and innovation in Sweden and Europe (Hellsmark et al. 2016; Peck et al. 2009), biorefinery technologies have been described as being stuck in a "valley of death", i.e. not being able to progress beyond the pilot and demonstration stage towards commercial scale production and diffusion (Mossberg et al. 2017). Apart from the large investment costs for new commercial scale plants, which certainly is a barrier for deployment and diffusion of these technologies, this has been explained with policies having been fragmented and too focused on biofuels (Hellsmark and Söderholm 2017), as well as limited capacity among actors to adopt to the changing environment (Hansen and Coenen 2017) and form new collaborations outside existing networks (Voytenko Palgan and McCormick 2016).

1.4 Aims and research questions

Progress in natural science and engineering has come far in solving important challenges for biorefineries in terms of technologies for processing, conversion, and separation. It is however clear that technological as well as other types of barriers remain and must be overcome for biorefineries to be implemented and diffused. It is also evident that these barriers must be addressed and analysed from perspectives that go beyond technology. This is the reason for studying the issue using the transition frameworks that are introduced in more detail in the next chapter. These frameworks allow for multi-faceted analyses of the issue by spanning material, economic, discursive, and institutional aspects. The thesis thus complements traditional engineering research in showing how technological development is situated in a social context that enables and constrains innovation for a transition in different ways.

The thesis aims to advance the understanding of how collaborations and expectations of different actors contribute to shaping innovation and socio-technical transition pathways. To achieve this it investigates how actors engaging with innovation for biorefineries combine and integrate knowledge about different technologies, markets, and industries to develop and enable new types of socio-technical configurations for the bioeconomy. It takes a systems perspective on the question of socio-technical change towards a bio-based production of chemicals, materials, and fuels – with an emphasis on how actors engaging with this task break away from established patterns and create new ones. The empirical focus of the thesis is biorefinery innovation in Sweden, where technological innovation for biorefineries has been supported and promoted intensely during the past decade.

The overarching aim was further refined into three research questions that will be addressed throughout this introductory essay and that guided the research in the appended papers. These specific research questions were the following:

RQ1. What are the systemic characteristics of innovation for biorefineries?

RQ2. How do collaborations and networks shape innovation for biorefineries?

RQ3. In what ways are expectations and institutions shaping pathways of innovation for biorefineries?

1.5 Overview of papers

To this thesis four papers are appended, which present the details of the research conducted. The papers tackle the topic of innovation for biorefineries and their role in the transition to a bioeconomy using different methodological approaches and data as well as with different theoretical foci. An overview of the papers is presented in Table 1.

Paper I, *Technological innovation systems for biorefineries - A review of the literature,* can be read as an introduction to the topic of innovation for biorefineries. The paper presents current knowledge about innovation for biorefineries and identifies remaining gaps in the knowledge using the framework of technological innovation systems and thus contributes to answer RQ1. The paper uses literature mainly about the European and North American context and has a particular focus on forest biorefineries, but its findings are relevant to a wider biorefinery discourse than the one focused on forest biorefineries. Some of the knowledge gaps identified are then addressed by the following papers.

Paper II, *Innovation in the bioeconomy – Dynamics of biorefinery innovation networks*, takes as starting point the oftentimes emphasised need for extensive collaboration in the bioeconomy. As innovation for biorefineries must integrate knowledge about biomass feedstocks, separation and conversion processes, as well as markets for energy, chemicals, and other products actors with knowledge about these different aspects need to collaborate. Using social network analysis tools the paper studies the build-up and evolution of the Swedish biorefinery innovation network 2004-2014, a period during which the Swedish innovation system for biorefineries developed and matured. The paper thus addresses both RQ1 and RQ2, as it takes a close look at how collaborations for biorefinery innovation have developed through different support schemes.

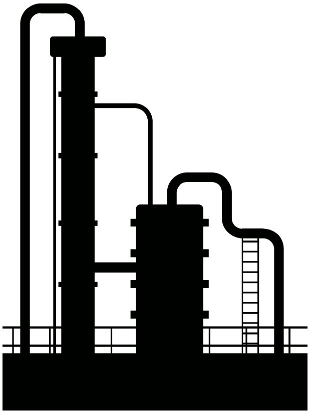
In Paper III, *Narratives of biorefinery innovation for the bioeconomy – Conflict, consensus, or confusion?* the viewpoint is shifted from a network based and historical one to one focused on contemporary expectations by actors in the system. The paper addresses RQ3 on the nature of expectations for biorefineries and their contribution to the bioeconomy. The paper approaches these expectations as elements of the bioeconomy discourse and identifies their expression in specific transition narratives using Q methodology. Empirically the work is based on interviews and Q sorts by individuals who are all, in different capacities and from different positions, working with innovation for biorefineries in Sweden.

In Paper IV, *Local initiatives and global regimes – Multi-scalar transition dynamics in the chemical industry*, RQ2 and RQ3 are approached from an institutional perspective, focusing on how global and local institutional rationalities interact in enabling and constraining innovation for renewables in the chemical industry. The paper explores the concept of a global regime, the globalised institutional rationality in a socio-technical system, and how it interacts with local sustainability transition efforts. The empirical work is a case study of a collaborative sustainability initiative in the Swedish chemical industry and how it is influenced by institutional pressures which work to support and suppress a transition from the fossil-based regime in the sector, the emergence and structure of which is also analysed in more detail.

