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ENVIRONMENTAL ASSESSMENT OF EMERGING TECHNOLOGIES

THE CASE OF ALTERNATIVE TRANSPORT FUELS

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Abstract

There are several methods to evaluate the environmental performance of new technologies. The purpose of this thesis is to contribute to the methodological development of environmental assessments, with contributions from life-cycle assessment (LCA), theories on technical change and socio-technical scenarios.

LCA, or 'well-to-wheel studies', is a widely used tool for evaluating the environmental performance of alternative transport fuels. However, the methodology is usually not adapted to answer questions regarding strategic technology choice. Suggestions are presented that could increase the usefulness of LCA in this respect. A 'net output approach' is used, where fuels are used for their own production and distribution. Background system changes and the size of by-product markets are studied, and it is shown that these factors can have a large influence on the results. Studies of LCA type can be used to give information on which fuels that have a low environmental impact today, and which are promising in the long run. However, it is suggested that also dynamic processes of technical changed need to be taken into account in the selection of technologies.

In a study of the history of alternative transport fuels in Sweden, we show that also short-term options can contribute to the development towards more promising long-term options. Investments in alternative fuels during the years have not only resulted in physical artefacts and new explicit knowledge, but have also created dedicated actors and changed tacit knowledge and normative rules. Positive feedback loops related to actors, knowledge and rules have created more actors and changed regulation, and an ability of alternatives to survive. At the same time, the growth of some alternatives has favoured others, due to overlaps in socio-technical systems.

However, the growth of alternatives is still very much dependent on exogenous factors and policy. The balance between short-term and long-term options in the transition of the transport system is illustrated through the use of socio-technical scenarios. These show that there is a risk that any policy could result in a negative development for renewable alternatives, but they also suggest that there are opportunities for growth. Policy could balance the development in different parts of the system, and make use of short-term options to contribute to more radical changes in the transport system.

Keywords: environmental assessment, life-cycle assessment, LCA, technological systems, technological transitions, socio-technical scenarios, technology path assessment, sustainable development, alternative fuels, biofuels, transport

List of publications

Appended papers[1]

Paper I:
Time and Scale in Life Cycle Assessment:
The Case of Fuel Choice in the Transport Sector
Karl M. Jonasson and Björn A. Sandén

(Accepted for publication in International Journal of Heavy Vehicle Systems)

Paper II:
Variety Creation and Co-Evolution among Contenders:
The Case of Alternative Transport Fuels in Sweden 1974-2004
Björn A. Sandén and Karl M. Jonasson

(To be submitted for publication)

Paper III:
Exploring technology paths
The development of alternative transport fuels in Sweden 2005-2020
Karl M. Jonasson and Björn A. Sandén

(To be submitted for publication)

Other publications

Time and Scale Aspects in Life Cycle Assessment of Emerging Technologies:
Case Study on Alternative Transport Fuels
Karl M. Jonasson and Björn A. Sandén

(CPM-report 2004:6, Chalmers University of Technology, Göteborg, Sweden)

Variety Creation, Growth and Selection Dynamics in the Early Phases of a Technological Transition:
The Development of Alternative Transport Fuels in Sweden 1974-2004
Björn A. Sandén and Karl M. Jonasson

(ESA-report 2005:13, Chalmers University of Technology, Göteborg, Sweden)

[1] The appended papers are not included in the electronic version of the thesis.

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The interviews made during the last year contributed with invaluable insight into the history of alternative fuels, and I am very grateful to those who took their time to tell often more than asked for. Thank you also to the participants of the workshop on October 19, 2005. I hope we can make something more out of this.

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Contents

1 Introduction

1.1 Background

The problem of climate change is today seen as one of the most important environmental issues. In the United Nations Framework Convention on Climate Change it was agreed that the concentration of greenhouse gases in the atmosphere should be stabilised 'at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992). The greenhouse gas contributing the most to climate change is carbon dioxide (CO_2), mainly emitted from the combustion of fossil fuels, such as oil, natural gas and coal (IPCC 2001). The transport sector stands for an increasing share of the total greenhouse gas emissions and oil use (IEA 2005) and is to 96 % dependent on oil (IEA 2002). At the same time, oil is a finite resource and the oil price is expected to rise during the coming decades (EU 2003c).

The oil use increase could be mitigated by reductions in transport activity and more efficient vehicles, but there is nevertheless a need for technologies that could perform the same task without large emissions of greenhouse gases and use of finite resources. Several candidate technologies exist, differing with regard to greenhouse gas emissions, regulated emissions, resource use, technical maturity, infrastructure requirements, costs and safety. In the European Union (EU) directive 'on the promotion of the use of biofuels or other renewable fuels for transport' indicative targets are set for the introduction of such fuels. The target is 2 % of petrol and diesel used for transport purposes at the end of 2005, and 5.75 % at the end of 2010 (EU 2003a).[2] Though the targets set in the directive are ambitious from a political point of view, the physical potential of supplying Europe with sufficient amounts of renewable fuels in the short run will not be a problem, particularly as fuel can be imported from outside the EU (Sandebring 2004). In a more long-term perspective, with larger volumes and a higher market share, competition for agricultural land will become an important global issue, as both food and energy crops need to be produced (Azar 2005).

Different assessment methods are used to choose which fuels that are to replace oil in the transport sector, for example life-cycle assessment (LCA) (Weiss et al. 2000; Ahlvik & Brandberg 2001; Edwards et al. 2003) and energy system models (Azar et al. 2003; Gielen et al. 2003). Environmental performance, efficiency (regarding use of natural resources) and costs are commonly calculated and can give important information about different technologies. Such properties will, however, change over time, and with the way and at what scale the technologies are implemented in

[2] The percentages refer to the energy contents of the fuels.

society. Also societal changes may affect these properties. To some extent these effects can be accounted for by modifying existing methods, and in this thesis some suggestions are given for LCA.

Energy-system models optimise costs over a certain period of time under resource and emission constraints, while LCA is developed to analyse the environmental impact of a product in the present state, or of minor adjustments to the system. But what will the long-term environmental consequences be, of investing in a new technology today? To answer this question, dynamic effects of technical change on all parts of the socio-technical system, more far-reaching than those anticipated in LCA, need to be included in the assessment. Investments may for example lead to improvements and more investments in a technology, and a development favouring or hindering other new alternatives with even better (or worse) environmental performance.

1.2 Research questions and scope

The purpose of this thesis is to contribute to a widening of environmental assessment methodology, to make it more useful in guiding strategic technology choice. The research question is:

> *How should assessments of the environmental performance of emerging technologies be made in sectors where radical system changes are sought?*

The question is investigated within a case study of alternative transport fuels, including both renewable and non-renewable fuels. There are many ways to reduce emissions and resource use in the transport sector. I have consequently left out other ways than alternative fuels that can be used in cars or heavy vehicles to provide the functional unit vehicle kilometre. Smaller cars, increased efficiency of power trains, and more radical changes of the transport sector are not included, though such measures may be important.

