THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Environmental Assessment and Strategic Technology Choice

The Case of Renewable Transport Fuels

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Department of Energy and Environment
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Göteborg, Sweden 2008

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Göteborg 2008
ISBN 978-91-7385-195-4

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie Nr 2876
ISSN 0346-718X

ESA-report 2008:17
ISSN: 1404-8167

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Chalmers Reproservice
Göteborg, Sweden 2008

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The Case of Renewable Transport Fuels

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Abstract

The scale of the required changes is huge, and time is limited if we are to avoid the most severe effects of climate change. To reduce greenhouse gas emissions from road transport, several fuels and electricity originating from renewable energy sources have been proposed, all of them in different stages of development and with various and shifting environmental impacts. This thesis aims at increasing the usefulness of environmental assessments of emerging technologies as a basis for strategic technology choice. Recommendations for the design and interpretation of such assessments are presented, with a special focus on life cycle assessment (LCA) methodology. A long time perspective, the possibility of system change, and the inclusion of socio–technical change processes allows for the revision of methodological assumptions normally made in LCA of current products. To guide the selection of technologies, there is need for assessment both of technology and of interventions.

For the assessment of technology, an attributional approach is applied. Paper I discusses and tests the feasible futures and future performance to be considered in attributional LCAs. The results indicate that the environmental impact attributable to a number of selected fuels, as well as the ranking of them, largely depend on assumptions regarding background systems and by-product use.

For the assessment of interventions, a consequential approach is applied. Extensive studies of socio–technical change processes contribute insight into relevant cause–effect chains that can be included in environmental assessments of emerging technologies. A comparison between the Swedish and the Dutch innovation systems for renewable fuels reveals the unfolding of dynamics influenced by shared background factors (Paper II). An investigation of the Swedish history of alternative fuels is used in developing a framework for analysing interaction between emerging technological systems (Paper III). Insights into socio–technical change processes are then used to elaborate scenarios for the future development of renewable fuels in Sweden resulting from current policy choices (Paper IV). In a final paper (Paper V), historical and future cause–effect chains are taken into account in a consequential LCA of ethanol of varying origins in Sweden for the 1990–2020 period. It is concluded that for emerging technologies in an early stage of development, the contribution of an intervention to system change may be more important than the direct change in environmental impact.

Finally, it is suggested that all aspects of socio–technical change and the resulting environmental impact may not have to be included in quantitative environmental assessments, such as LCA. ‘Environmental assessment’ could very well include a group of parallel studies that illuminate different cause–effect chains resulting in changed environmental impact, and that are part of a society-wide learning process.

Keywords: environmental assessment, life cycle assessment (LCA), socio-technical change, strategic technology choice, renewable fuels

List of publications

Appended papers

This thesis is based on the work contained in the following papers:

I. Hillman, K. M. and Sandén, B. A. (2008): Time and scale in Life Cycle Assessment: the case of fuel choice in the transport sector, International Journal of Alternative Propulsion 2(1): 1–12.

II. Hillman, K. M., Suurs, R. A. A., Hekkert, M. P. and Sandén, B. A. (2008) Cumulative causation in biofuels development: a critical comparison of the Netherlands and Sweden, Technology Analysis and Strategic Management 20(5): 593–612.

III. Sandén, B. A. and Hillman, K. M. (2008): A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. Manuscript.

IV. Hillman, K. M. and Sandén, B. A. (2008): Exploring technology paths: the development of alternative transport fuels in Sweden, 2007–2020, Technological Forecasting and Social Change 75: 1279–1302.

V. Hillman, K. M. (2008): Accounting for Socio-Technical Change in Consequential LCA of Emerging Technologies. Manuscript.

Other publications by the author

The following papers contribute to the summary part of this thesis, while not being fully represented in the appended papers:

- Jonasson, K. M. and Sandén, B. A. (2004). Time and Scale Aspects in Life Cycle Assessment of Emerging Technologies: Case Study on Alternative Transport Fuels. CPM-report 2004:6, Chalmers University of Technology, Göteborg, Sweden.
- Sandén, B. A., Jonasson, K. M., Karlström, M. and Tillman, A.-M. (2005). LCA of Emerging Technologies: A Methodological Framework, LCM2005 – Innovation by Life Cycle Management, 5–7 September 2005, Barcelona, Spain.
- Sandén, B. A. and Jonasson, K. M. (2005). Variety Creation, Growth and Selection Dynamics in the Early Phases of a Technological Transition: The Development of Alternative Transport Fuels in Sweden 1974–2004. ESA-report 2005:13, Chalmers University of Technology, Göteborg, Sweden.
- Jonasson, K. M. (2005). Environmental Assessment of Emerging Technologies: The Case of Alternative Transport Fuels. Licentiate thesis. ESA-report 2005:14, Chalmers University of Technology, Göteborg, Sweden.
- Hillman, K. M. (2007). LCA and Strategic Choice of Biofuels. SETAC Europe 14th LCA Case Studies Symposium, Göteborg, Sweden, 3–4 December 2007.

Acknowledgements

This work has been funded by several organisations, which are greatly acknowledged. These are, in chronological order, the Centre for Environmental Assessment of Product and Material Systems (CPM) formed by Chalmers, Vinnova and industrial partners; Göteborg Energy Ltd. Research Foundation; RIDE (R&D, Innovation and the Dynamics of Economies) at Chalmers; and Volvo Research and Educational Foundations (VREF).

I would like to thank all the people out there who have contributed with comments, stories, and data during the work with this thesis, particularly the interviewees (listed in the Appendix), the CPM reference groups and various industry contacts. I am grateful for critical and helpful remarks brought up by Staffan Laestadius at my licentiate seminar. Thank you also to Roald Suurs and Marko Hekkert for fruitful cooperation, and for inviting me to Utrecht University in 2006.

It has been a great pleasure working with this thesis at Environmental Systems Analysis (ESA), and the gathered competence in systems analysis, environmental assessment and socio-technical change has been invaluable through the years. I am indebted to my PhD supervisor Björn Sandén, who has provided inspiring and constructive supervision and support since the start. I would like to thank my examiner Anne-Marie Tillman for critical comments and useful advice, and for providing insights into LCA development. I am also grateful for helpful suggestions and engaged support from Staffan Jacobsson. In addition, I have valued the occasional discussions with Sverker Molander and Bengt Steen. In fact, the working days would not have been the same without all my colleagues at ESA, with whom I have shared numerous lunch and fika hours. Particularly I am glad having been able to share the ups and downs of PhD studies with my room mate Emma Rex.

Finally, there are some people that have brightened up my life outside working hours. Though we are geographically spread throughout Göteborg, Sweden and Europe, I highly value friendship with a number of people – you know who you are. I am happy that my grandparents find an interest in my work, that my sister Anna has moved to Göteborg, and that my parents have provided me with neverending support since day one. During the past few years, I have also appreciated getting to know the Hillman families. Finally, Stina, you keep reminding me of what is important in life, now also with help from Vera. I guess spending more time with you, Herr Gurka and ‘plyschmasken’ is part of the answer.

Karl Hillman (Jonasson until August 2007)
Göteborg, October 2008

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1 Introduction

Climate change will alter conditions for life in most parts of the world, and for many people radical changes in the environment will threaten natural production systems and living areas (IPCC, 2007). At the same time, health and environmental problems resulting from air and water pollution are imminent in many regions. These problems can largely be attributed to society' s use of fossil fuels for energy services, such as heat, electricity, and transport. There is a massive dependence on current energy systems and, though fossil resources are limited, enough still remain to cause persisting health and environmental problems.[1] Coal supplies 25% of human energy demand, and reserves of it amount to 133 times current annual consumption. Oil, the dominant resource for transport fuels, supplies 35% of human energy demand. Conventional oil reserves are limited, corresponding to only 42 years' use; unconventional sources, however, will extend the resource base, though entailing worse environmental performance. Finally, natural gas is less polluting, but still causes considerable emissions of the greenhouse gases (GHGs) causing climate change. Natural gas supplies about 20% of human energy demand and reserves of it are limited to 60 years at the current use rate.

Climate change and pollution problems can be mitigated by reducing the use of energy and fossil fuels. However, as industrial societies are largely dependent on energy and transport systems, there is also a need for energy sources without the large negative effects related to fossil fuels. The scale of the required changes is huge, and time is limited if we are to avoid the most severe effects of climate change. For road transport, several alternative resources and technologies are proposed, all of which have different advantages and disadvantages in relation to health and environment. To guide the selection of technologies, there is need for environmental assessment both of technology and of interventions. Assessing the environmental performance of emerging technologies is no trivial matter, however. In particular, the scale of the required changes and the time perspectives involved need to be taken into account. This thesis discusses the design and interpretation of such assessments by means of a case study of renewable fuels for road transport.

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[1] The figures in this paragraph are from IEA (2006) and BP (2008). Reserves are defined as the quantities that 'with reasonable certainty can be recovered in the future from known deposits under existing economic and operating conditions' (BP, 2008). Thus, the quantities given may change with technical and economic development.

1.1 Alternative transport fuels

Various forces are driving the introduction of alternatives to petrol and diesel in the road transport sector. Some alternatives are based on fossil fuel resources other than conventional oil, and are intended to reduce dependence on oil and/or reduce air pollution. However, these energy sources will still contribute substantially to climate change, if not combined with future technology for carbon capture and storage (CCS) and production of carbon-free energy carriers, such as hydrogen or electricity (see, e.g., Azar et al., 2006). Nuclear power, though it may provide carbon-neutral energy carriers, poses other problems. Alternative to these non-renewable options, fuels based on renewable resources could help mitigate all the problems mentioned. Such fuels are here termed 'renewable fuels' and are typically based on biomass, wind, hydro, or solar energy.[2] There are also other influential forces, in addition to health and environmental concerns, driving renewable energy development, mainly a desire for energy security and the utilization of biomass-based fuels (biofuels) to increase agricultural profitability. If introduced without care, there is a risk that renewable fuels could also exacerbate certain environmental problems, such as eutrophication and loss of biodiversity.

Most of the technologies needed to produce renewable fuels are still under development, and some exist only on a pilot scale. The current performance of these alternatives is poor and the costs are high, and future performance and costs are uncertain. Improvements largely depend on learning from increased adoption and on general technical progress. Against this, established technologies benefit from over a century of learning and from the entrenchment of current practices. This has resulted in the current energy system being locked in to the use of fossil fuels (Unruh, 2000). Thus, there is an imminent risk of ongoing reliance on fossil fuels and that the only alternatives developed will be based on coal, natural gas, and unconventional oil. The development and implementation of new technologies takes time: to bring promising renewable fuels 'to the shelf' and have them selected 'from the shelf' in coming decades will entail a range of measures (Sandén and Azar, 2005).

There is political will worldwide to increase the use of renewable fuels in the road transport sector. Among the most ambitious initiatives is the European Union's directive from 2003. In this 'Biofuels Directive' (EU, 2003). It states that EU member states should set targets for the introduction of and use of renewable fuels, with an indicative target that by 2010, 5.75% of petrol and diesel used for transport should be replaced by renewable

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[2] This is in line with the European Union's directive 'on the promotion of the use of biofuels or other renewable fuels for transport' (EU, 2003). 'Biofuels and other renewable fuels' are defined in the directive as liquid or gaseous fuels produced from biomass or other fuels originating from renewable energy sources. In this thesis, electricity from renewable energy sources is also considered a 'renewable fuel'.

fuels. The Directive is currently under revision; the suggested 2020 target is 10%, accompanied by a certification scheme to prevent negative social and environmental effects and stimulate more favourable technologies and practices (EU, 2008).[3]

1.2 Environmental assessments

There is a wide range of environmental assessment methods and analytical tools that can be used to guide the selection of technologies (Wrisberg, 2002), and various energy system models are used to study the optimal allocation of resources for heat, electricity, and transport under emission constraints (Azar et al., 2003; Gielen et al., 2003).[4] One of the most commonly used methods to compare different alternative technologies is life cycle assessment (LCA). The basis of such assessment is a model of the technical system covering the full life cycle of a product or service, i.e., from raw material acquisition, through processing and transport, to final use and waste treatment. In LCA, data regarding all physical inputs to the technical system and outputs from the technical to the natural systems are collected and translated into potential environmental impact. The results are related to a certain functional unit of the studied product, for example, 1 MJ of electricity or 1 vehicle-km. The procedure for performing an LCA is quite straightforward, and has been standardised by ISO (ISO, 1997; ISO, 2006a). Basically, LCA is used to analyse the potential environmental impact associated with a product, service, or production process. Studies can be either *attributional*, i.e., considering the impact attributable to the life cycle of a product in a certain background system,[5] or *consequential*, analysing the impact resulting from a technology-related intervention, such as a change in the product life cycle or the adoption of a new product (Ekvall, 1999; Tillman, 2000; Curran et al., 2005; Sandén et al., 2005; Höjer et al., 2008).

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[3] These revisions are being made partly in reaction to recent debate on the introduction of certain renewable fuels mainly based on agricultural crops (see section 2.2 for various perspectives on this). It is still uncertain what the outcome will be in terms of policy.

[4] There are also other kinds of tools, for example, for procedural environmental assessment, typically focused on the process of taking environmental issues into account in various kinds of projects and organisations; see, for example, Finnveden and Moberg (2005) for an overview of environmental systems analysis tools.

[5] The assessed technologies make up the *foreground system*, which consists of the processes affected by decisions based on the study (Tillman, 2000); the *background system* consists of all other modelled processes.

LCA methodology is commonly used as a basis for decisions relevant to the short and medium term; central fields of LCA application are as follows:[6]

- Analysing changes in the life cycle of a product, such as selecting different production process options,
- Informing product development and product strategies,
- Comparing existing products with similar functions, for example, in a procurement situation,
- Assessing criteria related to eco-labelling schemes, and
- Learning about products and processes from a life cycle perspective.

These applications, for which LCA methodology was primarily developed, account for most LCA use. Even at an early stage, however, the applicability of LCA to support longer-term strategic decisions was identified (e.g., Baumann et al., 1994). Such decisions involve the 'development of new and most probably creative answers to unique situations' (Baumann and Cowell, 1999).[7] Case studies, mainly directed towards policy makers and firms, have been performed to support strategic decisions. Such studies are frequent in the field of transportation fuels, where LCAs – often called well-to-wheel (WTW) studies – are presented to guide the selection of different combinations of raw materials, production processes, and fuels among different actors. However, the methodology is still poorly adapted to the study of emerging technologies at different stages of development, technologies that may eventually be adopted on a larger scale and in radically changed systems, including new materials, infrastructure, and user practises. Thus LCA is also less suited to guide strategic technology choice beyond the short-term optimisation of products and processes. Nevertheless, I have perceived overconfidence that LCA results could provide comprehensive basis for decisions.

Some work has been done on improving the usefulness of LCA for strategic technology choice.[8] Depending on the type of study – attributional or consequential – two main paths are followed:

1. Assumptions of the feasible futures and future performance of technologies, and
2. Modelling selected cause–effect chains related to interventions

Still, most studies focus on specific products, and assumptions and methodological choices are very much dependent on historical, current, or near-future practices and background

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[6] Several authors have catalogued the application areas of LCA (see, e.g., Lindfors et al., 1995; Wenzel et al., 1997; Weidema, 1998; Baumann and Tillman, 2004).

[7] Baumann and Cowell (1999) in turn refer to March and Simon (1958).

[8] See European Commission (2007) a for a recent discussion of sustainability assessment, where studies of future technologies are referred to as 'level-2 assessments'. Research needs related to life cycle assessment are also identified in the CALCAS project (CALCAS, 2008).

systems. There is thus a risk that both changes in the performance of emerging technologies and the effects of adopting them on further developments – and potential environmental impact – may be poorly estimated. Referring to the first path, it would be desirable to capture the inherent properties of more generally defined technologies and their performance in different future systems. Regarding the second path, in the case of emerging technologies, a broader set of longer-term cause–effect chains would be relevant to study (Sandén and Karlström, 2007), due to their influence on the development of socio–technical systems. A decision to invest today in an immature technology may contribute to future large-scale adoption and changed environmental impact; at an early stage of development, new actors are involved, knowledge is gained, and values are changed, possibly resulting in further investment decisions favouring the technology. Such processes of socio–technical change, particularly in the field of energy technology, have been studied in recent research into technological innovation systems (TIS) (e.g., Bergek et al., 2006) and technological transitions (e.g., Elzen et al., 2004a).

The primary interest of this thesis is in the implications of socio–technical change for environmental assessment, recognising the possibility of increasing the relevance of the results to be used for strategic technology choice. Furthermore, this will contribute insight into the development processes in which environmental assessments are used. Technologies are not selected once and for all; they are part of an evolutionary process and may be adopted concurrently and/or sequentially by different actors. This is particularly relevant in the case of transport fuels, where the need for new alternatives is urgent while the development of various technologies is uncertain and resources are limited.

1.3 Purpose and research questions

The purpose is to increase the usefulness of environmental assessments of emerging technologies as a basis for strategic technology choice by taking socio–technical change into account. The main research question is thus related to methodology:

> *Q How should environmental assessments be made, so as to inform decisions that strive to contribute to the radical environmental improvement of large systems?*

This question will be addressed in relation to the two paths of life cycle assessment (LCA) methodology, i.e., assumptions of future performance and modelling cause–effect chains, applied to renewable transport fuels.[9] A long time perspective, the possibility of system change, and the inclusion of socio–technical change processes allows for the revision of

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[9] The focus of this thesis is on the inventory part (LCI) of LCA, while the impact assessment part (LCIA) is left out. For LCIA to be meaningful, however, the LCI results used as input need to be relevant.

methodological assumptions normally made in LCA of current products. This implies the reconsideration of what are regarded as 1) feasible futures and future performance of technology, and 2) relevant cause–effect chains related to interventions. Furthermore, interpretation and limitations of LCA are discussed.

The main research question (Q) is broken down into five sub-questions (Q_I–Q_V), each with a different focus, addressed in the appended papers and throughout this thesis (see Table 1); considering these sub-questions will help when it comes to answering the main question. First, in Paper I, common assumptions in attributional LCA are discussed and tested in relation to the longer-term perspective and large-scale adoption of renewable transportation fuels. Papers II–IV investigate cause–effect chains in the socio–technical system around renewable transport fuels, to gain insight into the consequences of technology-related interventions. In Paper II, continuous cause–effect chains, i.e., cumulative causation, in two technological innovation systems (TISs) are analysed in terms of exogenous factors and endogenous dynamics. A framework for studying the interaction between different emerging technologies is developed in Paper III, illustrated by a case study of the development of renewable fuels in Sweden. Paper IV elaborates on socio–technical scenarios, to explore future cause–effect chains resulting from current policy interventions. Finally, in Paper V, historical and future cause–effect chains are taken into account in consequential LCA.