Table 1. Overview of papers.
Summary of the papers appended to the thesis and their contribution to answering the research questions posed in the thesis.

	Paper I	**Paper II**	**Paper III**	**Paper IV**
RQs adressed	RQ1	RQ1 & RQ2	RQ3	RQ2 & RQ3
Methodology	Literature review	Statistical social network analysis	Q methodology	Case study
Empirical focus	Innovation system knowledge about biorefineries in western countries	Collaboration network for bio-refinery technology innovation 2004-2014 in Sweden	Narratives of innovation for developing a bioeconomy in Sweden	Collaborative sustainability initative of the Stenungsund chemical cluster
Theoretical focus	Structure and functions of technological innovation systems for biorefineries	Dynamics of networks for transformative innovation	Framings and narratives in socio-technical transitions	Global and local institutional pressures for transformative change
Data	Published research literature	Database produced from collaborative innovation project descriptions collected from SEA and VINNOVA	20 sorts of a Q sample of statements gathered from Swedish newsprint articles and other publications	Interviews, documents, presentations, and secondary literature
Findings	Difficulties in cross-sectoral collaboration hinder biorefinery innovation. Lack of absorptive capacity and limited knowledge bases are barriers for adoption of biorefinery innovations.	The biorefinery innovation network grew significantly during the period, and its diversity increased as different actors entered but remains clustered around central actors.	Contrary and contradictory narratives of biorefinery innovation for a transition to a bioeconomy are divided on aspects of products, knowledge, and policy.	Local transition initiatives and their impact are shaped by and dependent on regime structures on multiple scales limiting the possibilities for the actors in Sustainable Chemistry 2030 to break with regime logics.

2 Theoretical background



Although the thesis is focused on aspects of technological innovation for biorefineries, an important part of the understanding of technological innovation is that technology is always but a part of a complex system comprising as well the technology as it does human actors, their relations to technology, and to each other. The thesis is thus not occupied with the study of strictly technological systems but of socio-technical systems. The research was informed by concepts and theories originating in the fields of innovation and transitions research that has developed over the past fifteen years. The following chapter presents the key ideas and conceptual roots on which the research builds, but does not aim to give a complete overview of the field.

2.1 The systemic nature of innovation and technological change

The question regarding what role technology has in determining the development of social and economic structures dates back to Karl Marx and his assertion that "the hand-mill gives you society with the feudal lord; the steam-mill, society with the industrial capitalist". While this form of technological determinism has largely been rejected by historians and philosophers of technology (Smith and Marx 1994) technology remains a crucial aspect of understanding modern society and its development (Misa, Brey, and Feenberg 2003). The understanding of innovation as a process of economic and social development was further developed in the works of Schumpeter, who famously coined the term *creative destruction* to describe how the capitalist economic structure itself generates the forces that revolutionises it "from within, incessantly destroying the old one, incessantly creating a new one" (Schumpeter 1950, p. 83).

Technological innovation and change has since been the centre of much research, which has emphasised that technological and social developments shape and form each other in a co-evolutionary process, and that this process is inherently systemic. Understanding the world as composed not only of elements but of systems has become an important part of many scientific disciplines (Ingelstam 2012). Systems thinking originated in technological research with grand ambitions to describe how components and their interactions can be understood with similar concepts, irrespective of the nature of the system. Early contributions on cybernetics (Wiener 1961) and general system theory (von Bertalanffy 1968) were both inspired by natural systems, but aspired to describe systemic characteristics in general. Following advances in mathematical modelling quantitative systems analysis was expanded greatly (Flood and Carson 1993), leading to ambitions to model the whole world and its limits as a dynamic system bound to collapse (Meadows et al. 1972). More hopeful views argued that knowledge about systemic problems would enable more informed processes of innovation that can help avoid destruction and depletion of resources (Freeman 1996). The directionality of innovation, its tendency to follow path-dependent trajectories (Dosi 1982) have since intrigued large groups of researchers who have offered a range of different explanatory models for how to understand them, e.g. emphasising the socially constructed nature of technological systems (Bijker, Hughes, and Pinch 1987), highlighting the interdependencies of technologies in large technical systems (Hughes 1986), describing technological innovation as an evolutionary process in the economy (Nelson and Winter 1977), and pointing to the technology as an arena for political struggle (Feenberg 2002). These contributions have greatly advanced the understanding of technological innovation and change as being bound not merely by the laws of motion and thermodynamics, but also its social context, and how it in turn is part of forming this context through a co-evolutionary process.

The understanding of innovation and socio-technical change as a systemic phenomenon matured through the concept of innovation systems (Edquist 1997), an analytical construct which was initially focused on nations (Lundvall 1988; Freeman 1987), although it later came to be used to analyse also technologies (Carlsson and Stankiewicz 1991), regions (Cooke, Gomez Uranga, and Etxebarria 1997), and sectors (Malerba 2002). This systemic view rejects the idea that innovation progresses linearly from research to development and finally commercial adoption – instead it argues that innovation occurs interactively throughout the system that is defined by its actors, their networks, and institutions. The actors in the system are firms throughout the value chains, universities, government bodies, industry associations, NGOs, individual entrepreneurs, as well as users, i.e. all actors who engage with the technology as it emerges. Through different types of interactions, e.g. trade, cooperation, and lobbying, the actors form networks that make possible the exchange of knowledge, experience, and expectations. The institutional infrastructure is what guides the activities of the agents through regulations, norms, and routines – be they formalised as laws and standards, or informal such as engineers' rules of thumb and other practices. Identifying instruments for guiding and steering innovation towards specific missions and aims has been an important outcome of this research field. It has highlighted the role that policy has to play in shaping the system (Borrás and Edquist 2013; Mazzucato 2016) and in overcoming the different types of failures that characterise systems locked in to unsustainable technologies, practices, and institutions (Weber and Rohracher 2012; Jacobsson, Bergek, and Sandén 2017).