The intended audience is researchers, LCA practitioners, technical analysts, energy authorities, policy-makers, and stakeholders within related industries.

The geographical boundary used in the LCA study of Paper I is EU-15, but there are connections with other parts of the world regarding some imported products. At the time of the study, the number of member states in the EU was 15, and market information was readily available. Current data is used, but the calculation procedures suggested are supposed to reduce the importance of an explicit time frame.

In Papers II and III, the development of alternative transport fuels in Sweden is studied, and foreign influence is treated as external forces. It can be argued that this perspective is too narrow, and that the international development for the whole energy system should be taken into account. However, an empirical study needs its system boundaries, and this study shows that the Swedish development indeed is dependant on the international development, but that the process also is very much dependant on the national or even local situation. The time frame in Paper II is 1974-2004, and in Paper III 2005-2020.

1.3 Outline and method

The subject of the case study is introduced in Section 2, and issues concerning raw materials, production and use of alternative transport fuels, relevant for the context of the study, are presented.

Section 3 begins with a description of LCA and its use for emerging technologies and alternative fuels. Previous work applying LCA methodology is reviewed in Section 3.1, modifications of the methodology are suggested, and some results from the modified LCA of Paper I are presented in Section 3.2.

Due to limitations in the LCA perspective, section 4 puts environmental assessments into a wider perspective, taking dynamic processes of technical change into account. In Paper II, insights from social construction of technology (SCOT) (Bijker 1995), historical studies of large technical systems (Hughes 1983; Kaijser 1994), 'transition management' (Hoogma et al. 2002; Elzen et al. 2004a; Geels 2005) and studies of 'technological systems' or 'technology-specific innovation systems' (Carlsson & Jacobsson 1997; Jacobsson & Bergek 2004) are used to work out a theoretical framework that is used to analyse the development of alternative transport fuels in Sweden. The development of the framework and the collection of empirical material were done in parallel, thus affecting each other. The framework was adjusted to include phenomena found through empiric work, and the questions asked during interviews and literature studies were influenced by the framework. The framework is described in Section 4.1.

Government budget and energy bills, reports from governmental agencies, consultancy reports and technical journals are used as references for the empirical work in Paper II. These are supplemented by information from some 30 interviews made with consultants, lobbyists and people from governmental agencies, vehicle producers and oil distributors. They were selected according to their experience, expertise and authority. The framework is used to structure the empirical material from literature and interviews and analyse the development of alternative transport fuels in Sweden from 1974 until 2004. Some conclusions from the history in Paper

II are highlighted in Section 4.2. The framework and the conclusions from the history are also used in Paper III in the construction of socio-technical scenarios (Elzen et al. 2002; Elzen et al. 2004b).

2 Alternative transport fuels

Transport fuels can be categorised in different ways, according to technical properties and environmental performance. 'Alternative transport fuels' normally means all fuels that are alternatives to normal petrol and diesel. Thus fuels originating from non-renewable resources, such as natural gas and liquid petroleum gas (LPG), fuels produced from e.g. coal, oil and natural gas, and hydrogen produced with non-renewable electricity are included. Non-renewable alternative fuels will not be long-term options to solve the climate problem, but they can play an important role in the transition, favouring or delaying the introduction of renewable alternatives.[3] These are fuels produced from for example oil crops and waste oil, starch and sugar crops, cellulosic materials and organic waste, and hydrogen produced with renewable electricity or directly from solar radiation (see Table 1). In the EU biofuel directive, the term 'biofuels and other renewable fuels' is used, meaning fuels produced from biomass, or using renewable energy for their production (EU 2001; EU 2003a). Either 'biofuels' or 'renewable fuels' are used to denote such fuels in this thesis.

In Sandebring (2004) three generations of renewable fuels are distinguished. The first generation refers to the alternatives available today, i.e. imported ethanol and wheat ethanol, biogas and FAME.[4] The second generation is cellulosic ethanol (ethanol from wood) and synthesized fuels produced from gasified biomass, such as methanol, Fischer-Tropsch (FT) diesel and dimethylether (DME). The third generation is hydrogen and unknown alternatives. Alternatives frequently occurring in the assessment literature are listed in Table 1, classified according to the three generations, and the kind of resources that can be used for their production.[5] Besides resource use, the fuels differ regarding technical maturity, infrastructure requirements, costs, safety, and life-cycle efficiency.

Some fuels are better suited for use in certain engines, of which various types of the Otto and the diesel engines are the most common. A more efficient future energy converter is the fuel cell, supplying an electric motor with electricity. It is mainly demonstrated with hydrogen or methanol, but in combination with a reformer other fuels could be used. In addition, all alternatives can be combined with hybrid technologies to increase the efficiency of the power train. This gives a system with a combustion engine (or a fuel cell), batteries and electric motor(s),

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[3] Possible exceptions are hydrogen produced with nuclear technology, posing other problems, and hydrogen produced from coal with carbon capture and sequestration.
[4] FAME (fatty acid methyl esters) produced from rapeseed is called RME (rapeseed methyl ester). FAME is popularly called biodiesel.
[5] Of course there are some other options. The fuels and resources mentioned here are those mainly discussed in a European perspective, import included. Direct use of electricity in electric vehicles is for example not included.

where the engine can be run at optimal speed to charge the batteries and sometimes be turned off, the efficiency of the electric motor is utilised, and braking energy can be regenerated. If the batteries also can be charged from the electricity grid, the vehicle is called a plug-in hybrid.

Table 1: A selection of alternative fuels and possible resources present in the literature. It should be noted that all renewable resources cannot be harvested everywhere in the world, which is also the case for non-renewable resources. Direct use of electricity is not included.

	Fuel	Non-renewable resources	Renewable resources
1st generation	Ethanol		Sugar Starch (e.g. from wheat)
	FAME (fatty acid methyl esters)[a]		Oil crops (e.g. rapeseed) Waste cooking oil
	Methane (natural gas/biogas)	Natural gas	Waste and sludge Grasses
2nd generation	Ethanol		Cellulose (wood)
	Methanol Fischer-Tropsch (FT) diesel Dimethylether (DME)	Natural gas Coal	Biomass[b] Waste Black liquor
3rd generation	Hydrogen	Non-renewable electricity Natural gas Coal Nuclear power[c]	Renewable electricity Biomass[b] Waste Black liquor Solar radiation[c]
	Unknown alternatives	?	?