Table 1: Titles and research questions of Papers I–V.[10]

Paper	Title	Research question
I	Time and scale in life cycle assessment: the case of fuel choice in the transport sector	Q_I: What are the time- and scale-dependent choices involved in LCA, and how can they be treated when assessing emerging technologies?
II	Cumulative causation in biofuels development: a critical comparison of the Netherlands and Sweden	Q_{II}: What are the drivers of and barriers to cumulative causation in Sweden and the Netherlands, and how can differences and similarities between the countries be related to policy makers and entrepreneurs?
III	A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden	Q_{III}: How do supposedly competing emerging technologies interact during their growth?
IV	Exploring technology paths: the development of alternative transport fuels in Sweden 2007–2020	Q_{IV}: What are the implications of current policy choices for the development of the technological system of renewable transport fuels in Sweden?
V	Accounting for Socio-Technical Change in Consequential LCA of Emerging Technologies	Q_V: How can socio–technical change be taken into account in consequential LCA of emerging technologies?

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[10] The exact wording of the questions used in the summary part of the thesis is adjusted from what is used in Papers I-V. Still, the meaning is essetially the same.

All five papers contribute to the overall thesis, but there are also connections between the papers themselves. First, Paper I develops theoretical concepts and typology referred to in Paper V. Second, the empirical material documented in Sandén and Jonasson (2005b) is used in Papers II–IV. In addition, the cause–effect chains studied in Papers II and III are considered in the socio–technical scenarios elaborated on in Paper IV; these scenarios are then used in Paper V.

1.4 Scope of the thesis

With this thesis, I seek to contribute to making environmental assessments more compatible with insight into socio–technical change. In addition, I would like to build awareness of the *context* of strategic technology choice and of how environmental assessments can be applied to this context. The wider context of how technology-related interventions change the prerequisites for further choice is included at a societal level, including the interaction between different kinds of actors. Relationships among individuals or within firms, such as the specific role of environmental assessments in decision-making processes and participative methods, are not considered in this work.

The focus here is on *technologies* providing a certain *function*, i.e., renewable energy supply in road vehicles. The word 'technology' denotes a combination of resources, processes, fuels, and related uses that constitute the life cycle. The main research question is methodological: 'How should environmental assessments be made …', i.e., methodology is developed through a case study of technologies delivering the stated function. Thus the aim is not to give a comprehensive overview of all possible ways to provide the function, which is why only a small number of technologies and environmental impacts are included in the LCA parts of the thesis; nor are other sectors, such as the heat, electricity, and food sectors, analysed.[11]

In the studies of historical development, the time perspective extends 30 years back in time, while when considering strategic technology choice it extends roughly 30 years ahead. Then most current decisions regarding production, infrastructure, and vehicles are not directly influenced by existing investments[12].

The geographical scope is as follows: Europe in Paper I, Sweden and the Netherlands in Paper II, and Sweden in Papers III–V. The mostly national focus can be justified by the fact that at an early stage, before competing on a global market, new technologies are often adopted locally on a small scale with weak connections to the world outside. Though technology may be global, renewable transport fuels are still disfavoured by the current

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[11] Nevertheless, these aspects influence the development studied in Papers II–IV.

[12] This time perspective has been called the 'very long term' (Frischknecht, 1997).

system, and largely depend on national institutions, such as laws and culture. Of course, this is also a matter of system delimitation.

1.5 Research process[13]

The thesis project has several points of departure. The main research question followed on the results of a thesis published by Andersson (2001) at the Division of Physical Resource Theory at Chalmers University of Technology. This led to a research project at the Division of Environmental Systems Analysis (ESA), also at Chalmers, which had a tradition of LCA methodology development (see, e.g., Ekvall, 1999; Tillman, 2000; Baumann and Tillman, 2004; Karlström, 2004). The design of the project was also influenced by the innovation system tradition (e.g., Carlsson, 1997; Jacobsson and Johnson, 2000; Bergek, 2002). My research into the assessment of emerging technologies today represents one of the main paths followed at ESA in recent years, involving several researchers.

My first work on the LCA of renewable transport fuels (Paper I) was based on literature data, and on methodological discussions in the scientific literature and at methodology- and case-related workshops and conferences. During this work, I recognised that several emerging technologies have played different roles in history due to their specific performance attributes and different stages of development, and in relation to different objectives. There was no choice situation characterised by a set of functionally equivalent alternatives, one or a few of which should be selected once and for all. Actually, different alternatives can be adopted in sequence and/or concurrently by different actors. For this reason, and particularly to investigate how alternatives interact with each other, theories on socio–technical change were employed.

The specific case of renewable transport fuels was then studied through participating in industrial conferences and meetings, reading consultancy and government reports, and interviewing key actors (listed in the Appendix). Conferences and written material helped greatly in identifying actors and gaining background information for the interviews. The interviews contributed important insight into the development of alternative transport fuels in Sweden, which could not have been gained from the literature. Due to the use of open-ended questions, the interviews also guided the search for written material, helped identify more key actors, and gave rise to further interview questions.

Theoretical ideas were mainly borrowed from research into technological innovation systems (TIS) (Bergek, 2002) and the multi-level perspective (MLP) on the

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[13] This sub-section is inspired by Dubois and Gadde (2002).

transformation of socio–technical systems (Geels, 2002b); these ideas contributed to the formulation of a preliminary research framework. In daily work, the empirical material was continuously (re)described in terms of the evolving framework and documented in different versions on an ongoing basis (Jonasson, 2005; Jonasson and Sandén, 2005; Sandén and Jonasson, 2005b; Sandén and Jonasson, 2005a). Mismatch between empirical findings and the frameworks prompted us to explore different avenues in three different papers.[14]

Paper II used an operationalisation of the TIS framework, and processes of cumulative causation were studied in more detail. Paper III consulted building blocks of community ecology (Odum and Barrett, 2005) and technical modularity (Baldwin and Clark, 2000; Murmann and Frenken, 2006) in analysing the interaction between emerging technologies (or technological systems). In Paper IV, parts of the frameworks were combined with techniques for constructing socio–technical scenarios (Elzen et al., 2002). Finally, in Paper V, the historical developments (documented in Sandén and Jonasson, 2005b) and the scenarios treated in Paper IV were used to illustrate cause–effect chains in relation to consequential LCA.

1.6 Thesis outline

Section 2 provides an overview of existing and future renewable fuels, and arguments put forward in relation to such fuels are presented. The context in which environmental assessment can be used to support strategic technology choice among various actors is described in section 3. Basic principles following from a systems perspective are explained and general concepts used in the thesis are introduced in section 4. In section 5, contains a review of relevant literature on socio-technical change and gives more detailed insight into cause–effect chains in socio–technical systems, ending with selected results of Papers II-IV (sub-sections 5.4–5.6). The synthesis between environmental assessment methodology and socio–technical change is made throughout section 6, ending with selected results of Papers I and V (sub-sections 6.2 and 6.3). Conclusions regarding the design and interpretation of environmental assessments are offered in section 7. This is followed by some perspectives on strategic technology choice resulting from the different studies of renewable transport fuels (section 8). Finally, suggestions for further work are presented in section 9. A list of interviewees is placed in the Appendix.

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[14] Due to the iterative process of performing, writing, and publishing a study, some work on different papers was done concurrently.

2 Renewable transport fuels

Various alternatives to petrol and diesel have been proposed as means to mitigate the environmental problems related to road transport. In particular, liquid and gaseous fuels as well as electricity originating from renewable energy sources can play important roles, as they have the potential to reduce GHG emissions.[15] This section starts with an overview of existing and future renewable fuels (or fuel chains), followed by a recapitulation of the main options for reducing the environmental impact of transport. Though not studied in this thesis, carbon-neutral transport may also be provided by nuclear energy or fossil fuels with carbon capture and storage (CCS), in combination with the production of carbon-free energy carriers, such as hydrogen and electricity.

2.1 The alternatives

In recent years, many publications and comments about renewable fuels, or biofuels, have distinguished between at least two generations of such fuels.[16] The first generation normally refers to fuels produced using existing technologies and based on agricultural crops that can also be used for food production. In addition, residues from agriculture, organic waste, animal manure, and sewage sludge can be used to produce first-generation renewable fuels. Primary examples of such fuels are ethanol produced by fermenting starch and sugars, biogas by anaerobically digesting organic materials, and fatty acid methyl esters (FAME) by transesterifying vegetable and animal oils and fats.[17] The second generation of renewable fuels is instead based on cellulosic materials, i.e., non-food grasses and trees, cellulosic residues from forestry and agriculture, and wood waste. The two main groups of second-generation technologies are ethanol produced by hydrolysis and fermentation, and synthesised fuels produced by gasifying biomass. The latter group includes methanol, Fischer-Tropsch (FT) diesel, dimethylether (DME), hydrogen, methane, and possibly also ethanol. Hydrogen and electricity from renewable energy sources normally fall outside this categorisation into generations. These technologies can be based on biomass as a raw material, but also, for example, on wind, hydro, and solar energy. Sandebring (2004) also proposes a third generation referring to hydrogen and unknown alternatives.

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[15] For biomass-based fuels, the carbon in the raw material is part of the carbon cycle; other renewable energy sources do not rely on chemical reactions involving carbon atoms.

[16] Often the more specific term 'biofuels' is used, which refers only to renewable fuels based on biomass; these fuels have been the main focus so far in this work.

[17] Fatty acid methyl esters (FAME) produced from rapeseed are called rapeseed methyl ester (RME). FAME is also called 'bio-diesel'. However, that term can also, or alternatively, refer to other liquid fuels that can be used as diesel substitutes (as is the case in Paper II).

The technologies for producing and using renewable transport fuels are in different stages of development, and most technologies for producing second-generation renewable fuels exist only on a pilot scale. As some second- and third-generation technologies are approaching the market, the categorisation into generations is becoming less useful. In discussing performance and environmental impact in relation to technology choice, it becomes more relevant to distinguish between specific fuel chains. In addition, several other distinctions between fuel generations have been suggested by various actors, confusing the discussion. In the depiction of different fuel chains in Figure 1, future options are distinguished from those on the market today (i.e., 2008).[18] In addition, new processes and fuels will likely emerge, and new resources may become interesting for fuel production when conventional ones become scarcer.

Fuel chains also include the consumption of fuels in vehicles, for which various power trains may be considered (not included in Figure 1). The energy efficiency of the combination of power train and vehicle determines the fuel consumption and thus the GHG emissions per kilometre driven. For other emissions, additional factors come into play. Some fuels are better suited for use with certain power trains, though over time technology can also be developed for new combinations. The most common power trains in vehicles today are the Otto and diesel combustion engines, while the HCCI engine, a combustion engine under development, combines features of the Otto and diesel engines.[19] Another future power train is the fuel cell, supplying an electric motor with electricity. This has mainly been demonstrated using hydrogen or methanol, but in combination with a fuel reformer, a fuel cell could also use other fuels.

All power trains can be combined with hybrid technologies to increase efficiency. These technologies give a system comprising a combustion engine (or fuel cell), batteries (or other energy storage), and electric motor(s); the engine charges the batteries that power the motor, or the engine and the motor are both connected to the transmission. The major advantages of this system are that the engine can be run at an optimal speed and sometimes be turned off, the high efficiency of the electric motor is exploited, and kinetic energy can be recycled through regenerative braking. A vehicle that can also charge its batteries from the electricity grid is called a plug-in hybrid; the market introduction of this technology has been announced for coming years.

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[18] 'Present on the market' does not necessarily mean that all actors can easily choose between all these fuel chains, but that they are commercially represented.

[19] HCCI stands for homogenous charge compression ignition.

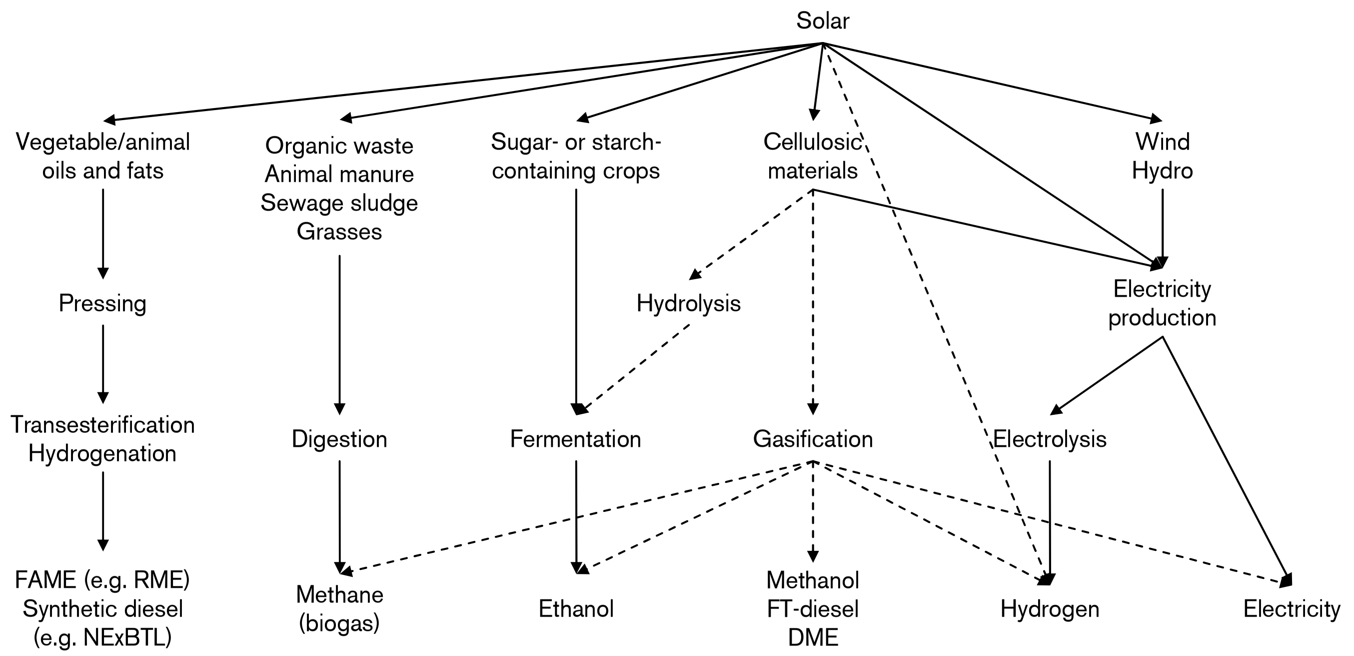

Figure 1: Renewable transport fuels and their respective value chains, i.e., raw materials and production processes; all the included fuels originate from solar energy. Unbroken lines indicate existing paths, while dashed lines represent paths that are under development. Oils and fats, sugar and starch, and cellulosic materials may also be derived from residues and waste.

An important property of some fuels is that they can be blended and used with others, the most common examples being ethanol in petrol and FAME in diesel. Such blends can be used in one or several power trains, provided combustion conditions and materials used are compatible with the blends, facilitating the gradual introduction of renewable fuels. FT diesel mixed in conventional diesel and hydrogen in methane are other examples of such blended fuels. Vehicles that are adjusted to run on a large share of ethanol are called flexifuel vehicles. Another option for combined use of different fuels can be exemplified by bi-fuel vehicles, which have one tank for petrol and one for methane. From Figure 1 it can also be concluded that most renewable fuels can be produced via different chains, increasing the flexibility of supply. Another important technical similarity between methanol, FT diesel, DME, methane, and hydrogen is that they all can be made from synthesis gas produced from biomass.[20]

The various possible fuel chains in different stages of development also differ with regard to infrastructure requirements, costs, practicability, safety, life cycle efficiency, and environmental impact. These differences have opened up debate on the choice of renewable transport fuels and their potential role in mitigating environmental problems.

2.2 Complementary options

Various reasons are cited to justify and promote the use of different renewable fuels in the transportation sector, such as reduced greenhouse gas (GHG) emissions and oil dependence, regional agricultural development, and improved local environment. Particularly in recent years, there has been increasing interest among policy makers and firms in the possible benefits of renewable fuels. However, there are critical voices as well; here, a number of arguments are presented, to further clarify and frame the current case study.

Alternative fuels offer one way to reduce the environmental impact of the transport sector, but as indicated in the introduction, there are other complementary options for reducing such impact. First, transport activity may be reduced. Improved logistical systems and better planning of societies and urban areas may reduce transport distances for labour and food, for example. In addition, a focus on 'virtual mobility' instead of transport highlights the possibilities for transferring information in the form of, for example, telephone and video conferencing. A more radical criticism concerns the actual need for transport, referring to the ultimate goal of human well-being. The idea is that long-distance travel and the consumption of products do not themselves represent parts of

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[20] Synthesis gas can also be produced from fossil fuels, such as natural gas and coal.

the goal, but rather *means* for reaching the goal, and that there may be other, more environmentally benign means that also contribute to human well-being.

Second, even without reducing transport activity, the use of energy could be reduced. A partial shift to more efficient transport modes is one option, for example, from road to rail, from air to sea, or from motorised vehicles to bicycles. For different transport modes, energy use can be reduced through increased public transport, car sharing, and collective transport of goods. If more goods or people are transported in each vehicle, the total number of vehicle kilometres, and hence energy use, can be reduced. Furthermore, there is a potential to improve the energy efficiency of vehicles by optimising their size, weight, and performance, and by improving power train efficiency through technical development and eco-driving practices. For example, in Sweden and elsewhere, excessively large vehicles such as sport utility vehicles (SUVs) are being criticised and sales of them are declining, while smaller vehicles are being introduced to the market. In coming years, there are high expectations that hybrid and plug-in hybrid technology will increase the energy efficiency of cars and heavy vehicles.

Finally, non-renewable and renewable alternatives to petrol and diesel may help reduce the environmental impact of the fuel chain. Here, we focus on renewable alternatives, which so far mainly have been proposed for use in road transport. As hydrogen and electric vehicles are barely available on the market, the primary focus has been on renewable fuels based on biomass, i.e., biofuels.[21] One of the main issues then concerns the best use of limited production of biomass. Energy system studies have investigated the most efficient use of biomass to reduce GHG emissions (Azar et al., 2003; Gielen et al., 2003; Gustavsson et al., 2007). It has often been argued that it is more cost-efficient if a certain amount of biomass is substituted for fossil fuels in producing heat and electricity instead of transport fuels.