2.2 Socio-technical transitions towards sustainability

Responding to calls for transforming contemporary socio-technical systems towards sustainability, e.g. the policy agenda for the bioeconomy, the research field on sustainability transitions has emerged. The field is focused on the study of socio-technical systems going through processes of fundamental change from one structural configuration to another, aiming for more sustainable configurations (Markard, Raven, and Truffer 2012; Smith, Voß, and Grin 2010). Key to such structural change is the overcoming of different types of lock-in that exist in mature systems. Economies of scale, learning, and network together with adaptive expectations form positive feedback loops that create the path-dependent development of markets, technologies and institutions (Arthur 1994), mechanisms that have all been working to establish the 'carbon lock-in' from which society is now seeking an escape (Unruh 2000; Unruh 2002). More innovation is however not enough of a solution, care must be given to the nature of innovation when asking it to lead towards more sustainable pathways of development (Leach et al. 2012). Sustainability transitions are thus wide in scope and not simply about substituting one technology for another, but rather about change in several dimensions related to the provision of specific products and services, e.g. organisational, institutional, political, and cultural change (Grin, Rotmans, and Schot 2010). A set of conceptual frameworks have been developed within the research field: technological innovation systems (TIS) which is concerned with the emergence of specific technologies and the barriers for their diffusion (Bergek et al. 2008; Hekkert et al. 2007); the multi-level perspective (MLP) which explains transition dynamics as interactions between three different levels of socio-technical structuration – niches, regimes and landscapes (Geels 2002; Geels 2005); strategic niche management which is focused on developing and supporting emerging niches to trigger transitions (Kemp, Schot, and Hoogma 1998); transition management which is focused on coordinated governance models for transitions (Kemp, Loorbach, and Rotmans 2007; Rotmans, Kemp, and van Asselt 2001). The two former frameworks were the main influences for the work presented in this thesis. Despite having shared roots the frameworks also have important differences that make them complementary rather than overlapping (Markard and Truffer 2008).

While emphasising the social embeddedness of technology, the TIS framework has demonstrated the need to carefully consider the characteristics of specific technologies in transitions to more sustainable systems (Jacobsson and Bergek 2011) as technology neutrality is an insufficient guiding principle to support transformative change (Azar and Sandén 2011). Shifting to a processual rather than a structural analysis of systems, the TIS literature has focused on identifying key processes or functions that influence the development of specific technologies or technological fields (Hekkert et al. 2007; Bergek et al. 2008). By structuring the analysis around these system functions common barriers that hinder renewable energy and other sustainable technologies have been identified. These barriers include short-sightedness of expectations and policy support, lack of material and knowledge infrastructure, and inefficient network structures (Negro, Alkemade, and Hekkert 2012). Through the translation of identified weaknesses to policy interventions the approach has provided a foundation for discussing not only traditional research policy instruments but also the importance of systemic instruments (Wieczorek and Hekkert 2012) and policy mixes (Reichardt et al. 2016). Despite not having an explicit focus on the nation-state as an analytical unit, TIS research has to a large degree taken national system boundaries for granted (Coenen 2015). Recent contributions have thus elaborated on both the need for a more nuanced view of the local context (Bergek et al. 2015) and how contacts across national boundaries influence local dynamics (Binz, Truffer, and Coenen 2014) and create globally connected systems (Binz and Truffer 2017).

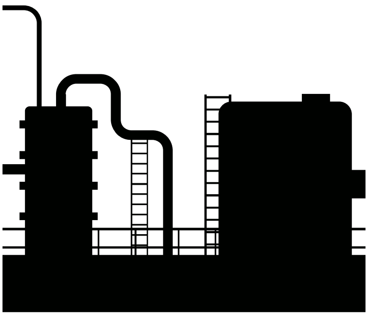
Instead of focusing on specific functions, the multi-level perspective on transitions draws on the sociological concept of structuration to analyse the dynamics of change as taking place in differently structured levels of the system: niches, regimes, and landscapes. Socio-technical systems are thus assumed to be dynamic but with a high degree of stability, which is attributed to its socio-technical regime. The regime has been defined as "the rule-set or grammar" (Rip and Kemp 1998) that "orient[s] and coordinate[s] the activities of the social groups that reproduce the various elements of socio-technical systems" (Geels, 2011, p. 27). However, regimes are not eternal – new regimes can develop around radical innovations if the support from societal actors, infrastructure, and related technologies is substantive. A transition can thus be understood in terms of the change from one regime to another. Such changes occur in different ways, e.g. through pressure from innovative configurations emerging from new niches, through pressure from exogenous macro-level developments, or through continuous adaptation to a changing environment (Geels and Schot 2007). Recent contributions have used insights from institutional theory to further elaborate on the regime concept as a specific, institutionalised rationality that provides actors with routines and legitimacy within the system (Wirth et al. 2013; Fuenfschilling and Truffer 2014; Smink, Hekkert, and Negro 2015). These institutionalised rationalities are of course dependent on local traditions and regulations, but have been shown to be remarkably similar across contexts, forming global structures, by which actors must navigate and are bound (Fuenfschilling and Binz 2018).