[a] FAME produced from rapeseed is called RME (rapeseed methyl ester).
[b] Biomass includes all kinds of crops and ligno-cellulosic materials.
[c] Denoting integrated production of hydrogen from nuclear technology and solar radiation, i.e. without producing electricity in the process.

Discussing transitions to new alternatives, one important property of some fuels is that they can be blended with some other fuel. This opens for a gradual shift on the user side, provided that materials are compatible with the blends. The most common examples are ethanol in petrol, FAME and FT-diesel in conventional diesel, and hydrogen in methane. From Table 1 it can also be concluded that most alternatives can be produced from several resources, which facilitates the implementation on the user side. Another important technical similarity exists for methanol, FT-diesel, DME and hydrogen, which all can be made from synthesis gas produced from natural gas, coal, biomass or waste.

3 Life-Cycle Assessment (LCA)

Life-cycle assessment (LCA) is a method to analyse the environmental impact related to a product. Data on resource use and emissions are collected, for all stages of the product-life cycle, including raw material acquisition, refining, production, transports, use and waste handling. Potential environmental impact is calculated using known cause-affect chains in the environment, and presented for selected impact categories, e.g. global warming potential, eutrophication potential, ozon-depleting potential etc. The method is mainly used to identify which life-cycle stages that contribute the most to the environmental impact of the product, or to analyse effects of decisions regarding changes in production practices.[6]

LCA has been used to evaluate the environmental performance of road transport, and to find which parts of the vehicle life-cycle that contribute the most to the environmental impact of transport. It can be recognised that the fuel used in a vehicle stands for the major part of the environmental impact during the vehicle life-cycle (IEA 2005), and that differences in environmental impact from vehicle production are small (Weiss et al. 2000).[7] This has resulted in that many studies leave out the production of the vehicle, only looking at the fuel life-cycle. These are often called well-to-wheel (WTW) studies, resembling the notion of 'cradle-to-grave' in LCA. Sometimes only the well-to-tank (WTT) part is included, and sometimes, for the purpose of transparency, the well-to-tank and tank-to-wheel (TTW) results are presented separately. The vehicle is represented by the efficiency of the power train in the TTW part and the functional unit is usually vehicle kilometre. The vehicles used with different fuels should preferably have similar technical properties, such as size, power and safety properties, and should be used under similar circumstances.[8]

3.1 Previous work

Different studies give different results and recommendations, due to a variation in goal and scope, data estimations, and calculation procedures. Attempts are made to manage this problem, by trying to involve all relevant stakeholders in the LCA process, or by gathering information from several studies and compile the results in a common format. For transport fuels, two major examples of the former are performed by Contadini et al. (2002) and Concawe, EUCAR and JRC (Edwards et al. 2003), while the latter can be exemplified by MacLean & Lave (2003) and the EU project VIEWLS (2005). In addition, Contadini & Moore (2003) use

[6] Accounts of current LCA practices is presented in Baumann & Tillman (2004), and in Rebitzer et al. (2004) and Pennington et al. (2004).
[7] With radically new vehicles and fuels this relation may not hold.
[8] Vehicle use is often simulated using certain standardised driving cycles.

uncertainty analysis and a Monte Carlo method in their calculations, to account for data variations.

However, most studies are performed with an approach, where the timeframe is explicit, which means that prospects for improved performance within a certain time period are used for the comparison of fuel life-cycles (Weiss et al. 2000; Ahlvik & Brandberg 2001; Edwards et al. 2003). Future performance of all known technologies and foreseen combinations is included in comprehensive studies (GM 2001; Wang 2001; GM 2002). Much effort is put into making these studies as correct as possible, but the results may not be relevant to suggest which fuels that are promising in the long run. Future prospects when the studied technologies are used in a partly new system are seldom investigated, though changes in the energy system and in agricultural practices may be important.

Several authors try to approach these problems by modifications of LCA methodology. Ekvall (2002) accounts for the status of the LCA development, and points out the prospects for, and problems with including market effects and rebound effects in LCA. Weidema et al. (1999) provide a procedure for identification of technologies affected by marginal change of technologies in the current system. However, marginal contribution to radical system change may be even more relevant for guiding strategic technological choice, which is put forward by Sandén & Karlström (2005).[9]

Another way of dealing with radical system changes within the methodology for LCA is to use scenarios comprising important parts of the future system. This is suggested by for example Weidema et al. (2004), introducing the cornerstone scenario approach. Pehnt (2006) sets up a number of dynamic parameters to account for future changes in recycling of raw materials, electricity supply, production processes, and technical performance of the final product. Eriksson et al. (2005) introduce the concept of 'complex marginal electricity production', using a dynamic optimising model, to include effects on utilisation and investments of marginal changes of the electricity market. Two resulting scenarios are used in an LCA of fuels for district heating. The idea of scenarios is brought up in the modified LCA presented below.

[9] The results in Sandén & Karlström (2005) are based on experience curves, while the idea of including effects related to system change is taken a step further, including the whole socio-technical system, in Section 4 of this thesis.

3.2 Modified LCA of alternative fuels

In Paper I, we identify a need for research on the use (or non-use) of assumptions regarding time and scale in LCA of alternative transport fuels.[10] To begin with, we present a proposal for a modification of LCA typology building on previous work summarised by Ekvall (2002). This is revised and presented in Sandén et al. (2005).[11] We distinguish between retrospective and prospective, attributional and consequential, and product and technology LCA. The first division relates to time, where retrospective studies look back at historic environmental impact, while prospective studies look forward at future environmental impact. The second division is connected to responsibility. In attributional (or state-oriented) studies, the product is made responsible for a share of the total environmental impact in a certain state, and average data is used. In consequential (or change-oriented) studies, the product is made responsible for the change in environmental impact when the state is changed, and marginal data is used. Usually retrospective studies are attributional and prospective studies are consequential, but the opposite is also possible if a historic or future state is chosen as a basis for the assessment. A final division is that between product and technology LCA, where product LCA focuses on a specific product, using site-specific data. The results of product LCAs could be too narrow to represent the environmental performance of a technology (Karlström 2004). Hence, technology LCA deals with a more general technology, and general data, forecasts and several alternative scenarios can be used.

In Paper I, methodology for prospective, attributional technology LCA is developed. The main problem then is to analyse a relevant state. Analysing technologies used on a small scale today, but with large prospects for expansion, the study of future states are considered most relevant. The life-cycle environmental impact in a future state is, however, dependent on technical change of the studied product system, changes in background system, resource availability and by-product markets. The case study is mainly focused on changes in background system and by-product markets. Technical change and resource availability are only covered in brief.

