Technological Learning in the German Biodiesel Industry

An Experience Curve Approach to Quantify Reductions in Production Costs, Energy Use and Greenhouse Gas Emissions

N.A. Berghout, May 2008

Picture on cover: rapeseed field (adapted from: www.bio-d.co.uk)

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N.A. Berghout

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Student number: 0168424

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University: Utrecht University, Copernicus Institute, The Netherlands

Supervision:

Dr. H..M. Junginger	*Department of Science, Technology and Society*
	Copernicus Institute, University Utrecht, The Netherlands
Dr. A.P.C. Faaij	*Department of Science, Technology and Society*
	Copernicus Institute, University Utrecht, The Netherlands
Dipl.-ing M. Wörgetter	*BLT* (*Biomass – Logistics – Technology) Institute*
	Wieselburg, Austria

Address author:

Address: Morelstraat 50 bis / 3552 GP / Utrecht / The Netherlands

E-mail: n.a.berghout@students.uu.nl / berghoutniels@hotmail.com

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Preface

This thesis is the result of my final project for the Master *Energy Science* at the University Utrecht. As the title indicates, this research aimed to investigate technological learning in the German biodiesel industry. For my research, I spent over three and a half months at the BLT (Biomass – Logistics – Technology) institute in Austria for data collection.

When I started this research project, it was very hard for me to comprehend the extensiveness and complexity of the research topic. As the research was progressing, I became more and more aware of the challenge to collect reliable data and combine theory and practice in a successful way. The multiple dimensions of the German biodiesel industry made this research complex as well as interesting. I have enjoyed the numerous conversations with biodiesel experts and was encouraged by the positive reactions from people all over Germany and Austria. I hope this thesis will provide new insights in the field of biofuels.

I would like to thank several people for their support and aid during the research process. Martin, I have enjoyed your optimistic and motivating way of supervising. You were always available and provided me with solutions necessary to overcome my scientific struggles. I have appreciated your guidance and valuable contributions throughout the entire research process! Andre, I would like to thank you for your comments and for sharing your scientific experience with me. You showed me the importance of keeping track of the big picture instead of focusing too much on details. My special thanks are to Manfred Wörgetter for giving me the opportunity to collect data at the BLT. Your impressive amount of contacts in the field of biodiesel enabled me to get in touch with Germany's foremost biodiesel experts. I enjoyed our conversations on biodiesel as well as other topics. I would also like to thank all the interviewees and contacted experts for their valuable time and contributions to a better understanding of the developments in the German biodiesel field.

I would like to thank the following fellow-students for their company on the ninth floor of the Van Unnik building: Ariane, Bas, Junying, Karolina and Tim. Finally, I would like to thank my family and friends for their highly valued visits in Austria and Germany (Christian, Marieke, my mother, Corrie, Rosanne, Michiel, Rick and my father) and their continuous support during the whole research process!

Niels Berghout
Utrecht, May 2008

Contents

Executive summary

Introduction

The wish of the German government to fight climate change, improve energy security and stimulate rural economies has resulted in the current world leading position of Germany in biodiesel production. Biodiesel derived from rapeseed, so-called Rape Methyl Ester (RME), shows several advantages compared to petroleum diesel: lower greenhouse gas (GHG) emissions, lower dependency on import fuels and the provision of an alternative income for German farmers. For the year 2020, the German government has laid out the ambitious goal to achieve a 10% biofuel share in its fuel strategy; a target in which RME will most likely continue to play a major role. Today, RME is still not an economically viable transportation fuel without the agricultural subsidies and supporting German tax regime, which has just been withdrawn. Other drawbacks of RME are the inefficient use of biomass, the low fuel yield per hectare and the meager CO_2 emission reductions. To date, no comprehensive analysis has been performed on the long-term development of the production costs and environmental performance of RME. Furthermore, to the author's knowledge, the experience curve tool has not been applied before to assess technological learning in German RME production.

Objective & methodology

The main objective of this study is to assess technological learning in German RME production by quantifying reductions in production costs, primary energy use and GHG emissions. Furthermore, an outlook is given based on the improvement potential of RME. The analysis of the production chain of RME is divided in rapeseed production and industrial processing into RME. Data were acquired from biodiesel plants, technology providers, literature studies and LCA datasets. Several key experts were interviewed to identify the underlying factors driving the quantitative reductions over time. This study employs the experience curve tool to quantify technological learning. An experience curve relates the developments in production costs with the cumulative quantity produced, which in turn represents the experience in the industry. Production costs tend to decline with a fixed rate with every doubling of the cumulative production due to technological learning. This research is most likely the first to explore whether GHG emissions can be used as an alternative performance indicator for technological learning.