2.3 Theoretical points of departure in the papers

The papers appended to the thesis draw from and build on these theoretical foundations in different ways. Paper I follows the TIS framework, presenting an analysis of the research literature based on six systems functions: (i) knowledge development and diffusion, (ii) entrepreneurial experimentation, (iii) influence on the direction of search, (iv) resource mobilisation, (v) market formation, and (vi) legitimation. It thus largely follows the outline of functions by Bergek et al. (2008), although it omits a seventh function – development of positive external economies. This function has however been difficult to operationalise as it overlaps with other functions and has thus in many later contributions been omitted or substituted.

Paper II focuses on one of the core structural elements of the innovation system for biorefinery technologies, the network of actors engaged with innovation for biorefineries. As previous contributions have underlined the necessity for new types of collaborations and partnerships for innovation in the bioeconomy, the paper focuses on the evolution of the biorefinery innovation network through actors' choices when forming alliances and partnerships. Paper III emphasises the role that discourse has in shaping possible pathways for a transition. It investigates how actors articulate support for certain expectations in their narratives about the transition to a bioeconomy and the role of biorefineries in this transition. Finally, Paper IV analyses the characteristics of the regime for chemicals from an institutional perspective and thus builds on the MLP. Especially it draws on the concept of a global regime that shapes the possibilities for a local transition. Through studying the struggles of a local sustainability initiative it finds areas of support and suppression in local and global rationalities, which both affect the development at the local level.

3 Research process and methodological considerations



The writing of a thesis is a long path with countless turns and bends. The route to studying socio-technical change processes in the context of biorefineries was by no means an easy one to find or follow, starting with a background in engineering without an interest in researching technology itself, but rather in the social context of technologies. This chapter describes the research process that led up to writing this thesis, the results of which came out of several different projects using different methodological approaches. The methodologies used for the different papers, and their relevance for transitions research, are then introduced.

3.1 Research process

This thesis is not the outcome of a single research project using a homogenous design from its early beginning to the very end. Rather it is the outcome of several different research projects that have all been focused on how biorefineries emerge as new socio-technical configurations in a time of climate change adaption, resource depletion, and business strategy reorientation. As the question of how innovation for biorefineries works is indeed very large and cannot be answered fully within a thesis, the work presented here has aimed to investigate certain aspects of this highly complex process. The thesis builds on four papers, each of which presents research conducted using a different methodology. The mixed methods approach allows for the investigation of the topic of biorefinery innovation from different aspects and angles. Paper I is a literature review, of which there is little to be said in relation to methodological aspects apart from the details presented in the paper. Paper II takes a network approach to the phenomenon of collaboration and combination of knowledge for innovation and conducts a statistical analysis of network dynamics. Paper III focuses on expectations expressed in transition narratives, which are identified and analysed using the quali-quantitative Q methodology. Paper IV is a qualitative case study of how global and local institutional rationalities affect a local initiative for transformative change in the chemical industry. The methodological approaches are introduced in the following subsections, but a few words on how they complement each other and fit with the philosophical position of the thesis are needed.

The starting point for the thesis is the study of technology not as an isolated phenomenon but as part of a dynamic socio-technical system which is constantly being (re)invented, (re)interpreted, and (re)negotiated. Socio-technical configurations do not change by their own actions, but are the outcomes of social processes in which actors have different expectations and aim for certain outcomes. The socio-technical system therefore does not consist of only the individual actors and the technological artefacts, but also the relations between actors and technologies as well as the rules and institutions guiding and constraining their actions. The appended papers each focuses on one of these aspects and how they affect the development of biorefineries as new socio-technical configurations. Paper II aims to shine a light on the participation of different groups of actors in innovation activities, as well as their relations and connections to each other. Paper III centres on lines of conflict and agreement regarding the emerging bioeconomy transition and how actors perceive the role of themselves and others in this dynamic process. Paper IV in turn addresses how different institutions both enable and constrain actors aiming to enable new configurations. Thus, although the methodological approaches may seem radically different they all connect to the underlying understanding of socio-technical change as inherently systemic. The research is based on an understanding of these social phenomena as inherently real, i.e. the research questions are approached from a realist standpoint although with mixed methodological tools (Maxwell and Mittapalli 2010). Albeit that the mixed methods approach presents challenges for research in ensuring the commensurability of the methodologies, it enables a productive, multidimensional analysis of the different aspects that are at play in shaping and forming technologies and social relations.

3.2 Social network analysis of collaborative innovation projects

The application of social network analysis (SNA) for the study of innovation has mainly focused on mapping networks of technology, communication, and collaboration, of which collaboration networks has been the most common theme (van der Valk and Gijsbers 2010) and has provided researchers with new tools for understanding the intricacies of cooperative innovation (Pyka and Scharnhorst 2009). Even though networks are acknowledged as important structural elements in transitions research the use of formal network analysis has not been common. Previous contributions making use of network analysis in the field have focused on the role of network structure and composition for emerging technologies (van der Valk, Chappin, and Gijsbers 2011), how networks contributes to technological diversity in innovation systems (van Rijnsoever et al. 2015), and how resources within an innovation system are diffused through its networks (Musiolik, Markard, and Hekkert 2012). These contributions have all pointed to the importance of paying more attention to the network aspects of socio-technical systems, and the approach used in Paper II adds to this by showing the relevance of also considering the dynamics of networks.