The first observation is that performance data should be used with care. Though expert estimates may enhance data quality, the future is uncertain. Technical change is related to both scale factors and development over time, including phenomena such as economies of scale, economies of scope, and process and system optimisation (Grübler 1998). Not only the performance of certain technologies is affected, but the relevance of the selected scope and alternatives included in the studies change, as well. These issues could not be accounted for

[10] A more extensive presentation of the results in Paper I is found in Jonasson & Sandén (2004).
[11] Similar thoughts are discussed in Curran et al. (2005).

within the scope of Paper I, and we choose to use selected data from the recent WTW-study performed by Concawe, EUCAR and JRC (Edwards et al. 2003).

Our study is of WTT type, which implies that raw material acquisition, farming processes, transport, fuel production and distribution are included. The functional unit is 1 MJ of fuel used for other purposes than fuel production (see below). The studied alternatives are ethanol and RME produced from wheat and rapeseed today, and methanol produced from short rotation forestry, with production technology not yet commercialised. The environmental indicators used are greenhouse gas emissions and agricultural land use.

For the analysis, we need a definition of background and foreground systems, frequently used in prospective LCA. The foreground system consists of the processes affected by decisions based on the study, and the background system consists of all other processes, affected by changes in the foreground system (Tillman 2000). Here, the foreground system includes processes for production of biofuel, while the background system stands for the supply of electricity, input materials and fossil fuels. Changes in background system could be related to time (not affected by the foreground system), e.g. the use of new energy technologies or bio-based input materials, but they can also be related to the scale of production of the functional unit (indirectly affected by the foreground system), e.g. that a fuel is used for its own production and distribution.[12]

We introduce what we call a 'net output approach', which implies that the studied biofuels are used for biofuel production.[13,14] This means that biofuel production is not burdened with the environmental impact from the use of fossil fuels, connected to the current system. This seems fair, if the aim of introducing alternative transport fuels is to change the current system. The net output approach can be used for any scale of production and for other products than fuels.[15]

Three different background systems from Paper I are used here. The first one, used in the 'the mixed cases', reflects the current situation in EU-15, with process heat and electricity produced from a mix of different energy resources, mainly coal, oil, natural gas and nuclear. In 'the coal cases' all process heat and electricity is instead produced from coal, and in 'the wood cases' it is produced from wood, coming from short rotation forestry. It is shown that the greenhouse gas emissions and

[12] Studying large technological changes, some background systems eventually become part of the foreground system.
[13] For this purpose, the biofuel is assumed to directly replace diesel on an energy basis.
[14] A similar approach is presented for a closed system by Kim & Dale (2002).
[15] An example for photovoltaics is introduced in Sandén (2004a).

agricultural land use for especially wheat ethanol and RME is affected by the background system (see Figure 1).[16]

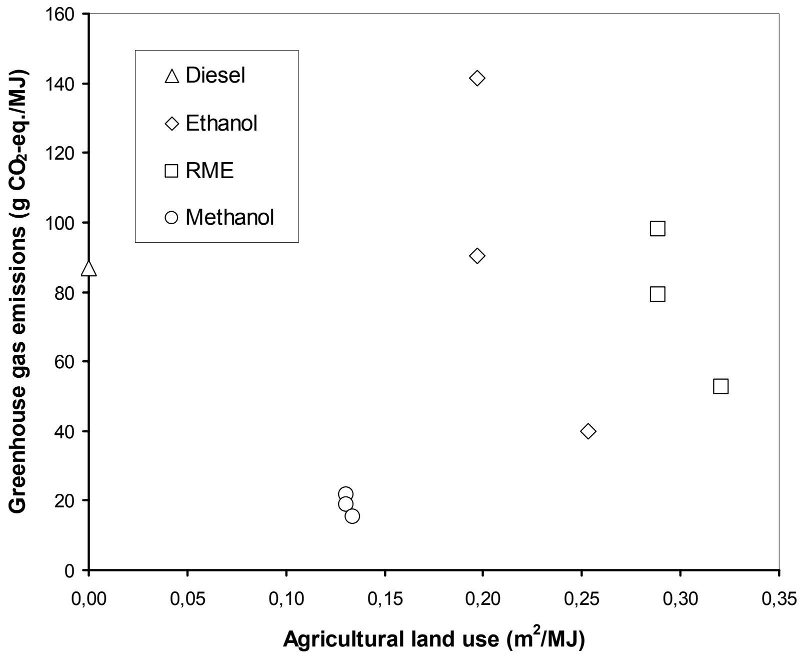

Figure 1: Greenhouse gas emissions and agricultural land use from the life-cycle of ethanol, RME and methanol, for the coal, mixed and wood background systems. The use of by-products is not included. The coal cases give the highest greenhouse gas emissions and the wood cases give the lowest emissions for the three biofuels. The value for diesel production is shown for comparison.

The scale of resource use for production of emerging technologies will also affect their respective environmental performance. On a small scale, raw material may be taken from by-product flows (Andersson 2001). For renewable fuels, the biogas provides a telling example. It has traditionally been produced from waste flows from agriculture, households and sewage treatment, but with an increasing scale the possibility to grow crops for production of biogas arises (Svensk Biogas 2005). This will definitely alter the environmental performance of biogas. Furthermore, the amount of land available for supplying certain crops may be limited. There are several studies on biomass availability in Sweden and in the world. IEA (2004)

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16 The value for diesel is shown for comparison, and includes CO_2 emissions from final combustion. These are not included for renewable fuels, as they are part of the natural carbon cycle.

looks at the situation for the first generation of biofuels, while recent studies of reported global biomass availability, and on competition for different uses are performed by Hoogwijk et al. (2003) and Berndes et al. (2003).[17]

As well as different resources are available in limited quantities, markets for by-products may be limited. Avoiding allocation through system expansion, as recommended by the ISO standard for LCA (Ahlström 2002), this will have an effect on the result for certain products. The explanation is that the studied product is credited with the avoided environmental impact from production of other products, due to the use of by-products. Here the size of by-product markets is illustrated by two different market shares for biofuels, as a percentage of the amount of petrol and diesel used in EU-15 today. A small market share implies that by-products are used according to current practices (Figure 2), while a medium market share implies that the current and near-term by-product markets saturate, and by-products are mainly used for heat production (Figure 3).[18]