Results

Rapeseed production costs declined by 70% from €845/tonne[†] in 1971 to €251/tonne in 2006. The fertilizer costs show the highest contribution to overall cost decline. The main drivers behind the cost reductions have been increasing rapeseed yields, lower fertilizer usage and improved rapeseed varieties. The costs for industrial processing of rapeseed into RME (including capital costs, but excluding by-product credits) have declined by 31% from €0.47/liter in 1991 to €0.33/liter in 2004. The esterification process shows the highest cost reductions and contribution to overall cost decline. The main reasons behind the cost reductions are efficiency gains in the esterification process due to scale effects, higher plant yields and modern processing systems. Total *hypothetical* production costs, i.e. the sum of rapeseed production and industrial processing costs minus by-products credits, have declined with 23% from €0.99/liter in 1991 to €0.76/liter in 2004. Improvements in rapeseed

[†] All costs were corrected for inflation and converted to euros ($€_{2007}$)

production and industrial processing account for respectively 65% and 35% in the total cost reductions. However, the *actual* total production costs, which are determined by *boundary conditions* and *prices* instead of *costs*, have increased in recent years, because of the less favorable tax regime, higher raw material prices and lower by-product prices.

Despite the multitude of published LCA studies available, only two original German datasets were compiled over time (years 1993 and 2000). Several non-German datasets were used to examine the situation for the year 2007. Primary energy use and GHG emissions associated with the rapeseed production have been reduced with respectively 49% and 28% over the period 1993-2007 (see also figure A-I). The decline in the required amount of raw materials accounts for 79% of the primary energy reductions and for 82% of the CO_2-equivalents reductions (direct processes). Efficiency improvements made in raw material production account for the supplementary reductions (indirect processes). Lower (nitrogen) fertilizer usage per tonne has been the main driver for the reductions, which in turn is a result of higher yields and improved rapeseed varieties. As for the industrial processes, the results show an unexpected increase for the primary energy use and CO_2-equivalents of respectively 24% and 23% over the period 1993-2007. The increases over time were mainly due to higher indicated electricity and natural gas requirements in the underlying datasets. The quantitative results contrast anecdotal expert reports, which assert that energy requirements declined over the years. Overall, the quantitative results show that improvements in environmental performance (including by-product credits) of the rapeseed production outweighed the deterioration in environmental performance of the industrial processes over the period 1993-2007. A total decline of 21% was observed for the primary energy use and 36% for the CO_2-equivalents.

A reliable experience curve was constructed for the rapeseed production with a progress ratio of 80.4% ± 1% (R^2 = 0.97). However, the progress ratio is significantly influenced by the chosen value for the initial cumulative production. The experience curve for the industrial processing showed a low correlation (R^2 = 0.66), but might be a result of data limitations. The calculated high progress ratio (97.6% ± 1%) implies a low technological learning rate. The progress ratio of the experience curve for the total *hypothetical* production costs is 96.7% ± 1% (R^2=0.84) (see figure A-II). The high, i.e. unfavorable, progress ratios for the industrial processing and total production chain were partly due to the low value for the initial cumulative production. The limited amount of LCA datasets available hampered the construction of experience curves for the primary energy use and GHG emissions.