Although the innovation literature has emphasised that networks are integral parts of the system, the actual function and behaviour of networks has been paid little attention. The increasing analytical focus on and understanding of networks in both physical and natural sciences (Borgatti et al. 2009) has led to it being described as a new paradigm (Borgatti 2003), and even a new science (Barabási 2003) as it seems that very different phenomena can be explained in terms of their network characteristics. Network analysis moves the focus of research from individual motives and characteristics of actors to the context of a group of actors and their interactions. Taking a network perspective on a socio-technical system thus means to study not only the individual actors' efforts in generating, diffusing, and utilising technology, but rather how this happens through their cooperative efforts.

SNA has been employed to answer widely diverging questions about the structure, emergence and outcome of networks and the actors that constitute them. Moving from a static understanding of networks and their structural characteristics for the actors – such as the importance of weak ties (Granovetter 1973) and structural holes (Burt 2004) – increasing focus has been given to the evolution of networks. The development of advanced methodological tools based on complex systems analysis has enabled new tools for analysing and modelling the structure and dynamics of social networks. In this toolbox are different types of models, e.g. blockmodels which aim to describe networks in simplified or equivalent structures (Doreian, Batagelj, and Ferligoj 1999) and statistical models for estimating parameters that can describe key properties of the networks. Such statistical models are used both for cross-sectional analysis, e.g. latent space models and exponential random graph models (ERGM) which focus on static and structural aspects of networks, and dynamic network analysis, e.g. dynamic ERGM and actor-oriented models (Snijders 2011). Focusing on how different actors collaborate for the innovation of biorefineries Paper II made use of a stochastic actor-oriented model called SIENA, available as the Rsiena package for the statistical computing environment R (R Core Team 2017). The network data used for the analysis was a database of Swedish collaborative innovation for biorefinery technologies. The database was produced by the authors from documents describing projects partially funded by the Swedish Energy Agency or Vinnova, the Swedish Innovation Agency, two governmental agencies active in supporting research, development and innovation in the field.

The chosen approach to analysing innovation networks focuses on the evolution of the network and how actors create and maintain connections. Although it provides a macro-level understanding of the factors that drive this evolution the approach does not give detailed explanations of how individual actors reason and prioritise when choosing partners for collaborations. It is thus limited regarding the possibility to provide justifications or arguments from actors the network, something that must be investigated through qualitative approaches.

3.3 Analysing transition narratives using Q methodology

Q methodology, which is a combined quali-quantitative research methodology designed to capture and analyse subjectivity in relation to specific topics, was originally developed in social psychology (Stephenson 1935), but its usefulness for unpacking conflicting perspectives and narratives has later been proven in many fields (Brown 1980). Although Q has been extensively used to study perspectives on sustainability and environmental policy (Addams and Proops 2000; Barry and Proops 1999) it has only recently been introduced in transitions research. Hermwille (2016) called for transition scholars to give more attention to narratives in transition discourses and pointed to Q methodology as a useful tool for this purpose, a call that was first answered by Gruszka (2017). Paper III responds to this call not only by making use of Q, but also by showing how the identified narratives can be rigorously compared and contrasted with each other to identify tensions and conflicts in the discourse. The way Q methodology is employed in Paper III can thus be seen as a form of structured, semi-quantitative discourse analysis. Identifying and analysing narratives and their conflicts allows for the unpacking of a discourse that on the surface may seem homogenous – most actors claim to support the development of a bioeconomy and innovation for biorefineries – although there are significant differences in their expectations and perspectives on the matter.

The initial part of Q is the development of the concourse, which is a set of statements about the topic of interest that captures different views and aspects of topic. Concourses can be developed in different ways, e.g. from interviews or other materials covering the topic. Given that the methodology aims to study subjective perspectives it is important that "the statements are matters of opinion only (not fact), and the fact that the Q sorter is ranking the statements from his or her own point of view is what brings subjectivity into the picture" (Brown, 1993, p. 93-94). The concourse is thus constituted by statements relating to values, opinions, and beliefs connected to the topic, which for Paper III was statements from Swedish newsprint, strategy documents, and other texts about biorefineries and the bioeconomy. From the concourse a subset of statements is chosen, reflecting the different domains and areas identified in the concourse. This subset is the Q sample which purposely sampled participants – for this study they all were professionally involved in working with technology or policy development for the bioeconomy – are prompted to sort according to their understanding of the topic. Participants conduct the Q sort individually, followed by an interview with the researcher to allow for a discussion around how the statements are interpreted –

qualitative data that helps the interpretation of the factors and perspectives that emerge in the analysis. The Q sorts are the basis for a quantitative factor analysis of the correlation between participants' sorts and not individual statements, identifying perspectives and narratives on the topic shared by groups of participants (Zabala 2014). The factors identified quantitatively are then interpreted as narratives which explain the reasoning behind different positions in the present discourse.