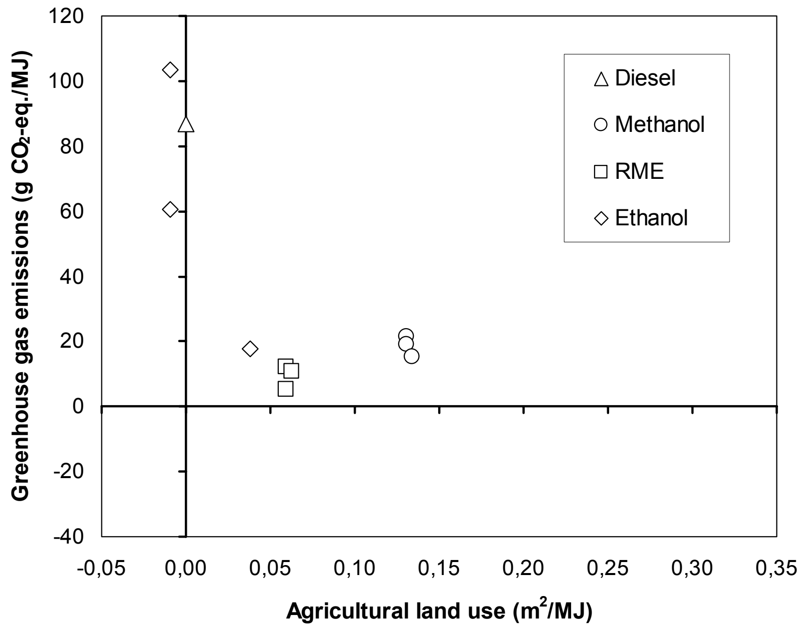

Figure 2: Greenhouse gas emissions and agricultural land use from the life-cycle of ethanol, RME and methanol for small market shares (current by-product use). The coal cases give the highest greenhouse gas emissions and the wood cases give the lowest, except for RME where the coal case give the lowest emissions. Negative values are due to the system expansion method. The value for diesel production is shown for comparison.

[17] The influence of resource limitations is not included in the results presented here.
[18] Market data is taken from various sources. For details, see Paper I.

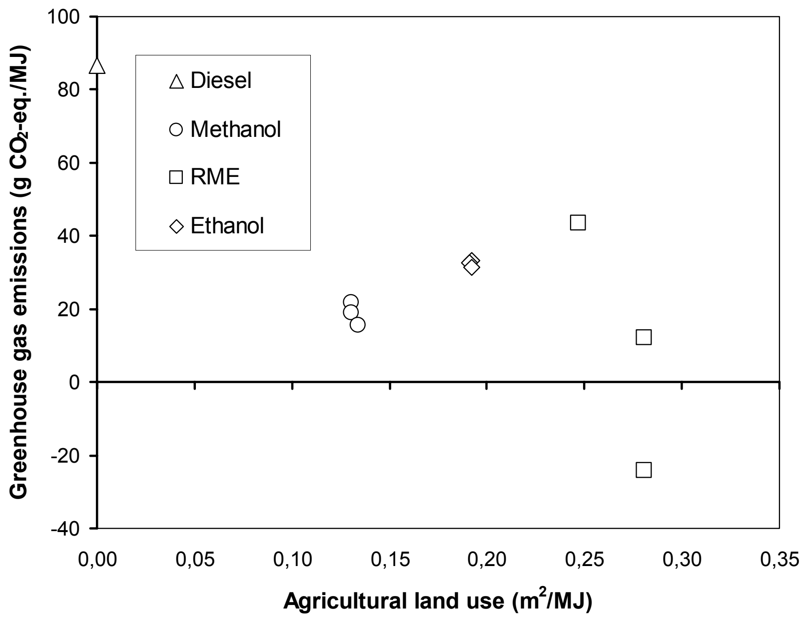

Figure 3: Greenhouse gas emissions and agricultural land use from the life-cycle of ethanol, RME and methanol for large market shares (by-products mainly used for heat). The coal cases give the highest greenhouse gas emissions and the wood cases give the lowest, except for RME where the situation is the opposite. Negative values are due to the system expansion method. The value for diesel production is shown for comparison.

The results clearly show that greenhouse gas emissions and agricultural land use vary with the scale of production, particularly for ethanol and RME. Agricultural land use increase with larger market shares, while greenhouse gas emissions are very much dependent on the background system. For wood methanol, results are more robust.

Of the few fuels studied in this LCA, RME, and ethanol used in a wood background system shows the best environmental performance when looking at small market shares (Figure 2). If we are aiming for large market shares for biofuels, methanol shows the best environmental performance, with the only exceptions that RME has lower greenhouse gas emissions in the mixed and coal cases. These results should not be used for choosing background system, but reflects the performance of the studied transport fuels in situations where we have different background systems. The interpretation should not be that it is a good solution to go for a coal background system and use RME for transport, as the environmental performance of the whole system is not included.[19]

Variations in agricultural land use can be interpreted in various ways. If land is used more efficiently for one alternative, either more transport fuels can be produced, or the saved land can be used for growing other energy crops. Swanston & Newton (2005) investigate the role of yield variations when land is scarce. As an example, a higher yield in production of wheat for ethanol leaves some land area that can be used for growing willow. If willow is used to replace coal in electricity production, the environmental gain with a higher yield is positive.

The results of this modified LCA suggest that there are two options. One is to go for the alternatives showing less environmental impact on a small scale in the current system, and the other is to go for those that are promising on a larger scale in a future system. An important question is how such a result should be interpreted in connection to strategic technology choice. Should all effort be put into developing promising long-term technologies, while the others are scrapped? Or can investments in less promising, short-term alternatives contribute to more radical system change in the longer run?

The technology for production of methanol from short rotation forestry is not commercialised, while wheat ethanol and RME have been sold on a market for some years. LCA can be used for policy-making and consumer choices today, but the results are limited to the environmental performance of one product in a steady state, or one additional product influencing the present state on the margin. It says little about dynamics and what an actual policy-choice or investment will lead to in terms of further development of the technology and the background system, and related economic, social and political effects. Technology path assessment is used to enter deeper into these issues in the following section.

[19] The low greenhouse gas emissions for RME used in a coal background system are due to that the by-products replace coal for heat production.

4 Technology Path Assessment

The environmental impact of emerging technologies is not only dependant on the technical properties accounted for in LCA. Investing in a technology has several secondary and higher order effects which are not directly related to environment. Sandén & Karlström (2005) discuss which cause-effect chains that should be included in consequential LCA, and illustrate by calculating the marginal contribution to radical system change of investing in a fuel cell bus. The illustration is based on experience curves, which gives information about historic trends in cost reductions for a certain technology, or group of technologies, related to cumulative production. Experience curves is a way to quantify the aggregated result of complex dynamic processes of technical change (Grübler 1998). However, the effect of experience on related technologies is not included, and future relations between costs and cumulative experience for specific technologies are uncertain. In addition, there are evolutionary mechanisms not related to cost.