Another important issue concerns the competition between food and fuel for agricultural land and crops. As existing renewable fuels largely rely on food crops, increased demand will have an effect on food prices and the use of agricultural land (see, e.g., Johansson and Azar, 2007). On the one hand, due to differences in purchasing power between people around the world, an increasing share of crops and land may end up being used for fuels and a decreasing share for food, thus aggravating hunger and starvation among the poor (Runge and Senauer, 2007). On the other hand, increasing demand for agricultural crops may create opportunities for impoverished farming populations, provided resources are properly distributed (see, e.g., Azar, 2005). In principle, at a global level, there are large

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[21] There are a few models of hydrogen and electric vehicles, but for practical and economic reasons these have not yet been widely adopted.

unused land areas and areas that could be used more efficiently, making additional land available for energy crops (see, e.g., Hoogwijk et al., 2005). However, competition for land may still be a critical issue at the local level. In addition, putting uncultivated land into crop production may increase soil emissions, possibly with a large environmental impact.

The potential negative effects related to the increased adoption of renewable fuels have resulted in recommendations of caution from several actors, particularly regarding first-generation biofuels (e.g., Worldwatch Institute, 2006; FAO, 2008). The possibility of introducing different kinds of certification schemes to avoid undesired effects is attracting increasing attention, for example, in the EU (EU, 2008).[22] However, Clift and Mulugetta (2007) argue that the introduction of biofuels is generally not a good idea, because biomass resources can be put to better uses; they maintain that fuels and electricity from coal coupled with CCS will eventually be the preferred choice for road transport. One problem with this reasoning is that CCS is still an unproven technology at a large scale and its introduction may take a long time. Without CCS, the environmental impact of coal-based fuels will be much larger than that of the petrol and diesel used today. In addition, fossil fuels coupled with CCS will only be carbon neutral if carbon-free energy carriers are produced, such as hydrogen and electricity. If liquid fuels are produced, GHG emissions from vehicles will still be in the same range as from petrol and diesel. Another option would be nuclear energy for producing hydrogen and electricity, though this poses its own particular security and waste problems.

The long time scales related to developing and adopting new technologies and the urgency of some environmental problems imply that renewable fuels also need to be explored. The perspective of this thesis is that renewable fuels in different stages of development are considered part of socio–technical change processes. Most of the technologies discussed are still unproven at a large scale and may not be able to replace all the petrol and diesel used today. However, renewable fuels may still play a role in a transition towards a radically changed transport system.

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[22] In addition, national certification, verification, and labelling schemes have been proposed throughout the EU.

3 Environmental assessments in context

This thesis contributes not only to methodology development for its own sake, to improve the work of researchers, analysts, and practitioners in the field of environmental assessment. It also provides insight for policy makers and firms that are commonly informed of and affected by assessment results, so that they can interpret these in relation to the purpose and underlying assumptions of the assessment. Considering strategic technology choice, my view of the context of environmental assessments can be illustrated by a 'lobbying triangle' (see Figure 2), where the information flows are related to the design of assessments and assessment results:[23]

1. Assessment results informing policy and firm strategy,
2. Policy influencing firm strategy through the use of assessment results,
3. Firm strategy influencing policy through the use of assessment results, and
4. Firm strategy and policy influencing assessment design, i.e., what is assessed and how assessments are made and interpreted, through, for example, data supply, reference groups, and funding. This final path of influence is important in assuring that assessments are in line with societal interests and receiver needs. In this context, there is also a risk that assessments are too much steered by a few influential actors.

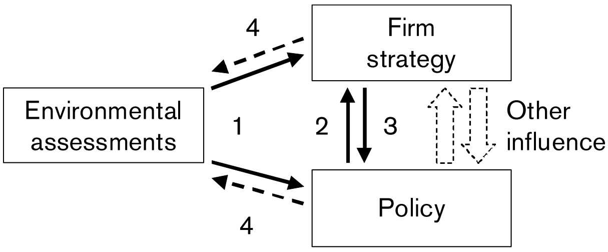

Figure 2: The context of environmental assessments constitutes 'a lobbying triangle', where assessments influence and are influenced by firm strategy and policy (black lines indicate information regarding assessment results, while dashed lines indicate information regarding the design of assessments). Of course, there are several other ways in which firm strategy and policy influence each other (indicated by grey block arrows).

Whether explicitly or not, a decision regarding technology policy or strategy usually implies a certain amount of technology choice, as some technologies will be more favoured than others. In addition, the decision situation in which strategic technology choices of renewable fuels are made varies between actors. Different actors have different

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[23] Tomas Rydberg is thanked for suggesting the name 'lobbying triangle'.

goals, interests, and resources limiting their decision domain in the short term, for example, to fossil fuels, agricultural products, gasification technology, or electric motors. I will ignore such limitations in discussing assessments in this thesis. It can be argued that over long enough periods, actors' goals and interests may change, for example, according to what is seen as environmentally preferable. Accordingly, the focus here is on different kinds of choice situations, as described below (see also Table 2:).

Environmental assessments can be helpful when formulating relevant policies, in the form of, for example, market incentives, investment programmes, regulations, purchasing guidelines, targets, and visions. This can be done at different levels (i.e., local, regional, national, EU, and global) and with different time perspectives, targeting technologies at different stages of development. For firms involved or potentially involved in producing fuels, vehicles, equipment, etc., environmental assessments provide information about technologies that are environmentally promising on different time scales. This can be used as a basis for strategic decisions regarding the future role of existing technologies (product strategies), R&D for new technologies, marketing, and investment strategies. For governments, authorities, firms, and other organisations and individuals, environmental assessments can also be used as a basis for purchasing decisions regarding transport services, vehicles, and fuels.[24] However, the possibilities to stimulate change differ between actors. For instance, though groups of users can in principle contribute to bringing new technologies to the market by expressing particular demands, their interest in farther-reaching future technologies may be limited.

Last but not least, there are two more fields in which the kind of assessments discussed here are of interest: education and public debate. Different kinds of actors contribute to disseminating knowledge of technologies, such as teachers, researchers, policy makers, firms, and other organisations. In addition, the public are part of an environmental debate on transport and renewable fuels, a debate conducted through various media and organisations, and as voters; here also policy makers and firms play a role in disseminating assessment results.

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[24] I principle, any purchase of a product or a service (not only transport) could involve an explicit demand that environmentally benign transport should be used throughout the life cycle.

Table 2: How the choice situation appears to actors in different roles in relation to renewable transport fuels.

Role	**Actor(s)**	**Choice situation**
Policy maker	Governments and authorities	Policy formulation including market incentives, investment programmes, regulations, purchasing guidelines, targets, and visions
Producer (of the studied technology and of supporting technologies)	Firms	Product strategies, R&D for new technologies, marketing
Investor	Firms (e.g., venture capital firms), governments, and individuals	Capital investment strategies
User	Governments, authorities, firms, other organisations, and individuals	Purchasing and public procurement
Educator	Teachers, researchers, policy makers, and firms and other organisations	Knowledge dissemination
Debater, advocate, lobbyist, and voter	Media, researchers, various organisations, and voters	Influencing policy makers and firms

Above, I use the term 'assessment results'. These include not only calculated figures presented in bar charts, such as the GHG emissions resulting from the life cycle of one megajoule of a range of different fuels. As highlighted in the LCA standard (ISO, 1997; ISO, 2006a), there are methodological choices and assumptions regarding the life cycle that have to be communicated together with the figures. As we will see, this is particularly important for emerging technologies, for which assumptions regarding future development are crucial for the results.

4 A systems perspective[25]

Various theories, most of which build on a tradition of systems studies, provide the basis for this thesis. To put the work in a theoretical context, the basic principles following from a systems perspective are explained and concepts used in the thesis are introduced at a general level. More specific theories and methods used in the individual papers are described in later sections together with the results.

First of all, a system can be regarded as comprising a number of components and the relations between them. Due to the interaction between components, a system acquires properties that the separate components do not have, i.e., a system is more than the sum of its parts. A clear distinction is usually made between a 'real' system and a system model, where the latter is the product of an analyst and made for a purpose. The components that constitute the system model are usually determined in relation to the purpose for which the model is developed. In general, the system components make up some kind of coherent whole, for example, by working towards a common goal.

By including some specific components (and relations) in the system model, the existence of a system boundary and possible relations between the system and its environment are envisaged. Referring to this boundary, a distinction can be made between *internal* and *external* phenomena. Internal change arising from within a system is considered *endogenous*, while internal change caused by factors outside the system is considered *exogenous*. In practice, it is often useful to consider a hierarchy of systems at different levels, such as an overall system comprising a number of interacting sub-systems. The sub-systems can be of different kinds, including technical, natural, and social systems. Together they determine the properties of the overall system and the relation between the system and its environment (see Figure 3:).

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[25] This section is partly inspired by Baumann (1995) and Ingelstam (2002).

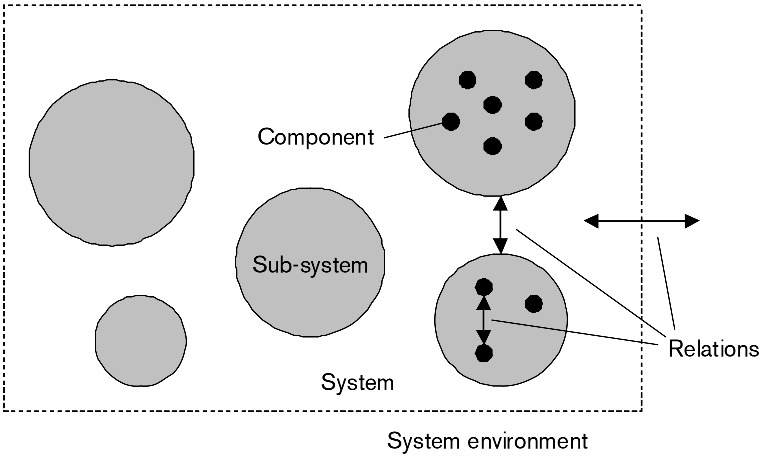

Figure 3: Schematic depiction of a basic system model including components, sub-systems, system boundaries, system environment, and examples of relations between components, sub-systems, and between the (overall) system and its environment (indicated by double-ended arrows).

This basic model of a system can be used in several fields, and theoretical building blocks from a large range of scientific areas can be used in the analysis of a given phenomenon. One of the most influential examples is that of the positive and negative feedback mechanisms that were originally studied in control engineering (see Figure 4). Feedback is the reaction to an output signal that is 'fed back', adjusting the reference signal. Negative feedback implies a negative influence on the reference signal (damping), while positive feedback implies a positive influence (amplification). The combination of negative and positive feedback can result in different kinds of variations in output signal, as well as eventual extinction or uncontrolled growth.

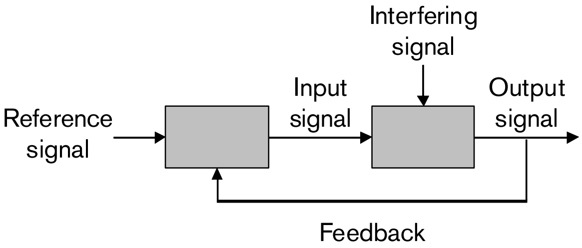

Figure 4: A simple model of feedback originating from control engineering. An input signal is modified due to an interfering signal, resulting in an output signal. The feedback mechanism implies a reaction to the output signal that is 'fed back', adjusting the reference signal (adapted from Ingelstam, 2002).

The life cycle model is a typical representation of a technical system, with sub-processes that are connected by physical flows that include feedbacks and with flows crossing the system boundary between the technical and natural systems (see Figure 5). Resources and other inputs enter the technical system from the natural system, while various outputs leave it. Usually, all flows are normalised to a functional unit representing the studied product or process.[26]

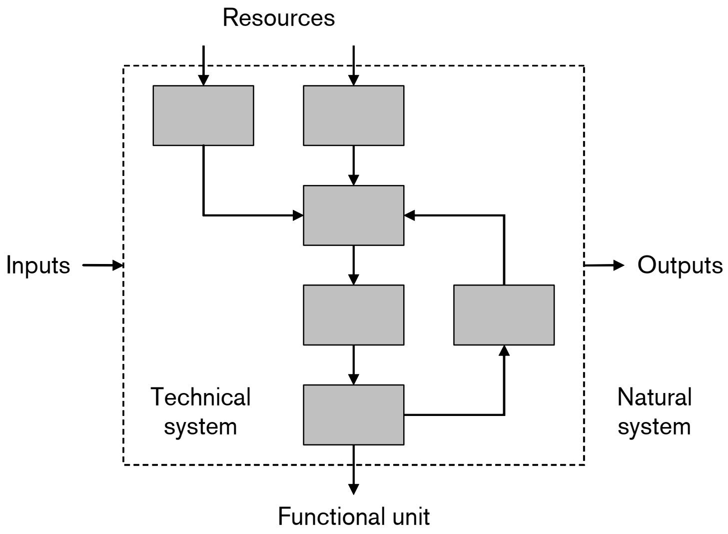

Figure 5: An example of a technical system modelled according to the life cycle model, including the system boundary (dashed line) and sub-processes (grey boxes) connected by physical flows, also involving feedback.

Traditionally, system methods have largely dealt with optimisation processes, and the results have been directed towards the owner of the problem, i.e., the decision maker (see, e.g., Churchman, 1978). Checkland (1999) calls this 'hard systems thinking'. However, as pointed out by, for example, Checkland (1999) and Ingelstam (2002), 'hard systems thinking' seldom applies to real-world problems, such as finding solutions to environmental problems or conflicts between nations. Such problems are 'wicked', which means that they are ill-defined and inherently unsolvable; suggested solutions are not true or false but better or worse (Rittel and Webber, 1973), and the actors involved commonly have different goals, priorities, and world views. For these reasons, another kind of systems approach is proposed, 'soft systems thinking', which implies a learning process without clear goals or with several goals (Checkland, 1999). During the process, different

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[26] See also Baumann (1995) for a description of the life cycle model from a basic systems perspective.

goals and fulfilment criteria may be weighed, questioned, and modified (Ingelstam, 2002).[27] For this thesis, a softer approach is applied.

Analysing consequences of technology-related interventions, also cause-effect chains and feedback in the social system need to be considered. The co-evolution of technology and society, or socio-technical change, has been the focus in recent literature on technological innovation systems (TIS) (Bergek, 2002), technological transitions (Rip and Kemp, 1998) and socio-technical systems (Geels, 2004). In turn, these approaches have been developed from different theories, such as innovation studies (Freeman, 1974; Malerba, 2004), evolutionary economics (Nelson and Winter, 1977; Dosi, 1982), large technical systems (Hughes, 1983; Hughes, 1987) and social construction of technology (SCOT) (Bijker et al., 1987). Some authors even suggest that technology and society constitute a 'seamless web' developing together, and that they cannot be easily separated (Hughes, 1986).

Most scholars studying TISs and technological transitions use case studies to identify structures and processes contributing to socio–technical change, and try to find relationships and patterns in how different components – structural elements – are connected and develop over time. A vast range of empirical fields have been investigated to generate recommendations for decision makers and further develop theory. Thus, in an indirect sense, this thesis builds on analogies from different fields (as explained by Arbnor and Bjerke, 1977).

Implementing a decision informed by systems studies can be termed an *intervention*, i.e., a 'purposeful action by a human agent to create change' (Midgley, 2000). In this thesis, environmental assessments and studies of socio–technical change are consulted to develop the basis for decisions regarding strategic technology choice. As well, working with systems studies to formulate the basis of decisions means that we are dealing with some kind of intervention, most obviously through the results presented (by influencing decisions). In addition, it can be argued that scientific observation is a special case of intervention (Midgley, 2000). The scientist is intervening through the choice of system under study, system boundaries, and theories and methods applied as such methodological choices affect the results achieved (see

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[27] An important example comes from the field of sustainability, where, for example, environmental and economic goals are of concern. Two broad perspectives on sustainability can be distinguished: 'weak sustainability', which implies that manufactured capital can be substituted for natural capital, and 'strong sustainability', which implies that natural capital is not substitutable (Ness et al., 2007). From the weak sustainability perspective, biodiversity, for example, can be valued in economic terms and then exchanged for economic profit. From the strong sustainability perspective, specific species are invaluable and have an inherent right to exist. A similar differentiation can be made when considering different kinds of environmental goals, such as climate change, eutrophication, biodiversity, etc.

Figure 6). Without going into details as to how and by whom problems are defined, problem definition can be added as another form of intervention.[28]

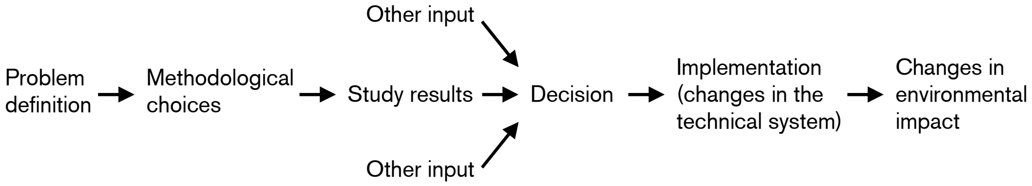

Figure 6: The most obvious interventions are the decision and implementation, which directly change the environmental impact, but the problem definition, methodological choices, and presentation of study results can also be considered interventions (modified from Ekvall et al., 2004).

Of course, the choice of, for example, study object, system boundaries, and methods can be more or less wise. To form the basis for informed decisions, these different kinds of interventions preceding decision and implementation need to be clarified and motivated. Midgley (2000) suggests some kind of boundary critique to determine what values the boundaries reflect, and what implications this may have for the results of systems studies. Particularly in environmental studies, knowledge that the definition of 'improvement' differs between actors, not least between our generation and future ones, needs to be considered.[29] Various approaches to including different perspectives in systems studies are suggested in the literature (Churchman, 1968; Churchman, 1979), such as the involvement of multiple stakeholders and 'methodological pluralism and mixing methods' (Midgley, 2000).[30] In addition, developments in the real world will be partly unexpected, so the intervention methods will need to change over time.

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[28] Ingelstam (2002) suggests that for some controversial issues, the problem formulation may be more important than its solution, as in the case of nuclear power.

[29] See section 6.1 on the shift of values over time in the development of alternative fuels in Sweden.

[30] Thus not even the methodology discussed in this thesis should be regarded as the only suitable one.

The problem of steering the transition to a transport system that is better for the environment is an example of a wicked problem, for which more or less soft systems thinking is necessary. Even when using a seemingly hard methodology like LCA, methodological choices and results are part of a softer learning process, involving discussion with different actors (as indicated in section 3). More specifically, this thesis stresses the necessity of methodological reflection in relation to numerical results. Of course, it would be convenient to be able to obtain ready-made results that could be fed into ‘a decision making machine’, but this would imply hiding a number of crucial choices made in performing a study.[31]

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[31] See Bengtsson and Tillman (2004) regarding the role of science in an environmental controversy concerning sewage sludge, and Stirling (2007) for a general discussion of the role of science in the social choice of sustainable technology.