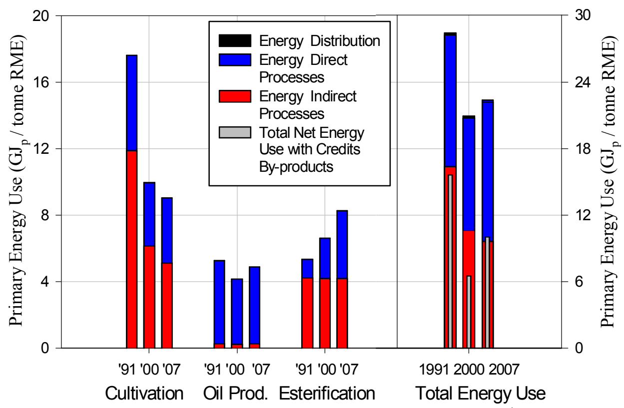

*Figure A-I: Primary energy necessary for RME production**

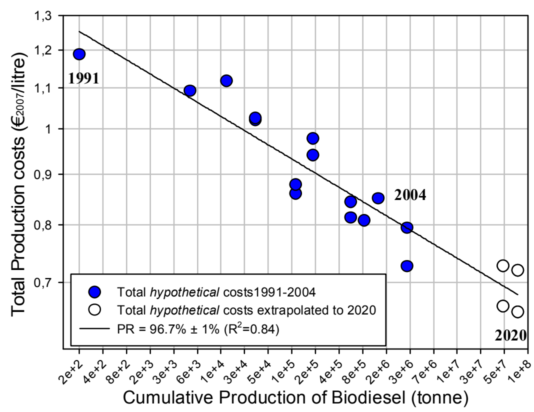

Figure A-II: Experience curve for total production costs

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* ***Direct processes*** *refer to the actual processes of the life cycle of RME (mechanical labor in agriculture, oil extraction, oil refining, esterification, etc.);* ***indirect processes*** *refer to the production of indirect compounds necessary for the direct processes (fertilizer, chemicals, sodium hydroxide, methanol, etc).*

By extrapolating the experience curve, the total *hypothetical* production costs were projected to be within the range of €0.65-0.73/liter in the year 2020, implying a cost reduction of 9% compared to the year 2004 (see figure A-II). Unfortunately, no quantitative projection could be made for the primary energy use and CO_2-equivalents in 2020. Improved rapeseed varieties and lower fertilizer and chemical usage are expected to become the main causes for future cost reductions and improvements in environmental performance of rapeseed production. Scale effects, improved by-product processing and more optimal logistics are expected to be the causes for improvements in the industrial processing system. However, despite the considerable projected *cost* reductions, the economic competitiveness of RME will mainly be determined by the boundary conditions (raw material prices, tax regime, etc). Further reductions in GHG emissions will most likely be driven by the incentive - as created by the German Biomass Sustainability Ordinance - to enhance the GHG reduction potential; a key feature that will play a significant role in the determination of the future RME price.

Conclusion

Production costs have declined over the entire RME production chain. Higher yields, lower fertilizer usage and improved rapeseed varieties have been the main drivers behind rapeseed cost reductions. Scale effects, higher plant yields and modern processing systems have been the main contributors to cost reductions in the industrial process. The experience curve tool can be applied to quantify technological learning as cost reductions in rapeseed production, industrial processing, and thus, the entire production chain. Significant reductions in primary energy use and GHG emissions were achieved for the rapeseed production. Although quantitative results indicate an increase in primary energy use and GHG emissions for the industrial processes, several key experts report an improvement of the environmental performance over time. The use of primary energy use and/or GHG emissions as alternative performance indicators for technological learning was not possible due to data limitations.
Further cost reductions and improvements in the environmental performance are expected for RME production as a result of improved rapeseed varieties, lower fertilizer and chemical usage, scale effects of biodiesel plants, improved by-product processing and more optimal plant logistics. However, the future economic competitiveness of RME remains unclear as it will mainly be determined by boundary conditions and the Biomass Sustainability Ordinance. As the potential for further reductions in production costs and GHG emissions of RME is limited compared to promising prospects of second generation biofuels, the economic competitiveness of RME might deteriorate in the long term.

Abbreviations

Institutions

ABI	Austrian Biofuels Institute
BLT	Biomass – Logistics – Technology Institute
Concawe	Oil companies' European association for environment, health and safety in refining and distribution
IFEU	Institut für Energie- und Umweltforschung (Institute for Energy and Environmental Research)
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft (Association for Technology and Structures in Agriculture)
UFOP	Union zur Förderung von Öl- und Proteinpflanzen (Union for the Promotion of Oil and Protein Plants)
ZMP	Zentrale Markt- und Preisberichtstelle (Central Market- and Price Report Place)

Abbreviations

B05	Admixture of 95% petroleum diesel and 5% biodiesel
B100	Neat biodiesel
DM	Deutsche Mark
EU	European Union
FRG	Federal Republic of Germany
GDR	German Democratic Republic
GHG	Greenhouse gas
GJ	Giga Joule (=10^9 Joule)
Ha	Hectare
L	Liter
LCA	Life Cycle Assessment
MJ	Mega Joule (=10^6 Joule)
NEDC	New European Driving Cycle
PR	Progress ratio
R^2	Degree of correlation
RME	Rape Methyl Ester