This leads us to the literature on socio-technical development, and 'technology path assessment'.[20] The theoretical framework developed in Paper II and III, and presented in Section 4.1, is to a high degree based on theories of technological systems and technology-specific innovation systems (Carlsson & Jacobsson 1997; Jacobsson & Bergek 2004) and technological transitions (Elzen et al. 2002; Hoogma 2002; Geels 2005).[21] It was elaborated in parallel with the empirical studies of the development of alternative transport fuels in Sweden 1974-2004. The resulting concepts are here presented in brief.

The effects on the socio-technical system of investing in certain alternatives, and the question of co-evolution of alternatives are investigated in Section 4.2, concluding the history of alternative transport fuels in Sweden (Paper II).[22] Finally, the theoretical framework is used to construct socio-technical scenarios (Elzen et al. 2002; Elzen et al. 2004b). The choice between short-term and long-term options is illuminated in a study of the future development of the socio-technical systems connected to alternative fuels. The scenarios (from Paper III) are summarised in Section 4.3.

[20] The expression 'Technology Path Assessment' is used in Sandén (2004b) and relates to an intention to connect classical assessments of benefits and disadvantages of different alternatives with dynamic processes of technical change.
[21] See paper II or III for a more detailed theoretical background. The empirical material is more thoroughly described in (Sandén & Jonasson 2005).
[22] The empirical material is more thoroughly described in (Sandén & Jonasson 2005).

4.1 Theoretical framework

The study object is not a single end product, a transport fuel, but a system of interrelated technologies. Accepting the kind of road vehicles used today, leaving out more radical changes in the transport system, these technologies are related to 'unit processes' such as raw material extraction, fuel and vehicle production, and final use of vehicle and fuel. Inspired by the life-cycle perspective, the production chains are the first contribution out of three to describe system structure (Figure 4).

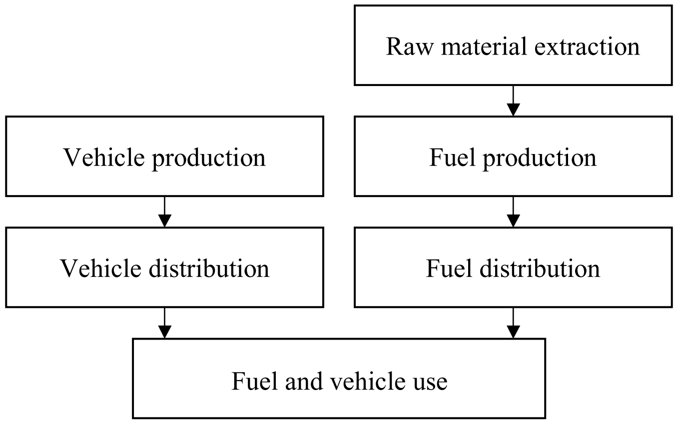

Figure 4: Different 'unit processes' build up production chains.

The second contribution implies a widening from a technical, to a socio-technical (ST) system, identifying various elements, what we call stocks and structures of the ST-system. In addition to the physical artefacts, these are actors, including both individuals and formal and informal networks, institutions, and relations between actors, artefacts, and actors and artefacts. Institutions include explicit and tacit knowledge, and regulative and normative rules (Table 2). Explicit knowledge and regulative rules are codified in text, while tacit knowledge and normative rules exist within actors.

Table 2: Elements of the ST-system (stocks and structures).

Actors (individuals, and formal and informal networks)
Physical artefacts (including controlled natural systems)
Relations (formal and informal, between actors, artefacts, and actors and artefacts)
Institutions (rules)
Knowledge/beliefs (explicit and tacit cognitive rules)
Norms (regulative and normative rules)

The final building block is a description of the relation between different ST-systems. Here we use the three-level perspective of socio-technical change proposed by Geels (2002), supplemented by a geographical boundary suiting the case study (Figure 5). In this perspective, emerging technologies appear on the *niche* level, constituting niche ST-systems. Actors, relations, institutions and physical artefacts connected to entrenched technologies belong to the *regime* level, and determine the normal way to provide society with products and services. There is also a higher *landscape* level containing issues not under control of separate regimes and niches, e.g. societal currents, general politics and general economic situation. However, the landscape can be influenced by regime changes in the long run (Figure 5).

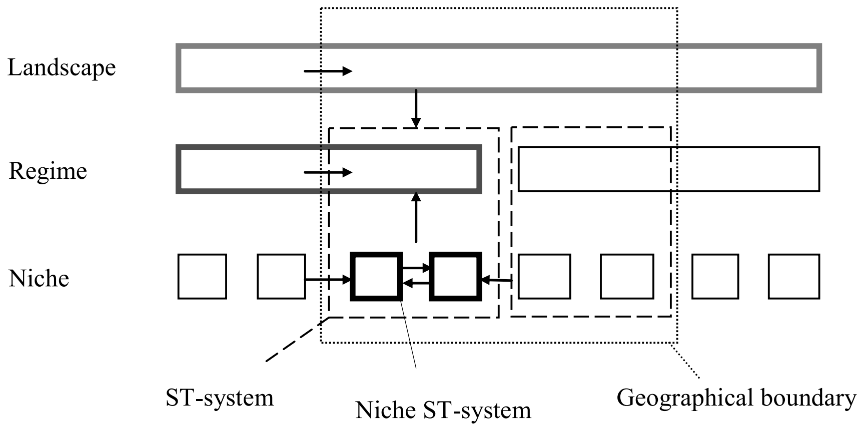

Figure 5: The three-level perspective on technical change, adopted from Geels (2002). The niche ST-system is affected by exogenous forces coming from the landscape level, from regimes or niches of other ST-systems inside or outside the geographical boundary, or from other niches within the same ST-system. (Niche ST-systems may also be adopted by the regime, or contribute to the creation of a new regime.)

The two main issues for the framework to illuminate is how alternatives can grow in a highly entrenched system, and if growing alternatives lock out or favour other alternatives. These issues are central in Paper II studying the history, and in Paper III they are studied in connection with the choice between short-term and long-term alternatives.

The first issue can be studied in terms of endogenous and exogenous forces of change. Landscape changes can create pressure for change of the regime, and open up spaces for new niche ST-systems. Except from the landscape level, exogenous forces come from regimes or niches of other ST-systems inside or outside the geographical boundary, or from other niches within the same ST-system.

Endogenous forces result from positive and negative feedback loops generated within the niche ST-system, emanating from the current set of stocks and structures. Virtuous circles can be created due to learning and economies of scale on the production side, and decreased uncertainty and increased service on the user side. Increased adoption can also result in advocates, working for adjustments of regulative rules and more funding (Jacobsson et al. 2004). In short, the interplay between endogenous and exogenous forces determines the growth of the ST-system.