5 Socio–technical change

Some recent literature using a systems perspective to study socio–technical change was briefly introduced above. In this section, I will go into more detail on what has been learned about cause–effect chains in socio–technical systems. Later (section 6.3), this will be used to assess consequences of technology-related interventions. This section first reviews the relevant literature and then presents two influential frameworks. Some general concepts used in Papers II–IV are introduced, and these papers are presented and discussed in subsequent sub-sections (5.4–5.6).

Traditionally, the literature on socio–technical change has focused on the emergence and growth of new innovations with better price/performance ratios than previous technologies. It is important to note, however, that as societal demands are changing so is what is considered 'better performance'. In our case, the societal view of the environmental problems related to transport has changed considerably over the past decade. Thus, alternative technologies with potentially better environmental performance than the dominant ones are attracting increased attention. However, the introduction of new technologies is being held back by the inertia of the system.

To understand the development of technology, we need to consider technologies as systems of social and technical components interacting with each other, as proposed in the literature on large technical systems (LTS) (Hughes, 1987) and socio–technical systems (Geels, 2004). Components can be categorised in various ways. Hughes (1987) includes both physical artefacts (including manipulated natural resources) and non-physical artefacts, such as organisations, scientific artefacts, and legislative artefacts, as well as so-called 'system builders' that contribute to the social construction of artefacts. While Hughes' (1987) definition of 'technological system' entails the components contributing to a common goal, Geels' (2004) definition of 'socio–technical system' includes the elements necessary to fulfil a certain societal function. In that case, 'relevant social groups' (Bijker, 1995) and 'users' (Geels, 2004) would also be included in the system. In the present thesis, the overall focus is the socio–technical system surrounding renewable transport fuels, i.e., the function of supplying renewable energy to road vehicles. In addition, different sub-systems around more narrowly defined technologies are also studied (see section 5.3 for definitions).

5.1 Entrenchment and competing technologies

As a technology (or technological system) grows, it gathers momentum as the mass of technical and social components develops in a certain direction. A vast range of different actors becomes committed to the technology and physical artefacts builds up (Hughes, 1987). Along with the technologies, normal ways of solving problems through the use of science, technology, and materials are also evolving, making up a 'technological regime' (Nelson and Winter, 1982) or 'technological paradigm' (Dosi, 1982).[32] In this paradigm, innovations are mainly incremental, following natural trajectories determined by the selection environment shaped by the current paradigm (Nelson and Winter, 1977). Thus, more radical innovations are less likely to occur in the context of an existing technological paradigm.

The technological development is a cumulative (Dosi, 1982) or path-dependent (Arthur, 1994) process, and what happens in an early phase may have a large influence on the eventual outcome.[33] Entrenched technologies have acquired advantages in the competition with new ones, in that they are already widely used. This advantage can be explained by 'learning by doing' (Arrow, 1962) and what Arthur (1988) calls 'increasing returns to adoption' due to, for example, learning by using, network externalities, economies of scale, and technological interrelatedness. Such positive feedback implies that a technology taking the lead – for any reason – is likely to increase its advantage with time due to positive feedback. New technologies, on the other hand, typically suffer from poor technical and economic performance, and from unfavourable regulations and policies adjusted to entrenched technologies. New technologies are less known and understood, and risk-averse policy makers and firms are likely to stick to the more widespread technologies (Arthur, 1988). In addition, a given new technology is likely be in competition with other new technologies (Windrum, 1999).

It has been observed that competition between technologies often results in the emergence of a dominant design; characteristically, innovation then becomes increasingly focused on the production process, while product design remains more or less fixed

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[32] The concept is further developed by Unruh (2000), who emphasises the connection between private and public institutions in a 'techno–institutional complex'. Some technological systems, such as those involving oil and automobiles, have an immense influence on society, possibly for several decades, thus forming the basis of what Freeman and Louçã (2001) call a 'techno–economic paradigm'. A new techno–economic paradigm is the result of the structural transformation and organisational innovations needed in the carrier branches (leading sectors), which by definition make use of key factors (core inputs) and related technologies (Perez, 1983).

[33] Note that the model of Arthur (1988) does not take into account that technologies can be of different ages, i.e., they are not introduced at the same time. This point has been made by various authors, such as Foray and Grübler (1990) and Islas (1997).

(Abernathy and Utterback, 1978). Anderson and Tushman (1990) suggest that dominant designs should not be considered a final state, but as a recurring phenomenon that is broken by ‘technological discontinuities’. These may be in the form of radical technological change resulting in a period of variation and selection eventually leading to the emergence of a dominant design, developing through incremental change (Murmann and Tushman, 1997).[34] For pervasive technologies, such ‘technology cycles’ may imply that technological paradigms are replaced in cyclical patterns. An important complement to the dominant design concept is the possibility of market differentiation resulting in different dominant designs in different niches (Windrum and Birchenhall, 1998). As well, local conditions can be a reason for the development of multiple dominant designs (Marechal, 2007).

In the case of the energy system, the above-mentioned mechanisms have led to a situation of technological and institutional lock-in to fossil fuels (Unruh, 2000). Unruh (2002) argues that the lock-in is too strong to be broken by those involved in it, and that exogenous forces will be needed (e.g., a climate crisis) to induce the required change. A different view is taken by Sandén and Azar (2005), who argue that radical technical change seems feasible owing to the same mechanisms that created the lock-in, i.e., positive feedback in socio–technical systems. Crucial in this process are the measures that foster promising technologies while disfavouring inferior ones (e.g., fossil fuels without CCS).

It is no straightforward task to foster new technologies that are to deal with environmental problems, some of which are urgent in relation to the time scales of socio–technical change processes (see, e.g., Andersson, 2001). As with entrenched technologies, path dependency may result in a situation where one or several inferior technologies become locked in (David, 1985). Keeping a variety of new technologies available is a way to avoid the risks of ‘premature lock-in’, i.e., lock-in to technologies that are ultimately unable to complete the required transition (Sandén, 2004). However, maintaining variety may be costly, and reducing variety may be a way to afford the accelerated large-scale implementation of selected promising technologies. This point is particularly important in the case of emerging technologies that are to help mitigate urgent environmental problems. However, it is difficult to determine *ex ante* when the point has been reached at which the range of emerging technologies needs to be narrowed down.

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[34] See Ehrnberg (1996) for different definitions of technological discontinuities.

5.2 Two frameworks

In recent years, two prominent frameworks have evolved that address socio–technical change processes (Markard and Truffer, 2008). These are helpful in structuring one's thinking concerning particular cases, and as they build on existing theory, various kinds of patterns and mechanisms identified in history may be discerned.[35] The first is the technological innovation systems (TIS) framework, which originally focused on sectors (see e.g. Carlsson, 1997).[36] The more recent TIS literature focuses on the innovative activities related to particular technology fields (Bergek, 2002; Hekkert et al., 2007; Bergek et al., 2008a). This means that only the relevant relations between the studied technologies and the regime are of interest, and not the regime as such. The other framework is the multi-level perspective (MLP), which is mostly used to study broader regime transitions involving several types of innovations (Geels, 2002a; 2002b; 2004; 2005). These two frameworks have been applied in numerous case studies, particularly in the field of renewable energy, the results of which are frequently used to inform policy makers. This thesis deals with a smaller number of related technologies in an emerging state, i.e., not a single innovation or a complete transition, implying that both frameworks are useful. In fact, the case of renewable fuels is representing an early stage of a transition to carbon-neutral transport.

Much of the TIS literature uses a system definition based on that of Carlsson and Stankiewicz (1991), which is also the case in Paper II. There it is defined by the actors (i.e., organisations) and networks of actors and institutions (i.e., regulations, norms, and cultures) involved in the generation, diffusion, and use of a technology; this is also the overall function of the TIS.[37] Some studies also include the technology itself, i.e., artefacts and knowledge, in the TIS; this is done, for example, in Papers III and IV, and in Bergek et al. (2008b). In the tradition of innovation systems studies, there has been a strong focus on structures in explaining and comparing the performance of specific systems (see, e.g., Lundvall et al., 2002). However, due to large structural differences between TISs, comparisons are of limited value. In addition, little attention has been paid to the dynamics of structural build-up. In response, another performance indicator is proposed, based on *key processes* contributing to TIS growth. These processes are called system functions (Bergek, 2002), and several sets of such functions are proposed in the literature (Hekkert et al., 2007; see e.g. Bergek et al., 2008b; Markard and Truffer, 2008). The build-

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[35] Of course, there is a problem if thinking becomes too controlled and phenomena beyond the purview of the framework cannot be observed; this calls for boundary critique and the use of different frameworks (as suggested by Midgley, 2000).

[36] Carlsson (1997) instead used the term 'technological systems'.

[37] As we see it, this overall function of the TIS differs from the function of a technological system, which provides a certain societal function, such as transport (see Bergek et al., 2008b).

up of systems functions and the interactions between them over time can be analysed to identify the determinants of TIS growth.

The first conceptualisation of the multi-level perspective (MLP) was presented by Rip and Kemp (Rip and Kemp, 1998), taking into account both artefacts and skills, the surrounding structures and socio–technical aspects. The suggested concept is called ‘technological regime’, which is defined as ‘the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems – all of them embedded in institutions and infrastructures’ (Rip and Kemp, 1998, p. 338). This implies the development of the more cognitively focused regime (or paradigm) concept proposed in earlier literature (Dosi, 1982; Nelson and Winter, 1982). Geels (2002a) uses the term ‘socio–technical regime’ to further emphasise that various social groups, and not only engineers, may influence technological transitions. The regime can be seen as a meso level between a micro and a macro level. The macro level is the ‘socio–technical landscape’ containing the general values and norms of society, the economy, politics, the general infrastructure, etc. (Geels, 2002a). The micro level comprises ‘technological niches’ containing specific innovations and providing spaces where novelties can grow (Kemp et al., 1998).[38] The basic idea of dynamics in the MLP is that momentum builds up around innovations at the niche level. These innovations can grow due to ‘windows of opportunity’ created by tensions in the regime, possibly induced by changes at the landscape level that put pressure on the regime (Geels, 2002a).

As studied systems are delineated in different ways in the two approaches,[39] it is a delicate task to merge them into a single comprehensive framework. However, steps in that direction have been taken through workshops and meta-studies (see, e.g., Geels et al., 2008; Markard and Truffer, 2008). The assumption is that a joint framework would gain explanatory power. In this thesis, the two frameworks are used in a more complementary fashion (as described below).

5.3 Concepts used

Papers II–IV investigate cause–effect chains in the socio–technical system related to renewable transport fuels, to gain insight into the consequences of technology-related interventions. The concepts and framework elements used in each paper depend on the specific focus.

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[38] The fostering of niches has been the focus of the closely related literature dealing with strategic niche management (SNM) (e.g., Kemp et al., 1998; Hoogma et al., 2002; Raven, 2005).

[39] In addition, the definitions may vary between MLP studies (as pointed out by Markard and Truffer, 2008) and between TIS studies, for example, between Hekkert et al. (2007) and Bergek et al. (2008b).

First, in Paper II an operationalisation of the TIS framework presented by Hekkert et al. (2007) is applied in studying the endogenous dynamics of two nationally oriented TISs, i.e., around bio-diesel in the Netherlands and bio-ethanol in Sweden. The operationalisation is based on mapping a system's internal activities ('events') over time, and what this implies for the build-up of system functions. Patterns in the build-up of system functions say something about the overall functioning of the TIS. In the paper, these internal processes are supplemented by an overview of exogenous factors that influence the two studied TISs.

In Papers III and IV, we consider technological systems consisting of physical artefacts, actors, and rules linked in various ways. Together these components provide a certain function, i.e., the supply of renewable energy for road vehicles.[40] The *artefacts* concerned then consist of the studied technology and the technologies used to supply that technology, including 'manipulated' natural resources such as mines and agricultural land (as suggested by Hughes, 1987). Actors are the separate individuals, but can also be more or less strongly linked in different kinds of networks, such as firms, governmental bodies, and NGOs. As in Geels' socio–technical system (Geels, 2004), relevant social groups and users are included. *Cognitive rules* describe what actors and artefacts are able to do; they make up the knowledge in the system, appear in print, are carried within actors and embedded in artefacts.[41] *Normative* and *regulative rules* include the norms, attitudes, and regulations determining what actors and artefacts should and should not do.

The MLP is used in Paper IV to differentiate between niche-level activities and landscape or regime developments (see, e.g., Figure 2 in Paper IV). Such developments provide a background to the socio–technical scenarios, involving factors external to the emerging technological systems. To this background may also be added niche activities not related to renewable fuels in Sweden. In Paper IV, the *technological innovation system* is an analytical construct that is used to study the development of the technological system (Figure 7).[42] Together with external influence, changes in the technological system generate a set of innovation system functions (F_1–F_n) shaping the further development of the technological system.

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[40] For the purpose of understanding the dynamics, some non-renewable alternatives are also included in Paper III.

[41] Bergek et al. (2008b) instead refer to knowledge as being part of the technology.

[42] In the operationalisation of TISs applied in Paper II, the studied technology is left outside the system boundary; see below (section 5.4) for a discussion of the implications of this.

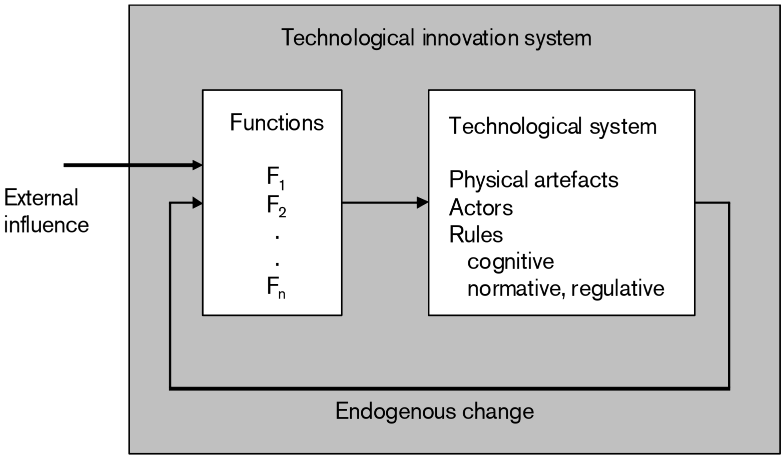

Figure 7: The innovation system can be described by a set of n innovation system functions (F_x) that correspond to the creation of the structural elements of the technological system. Functions determine how the structure develops, while the functions are determined by both the structure itself and external factors (figure and caption from Figure 1, Paper IV).

All technologies (or technological systems) can be said to co-evolve side by side. However, technologies do not appear at the same time (Islas, 1997), implying that the stage of development differs between them.[43] I consider the stage of development to be determined by the actual combination of structural elements (i.e., artefacts, actors, and rules) built up, which varies over time and between locations. Thus the relative strength in each dimension also varies between technologies. Due to the different stages of development of different technologies, even seemingly 'technology-neutral' interventions will favour the technologies having a structure better suited to the specific design of the intervention.[44]

Though the present research is generally delimited to the overall system of renewable fuels, more narrowly defined technologies are also studied. Papers III and IV apply several boundaries concurrently, so as to highlight different aspects of the growth process that are endogenous to the overall system. Narrower boundaries imply a possibility of analysing structural overlaps between technologies, as well as interaction between different technologies over time (see section 5.5 and Paper III).

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[43] Some consequences of this for the societal selection process are discussed by Windrum (1999).

[44] That no perfectly 'technology-neutral' policy exists in the field of hydrogen technology is highlighted by Hisschemöller et al. (2006). The need for deliberate technology-specific decisions is discussed by Sandén and Azar (2005).

5.4 Paper II: Cumulative causation

Paper II analyses continuous cause–effect chains, or cumulative causation, in two TISs. The studied systems are those related to bio-ethanol in Sweden and bio-diesel in the Netherlands. These are followed between 1990 and 2005. The research question is:

> Q_{II} *What are the drivers of and barriers to cumulative causation in Sweden and the Netherlands, and how can differences and similarities between the countries be related to policy makers and entrepreneurs?*

For the analysis, we use an operationalisation of the TIS framework based on event analysis developed by Hekkert et al. (2007). System functions are then defined as categories of events, i.e., 'actions taken by actors in the system' (Paper II, p. 596; see Table 3 for a list of the system functions studied). This definition is slightly different from the one presented in the previous section according to which a change in the technological system can be considered an event and where such events – under external influence – build up functions (see also Bergek et al., 2008b). Paper II identifies major external influences in the form of a number of exogenous factors that drive or hamper endogenous developments in different ways in the two cases. These factors are of both international and national origin, but are common to both countries and are generally unaffected by the specific TISs.

Following Hekkert et al. (2007), we choose to adhere to the generally accepted definition of TIS proposed by Carlsson and Stankiewicz (1991, p. 111), which reads: 'a network of agents interacting in the economic/industrial area under a particular institutional infrastructure (…) and involved in the generation, diffusion, and utilization of technology'. According to this definition, the institutions related to a technology are included in the system, while the technology itself is treated as an external factor. The effect of choosing this definition is that the possibility of technology directly influencing functions is excluded, for example, through physical properties or the mere existence of certain artefacts.

The analysis is based on narratives of key events in the Dutch and Swedish cases, based on studies of related developments in the two countries (see Sandén and Jonasson, 2005b; Suurs and Hekkert, 2008). Each event is assigned to a particular system function (according to Table 3); this way, the events serve as the empirical counterparts of system functions. A major feature of system functions is that they can interact, possibly resulting in a pattern of cumulative causation (Myrdal, 1957; Skott, 1994). Events drive other events, which in turn set in motion new events, eventually resulting in a richer realisation of system functions. For example, the successful realisation of an important research project (knowledge development) may result in a rise of expectations among policy makers (guidance of the search), which may subsequently trigger the start-up of a subsidy programme (resource mobilisation) to support even more research projects (knowledge development). In the narratives, contributions to system functions are indicated, and cumulative causation is identified by the existence of continuous sequences of functions. The circumstances resulting (or not resulting) in cumulative causation in the two countries are then compared and related to policy and entrepreneurial activities.[45]

Table 3: Each event is mapped on a system function, and can make either a positive or a negative contribution to the function.

System function	**Event types**
F_1: Entrepreneurial activities	Projects with a commercial aim, demonstrations, and portfolio expansions
F_2: Knowledge development	Studies, lab trials, pilots, and research programmes
F_3: Knowledge diffusion	Conferences, workshops, and alliances between actors
F_4: Guidance of the search	Expectations, promises, policy targets, standards, and research outcomes
F_5: Market formation	Market regulations, tax exemptions, and events constituting niche markets
F_6: Resource mobilisation	Subsidy programmes
F_7: Support from advocacy coalitions	Lobbies and advice

In Paper II, we demonstrate how the Netherlands and Sweden differed in stimulating the build-up of a comprehensive set of system functions, necessary for the successful development of the respective TISs. Due to continuity in the sequence of various entrepreneurial experiments and the emergence of cumulative causation, the Swedish renewable fuel TIS has already reached market expansion and social implementation stage, while the Dutch TIS has not yet progressed as far. This can be explained by exogenous factors and endogenous dynamics, i.e., the build-up of and interaction between system functions.[46]

We identified four major exogenous factors that influence the endogenous dynamics.[47] The first factor is oil supply insecurity, mainly captured by oil price change. Oil price shocks in the 1970s forced the search for alternatives, while decreasing prices in the 1980s became an economic barrier to the development of renewables. This only changed towards the end of the studied period, as the oil price began to increase. The second factor concerns worries about local air and water quality, which were on the political agenda

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[45] Possible circumstances identified include exogenous factors, functional patterns, and specific event types.