1. Introduction

The worldwide production of biofuels has reached unprecedented levels over the past years. Ascending crude oil prices, global warming issues and the wish to improve energy security propel many governments to create incentives for the use of biofuels in the transportation sector. Today's primary biofuels in use are bio-ethanol, derived from sugar and starch crops, and biodiesel derived from vegetable oils and fats. The two worlds largest bio-ethanol producers are Brazil and the United States, whereas Germany has taken the lead in the world's biodiesel production.

Germany has a long history with biofuels. Already in the early 1940s, trucks were equipped with on-board wood gasifiers to generate a biogas that was combusted in conventional engines (WWI, 2006). As of 1991, biofuels were re-introduced in Germany mainly in the form of biodiesel derived from rapeseed, so-called Rape Methyl Ester (RME), for three different reasons: the reduction of greenhouse gas emissions, improvement of energy security and the provision of an alternative income for German farmers. The biodiesel production shows an impressive growth over the years, starting with an annual production of 200 tonnes in 1991 to over two million tonnes in 2006. From 2004 onwards, the production capacity experienced a surge, leading to an overcapacity and a highly competitive biodiesel market. The current market is evenly divided between neat biodiesel (B100) and blended biodiesel (B05)[1]. For the year 2020, the German government has laid out the ambitious goal to achieve a 10% biofuel share in its fuel strategy; a target in which biodiesel will most likely continue to play a major role.

Despite the rapidly expanding biodiesel market, Germany has a long tradition of controversial debate on the use of biodiesel. Several drawbacks of biodiesel are the inefficient use of biomass, the low fuel yield per hectare, the meager greenhouse gas (GHG) emission reductions and the fact that biodiesel is not an economically viable transportation fuel without the agricultural subsidies and supporting tax regime. However, many products become technologically and economically more efficient as more experience is gained by the industry. An analysis into the long-term development of the production costs and environmental performance of RME could therefore be useful to provide insight in the past and (potential for) future improvements.

This study employs the experience curve tool to perform such an analysis. An experience curve relates the developments in production costs with the cumulative quantity produced, which in turn represents the experience in the industry. Production costs tend to decline with a fixed rate with every doubling of the cumulative production due to technological learning. In recent years, two studies performed a similar analysis into cane-ethanol production in Brazil (Wall Bake, 2006) and corn-ethanol production in the United States (Hettinga, 2007), both successfully using experience curves to quantify cost reductions as a measure for technological learning. Furthermore, Ramirez & Worrel (2006) and Hettinga (2007) explored whether energy requirements can be used as an alternative measure for technological learning. Although both studies found strong correlations between cumulative production and energy requirements for energy intensive products, more research is needed in this area.

[1] B05 is an admixture of 95% petroleum diesel and 5% biodiesel.

A variety of studies have been conducted into the costs (e.g. Fraunhofer, 2004; IFO, 2002; Keymer, 2000) and environmental performance (e.g. Borken *et al*, 1999; Reinhardt, 1993) of RME production in Germany for particular time periods. Furthermore, a *qualitative* analysis was performed into the success factors behind the development of the German biodiesel industry (ABI, 2001). However, no comprehensive overview exists on the *long-term* development of the production costs and environmental performance. Furthermore, to the author's knowledge, the experience curve tool has not been applied before to RME production in Germany.

The experience curve method demands a clear definition of the learning system under consideration, which in this study is confined to the Federal Republic of Germany over the period 1970-2007. The environmental performance is measured in terms of primary energy use and CO_2 equivalents corresponding with the three most important GHG emissions, viz. CO_2, CH_4 and N_2O. This research is most likely the first to explore whether GHG emissions can be used as an alternative performance indicator for technological learning. Furthermore, an outlook will be given based on the improvement potential of RME. Finally, efforts are made to identify the underlying factors driving the reductions in costs, primary energy use and GHG emissions. The objective of this study is as follows:

To assess technological learning in the production of rapeseed and Rape Methyl Ester in Germany over the period 1970-2007 by quantifying reductions in production costs, primary energy use and GHG emissions, analyze future prospects based on the improvement potential and identify the underlying driving factors.