The second issue concerns competition and co-evolution. Alternatives compete for a fixed amount of resources and attention, but at the same time the growing niche ST-systems may benefit from each other, or co-evolve. This happens when stocks and structures of different ST-systems overlap, due to similarities in technical components, but also on a conceptual and organisational level. This shows to be an important phenomenon in the history of alternative fuels in Sweden, as described in the next section.

4.2 Conclusions from the history of alternative fuels

The modern era of alternative transport fuels in Sweden started after the first international oil crisis in 1973. Then the main landscape driving force was to reduce the dependence on oil. In the middle of the 1980s, the oil price decreased and improvement of local air quality spurred the development within the field. Since the mid 1990s, mitigation of climate change has been most important, in recent years together with a decrease of the dependence on oil, due to awaited resource problems.

The regime answer in the first period was increased cracking of heavier oil fractions, which was facilitated by decreased oil use in other sectors. In the second period, exhaust gas treatment (e.g. the catalytic converter) and new fuel qualities were introduced, and recently low percentage blending of ethanol and RME into petrol and diesel has become common. Besides these adjustments of the regime, niche development of alternative fuels has continued.

The history confirms that transitions take a long time. After 30 years of development, the market share for alternative fuels is today only about 3 %, and most of them are used in low percentage blends. There is, however, a large variety of alternatives, stimulated by landscape changes, different niche initiatives at different locations through the years, and different support mechanisms. The variety has been maintained due to a large ability of alternatives to survive, and to grow. But how do alternatives grow?

Governmental and municipal investments and funding of research, development and demonstration (RD&D) have been decisive for most alternatives in question. Activities related to certain fuels have not only resulted in physical artefacts and new explicit knowledge, but, more importantly, in the creation of dedicated actors and changes in tacit knowledge and normative rules. The actors and networks have then worked for changed regulations and more funding, and new actors have been involved. These positive feedback loops related to actors and institutions seem to have been more important than those related to costs. Local networks and experiments, rather than assessment results and long-term strategies, has mainly influenced the use of alternatives this far.

Another conclusion is that alternatives have a large ability to survive. The plans for large-scale methanol introduction drawn up on a national level at the end of the 1970s were discarded when the landscape changed in favour of local solutions to air quality problems. Networks and knowledge built up around gasification technology survived in other ST-systems, though, and returned to the field of alternative fuels at the turn of the century, when changes in the landscape welcomed large-scale solutions. At the same time, wheat ethanol and methane survived the landscape shift away from local solutions, due to created legitimacy and regulative changes. Actors that had worked with city buses turned to flexifuel and bi-fuel cars, typical 'two-world technologies' (Kemp & Rotmans 2001) that can use both ethanol and petrol, and methane and petrol, respectively.

The niche market for city buses was important for the growth of ethanol and methane, and later flexifuel and bi-fuel cars, and low percentage ethanol blends constituted important markets. The first niche market for RME was in tractors, and it is now also used in blends, and small amounts of FT-diesel (produced from natural gas) are used in machines and a few vehicles for air quality reasons.[23]

Though endogenous factors have increased in force, the ST-systems related to alternative transport fuels are still small in Sweden, compared to the entrenched system. The development is still dependent on exogenous forces, and a lock-in point is not reached. Variety is increasing, and the growth of one alternative may very well improve the prospects for others. Several examples of such co-evolution can be seen in the history. Ethanol benefited from the vehicle competence built up around methanol in the early years, and biogas was included in a demonstration programme originally intended for ethanol. Wheat ethanol and wood ethanol are identical on the user side, and short-term introduction of wheat ethanol together with possible large long-term potential of wood ethanol favoured both alternatives. Biogas benefited from technology made for natural gas, while natural gas benefited from blending possibilities with renewable biogas, and with hydrogen. RME and

[23] RME is also blended in FT-diesel (FramTidsbränslen 2005).

ethanol share advocacy groups on the production side, both being made from agricultural crops. Gasification connects fuels that can be produced from synthesis gas, such as methanol, FT-diesel, DME and hydrogen. Organisations for environmental cars, started in the 1990s to promote electric vehicles, are now promoting several alternatives, including ethanol, methane and hybrid vehicles, and contribute to the consumer acceptance for alternative fuels as a group. Examples of negative effects due to overlaps in stocks and structures were mainly seen for bio-methanol, which suffered from a close relation to a fossil counterpart. To a lower degree, this was also the case for biogas.

There have also been overlaps with elements within regimes, of which low percentage blends is one noticeable example. In addition, support from other regimes in the form of political and economic strength from agricultural interests, energy companies and waste-handling utilities has sometimes played an important role for ethanol, natural gas and biogas, respectively.

From the history of alternative fuels, it can be said that investments set in motion development processes in niche ST-systems, enforcing endogenous forces. In several cases there are overlaps in ST-systems between alternatives, and developments related to one alternative may favour others. Shifting driving forces, with several niches and support mechanisms have created variety, which can be seen as a resource in the future development of the system. This is illuminated in the following section.

4.3 Socio-technical scenarios

Still today, we cannot say which will be the best alternative (or alternatives) to replace petrol and diesel in the long run. Coal and natural gas are not compatible with a reduction of greenhouse gas emissions, unless carbon sequestration and storage work out to be a sensible large-scale technology, and then only in production of hydrogen or electricity. However, there is an economic driving force to use these resources. Natural gas is scarce, but coal is abundant (WEA 2000).[24] At the same time, the expansion potential for the first generation of renewable fuels is limited. The domestic production potential in 2020 is estimated at about 10 % of current petrol and diesel used in Sweden (calculated from Sandebring 2004), and the effects of a future large-scale expansion of production in tropical regions are uncertain (Björsell 2004). In Paper III, we investigate how the choice between alternatives performing well when used on a small scale today, and future alternatives promising on a larger scale, may affect the development of alternative

[24] Hydrogen could also be produced with nuclear technology but this alternative is not included here.

fuels in Sweden. This is of immediate interest as regards present policy choices, in Sweden and in other countries.

The Swedish national strategy in the field of alternative transport fuels is presently characterised by market stimulation in the form of general tax exemptions for renewable fuels, as suggested in the EU biofuel directive (EU 2003a; EU 2003b), and incentives concerning vehicle taxation. These are supplemented by local initiatives, mainly parking fee subsidies and direct procurement of vehicles. In recent years, national funding of research and development (R&D) in the field has been 100-200 million SEK, which can be compared with the reduced tax income of above 1 billion SEK, due to the tax exemptions. Without expanding the state budget, a main issue for policy is the balance between market stimulation and R&D, favouring short-term and long-term options, respectively.