[46] In particular, our approach uncovers the dynamics endogenous to a given technological field, as influenced by a number of exogenous factors. Differences between the cultural, industrial, and political structures of the two countries are not considered as possible alternative explanatory variables.

[47] In Paper II, technology features are treated as a fifth exogenous factor.

throughout Europe from the 1980s on. This resulted in incremental innovations in the transport sector, but also became an argument for implementing renewable fuels. Third is EU agricultural policy, aiming at reducing the agricultural surplus and exploiting new markets. Starting in the 1990s, farmers received subsidies for keeping land fallow and for cultivating non-food crops, and in 2003 the 'Biofuels Directive' provided targets for biofuel introduction.[48] Fourth, the climate change debate attracted increasing attention starting from the end of the 1990s; because of their capacity to reduce CO_2 emissions, renewable fuels were seen as an interesting option.

Considering the circumstances that do and do not result in cumulative causation, we distinguish five themes relevant to policy makers and firms. First, policy measures were more effective when designed to target all TIS functions; as well, entrepreneurs were most successful in bringing about change when actions were directed towards facilitating multiple system functions at once. This is what actually makes cumulative causation possible.[49] Second, though various system functions were involved in realising interaction patterns in both countries, our analysis suggests that entrepreneurial activities were crucial in stimulating such dynamics. For most occurrences of cumulative causation at the early stages of development related to first-generation renewable fuels, the private and municipal entrepreneurs were prime movers, contributing to the build-up of support from advocacy coalitions, guidance of the search, and other system functions. Third, while initial policy measures were made possible by entrepreneurial activities, the continuation of entrepreneurial activities was strongly related to the presence of consistent policy support, which reduced long-term uncertainty. In both countries, the influence of policy programmes – whether positive or negative – was crucial. When the government issued consistent policy guidelines, entrepreneurial activities were initiated that fostered further event sequences – and cumulative causation – in the TIS. In contrast, the absence of consistent policy guidance had a destructive effect on further entrepreneurial activities. Fourth, our cases indicate that policy support can and should be provided at different levels, i.e., the regional, national, and EU levels, and that conflicting signals at different levels block further developments. Finally, our comparison demonstrates that the more productive situations were those in which national policy allowed for various technologies to develop concurrently, taking into account their individual stages of development. When hard technological choices were made by policy makers, important system functions were weakened. Technically less promising renewable fuels should thus not be underestimated with respect to their potential impact on cumulative causation.

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[48] The directive was increasingly legitimated by referring to energy security and climate change.

[49] This result more or less confirms the framework and the list of functions applied in the study.

5.5 Paper III: Interaction between technologies

Paper II develops a framework for analysing interaction between emerging technologies that are potential substitutes for each other. This framework is tested on and illustrated by examples from the development of alternative transport fuels in Sweden from 1974 to 2004. The research question is:

Q_{III} *How do supposedly competing emerging technologies interact during their growth?*

The paper is inspired by a model of ‘multi-mode interaction among technologies’ presented by Pistorius and Utterback (1997), which suggests other modes of interaction than mere competition. For this model, they borrow several modes of interaction between species from studies of population dynamics in organisational ecology. Three modes of interaction – competition, symbiosis, and predator–prey relationships – are distinguished, and it is stated that the mode can change over time (Pistorius and Utterback, 1997). In Paper III, with reference to the community ecology field, we consult a recent textbook that distinguishes nine modes of interaction between populations (Odum and Barrett, 2005); these can be reduced and collapsed to six modes of two-technology interactions relevant to our purpose (Table 4). The interaction between three technologies can then be divided into three two-technology relationships.

Table 4: Six modes of two-technology interactions (based on Odum and Barrett, 2005).

Type of interaction	Technology A	Technology B	General nature of interaction
Competition	-	-	Inhibition when shared resource or market is in short supply
Symbiosis	+	+	Interaction favourable to both
Neutralism	0	0	Neither population affects the other
Parasitism	-	+	Population 2 is benefited, 1 is inhibited
Commensalism	0	+	Population 2 is benefited, 1 is unaffected
Amensalism	0	-	Population 2 is inhibited, 1 is unaffected

Furthermore, we consider technologies as systems of lower-order sub-systems; these technologies are in turn sub-systems of higher-order systems. This view is borrowed from literature on design hierarchies and technical modularity (Clark, 1985; Baldwin and Clark, 2000; Murmann and Frenken, 2006). Instead of design hierarchies, however, we talk about the value chain as a hierarchy of lower-order sub-systems of production (upstream) and higher-order systems of use (downstream). Thus, we are able to study interactions at different levels in the value chain, interactions between technologies that are potential substitutes at the same level.

First, a number of static interactions can be identified. *Competition* then implies upstream competition for resources or downstream competition for markets. For technologies that are potential substitutes at the same level in the hierarchy, *symbiosis* implies that substitutes can be co-products of the same process (upstream) or can be used together (downstream) to increase performance or decrease cost. *Neutralism* is when two technologies use different or non-exclusive resources (upstream), or are used on separate markets (downstream).

Second, when we allow for changes in lower- and higher-order systems, a more dynamic picture of interaction appears. Two emerging technologies can now compete internally for resources and market shares, while simultaneously developing a shared resource supply and expanding shared markets (i.e., symbiosis), possibly at the expense of more established technologies. Emerging technologies may also develop in divergent directions to avoid direct competition for resource supply or market space, thus approaching neutralism. Furthermore, more asymmetric interactions are evident. *Parasitism* occurs when resource supply or applications developed by Technology A are taken over by Technology B, thus inhibiting Technology A. If the resource is a common good, Technology A is unaffected, resulting in *commensalism*. Finally, if resource supply or applications developed by Technology A are locking out and inhibiting Technology B while Technology A is unaffected, we have *amensalism*.

This conceptualisation is then combined with a definition of a technology as a more or less limited 'bundle of value chains' where delineation is dependent on the specific context. In addition, as described above (section 5.3), technologies are viewed as technological systems of artefacts, actors, and rules. Correspondingly, due to shared elements, interaction can take place in the material, organisational and conceptual dimensions. Overlaps in systems of production and use may involve several system elements and different interaction modes simultaneously, for instance when technologies compete for similar raw materials (upstream) while developing knowledge applicable to users of different technologies (downstream symbiosis).

Following Pistorius and Utterback (1997), we observe that the mode of interaction can change over time. Such shifts are not only related to the development of the technological systems themselves, but also to changing exogenous forces, such as a shift from concern for oil scarcity to air pollution and from pollution to climate change. The emergence and growth of one technological system can make use of various elements developed in several parallel systems. Hence, technologies can act as ‘bridging technologies’ (Andersson and Jacobsson, 2000) and timing may be critical.[50]

The history of alternative fuels in Sweden provides illustrative examples of the proposed interaction modes, observed with reference to different kinds of system elements. Between 1974 and 2004, several alternative technologies were present with varying intensities in different dimensions, influenced by shifting exogenous forces. In the following, selected examples of interaction from Paper III are presented.

The ethanol–methanol interaction in the 1980s is a case of commensalism developing into parasitism in which ethanol made use of downstream overlaps with methanol. Ethanol was able to benefit from being physically and conceptually similar to methanol in multiple ways. The fight to change taxes (regulations) to become fair or even beneficial to alcohols had been fought by methanol advocates but eventually came to benefit ethanol as well. The standard blends of methanol and petrol, i.e., M100, M85, M15, and M5 (referring to the percentage of methanol), had become well-known concepts; these concepts were taken over by ethanol in the form of the E100, E85, and E5 blends. Furthermore, technical knowledge and experience with alcohol fuel and flexifuel vehicles (that can run on mixtures of methanol and/or ethanol and petrol) had been gained and were retained by the Swedish car manufacturers Volvo and Saab.

The interaction between ethanol from different sources, mainly wheat and wood, originates in the obvious downstream overlap. The fuels have the same properties in the pure form (as bus fuel) and when blended with petrol (as E5 and E85). In addition, the same physical artefacts can be used, such as buses, cars, and filling stations, for ethanol from all sources. Given this downstream overlap, upstream actors representing different kinds of ethanol helped form the advocacy group, the Foundation for Swedish Ethanol Development (SSEU). The farmers’ organisation, which supported the construction of a wheat ethanol plant, saw a common interest in ethanol with forest regions, which regarded supplying the raw material for wood ethanol production as an opportunity. The resulting mode of interaction was symbiotic in terms of seeking regulatory change and creating expectations. Even early on, the expectations of wheat ethanol as a long-term solution were low. Due to the abundance of forests in Sweden, the expectations of wood ethanol were higher. On the other hand, wood ethanol initially needed the support of the advocates of wheat ethanol, the short-term option. It was argued that wheat ethanol could be used as a bridging technology awaiting the implementation of the long-term option. As

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[50] In Paper III, it is also suggested that the system functions of the TIS framework can be used to analyse the mechanisms underlying the interactions.

the wood ethanol system strengthened and imports of sugar cane ethanol increased, the arguments for wheat ethanol as a necessary short-term option lost strength.

Another group of interacting technologies are those sharing the thermal gasification process, a group including a large number of possible value chains at different stages of development.[51] The first activities in Sweden related to gasification and transport fuels appeared in the mid 1970s. Since then, a strong network of actors has grown around R&D for the gasification of various raw materials and the demonstration of methanol fuel blends for use in vehicles. The gasification process and methanol use represented downstream overlaps for the different value chains. In the 1980s and 1990s, gasification received scant attention in the transport sector, and overlap with the electricity system became more important. The gasification actor groups were able to maintain and increase their competence in the electricity domain when the fuel domain became inaccessible (amensalism). At a later stage, when large-scale biomass gasification had attracted increasing attention in the transport sector as a mitigator of climate change, these actors returned (commensalism) to promote not only methanol but also other renewable fuels produced from synthesis gas (symbiosis). For these technologies, gasification and biomass supply were parts of an upstream overlap. In addition, physical artefacts from the electricity system could be used; for example, a gasification demonstration plant developed for electricity production that had been decommissioned was able to be rebuilt to produce synthesis gas more suitable for transportfuel synthesis (amensalism).

Finally, starting in the 1990s, there have been several examples of interactions between alternative, mainly renewable fuels, as a group. These interactions highlight the importance of concepts and point to overlaps in attitudes and regulations. First, in 1991, political agreement on energy policy created space for entrepreneurial experimentation in the form of a national programme demonstrating the use of biofuels in heavy vehicles. This was initially launched to investigate and stimulate ethanol production and use, but an increasing share of the funding came to be used for biogas. The common biological origin represented an important physical and conceptual upstream overlap between biogas and ethanol, an overlap that increased the resources available for biogas (parasitism).[52] The national demonstration programme increased knowledge of and changed the legitimacy of renewable fuels as a group among many actors, including bus transit companies, municipal administrations, and vehicle manufacturers (symbiosis). In addition, consultants were hived off in the process, who advocated and facilitated the continued diffusion of renewable fuels and clean vehicles.

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[51] Biomass gasification is still at the pilot and demonstration project stages.

[52] Within the programme, there were also a few projects and studies of DME and methanol.

Second, the introduction of cars that can run on alternative fuels was made possible by the relative success of ethanol and methane in the bus niche, but also by the parallel demonstration of electric vehicles. Electric vehicle tests in the early to mid 1990s created municipal organisations that were large enough to test many types of vehicles and fuels, lumping them all together in the category 'clean vehicles'.[53] Electric vehicles were thus a bridge to other technologies in terms of actors and organisational routines.

Finally, actor groups and networks formed around ethanol and biogas, together with the farmers' organisation, lobbied for more favourable policies, such as general tax exemptions that were to benefit several renewable fuels, mainly ethanol, biogas, and RME. According to some, ethanol and methane vehicles helped each other stimulate the creation and growth of a market for 'clean vehicles'. In a small market for clean vehicles as a whole, growth of demand for one type would raise the general awareness and legitimacy and thus benefit all other types. Thus, the conceptual overlap between all alternative fuels was important to general car users. However, the different fuels did compete for markets and political attention at the municipal level, as most cities focused on one alternative fuel. In addition, vehicle manufacturers in Sweden looked for the single best alternative to include in their product portfolio.

5.6 Paper IV: Socio–technical scenarios

In Paper IV, building blocks from the TIS and MLP frameworks and the results of Papers II and III are used to explore future cause–effect chains. The projected development of renewable transport fuels in Sweden, 2007–2020, provides an illustrating case. The research question is:

> Q_{IV} *What are the implications of current policy choices for the development of the technological system of renewable transport fuels in Sweden?*

Paper IV uses a socio–technical scenario approach. It was introduced by Elzen et al. (2002; 2004b) and Hofman et al. (2004) in answer to the felt need for a more qualitative scenario-based approach that a) takes both technology and society into account, b) explains development processes, or technology paths, rather than just final outcomes, and c) puts more emphasis on niche and regime developments than do previous approaches.[54] It thus springs from the SNM tradition, with some influence from MLP.

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[53] The Swedish term for 'clean vehicles' is *miljöfordon*, which can be translated as 'environmental vehicles'. These include vehicles that can run on any alternative fuel or on electricity, and include hybrid electric, flexi-fuel, and bi-fuel vehicles.

[54] A similar approach is being developed by Markard et al. (2006).

Paper IV applies the socio–technical scenario approach, while also making use of the TIS framework. The focus is on various national policy choices and the development of the technological system for renewable fuels, under the influence of exogenous factors. The main system boundary includes all fuels from renewable energy sources. Regarding these as part of one technological innovation system, the system goal – within the time frame of the study – is to maximise the diffusion of renewable fuels regardless of type. Using this system boundary, more narrowly defined systems, such as that of first-generation renewable fuels, or, even narrower, that of ethanol from agricultural crops, could serve as components that contribute to the function of the wider innovation system. However, we also need to consider the internal dynamics of narrower systems when exploring the risk of premature lock-in to one or a few technologies caused by narrow circles of feedback; the growth of narrow systems could foster or block the development of other alternatives and thus the development of the wider system of renewable fuels.

We choose a relatively short time perspective for the scenarios, letting them end in 2020. Within this time frame, we do not think that any drastic changes in transport modes or how transport is integrated into society are realistic, and we assume no radical progress in vehicle technology. Thus, to reduce GHG emissions and replace fossil fuels in the road transport sector, alternative fuels and vehicles will be necessary. The adoption of alternatives and the replacement of petrol and diesel, however, will be far from complete at the end of the studied period.

The shorter time frame allows for higher resolution regarding the connection to current policy; previous developments and current conditions will largely determine developments in the period under study. The money used to finance tax reductions (in 2006) can alternately be spent on extended R&D support, accelerating the market introduction of second- and third-generation renewable fuels. The R&D programme could also be diversified. We suggest two main scenarios, starting in 2007. The scenario policies differ mainly in two points related to the market formation and knowledge development functions:

1. commitment and economic incentives aiming at rapidly expanding the market for first-generation renewable transport fuels, and
2. economic resources allocated to R&D for second- and third-generation renewable fuels.

Policy choices in both scenarios are intended to be realistic with reference to current conditions (2006). The main focus is on the first point in our *market-oriented* scenario (denoted M) and on the second point in our *technology-oriented* scenario (T).[55]

The difference in policy choices between the two scenarios is not substantial, but due to feedback loops they develop in divergent directions. In a first phase – 2007–2013 – in the market-oriented scenario (M), domestic production and the relatively widespread use of alternative transport fuels and vehicles create actors in the form of raw material suppliers, producers, and users supporting the alternatives. Limited new knowledge is gained, but the legitimacy of alternative fuels is generally increased. Physical artefacts, such as filling stations and vehicles, are adapted to fit the needs of first-generation renewable fuels. In the technology-oriented scenario (T), authorities and researchers are key actors. High technical competence is built up in connection with pilot production plants and demonstrations of second- and third-generation renewable fuels. Using petrol and diesel is increasingly questioned, while the early alternatives are criticised for high costs and limited potential.

Due to limitations in the supply capacity for first-generation renewable fuels, they will not offer a large-scale alternative to petrol and diesel in the long term. In view of this, both scenarios bifurcate in 2013 into two paths, marking the start of a second phase (2013–2020) characterised by stagnation or growth with regard to the introduction of second- and third-generation renewable fuels in Sweden (Figure 8).

In the growth paths (M+ and T+), the changes in structural elements lead to further growth and cumulative causation in the emerging technological systems, which decreasingly depend on exogenous forces. In the stagnation paths (M– and T–), this is not the case. In the market-oriented scenario (M–), the multitude of actors involved in first-generation renewable fuels and the lack of domestic knowledge of the second generation are key features. In the technology-oriented scenario (T–), many actors have no experience with renewable fuels and weaker market incentives limit industry interest. At the end of the studied period, the results in terms of *alternative* fuel use of the two stagnation paths are similar in that import of synthetic fuels made from natural gas and coal becomes necessary. The results of the two growth paths are also similar, instead displaying use of a great variety of *renewable* fuels.[56]

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[55] Market subsidies are today (i.e., 2006) approximately one order of magnitude larger than R&D spending, and shifting this balance would allow for more R&D in the technology-oriented scenario than in the market-oriented scenario. This has implications for the development of the structural elements of emerging technological systems.

[56] Here we choose these relatively pure scenarios, but other choices can also be made, for example, involving other exogenous forces.

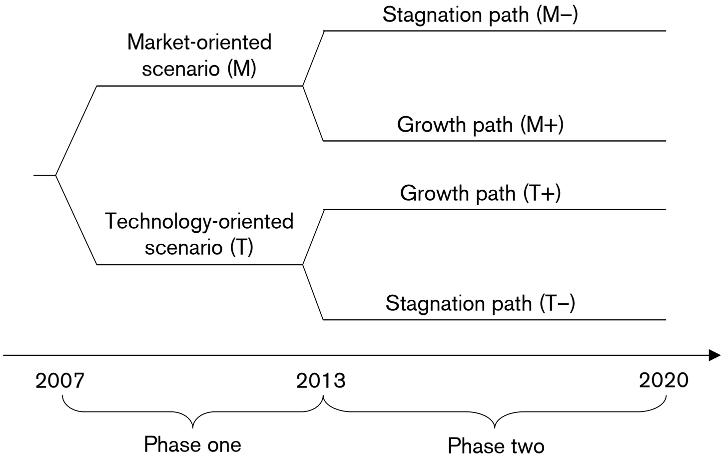

Figure 8: Market-oriented (M) and technology-oriented (T) scenarios for 2007–2020, with bifurcation points in 2013 resulting in two paths for each scenario. 'Growth' and 'stagnation' refer to the introduction of second- and third-generation renewable fuels in Sweden.