Although the sample size is small and the methodology therefore does not allow for statistical inference, i.e. generalisation to large populations, as participants are sampled purposely for their knowledge about the discourse and given the possibility to present their reasoning the methodology gives a thorough understanding of the arguments that structure the identified narratives. In this way Q methodology has the potential to open up discourses around different transition pathways and examine their potential to support transformative change along one pathway or another (Leach, Scoones, and Stirling 2010; Stirling 2008). The methodology also provides a deeper and closer understanding for how different actors view their potential to contribute to biorefinery innovation through their own capabilities and position in the system. The approach thus complements the macro-level network analysis as it provides arguments and reasons from different actors, and gives a wider view of expectations in the system than the single case study does.

3.4 Case study research

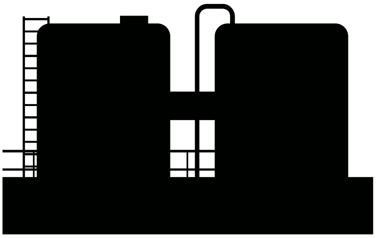
Case study research concerns itself with the study of an empirical phenomenon in its real context and has been one of the main methodologies used within transition research, e.g. for analysing niche emergence and regime response to growing external pressures. The case study is an intensive research strategy aiming for a rich and in-depth analysis of complex dynamics in a particular setting, exploring and explaining *how* and *why* certain things happen. As case studies are limited in scope, results are not suitable for statistical inference, but rather analytical, i.e. cases allow for deepening and building theory rather than generalising statistical patterns to populations or groups (Eisenhardt 1989; Eisenhardt and Graebner 2007). The selection of cases to study becomes an important part of designing the study to be able to answer the research question posed as inherent to the research strategy is the understanding that not all cases are similar. A suitable strategy for sampling cases naturally depends on the type of question posed but is commonly well informed by theoretical knowledge about the phenomena studied (Flyvbjerg 2006). For Paper

IV the case of the collaborative sustainability work of chemical companies in Stenungsund was chosen as this is a deviant case – a local initiative that attempts to break with the logics dominant in the sector – knowledge gained through earlier work on the chemical industry and by having engaged with the actors in the local setting in previous projects.

Case-studies are multi-faceted – they do not allow for the type of rigorous controlled testing that occurs in a lab, but are observed in their context in which many things occur simultaneously. Grasping the complexity of a case thus often requires the use of multiple types of data, such as interviews, documents, and observations. Interviews allow for collecting data from inside the process and are valuable data sources for understanding how events were perceived by actors close to the case, and gaining insights into aspects of the case that are less formal or not documented. To avoid the bias of specific actors other material, such as reports and other documents can be used for triangulation and to verify the information from interviews. Paper IV makes use of both semi-structured interviews with individuals who have been working in and with the local initiative as well as secondary literature and formal documents such as annual reports and presentations for triangulation as well as to identify generalised arguments and logics within the sector.

The case study provides a thorough and detailed understanding of the dynamics within a small group of actors and their collaborative work for a transition, i.e. transition dynamics in a very limited network. It thus complements the other approaches used as it gives a rich narrative and localised analysis of the process. The case study also illuminates how expectations are negotiated across organizations, sectors, and geographical scales.

4 Findings and discussion



The findings from my research are presented in detail in the appended papers. This chapter gives a summary of the findings as they relate to the research questions posed in the introduction. Thereafter follows a discussion of the implications of these findings for shaping the transition to a bioeconomy.

4.1 Summary of findings

The first research question posed addressed the systemic characteristics of biorefinery innovation, its structural and processual properties. It is evident that innovation for biorefineries has come a long way from the time when the term biorefining was conceived almost four decades ago, as shown in Paper I. Since then technological research and innovation has produced and diffused knowledge about many different possible biorefinery configurations, yet industrial actors seemingly find it difficult to move forward to implementation as this many times requires knowledge and resources they do not possess. Gaining access to the needed types of knowledge requires that actors develop new capacities or collaborations that can efficiently combine and make use of different types of knowledge. Fostering and maintaining such collaborations are however neither quick nor easy tasks as they require trust and shared commitment to the issue, which is highlighted in Paper II. Together with the scale of investments necessary to really test new biorefinery configurations, these aspects has been significant barriers for experimentation and adoption of biorefineries beyond the pilot and demonstration scale. Policy instruments for biobased fuels have enabled the creation of markets for these products, but there has been very limited support for other types of products, such as chemicals and materials. Conflicting discourses regarding biobased feedstocks and products derived thereof, e.g. regarding their climate benefits versus deforestation effects, have also acted as barriers to gaining legitimacy among both consumers and industrial actors for biorefinery technologies and products.

Secondly, regarding networks and collaborations for biorefinery innovation, the research shows that the Swedish network of actors engaged in collaborative biorefinery innovation has expanded considerably – growing from a small group of mainly research institutions to a large web comprised of actors from different sectors, as shown in Paper II. Actors collaborate in rather close groups, showing that trust is a very important issue for these collaborations, which could be explained by the fact that many actors are reaching outside their traditional spheres and therefore have high requirements on their partners. This type of collaboration also seemingly comes easier for actors from certain sectors than from other, with actors from the chemicals and petroleum industries having been more hesitant to engage. As knowledge and experience from these industries is crucial for deploying biorefineries their hesitancy may be a significant barrier moving forward. The collaborative effort of the chemical firms described in Paper IV shows the challenge for these firms to break with routines and practices that are institutionalised in the sector. Different traditions, aims, and understandings of the necessary conditions for making biorefinery investments feasible remain significant barriers for collaborations, especially when trying to move beyond the demonstration stage. Collaborations are however not only difficult across sectors, but also within the chemical sector, due to the global competition between the large corporations, and even within corporations as different subsidiaries and production sites struggle to acquire resources for innovation activities and investments.