The fact that a decrease of the tax exemptions would give more room for R&D is scrutinized in Paper III. Two scenarios for the period 2005-2010 (phase one) are worked out, where the main differences are connected to normative and regulative rules. The scenario policies differ regarding: (i) the commitment and incentives aiming at a market expansion for the first generation of renewable fuels, and (ii) funding of RD&D of the second and third generations. The scenarios are called market-oriented and technology-oriented, and are focused on the first and the second point, respectively. Using theory and conclusions from Paper II, this has implications for the further development of the niche ST-systems for alternative fuels. The stocks and structures built up during phase one are used as a base for the construction of the scenarios for the period 2011-2020 (phase two). Both scenarios bifurcate in 2011, each leading to one growth path and one stagnation path, with regard to the introduction of the second and third generations of renewable fuels in Sweden.

In the first phase, in the market-oriented scenario, domestic production and a relatively widespread use of alternative transport fuels and vehicles during the first phase, create actors in the form of raw material suppliers, producers and users, advocating the alternatives. Limited explicit knowledge is gained, but legitimacy for alternatives to petrol and diesel is created. Physical artefacts are adjusted to fit the first generation of renewable fuels. In the technology-oriented scenario authorities and researchers are key actors. A high technical competence is built up in connection with pilot production plants and demonstrations of the second and third generations of renewable fuels. Petrol and diesel are questioned, while the early alternatives are criticised for high costs and limited potential.

In the growth scenarios of the second phase, virtuous circles are created and the niche ST-systems develop and expand from their own momentum, and are to a decreasing degree dependent on exogenous forces. In the stagnation scenarios, this is not the case. In the market-oriented one, the multitude of actors involved in the first generation of renewable fuels, and the lack of domestic knowledge in the second generation are crucial issues. In the technology-oriented one, there is no experience with renewable fuels among a large number of actors, and the weakened market incentives make industry interest limited. At the end of the studied period, the results for the two stagnation scenarios are similar in that import of synthetic fuels made from natural gas and coal becomes necessary. The results of the two growth scenarios are also similar, but these present a great variety in the use of first, second and third generation renewable fuels.

What does this say about the choice between short-term and long-term alternatives? In the market-oriented scenario, we illustrate consequences of breaking the dominance of entrenched technologies and demonstrating a growing market potential for alternatives, but also the risks of a large focus on short-term options. In the technology-oriented scenario, we point out the value of not leaving out promising long-term options at this stage of the transition. Any choice could lead to a dead end, but also that the development in different parts of the ST-system, and existing forces of change can be used to contribute to the progress towards fuels with better environmental performance in the long run.

5 Conclusions

The purpose of this thesis is to contribute to the environmental assessment of emerging technologies, to make the methodology more useful in guiding strategic technology choice. The research question is how environmental assessments should be made in sectors where radical system changes are sought. The contributions come from the field of LCA, theories on technical change and socio-technical scenarios.

A modified LCA for wheat ethanol, RME and wood methanol is presented. The results show that the environmental performance of the biofuels is highly influenced by assumptions regarding background system and scale of production. In terms of greenhouse gas emissions and agricultural land use, some alternatives are the best options when used on a small scale in the current system, but if we look at a larger scale in possible future systems, other alternatives are more promising. Does this mean that all effort should be put into developing long-term technologies, while the others are scrapped? Or can investments in less promising, short-term alternatives contribute to more radical system change in the longer run? These questions are investigated using insights from theories on technical change, and the development of alternative transport fuels in Sweden.

The historical development shows the importance of putting alternatives in actual use. Investments and RD&D have not only resulted in physical artefacts and new explicit knowledge, but also in the creation of dedicated actors and changes in tacit knowledge and normative rules. Positive feedback loops related to actors and institutions have created more actors and changed regulation, and an ability of alternatives to survive. At the same time, the growth of some alternatives has favoured others, due to overlaps in stocks and structures of different niche ST-systems.

However, the growth of alternatives is still very much dependent on exogenous forces of change, such as landscape changes, and investments are today guided by different policies. Swedish policies include tax exemptions and vehicle-related incentives, favouring investments in short-term options, and funding of R&D, which would benefit long-term options. The balance between short-term and long-term options in the transition of the transport system is here illustrated through the construction of socio-technical scenarios. These show that there is a risk that any policy could result in a negative development for renewable alternatives, but they also suggest that there are opportunities for growth. Policies could balance the development in different parts of the ST-system, and make use of prevailing endogenous forces, to contribute to more radical changes in the transport system.

A first conclusion for environmental assessment methodology is that the intended role of studied products, and in what system they are to be used, is regarded. Then, analyses of LCA type could be used to give information on which alternatives that are promising in the short run and in the long run, respectively. The long-term options may not be commercial at the time of the study. However, taking dynamic processes of technical change into account could show that short-term alternatives can lock out other options, but also that they can contribute to the development towards long-term options. Thus, such processes need to be included in environmental assessments of emerging technologies

The implications for policy regarding alternative transport fuels are that support for both short-term and long-term alternatives is important. The balance between market stimulation and RD&D should be continuously analysed to make use of existing forces of change on the way towards better environmental performance of transport fuels.

6 Further work

There are several ways to go from here, to learn more about how to assess the environmental performance of emerging technologies. Of course, case studies can be performed within other fields, but here I will keep to proposals that can be connected to the present case. Four main issues for further work are presented.

First, more effort can be put into modifying LCA methodology. The intended role of certain future alternatives can be analysed, to make assumptions consistent with the purpose of introducing certain alternative fuels. Another option is to focus on finding robust alternatives, less sensitive to the assumptions made. Of course, more fuels than included in this thesis need to be assessed to enable any conclusion regarding the choice between alternatives.

Second, international comparisons of the growth and possible co-evolution of alternatives can be made. The development of alternative transport fuels in Sweden has been influenced both by landscape changes, and national and local initiatives. Results could be made more general when comparing with developments in other countries.

Third, quantification of results has not been in focus in our study of the Swedish development. There are possibilities to quantify the growth of stocks and structures in the ST-systems, in order to learn more about the importance of developing different parts of the system. Co-evolution could be better understood by studying the socio-technical overlaps in more detail. In addition, this could contribute to more specific conclusions regarding the balance between short-term and long-term options.

Finally, the socio-technical scenario approach could be further developed. During the final stage of the thesis work, a workshop was organised to test the usefulness of the theoretical framework. About 15 invited stakeholders attended the workshop, where the focus was on construction of scenarios and discussion of synergies between alternatives. The results suggest that more work is needed to make use of the theoretical approach.[25] The initiative has strong connections with constructive technology assessment (CTA).[26]

[25] The workshop was documented by Jonasson (2005).
[26] See e.g. Schot (2001).

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