The scenarios illustrate the divergent outcomes that could result from different policy choices. Structural elements related to one or several emerging technological systems are built up in a process of shifting modes of interaction. The specific combination of these endogenous forces and factors exogenous to the overall system of renewable fuels determines further changes of the system; divergent paths of development are possible depending on how external developments are interpreted and exploited by various actors in the system. The market-oriented scenario illustrates the consequences of breaking the dominance of entrenched technologies, indicating both the growing market potential of alternatives and the risks of a strong focus on market stimulation and first-generation renewable fuels. The technology-oriented scenario highlights both the value of fostering variety of niches at this early stage of the transition, through funding the research and development for new technology, as well as the risks of a poorly developed market.

In conclusion, there is a risk that any particular measure may lead the system into a dead end. However, if different actors in the technological system make use of existing structures and ongoing change processes, and if policy strives to balance the development in different parts of the system, a wide range of efforts can contribute to radically decreased environmental impact from the transport system.

6 Environmental assessment of emerging technologies

Insight into socio–technical change brings with it a perspective in which a large range of factors contributes to the adoption of particular technologies at particular times, which in turn determines the environmental impact. In addition, it provides the context in which environmental assessments are, or could be, performed and their results used to guide the selection of emerging technologies. The aim here is to develop and discuss methodology for such assessments, with a particular focus on the two paths of LCA.[57] The *attributional* approach is used to study the more or less inherent performance of technologies that eventually may be adopted on a larger scale and in radically changed systems. Second, the *consequential* approach is used to examine the contribution of technology-related interventions to changed environmental impact, by considering socio–technical cause–effect chains.

Both paths are examined in this section, by means of case studies in the field of renewable transportation fuels. Such fuels have been studied in a vast range of comparative assessments, many based on LCA methodology, which in this field is often called well-to-wheel (WTW) studies.[58] However, as observed by a number of researchers (Reijnders and Huijbregts, 2003; Bernesson, 2004; Quirin et al., 2004; Börjesson, 2006; Larson, 2006), different studies yield different results. This can be explained by differing choices in relation to the technologies studied and methodologies used. In this section, I will highlight a number of methodological choices that are particularly important when discussing strategic technology choice. This is followed by selected results of the two case studies of attributional and consequential LCA from Papers I and V, respectively.

To be able to say anything about future performance, studies need to be *prospective* (i.e., looking forward in time); to be useful for strategic purposes, not just the immediate future is of interest, as the primary aim is to inform decisions not directly bounded by current investments. In contrast, most existing retrospective and prospective LCAs usually reflect historical, current, or near-term performance. The time perspective must of course be clear from the goal and scope definition of an LCA, and should guide the choice of scope, technologies examined, and data (as described below).

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[57] Here, the focus is on methodological issues, particularly as related to the assessment of *emerging* technologies. General problems in LCA methodology are presented in a recent paper by Reap et al. (2008).

[58] See, for example, ViewLS (2005) for a list of many such studies reviewed in an EU project.

The use of LCA for decision-making support in firms and in policy formulation has been studied by many authors (e.g. Allen et al., 1997; Baumann, 1998; Frischknecht, 1998; Rex, 2008), and several authors also mention that LCA can be used as a basis for strategic decisions and planning (Baumann, 1995; Allen et al., 1997; Haes and Wrisberg, 1997; Frischknecht, 1998; ISO, 2006a). In the field of transport fuels, various approaches have been used to inform strategic decisions. For example, the results of a large number of sources can be analysed in aggregate studies (see, e.g., MacLean and Lave, 2003; ViewLS, 2005; Fleming et al., 2006). However, the results of aggregate studies will not be relevant if the included sources are not in line with the purpose of strategic technology choice. Another approach is to make estimates of future performance in combination with scenarios and/or uncertainty calculations (see, e.g., Weiss et al., 2000; Contadini and Moore, 2003; Pehnt, 2006; Edwards et al., 2007).[59] This thesis suggests further steps to take so that LCA studies are even less coloured by current conditions and better capture the inherent performance of emerging technologies. [60]

6.1 LCA of general technologies[61]

LCA was originally developed to analyse the potential environmental impact related to existing products (or services) and to small changes in product design and production processes. In many LCAs of renewable fuels, a specific product, produced at a specific plant, is used to represent an entire technology.[62] This can be particularly problematic for emerging technologies, where production processes are far from fixed, and data at best come from pilot plants using a specific process. In addition, as demonstrated in Paper III, evolving technologies interact in different groupings both concurrently and in sequence. For strategic purposes, it is questionable whether there is any point in discussing smaller process differences, for example, instead of considering them collectively as a single developing technology (or 'bundle of value chains'). To communicate that we intend to assess more general product chains, and not specific products, we speak of LCA of *general technologies* as opposed to of *particular products*.[63]

Current LCAs of renewable transport fuels often focus on a few selected impact categories, particularly global warming potential (measured by GHG emissions).

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[59] In addition, it should be noted that studies not performed for strategic purposes, indicating the historical or current status of different technologies, are nonetheless used in this context. However, in the LCA community it is strongly argued that the results of an LCA can only be interpreted in relation to the specific purpose of each study (ISO, 2006b) and that they should only be used for this purpose (Tillman, 2000).

[60] Inherent performance is constrained by physical and chemical properties, for example, though in practice there are also limitations related to the possible speed of socio-technical change.

[61] This section is partly based on Paper I and on Jonasson and Sandén (2004).

[62] Even when studies are not conducted this way intentionally, the *results* may be used in this way.

[63] This approach has also been suggested by Karlström (2004) and Sandén and Karlström (2007).

However, radically increased adoption of such fuels may aggravate other problems related to increased or more intense land use, such as loss of biodiversity, excessive water use, and emissions from soil. The last item may even imply higher overall GHG emissions.[64] Then the alternative use of land also becomes an important factor. Furthermore, environmental and other priorities among actors may change over time. For example, Sandén and Jonasson (2005b) distinguish three periods in the development of alternative transport fuels in Sweden. In the first period, 1974–1985, oil substitution was the main driving force for the introduction of alternatives. Then, between 1986 and 1997, improvement of local air quality was the primary aim. In a third period, beginning in 1998, mitigating climate change and achieving fuel supply security became dominant drivers for various actors. Such societal developments may influence the design of environmental assessments (see Figure 2). Paper I examines only GHG emissions and land use and Paper V only GHG emissions, deliberate limitations justified by the methodological character of this thesis, the aim of which is not to produce a comprehensive overview of environmental performance.

In view of certain impact categories, some current technologies may seem to be disqualified from future implementation, due to low production efficiencies, much waste, or large emissions. This makes them less suitable for large-scale adoption and for use in urban areas. However, a long-term perspective implies that there is time for technological development. Efficiencies and emissions to air and water could well decline through incremental technology development, making some technologies more interesting in the future. Likewise, more 'futuristic' technologies, promising in the long term but irrelevant today, may also merit consideration. For example, new crops and vehicle technologies, and new combinations of processes in the life cycle, are likely to appear in coming decades.

The time perspective and studied scale of adoption are also crucial for the choice of data in assessing the environmental impact of emerging technologies.[65] This can be explained by the fact that technology performance changes over time due to general technological development. But it also changes with increased scale, for two reasons. First, it changes with cumulative production due to learning-by-doing. Second, it changes with total annual production due to economies of scale and system optimisation. In addition, resource and by-product limitations may come into force (see also section 6.2 and Paper I). The data chosen simply reflect a certain stage in the continuous development of a technology.[66]

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[64] See, for example, Kløverpris (2007) for discussion of land use issues.

[65] 'Choice of data' here refers to the general representativeness of data as regards time and scale, and not the choice of average versus specific data or what references to consult.

[66] The problem of using historical data is also commented on by Höjer et al. (2008).

Thus, the assumed development trajectory of each technology will be highly relevant to the assessment.

The importance of scale also concerns the functional unit. The aim is to compare technologies that are intended – at least partly – to replace the extensive use of fossil transport fuels; by strictly focusing on the commonly used functional units, such as 1 MJ of fuel or 1 vehicle-km, the total scale of resource use and fuel production may be overlooked. Resource potentials related to specific technologies are limited and environmental performance change according to scale. On a small scale, waste and by-product flows can often be used in producing renewable fuels, but on a larger scale, dedicated crops may be needed. This is the case for biogas, which is mainly produced from sewage sludge and organic waste today, and small-scale FAME based, for example, on waste cooking oil. Furthermore, higher estimates of crop potential usually entail altered conditions related to land use and cultivation practices, which themselves affect the environmental performance.[67] Following from this, what are deemed relevant introduction rates, plant sizes, or vehicle fleets must be selected in accordance with the purpose of the study.

As stated in previous publications using slightly different terminology, LCA studies could either be attributional or consequential (Ekvall, 1999; Tillman, 2000; Curran et al., 2005; Sandén et al., 2005; Höjer et al., 2008). In attributional LCA, one or several historical or future states are studied, and the environmental impact attributable to the life cycle of a technology in that or those state(s) is considered. In consequential LCA, the environmental impact resulting from a technology intervention, such as changing the product life cycle or adopting a technology, is analysed. In principle, as pointed out by (Ekvall and Tillman, 1997), attributional studies explore the causes of an investigated system, while consequential studies explore its effects (Figure 9). Usually in LCA, the studied causes are only the direct physical flows, and the included effects are those related to marginal changes of the technical system. Three recent studies will serve as extreme examples of a broader set of causes and effects that can be included in attributional and consequential studies, respectively.

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[67] Such limitations may also be related to geographical factors and transport possibilities.

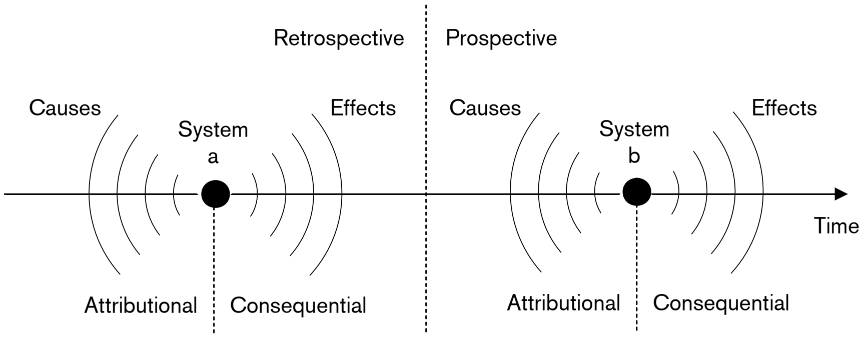

Figure 9: The investigated technology can be part of either a historical system (System a) or a future system (System b); correspondingly, studies can be either retrospective or prospective. In principle, attributional studies explore the causes of an investigated system, while consequential studies explore its effects (figure inspired by Ekvall and Tillman, 1997; Weidema et al., 2004; Sandén, 2008).

The first example is that of CNW Marketing Research (CNW, 2007), which presented an attributional study of the 'energy cost' of all car models sold on the US market, in which they include, for example, the energy cost of the design and development of different cars. New models that required considerable R&D, such as electric hybrid cars, are assigned a high design and development energy cost per car produced, as the cost is not distributed over a large volume of units. For more mature technologies, the energy cost of design and development is distributed over a larger volume of cars, and is thus much smaller per unit. For emerging technologies, it can be argued that a future situation of *large-scale* adoption is more relevant to the environment than current performance.

The other examples are Paper V and the study performed by Sandén and Karlström (2007), which are consequential studies applying a long time perspective and considering a broader set of effects. Sandén and Karlström (2007) calculate the contribution of an investment to future cost reductions, while other contributions to socio–technical change are also taken into account in Paper V. For mature technologies, the contribution of each decision to socio–technical change will be small and current performance is a relevant measure. For emerging technologies in an early stage of development and with a large potential for future emission reductions, however, the contribution to system change and resulting changes in environmental impact may be significant (see section 6.3 and Paper V).

Retrospective studies can hardly be used for strategic decisions about the future adoption of technologies. They can, however, yield information about important relations and mechanisms that are likely to apply in the future as well (see, e.g., Paper V).[68] Having said this, the usefulness and applicability of attributional and consequential LCA is still being debated in the literature (Ekvall et al., 2004; Ekvall and Andrae, 2006; Tukker and Jansen, 2006; Thomassen et al., 2008). Considering only prospective studies, the attributional perspective focuses on potential impact in future states, identifying *what technologies* we may strive for. This is different from the consequential perspective, which explores the effects of an intervention at a certain point in time, indicating *what interventions* that result in desired effects.[69]

As mentioned above, different ways to account for technical change are found in the literature. This thesis presents two different kinds of scenarios, applied to attributional (Paper I) and consequential (Paper V) LCA, respectively. Haes et al. (2004) suggest that scenario studies can add significant information to LCA studies of future technologies that are still under development. More specifically, I propose that strategic (Höjer et al., 2008) and cornerstone (Pesonen et al., 2000) scenarios could inform long-term decisions regarding firm strategy and policy. Frischknecht (1998) recognises that consistent scenarios about future status are required when considering very long-term decisions, suggesting that more effort should be put into modelling future states (i.e., attributional LCA) than the transition period to those states. Following from the above description of prospective attributional and consequential LCA, my view is that scenarios, both of future states and of change processes, are useful in guiding strategic technology choice. Paper I presents an attributional LCA of a number of future extreme ('stylised') states, mainly regarding the background system. In Paper V, contributions to socio–technical change (and resulting changes in environmental impact) are taken into account in a consequential LCA, using results from Papers II-IV.

6.2 Paper I: Stylised states in attributional LCA[70]

In Paper I, common assumptions in attributional LCA are discussed and tested in relation to a long time perspective and the possible large-scale adoption of renewable transport fuels. A selection of fuels relevant to the EU is studied: ethanol from wheat and RME from rapeseed produced using existing technology, and methanol produced from wood (short-rotation forestry) using gasification technology that is not yet commercialised. Life

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[68] As mentioned by Ness et al. (2007), there is an interesting paradox in that forecasting tools may seem less credible to policy makers than retrospective tools that are not developed to assess future developments. This is also discussed by Sandén and Harvey (2008).

[69] It should be noted that the interventions recommended in consequential studies will not necessarily result in states as pure as those recommended in attributional studies; interventions will typically intervene in the development of a complex system and not only of a few technologies.

[70] This section contains selected results from Paper I, while also including results from Jonasson and Sandén (2004).

cycle GHG emissions and agricultural land use related to 1 MJ of renewable fuel are calculated, mainly using literature data.[71] The research question is:

> Q_I *What are the time- and scale-dependent choices involved in LCA, and how can they be treated when assessing emerging technologies?*

The paper focuses on the design of environmental assessment, more specifically, the prospective attributional (i.e., state-oriented) LCA of technologies. The major methodological difficulty then is the selection of relevant states, i.e., the choice of what technologies *and* background systems to study. Various techniques may be used to guide the selection of states, such as the extrapolation of future developments (Pehnt, 2006) and formative scenario analysis (FSA) (Spielmann et al., 2005). In Paper I, we study a number of exemplary ‘stylised states’ that are unlikely to materialise but that could clearly illustrate important technological differences.[72] Taken together, these stylised states can provide an overall picture of the technology, though each state alone says little about inherent performance.

For convenience, the production processes examined in prospective LCA can be divided into a foreground and a background system, the foreground system comprising those processes directly affected by decisions based on the study. The background system comprises all other processes included in the study, processes indirectly affected by measures taken in the foreground system (Tillman, 2000). In Paper I, the studied states are characterised by differences in the respective background systems. Then the foreground system includes processes for production of renewable fuel, while the background system provides heat, electricity, input materials, and fuels. The background systems are typically linked with certain environmental impacts and – given a long-term perspective – are expected to change, partly for reasons similar to those justifying the introduction of renewable fuels. If changes in background system are not accounted for, promising technologies may perform worse in studies using current data to model the background system, than when eventually used in a future background system.

Changes in background system can be divided into those related to time (unaffected by the foreground system), such as new technology used for heat and electricity production and the transition to bio-based input materials, and those related to the scale of adoption of the studied technology (affected by the foreground system), such as renewable fuels

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[71] More specifically, the main data source is Edwards et al. (2003). Due to the limited scope of Paper I, the methodological choices highlighted above are only considered as far as the literature data allow; hence, quantitative results should not be directly used to guide the choice of fuels.

[72] This is similar to the cornerstone scenario approach discussed by Weidema et al. (2004), which aims to present ‘a broad range of plausible outcomes’, though their approach implies the use of more plausible scenarios.

used in producing renewable fuels.[73] Another kind of scale dependency relates to the use of by-products, affecting results through the system expansion method commonly used in prospective LCA.

In Paper I, scale-related changes are accounted for using a ‘net output approach’, in which a share of the studied renewable fuels is used for renewable fuel production. The functional unit is defined according to what is left for use outside the foreground system, which implies that the results are independent of this scale factor.

Regarding time-related changes, these are taken into account through studying different options for supplying heat, electricity, and input materials; three such options are presented here. The first one – the *mixed* background – reflects current EU-15 conditions, with process heat and electricity produced from a mix of energy resources (mainly coal, oil, natural gas, and nuclear) (Edwards et al., 2003). In the *coal* background, all process heat and electricity is instead produced from coal, and in the *wood* background it is produced from wood (more specifically, short-rotation forestry). The GHG emissions and agricultural land use, especially for wheat ethanol and RME production, have been shown to be affected by the background system (see Figure 10).

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[73] Regarding the study of radical system change, note that some background systems eventually become part of the foreground system.