The final question regarded how expectations and local as well as global institutions shape pathways for innovation for biorefineries. Expectations around biorefineries and their role in the emerging bioeconomy are expressed in narratives that find areas of consensus as well as conflict, as shown in Paper III. Three domains of conflict are identified: the importance of different kinds of products from biorefineries, divided between products of lower value such as energy and fuels on one hand, and those of higher value, such as advanced materials or chemicals on the other; the necessity of developing new knowledge compared to moving ahead using what is already known; and the need for policy interventions to spur and support firms and other actors in their development of biorefinery technologies, products, and their applications. As highlighted in Paper IV the chemical sector primarily frames sustainability as an issue of efficiency and enabling low-carbon transitions in other sectors, while the carbon lock-in in the chemical sector itself is rarely challenged. The case shows that in such a global regime, local initiatives will, also when supported by local management and policy programs, find resistance when challenging institutionalised logics to enable a transition towards new socio-technical configurations such as biorefineries. Four dimensions of transition dynamics that bridge the local and global levels are concluded to have affected the local transition initiative: institutional contradictions, internal competition, inadequate networks, and inconsistent aims and expectations. Identifying strategies to mitigate these multi-scalar dynamics is thus important for actors aiming to progress a transition agenda.

4.2 Discussion

Reorienting the socio-technical system for production and utilisation of chemicals, fuels, and materials towards a bioeconomy requires the overcoming of significant technological and institutional barriers. The focus of policy, research, and industrial development has previously primarily been on reducing the demand for direct application of fossil resources as fuels, which has enabled structural changes to the socio-technical systems for heating, electricity, and transportation. The task of reducing the dependency on fossil resources for other applications has however largely been overlooked which is why other industries have not yet fully had to deal with the challenge of such a transition. The chemical sector has even been able to deflect the challenge as a responsibility mainly for other sectors. In the chemical industry the largest efforts for reducing the intensity of fossil resource use have hitherto been directed towards improving the energy efficiency. Although these efforts are important and have led to reduced intensity in the use of fossil resources they are not confronting the fundamental dependency on fossil resources for the production of chemicals. A continued focus on innovation for energy efficiency and process improvement will therefore not be enough for a transition towards a bioeconomy, but innovation for biorefineries presents a promising pathway. This does however require of actors in the chemical and other sectors to commit to the transition, and not to continue expecting an exemption from it.

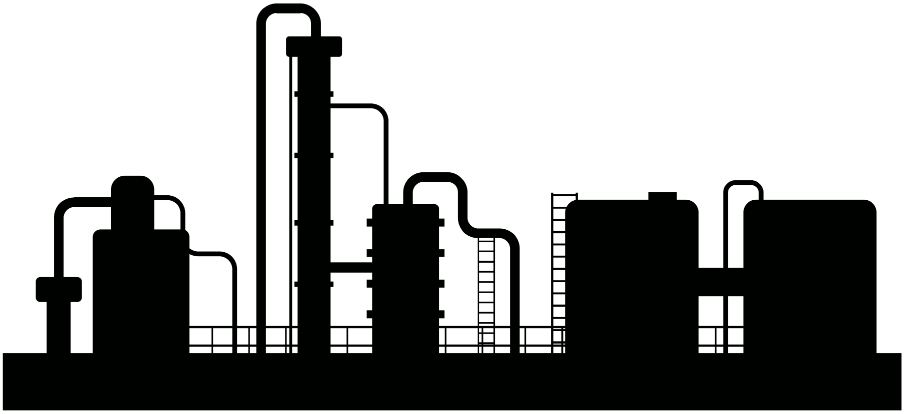
As other systems and sectors, e.g. transportation and energy, reduce their dependency on fossil fuels and increasingly use renewable energy and electricity to cover their energy demand, the chemical sector will be affected indirectly as it can no longer use residual streams from petroleum and gas processing that have previously been available at low costs. If the demand for the majority of petroleum, which is still fuels of different kinds, will no longer suffice to drive the exploration and exploitation of reserves, the chemical industry might well find itself having to cover an increasing part of the cost for these activities. Such a development may increase the pressure to look for alternatives and spur more activity in innovation for biorefineries. In current times of shale gas expansion and low petroleum prices, this situation seems unlikely but it may well become a reality in a not too distant future. Little attention does however hitherto seem to have been paid to this scenario.

Although the interest in engaging with innovation for biorefineries has been growing among both academic research institutions and firms, barriers exist for actors to move forward, especially when it comes to commercial scale implementation. Actors in the chemical sector seemingly remain hesitant to the field, as it constitutes a clear break with the dominant logics, capabilities and traditions in the sector. Overcoming this is a major concern as the knowledge among firms in the sector about both process technologies and markets is crucial for the success of biorefineries. To change existing networks and establish new types of partnerships both within the sector and across sectoral boundaries are difficult tasks. Continued and committed support by policymakers and intermediaries, who must also absorb and foster new competences and capacities, is thus likely to remain an important factor for a successful transition. Important intermediaries to consider here are the engineering and consultancy firms which themselves may have a lesser stake in continued operation of traditional, fossil-based production. Finding ways to push these actors towards innovation for biorefineries could thus prove to be a fruitful avenue.

The global nature of production, consumption, and innovation is an aspect that must not be overlooked in the research of and policy development for transitions. A key aspect of the challenge for a transition in the chemical sector is precisely its global structure, evident from the multi-national corporations that dominate the industry and the markets for feedstocks, products, and technologies, limiting the opportunities to develop local product or technology niches. This points to the need for not only local and national initiatives for a transition of the socio-technical system for chemicals away from its current carbon lock-in, but also for coordinated international and global efforts. To develop and support niches locally has been shown to be an effective way for certain types of transitions, but must not be seen as the role model for all transitions. Making use of existing international networks in the sector to build strength and support for emerging niches is a strategy which could potentially prove to be successful, but which requires the overcoming of new types of barriers, as was shown in the case on Stenungsund.

To accomplish the transition to a bioeconomy institutional changes are necessary – new alliances and cooperative efforts are possible, but require a disintegration of deeply institutionalised networks between the chemical and the petroleum industries as well as establishing new rationalities and logics for innovation. As innovation in the system is dominated by large companies focusing on economies of scale, it is difficult for new actors to partake in the competition, limiting the possibilities for transformational innovation and a transition towards new modes of production by new entrants. Rather it seems that the conflicts that exist between existing actors and their expectations must be resolved and overcome to find pathways that lead toward systemic change. This is one area where public sector initiatives and policy interventions are likely to be able to contribute, by identifying an agenda that can gather support by different actors. Although this will likely be met with opposition by some, possibly powerful and influential, actors, a commitment to technology neutrality is not very likely to lead to meaningful steps forward in the transition to a bioeconomy.

5 Concluding remarks



The thesis posed three different research questions regarding biorefinery innovation for a transition to a bioeconomy and made use of a combination of methods and data to provide answers to these questions. Empirically, the thesis has shown how the biorefinery concept presents a pathway for the chemical sector to break with its fossil carbon lock-in, but for this pathway to become realised important challenges remain to be solved. Theoretically, the thesis has explored how expectations and collaborations shape transition pathways.

Regarding how biorefinery technologies are supported and developed in the current innovation system it has been shown that although large efforts have been made in technological research to develop new biorefinery processes and value chains, the implementation and diffusion is lagging. Not only is this due to the material and financial problems of scaling up process technologies, but also difficulties in forming new alliances that would support the realisation of these value chains. The cross-sectoral nature of biorefineries has been stressed many times earlier, as they require knowledge about biobased resources as well as chemical processing. The chemical industry has however only hesitantly participated in this development. It is however clear that the potential success of biorefineries is not just dependent on more technological research and development to reach a stage of widespread acceptance and diffusion, although more research is needed on the integration of different types of biorefineries into existing systems that have been optimised for other purposes. Institutional barriers are especially difficult to overcome for biorefineries for more radical, complex, and valuable products than fuels and energy, despite the fact that a broader portfolio has been central in innovation for biorefineries for decades.

On the topic of how collaborations and networks shape innovation, it can be concluded that although collaboration does take place both within and across sectors it is difficult also in these networks to challenge structures that have been institutionalised during decades of globalisation. A local context that supports collaborative innovation can bring actors together, but such networks are fragile and costly for the participating actors. This indicates a need for absorptive capacity among actors aiming to progress pathways for biorefineries, although they are hampered by strategies and networks that largely follow traditional patterns and vested interests.

Finally it can be concluded that actors engaged with innovation for biorefineries and the transition to a bioeconomy have very different expectations on the dynamics of this transition. Actors in Sweden promote transition narratives that are both conflicting and contradictory, showing that on a national level there is not a shared vision for the transition. Within the chemical industry a group of Swedish actors have agreed on a vision, but the global regime constrains their efforts in differen ways and works to retain a status quo of fossil lock-in.

The overarching aim was to provide a deeper understanding of how collaborations and expectations shape and form transition pathways. It has been shown that collaborative work is not a simple panacea for breaking new ground for transformative innovation. Such collaborations are difficult and require actors to commit and invest in issues they are less knowledgeable about. Although their expectations may at first seem to be well aligned, it is likely that their underlying assumptions and preunderstandings will be less similar than it first appears. Negotiating such conflicts will require commitment from the involved partners to allow finding a common ground for moving forward. Institutionalised structures on both the local and global level, by which the different actors are bound, must be recognised to find new potential pathways, by firms and organisations in the field as well as by policymakers aiming to support such work.

Future research should further investigate the roles of different types of actors in networks for biorefinery innovation and how collaborating partners approach and negotiate expectations. As these expectations are closely connected to perceptions of legitimacy and social acceptance, it would be relevant to broaden the scope to include consumers and their opportunities for creating pressure for biorefineries. Further, the heterogeneity of actors is an aspect that needs more attention in transition research; multi-national corporations are not homogenous actors but are in themselves networks in which different ambitions, expectations, and interests struggle and are being negotiated. More knowledge is needed on how this affects transition agendas and initiatives, and in which contexts they are likely to benefit. As the chemical industry is far removed from end consumers such pressures will most likely be mediated by actors in-between, who may thus become important for shaping the discourse on possible transition pathways. This discourse will not be bound by the national borders, but is also dependent on global developments and events. Broadening the scope to look at international connections and networks would be relevant to understand possibilities for de-localising transition initiatives by anchoring them in global networks and allowing both industrial actors and policymakers to progress the transition to a bioeconomy.

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