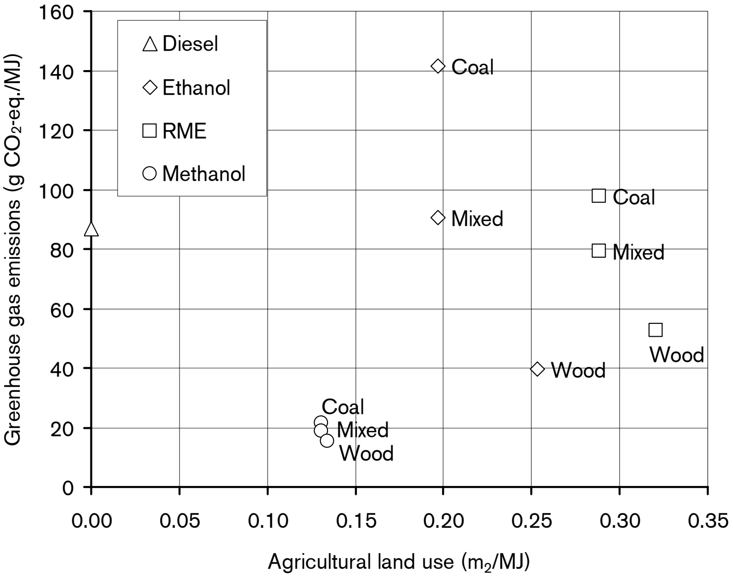

Figure 10: Greenhouse gas emissions and agricultural land use for the life cycle of ethanol, RME, and methanol for the coal, mixed, and wood background systems. The use of by-products is not accounted for. The coal background gives the highest greenhouse gas emissions while the wood background gives the lowest emissions for the three renewable fuels studied. The value for diesel production is shown for comparison. [74]

The production of many renewable fuels results in one or more by-products that can be used for various purposes. By-products include distiller's dried grains with solubles (DDGS) from producing ethanol and rapeseed meal and glycerine from producing RME, while there are no marketed by-products from the studied wood methanol production. In LCA studies, the environmental impact of the fuel production has to be allocated between the fuel and its by-products. In the ISO standard for LCA it is recommended that when inputs and outputs cannot be directly connected to a product, the system should be expanded to include the additional functions related to the by-products (ISO, 2006). Additional functions are largely determined by the availability and size of markets for the by-products, thus adding another kind of scale dependency.

In Paper I, we use a kind of system expansion (and thus a functional unit) that does not follow conventional attributional LCA practice, and thus warrants further explanation. First, the system is expanded also to include various functions of the by-products. This

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[74] The value for diesel includes CO_2 emissions from final combustion in vehicles; these emissions are not included for renewable fuels, as that carbon is part of the natural carbon cycle.

makes the functional unit a combination of the function of the fuel and other functions, and the analysis lives up to the principle of additivity usually acknowledged for attributional studies (Tillman, 2000).[75] Second, to make the different alternatives comparable, the equivalent functions of the by-products are subtracted. Then the additivity is lost. The result is that environmental impact credits are given to the studied technology to compensate for the avoided supply of products replaced by by-products.[76]

The size of by-product markets is illustrated by two different market shares of renewable fuels, as a percentage of the amount of petrol and diesel used in EU-15. A small market share (Figure 11) implies that by-products are used according to current practices (as animal feed and chemicals), while a medium market share (Figure 12) implies that the current and near-term by-product markets become saturated, and by-products are mainly used for heat production.[77] The results clearly indicate that GHG emissions and agricultural land use vary with the scale of adoption, particularly for wheat ethanol and RME. Agricultural land use increases with larger market shares, while greenhouse gas emissions depend greatly on the background system. For wood methanol, the results are more robust.

In conclusion, of the few fuels end impact categories studied in this LCA, RME used in any background system and ethanol used in a wood background system display the best environmental performance in the context of small market shares (Figure 11). If we are aiming for larger market shares for renewable fuels, methanol displays the best environmental performance, except that RME has the lowest GHG emissions in the mixed and coal background systems (Figure 12).[78] Thus, both the actual GHG emissions from the fuel life cycles and the ranking of the studied fuels are dependent on assumptions regarding background systems and by-product use.

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[75] The principle of additivity implies that the environmental impact of all functional units can be added to yield the total environmental impact.

[76] See also, for example, Weidema (2001) and Azapagic and Clift (1999a) for related discussions of co-product allocation.

[77] Market data are taken from various sources; for details, see Paper I and Sandén and Jonasson (2005b).

[78] The low greenhouse gas emissions for RME used in a coal background system are due to by-products replacing coal for heat production. As the environmental performance of the whole system is not included, these results should not be used for choosing the background system; rather, they reflect the performance of the studied transport fuels in the context of different background systems.

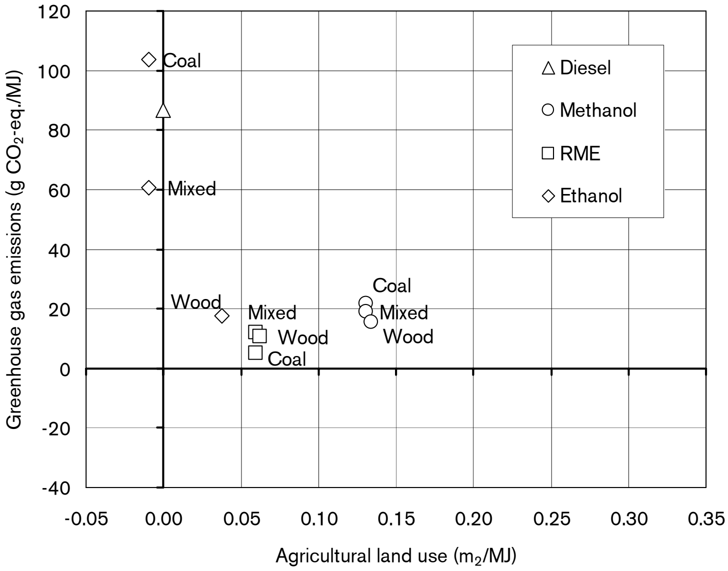

Figure 11: GHG emissions and agricultural land use for the life cycles of ethanol, RME, and methanol for small market shares (current by-product use). Negative values are due to the system expansion method. The value for diesel production is shown for comparison.

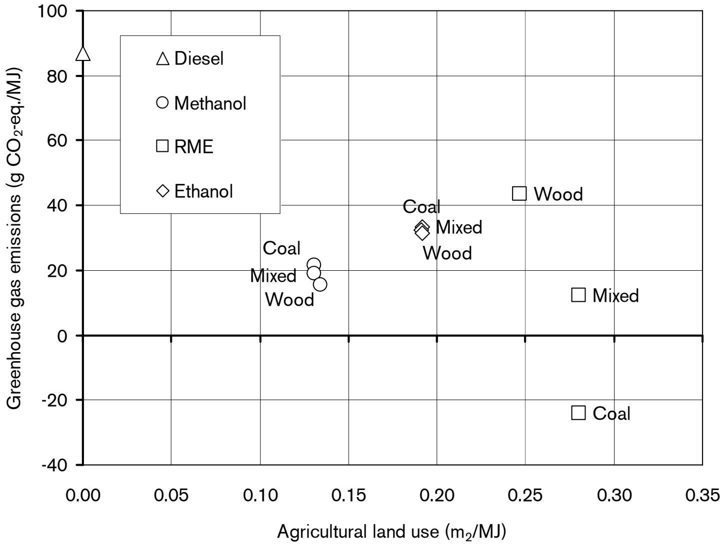

Figure 12: GHG emissions and agricultural land use for the life cycles of ethanol, RME, and methanol for large market shares (by-products mainly used for heat). Negative values are due to the system expansion method. The value for diesel production is shown for comparison.

6.3 Paper V: Socio–technical change in consequential LCA

Finally, in Paper V, historical and future cause–effect chains are taken into account in consequential LCA. The case of ethanol in Sweden, 1990–2020, is used to study the change in GHG emissions resulting from an intervention related to adoption of ethanol of varying origins at different points in time. The research question is:

> Q_V *How can socio–technical change be taken into account in consequential LCA of emerging technologies?*

Consequential (or change-oriented) LCA is used to study the change in environmental impact resulting from an intervention, such as a change in life cycle or the adoption of a new technology. Then a major methodological choice concerns what cause–effect chains to consider. For practical reasons, the cause-effect chains taken into account in consequential LCA have been limited both in terms of scope and how far they are followed. In this context, Sandén and Karlström (2007) have identified three levels of effects.[79]

First-order effects are governed by linear systemic response without any feedbacks. Such effects involve the direct change in environmental impact from the life cycle, and possibly also changed impact due to the replacement of the same function supplied by another technology. Assessing the potential environmental impact of a decision on technology adoption, this level corresponds to the attributional perspective, where the same technology is assessed.

Second-order effects are governed by negative feedback, typically resulting in the establishment of a new market equilibrium. Then the environmental impact is estimated from the difference between the old and the new equilibrium (see, e.g., Ekvall, 2000; Ekvall and Weidema, 2004).[80] For instance, Eriksson et al. (2007) introduce the concept of 'complex marginal electricity production', using a dynamic optimising model to include effects of marginal changes of the electricity market on utilisation and investments. For instance, rebound effects can be accounted for through studying negative feedback.[81]

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[79] Other categorisations of effects to be included in assessments are made by Berkhout and Hertin (2001) and Azapagic and Clift (1999b).

[80] See also Frischknecht (1998) and Weidema et al. (1999) on identification of marginal technologies and Mathiesen et al. (2007) for a review of marginal technologies used in past assessments.

[81] Rebound effects typically imply that the improved environmental performance related to a function results in decreased costs and increased total consumption. The total effect of the improvement could then be an increase in total environmental impact (see also Berkhout and Hertin, 2001).

Second-order effects are not considered in Paper V, but could in principle be calculated for different points in time.

Finally, third order effects are governed by positive feedback, including e.g. learning and cost reduction due to cumulative production (on the supply side). It can be argued that this results in increased adoption of the studied technology and substitution of the same function supplied by another technology. Sandén and Karlström (2007) propose quantification based on experience curves extended into the future, to illustrate how investments in a technology with a large potential for future emission reductions can contribute to future cost reductions, assumed to result in increased adoption and changed environmental impact.[82] What is not captured by experience curves are the changes on the demand side, not directly affecting the cost of the studied technology. For instance, an investment decision will not only build up knowledge related to a specific technology – partly captured by experience curves – but also other parts of the technological system. As demonstrated in Paper III, some system elements are specific while others are shared between different technologies. Taken together, such changes will influence the outcome of future decisions, possibly resulting in increased adoption of a number of related technologies and changed environmental impact.[83] In Paper V, these additional third-order effects are taken into account, as an alternative and extension of the work by Sandén and Karlström (2007).

First, historical developments and socio–technical scenarios are used to determine the adoption of ethanol in four different years (i.e., 1990, 2005, 2013, and 2020) and to calculate the environmental impact resulting from first-order effects. Second, studies of socio–technical change are used to argue that the adoption of ethanol contributes to future adoption of different ethanol technologies. It is assumed that this results in the replacement of the same function supplied by petrol and diesel, with accompanying changes in environmental impact. Finally, the result of third-order effects are quantified and compared with those of first-order effects.

Ethanol can be produced from various feedstocks and used in various fuel blends and vehicles. The ethanol used in Sweden in the studied period originates from a sulphite pulp plant, excess wine, wheat, sugar cane, and forest residues (wood). Today (i.e., 2008), an ethanol-based bus fuel is used in buses with diesel engines, E85 is used in flexifuel cars,

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[82] Experience curves are used to illustrate historic trends in cost reductions for a certain technology (or group of technologies) in relation to cumulative production.

[83] Thus also investments in a technology with a limited potential for future emission reductions may have a large effect, if contributing to increased adoption of related technologies with a larger potential.

and E5 is used in normal petrol cars.[84] The GHG emissions of these fuels depend on the specific life cycle, i.e., raw materials, production processes, transport to Sweden (if needed), fuel type, and vehicle fuel efficiencies.

Along with increasing adoption between 1990 and 2020, there is a change in the relative use of ethanol of different origins. This implies that the average life cycle emissions per litre will increase from an initially very low level, pass through a higher level, and finally decrease as a larger share of wood ethanol is introduced (Figure 13). The use of wood ethanol also implies a larger potential in terms of production volume being opened up. Including the substitution of petrol and diesel, the average emission decrease due to first-order effects is estimated to be between 1700 and 2100 g of CO_2-eq. per litre of ethanol in the four years studied. The variation can be explained by the use of ethanol of different origins and by the difference in efficiencies when used in different fuels and vehicles (i.e., bus fuel, E85, and E5).

Socio–technical studies of the history and future of renewable transport fuels in Sweden suggests (Papers II–IV) that a decision regarding the adoption of a specific ethanol technology often leads to other decisions influencing the further adoption of ethanol, implying changes in environmental impact. We estimated the contribution to socio–technical change of one litre of ethanol by the share of the cumulative ethanol use, and the result of socio–technical change was quantified by the total future emission reduction resulting from the use of ethanol fuels.[85] The results suggest that the emission reduction due to third-order effects is 44 million g CO_2-eq. per litre of ethanol in 1990, decreasing to 3800 g CO_2-eq. per litre up to 2020.

Thus, in an early stage, just after 1990, third-order effects are several orders of magnitude larger than the first-order effects (Figure 14). This result holds even if a probability factor of 1% is introduced, to account for uncertainties regarding the actual realisation of the studied scenario. For 2020, however, the results are less robust, and it can be questioned whether it is relevant to talk about any contribution to socio-technical change. It can thus be concluded that for emerging technologies in an early stage of development, the contribution to socio–technical change and resulting changes in environmental impact may be more important than the direct change resulting from adopting the technology.

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[84] E85 is a mixture of 85% ethanol and 15% petrol. Due to problems starting an engine using ethanol blends in a cold climate, the average ethanol content in Sweden is somewhat lower than 85% (Swedish Environmental Protection Agency, 2007). Flexifuel vehicles can run on any mix of E85 and petrol. The name ‘E5’ is used for petrol with the addition of 5% ethanol.

[85] Most of this reduction will take place after 2020, due to further adoption. However, it is assumed that the emission reduction per litre of ethanol will decrease to zero between 2020 and 2060 due to the introduction of more renewable fuels in the system, i.e., ethanol will not only replace petrol and diesel after 2020.

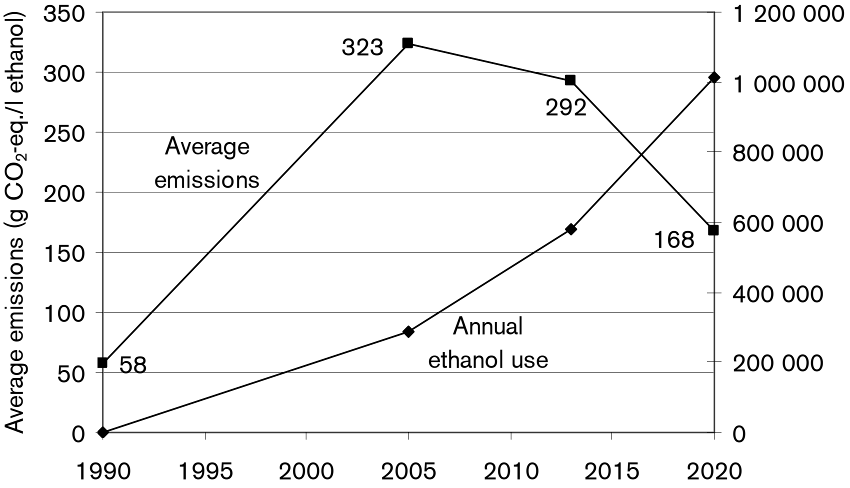

Figure 13: Average life cycle emissions per litre of ethanol in different years (left axis), weighted according to the share of ethanol of different origins and annual ethanol use (right axis). The cumulative use corresponds to the area under the curve for annual use.

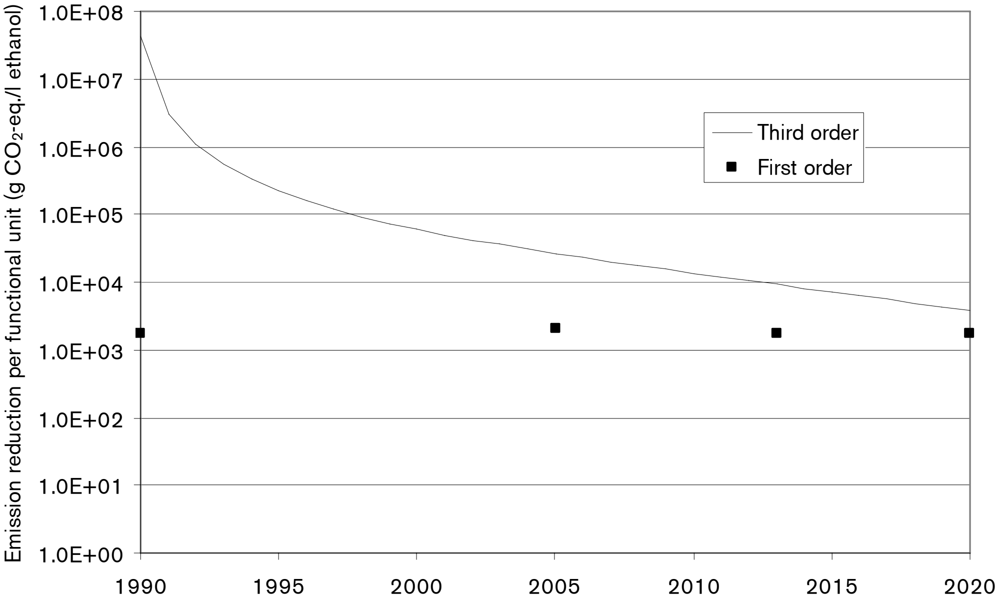

Figure 14: Contribution to future emission reductions per litre of ethanol in different years. The unbroken line is the reduction due to third-order effects. This can be compared with the results of first-order effects, indicated by black squares (note the logarithmic scale).

Considering the development of renewable transport fuels, also more pessimistic scenarios than the one presented in this paper can be imagined. For instance, the adoption of ethanol could delay the introduction of better alternatives and beneficial for coal-based fuels. In addition, there may be interaction on an international level, between different renewable fuels and between sectors, which can be discussed in relation to consequential LCA.

7 Conclusions

Several alternative technologies – i.e., combinations of raw materials, production processes, and fuels – are proposed for mitigating the environmental impact of road transport. To guide the selection of technologies by various actors, we need technology and intervention assessments. However, assessing the environmental performance of emerging technologies is no trivial matter. In particular, the scale of the required changes and the time perspectives involved need to be taken into account. By means of a case study of renewable fuels for road transport, this thesis aims to contribute to the development of appropriate methodology for the needed assessments. The purpose is to increase the usefulness of environmental assessments of emerging technologies as a basis for strategic technology choice by taking socio–technical change into account. The main research question is:

> *Q How should environmental assessments be made, so as to inform decisions that strive to contribute to the radical environmental improvement of large systems?*

This question is addressed in relation to life cycle assessment (LCA).[86] A long time perspective, the possibility of system change, and the inclusion of socio–technical change processes allows for the revision of methodological assumptions normally made in LCA of current products. Building on LCA methodology and socio–technical change theory in combination with case studies, general results regarding environmental assessment methodology and strategic technology choice are elaborated on.

First, some general conclusions regarding study design and the interpretation and use of the methodology are presented below. These are followed by more specific conclusions regarding attributional and consequential LCA, both of which can be useful as a basis for strategic technology choice. In addition, the possibility of using the results of different kinds of studies in environmental assessments is discussed, as alternatives or complements to extended LCA methodology.

Environmental assessments are always made for a certain purpose, and the results can only be interpreted and used in relation to that purpose and to the methodological assumptions made. For example, different actors have different decision domains in relation to strategic technology choice, and the options available change over time.[87] This means that the specific purpose of an assessment will have to differ between receivers and

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[86] The focus in this thesis is on the inventory part (LCI) of LCA.

[87] An overview of currently available (as of 2008) and future technologies in the field of renewable transport fuels is presented in section 2.1.

choice situations. By presenting the purpose and methodological assumptions together with more quantitative results, crucial strategic issues, such as trade-offs and constraints, may also be highlighted.

Studies of socio–technical change contribute to a picture of emerging technologies evolving side by side, all at different stages of development in terms of built-up structures, i.e., physical artefacts, actors, and rules (Papers II–IV). Technological performance will change over time and with the scale of adoption, and the technologies may come to be part of radically changed future systems. Thus, the time perspective and scale issues are crucial when assessing emerging technologies. For strategic technology choice, results regarding the current, or historical, performance of specific products are of little use. Clearly – whether being attributional or consequential – studies need to be prospective. However, as demonstrated in Paper V, retrospective studies can still be used to provide information about important relationships and development mechanisms.

We identified several important choices that need to be in line with the studied time perspective and scale of adoption. First, the choice of environmental impact categories considered in an assessment affects the results produced. Priorities may shift over time in accordance with societal values, as observed in Paper III and in Sandén and Jonasson (2005b); for example, the emphasis shifted from energy use to urban air quality and then to GHG emissions. In the future, radically increased adoption of renewable fuels may further change the relative importance of different assessment categories. Second, radically improved and more 'futuristic' technologies will be relevant to study, as longer time scales allow room for radical technological development. The choice of technologies included may also depend on the particular environmental issues of interest. Third, performance data basically represent one stage in the development of a technology and change with time and scale, i.e., general technical development, cumulative production, and total annual production. This implies that data should be chosen with care, and in line with the purpose of the study.

Considering prospective LCA, the attributional (or state-oriented) perspective focuses on potential impact in future states, identifying *what technologies* we should strive for. Then a crucial issue is the choice of states to study. For emerging technologies, the performance of *current* technology used on a small scale in *current* background systems is of little relevance to the environment. Instead, it is the potential environmental impact in *future* states with increased adoption and possibly changed background systems that is important. In Paper I, several stylised states are studied to capture more of the inherent properties of a number of renewable fuel technologies. The studied states are feasible but extreme and less probable, e.g., with background systems based purely on coal and biomass. In addition, a 'net output approach' is used, implying that the studied fuels are partly used for production processes and distribution. We demonstrate that not only the GHG emissions from each life cycle, but also the ranking order of RME and wheat ethanol (in terms of GHG emissions) differ between the studied states.

As well, the available resources change with time and scale. Extending the time frame and/or increasing the scale may imply that new kinds of resources have to be used or that performance will change. In producing renewable fuels, the use of waste and by-products may need to be complemented by dedicated crops, implying changed environmental impact; increased crop production will in turn result in the use of new land areas, possibly giving rise to other impacts. Furthermore, the availability of markets for by-products from the production of the studied fuel will change with the scale of adoption. This has an effect on the credits received in an LCA, as the use of by-products implies avoided production somewhere else. In Paper I, we demonstrate that not only the GHG emissions from each life cycle, but also the ranking order of RME and wheat ethanol (in terms of GHG emissions) are dependent on assumptions both regarding background systems and by-product use.

In contrast to the attributional perspective, the consequential perspective is used to explore the effects of an intervention at a certain point in time, indicating *what interventions* result in the desired effects. Of particular importance for emerging technologies in an early stage of development is that interventions contribute to system change, possibly resulting in future adoption of new and improved technologies and changed environmental impact. If the potential for future emission reductions is large enough and the intervention early enough, these effects will likely be larger than the direct effects of adoption. The contribution of an intervention to system change can be estimated in different ways. This thesis examines cause–effect chains in socio–technical systems, to be taken into account in environmental assessments. First, some general conclusions regarding cause–effect chains from Papers II–IV are presented.

Paper II examines the development of technological innovation systems (TISs) around groups of bio-diesel technologies in the Netherlands and of ethanol technologies in Sweden. A number of exogenous factors have driven and/or hampered the development of the two TISs, such as oil supply insecurity, local air and water pollution, EU agricultural policy, and the debate on climate change. These factors, both international and national in origin, are common to both countries, though with different effects on TIS dynamics. The identification of exogenous factors in Paper II, the discussion of technology boundaries in Papers III and IV, and references to the multi-level framework (MLP) and external influence in Paper IV point to the importance of taking other actors' actions and general system developments into account when assessing interventions.

The importance of endogenous forces is analysed in Paper II through a number of key processes ('system functions') contributing to system growth. These are entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resource mobilisation, and support from advocacy coalitions. In both countries, a comprehensive set of such functions proved necessary for the emergence of continuous cause–effect chains, i.e., cumulative causation, crucial for the successful development of the TISs. Activities related to different bio-diesel and ethanol technologies contributed to the build-up of system functions, while the exclusion of specific technologies had a negative effect on TIS dynamics. Having said this, there may of course be other valid reasons for avoiding certain technologies (e.g., environmental concerns).

Interactions between technologies are analysed in more detail in Paper III. It is suggested that such interactions can be related to structural overlaps, in terms of physical artefacts, actors, and rules, between technologies, defined as 'bundles of value chains'. The suggested framework involves six different modes of static and dynamic interaction: competition, symbiosis, neutralism, parasitism, commensalism, and amensalism. In the case of renewable fuels, influential interactions are identified between fuels from gasification, ethanol of different origins, ethanol and biogas, and, more generally, between different renewable fuels.

In Paper IV, the mechanisms identified in Papers II and III are used in the elaboration of socio–technical scenarios. The build-up of structures for different technologies is extended until 2020, and the interaction between different technologies is considered. The technological systems perspective is complemented by a multi-level model to account for the relation between exogenous and endogenous factors. The different scenarios are characterised by the relative strength of two system functions: market formation and knowledge development. The scenarios illustrate the divergent outcomes that could result from different policy choices. Structural elements related to one or several emerging technologies are built up in a process of competition and co-evolution. Forces endogenous and exogenous to the overall system of renewable fuels interact to determine further changes in the system; divergent paths are possible due to how exogenous factors are interpreted and exploited by various actors in the system.

The market-oriented scenario illustrates a) the consequences of breaking the dominance of entrenched technologies and demonstrating a growing market potential for alternatives, and b) the risks of a strong focus on market stimulation and first-generation renewable fuels. In the technology-oriented scenario, we identify both c) the value of fostering variety through funding the research and development for new technology and d) the risks posed by a poorly developed market.

In accordance with the studied cause–effect chains, it can be argued that early interventions contribute to future changes in environmental impact through promoting the adoption of new and improved technologies and increasing the replacement of old ones. Paper V takes this effect into account in a consequential LCA of ethanol technologies in Sweden for the period 1990–2020. The adoption of ethanol contributes both to decreased emissions per litre of ethanol and to creating a large opportunity in the form of wood ethanol. The resulting contribution to changed environmental impact, per litre of ethanol adopted in a certain year, is quantified by the future emission reduction divided by the cumulative use of ethanol so far. It is found that in an early stage (just after 1990), when cumulative use was small and the potential future emission reduction was large, this contribution was several orders of magnitude larger than the direct reduction per litre of ethanol replacing petrol or diesel. At a later stage (around 2020), results are less robust, and it can be questioned whether it is relevant to talk about any contribution to socio-technical change. Also more pessimistic scenarios can be imagined, e.g., involving that the adoption of ethanol delays the introduction of better alternatives. While results cannot be calculated with any precision, this extension of LCA methodology provides insight into the relative importance of different kinds of cause–effect chains relevant to emerging technologies.

Finally, it has to be acknowledged that not all aspects of socio–technical change and the resulting environmental impacts can be readily included in one comprehensive assessment methodology. As proposed by systems theorists such as Churchman and Midgley, it may not be desirable to aim for a single overarching methodology that tries to take all aspects of a system into account. The basis for decision making may not be improved by including all socio–technical mechanisms in quantitative environmental assessments, such as LCAs.[88] An alternative answer to the research question would thus involve methodological pluralism. 'Environmental assessment' could then include a group of parallel studies using different methodologies that illuminate different cause–effect chains resulting in changed environmental impact. This also creates an opportunity to take different kinds of goals into account, and involve different kinds of actors in the assessment process. For example, the methodologies used in this thesis – life cycle assessment (LCA), socio–technical scenarios, and studies of technological innovation system (TIS) functions – could very well contribute useful results without being incorporated into a single comprehensive assessment methodology.

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[88] A similar point is made by Sandén and Karlström (2007).

8 Perspectives on strategic technology choice

This thesis cannot be used to advocate the use of renewable fuels in general, or even of particular renewable fuels. Other important measures to mitigate the environmental impact of transport systems are proposed elsewhere, such as reducing the total use of energy through reducing transport activity and increasing vehicle efficiencies. If renewable fuels are to be used on a large scale, however, this thesis gives new insight into how to guide their selection. Building on existing methodology, theory, and frameworks allows for more general reflections on strategic technology choice as well. In section 3, it was stated that different actors have different decision domains. Bearing this in mind, the following is mainly directed towards actors that can make longer-term strategic choices regarding the adoption of emerging technologies.

In addition to the conclusions on how assessments should be made, I see two major problems regarding the use and interpretation of assessment results for emerging technologies. First, in attributional studies of future states, the more ‘futuristic’ technologies are likely to display better performance than the best technologies available on the market today (or that could be implemented in the near future). With such an interpretation there is a risk that only research in distant future technologies will be favoured, and that other kinds of investments will be postponed. According to this reasoning, there will always be more advanced future technologies ‘worth waiting for’. In contrast, Papers II–IV support the idea that several technologies in different stages of development need to develop concurrently.[89] Second, in consequential studies of near-term interventions, all relevant cause–effect chains cannot be rigorously accounted for, which could imply that only easily quantifiable effects are included. As demonstrated in Paper V, these effects may not be the most important ones for emerging technologies in an early stage of development. Both these problems call for the thoughtful use and interpretation of assessment results by different actors.

As we have seen, all technologies cannot be selected by all actors in all situations. The decision situation is determined by the actors and their goals, decision area, interests, etc. Even so, every actor should consider the contribution of strategic technology choice to changed environmental impact. *The* optimal technology will never be available to choose, but in every decision situation there are better and worse options. This thesis helps increase the possibility of better-informed decisions on strategic technology choice.

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[89] A more trivial reason for maintaining variety is that the futuristic technologies may not deliver on their promise, or at least may not develop along the anticipated paths.

Studies of socio–technical change also provide some additional perspectives on how different actors could relate to emerging technologies and strategic technology choice. The technological innovation system (TIS) framework suggests that a range of different key processes, called 'system functions', need to be present for a group of emerging technologies to grow. The branching out of system functions is determined by external influences and endogenous dynamics. From Paper II, we see that less promising technologies should not be underestimated with respect to their potential impact on cumulative causation. If the selection of technologies in the innovation system is narrowed down by policy, for example, there is a risk that some functions may be left behind.[90] Of course, there is need for a balanced view, as too much focus on inferior technologies may lead to a dead end, as demonstrated in Paper IV. This can be explained by the momentum built up around an emerging technology when actors become involved and other structural elements are adjusted, as indicated in Papers II–IV.

A range of timely and balanced policy measures that take the different stages of development of different technologies into account can then stimulate promising technologies and discourage inferior ones.[91] Due to ongoing development, the design of such measures requires that socio–technical change be continuously monitored. Furthermore, it is suggested in Paper II that to reduce uncertainty and provide for continuous entrepreneurial activities, policy makers at multiple government levels should give clear signals of desired developments and intended support programmes. It may be discussed how this advice can be accounted for simultaneously when designing policies. A broad range of policy measures can be imagined, each related to one or several technologies and system functions. However, it is beyond the scope of this thesis to review the various options for policy intervention.

In early stages of development, emerging technologies together challenge entrenched technologies as well as competing with each other. In Paper III, different modes of interaction in the material, organisational, and conceptual dimensions of technological systems are analysed. Following from this, strategic opportunities for interaction may be exploited by firms to stimulate the growth of selected technologies, through cooperation with actors representing seemingly competing alternatives. For example, Papers II and III particularly demonstrate that lobbying by different advocacy coalitions played a crucial role in the development of bio-diesel in the Netherlands and ethanol in Sweden. These coalitions consisted of different kinds of actors, for example, in agriculture, industry, and

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[90] In principle, one could imagine one technology contributing to all system functions. This also relates to the choice of system delineation; 'ethanol' can be studied as one technology or several more narrowly defined technologies, such as wheat ethanol and wood ethanol.

[91] Thus, strictly 'technology-neutral' policies are not relevant to emerging technologies (see also Sandén and Azar, 2005).

regions, and engaged in what they believed was desirable and feasible. It is suggested in Paper IV that different actors in the technological system can make use of existing structures and ongoing change processes in their efforts to contribute to system change, and that the role of policy makers is to balance the development in different parts of the system.

9 Further work

There is one obvious option for further work related to the case studied in this thesis, i.e., renewable energy for road vehicles. The longer time perspective of this thesis can be applied in performing environmental assessments of renewable transport fuels, such as an overview of a range of combinations of raw materials, production processes, fuels, and power trains. Either new studies can be conducted or existing ones reinterpreted in terms of how they can be used to inform strategic technology choice. However, referring to the different actors and decision situations described in section 3, the relevance of such general studies may be limited. Another option is to highlight crucial strategic issues, such as trade-offs and constraints, through more specific studies. For example, as a renewable fuel usually represents just one of several products of a certain process, it may be important to study entire production systems for fuels and co-products (e.g., in biorefineries) to gain a better understanding of the overall environmental impact in future states.

This thesis also highlights the opportunities for improving the specific methodologies used.[92] First, analytical environmental assessment tools may be further adjusted to inform strategic decisions. However, as indicated in the Conclusions, it may not be productive to incorporate all aspects of socio–technical change in a single comprehensive assessment methodology. Instead, an important complementary point of departure would be to investigate strategic decision-making processes in policy and firms, to build our knowledge of the role of assessments and of what forms the basis of technology-related interventions. Who has the responsibility for the environment in specific decision processes, and more generally, in processes of socio–technical change? Second, the merits of the different approaches used to study socio–technical change may be further tested and evaluated. In this thesis, building blocks mainly from the MLP and the TIS frameworks are used, and a complementary interaction framework is proposed in Paper III. Their respective strengths may be exploited to achieve even better understanding of socio–technical change processes and of specific cases.

The framework developed in Paper III suggests that there are changes in the structural elements of technological systems that spill over to seemingly competing technologies. Such spillovers, explained by structural overlaps, may not only occur within a specific functional domain, but also between sectors. For example, the change in values and norms connected with increased adoption of ‘clean vehicles’ may also benefit, for example, organic food. This way, one could imagine the management of specific technological

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[92] For example, this can be done by using case studies as a means of methodology development.

niches as a way to introduce technologies or lifestyles that overlap in any of the material, organisational, and conceptual dimensions of technological systems.[93]

It is concluded (in section 7) that the methodologies used in this thesis could be used for environmental assessment without being incorporated into a single comprehensive assessment methodology. This would imply the further development of procedural environmental assessment tools and participative methods, such as strategic environmental assessment (SEA) and constructive technology assessment (CTA).[94] These are forms of broad, though structured, learning processes among the actors involved in such assessments. Similarly, a range of separate assessment studies can be seen as part of a similar society-wide learning process, as analysts communicate their results and interact with other actors in society (see, e.g., Sandén and Harvey, 2008).

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[93] For example, it is possible that there may be societal rebound effects related to more environmentally benign transport, resulting in increased transport activity.

[94] See, for example, Kain (2003) on participative approaches, Finnveden et al. (2003) on the application of SEA in the energy sector, and Rip (2008) on CTA involving socio–technical scenarios.

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Appendix

The following people were interviewed in relation to the work published in Sandén and Jonasson (2005b) and Papers II-IV:

Interviewee	**Affiliation**	**Date**	**Interviewer(s)***
Bergström, Kjell A. C.	Saab Automobile	29 Sep. 2005	KJ
Brandberg, Åke	Ecotraffic ERD^3	4 Feb. 2005	BS, KJ
Brandel, Magnus	Swedish Peat Producers Association (STPF)	2 Feb. 2005	BS, KJ
Bucksch, Sören	Vinnova	26 Oct. 2004	BS
Carlson, Ingemar	Ingenjörsfirman Ingemar Carlson	9 Feb. 2005	BS, HJ
Carstedt, Per	BioAlcohol Fuel Foundation	31 May 2005	BS, KJ
Elam, Nils	Atrax Energi AB	18 Jan. 2005	BS, KJ
Flodin, Sten	SSEU (formerly)	27 Sep. 2005	KJ
Hedemalm, Per	Oroboros AB	24 Jan. 2005	BS, KJ
Herland, Erik	LRF and Lantmännen	2 Feb. 2005	BS, KJ
Hugosson, Björn	City of Stockholm	29 Jan. 2004	BS
Hådell, Olle	Swedish Road Administration	25 Aug. 2005	BS, KJ
Kock-Åström, Helena	Municipality of Linköping	15 Jan. 2004	BS, KJ
Landälv, Ingvar	Chemrec	3 Feb. 2005	BS, KJ
Lindblå, Göran	OKQ8	8 June 2005	KJ
Ramberg, Bo	Fordonsgas AB	20 Jan. 2005	BS, KJ
Rietz, Johan	Swedish Gas Centre (SGC)	9 Feb. 2005	BS, HJ
Rydén, Charlie	Protima AB	4 Feb. 2005	BS, KJ
Sjunnesson, Lars	Sydkraft AB	9 Feb. 2005	BS, HJ
Sunnerstedt, Eva	City of Stockholm	29 Jan. 2004	BS
Sävbark, Bengt	Ecotraffic ERD^3	4 Feb. 2005	BS, KJ
Tegnér, Lars	Swedish Energy Agency	20 Sep. 2005	BS, KJ
Udd, Sören	AB Volvo	28 Sep. 2005	KJ
Waldheim, Lars	TPS	25 Jan. 2005	KJ
Wallman, Stephen	BilSweden	29 Oct. 2004	BS, HJ, KJ

* BS = Björn Sandén, KJ = Karl Jonasson (now Hillman), HJ = Hanna Jönsson