The identification of past technological learning processes and underlying driving forces could provide insights for policy makers and scientists to facilitate and expedite the further deployment of RME and future generation biofuels. The results of this study will also be used to make a comparison with the cases for Brazil and the United States to examine whether similar developments can be discerned.

Three final remarks are given on this report. First, the processing of rapeseed into RME in Germany occurs at different levels, ranging from small-scale farms to industrial-sized biodiesel plants. This study aims to investigate the production costs and environmental performance associated with the *industrial-sized processing into RME*. Second, while the terms *RME* and *biodiesel* are often interchangeable in literature, this research makes a clear distinction. The term *biodiesel* refers to esters derived from oils and fats, whereas *RME* refers to the specific variant that is procured via the processing of rapeseed. Third, all costs and prices mentioned in this report have been corrected for inflation and converted to euros ($€_{2007}$).

As the German biodiesel industry is embedded in an intricate web of factors influencing the production costs, some basic knowledge on the technology, policy and market situation is essential to understand the results. This background information is given in chapter 2. Chapter 3 describes the employed theories and methodology, after which the data collection and processing are described in chapter 4. An overview of the results and a future outlook are given in chapter 5. Next, the sensitivity analysis (chapter 6) examines the impact of several methodological issues and assumptions on the final results. Chapter 7 reflects upon the limitations of the research and compares the results with the cases of Brazil and the United States. Finally, the conclusions and recommendations for policy makers and further research can be found in chapter 8.

2. Context

2.1 Technology

The production chain of Rape Methyl Ester (RME) can be split into three steps: rapeseed production, oil production (oil milling) and esterification. All three steps take place at different locations, albeit the oil mill facility and esterification plant can also be integrated. This section describes the consecutive steps of the RME production chain.

2.1.1 Agricultural process

In general, two different kinds of rapeseed plants (Brassica napus) are cultivated in Germany: winter rapeseed, with a share of 98.9%, and spring rapeseed, with a share of 1.1% (UFOP, 2007a; UFOP, 2007b). As winter rapeseed is today's most used feedstock for RME, the agricultural processes of winter rapeseed cultivation are described in this section. Most winter rapeseed designated for biodiesel purposes is cultivated on so-called set-aside land (Arnold *et al*, 2005). Rapeseed is an annual crop and has to be alternated constantly with other crops (mainly cereals) in order to avoid plant diseases and soil impoverishment. Rapeseed is therefore cultivated with intermediate periods of four years (Arnold et al, 2005). A short description will be given on the consecutive agricultural stages of rapeseed cultivation (see also figure 1).

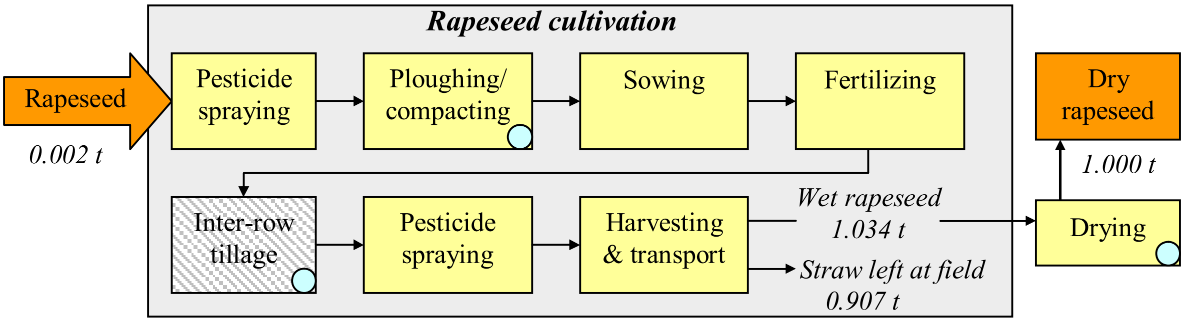

Figure 1: *Simplified overview of rapeseed cultivation process. The inter-row tillage is optional. The mass flows are given per tonne (t); energy intensive processes are indicated with a blue dot. (Data source: Schmidt, 2007).*

The first step of the rapeseed cultivation is the preparation of the field for the sowing process. Pesticides are sprayed on the field and the soil is ploughed and compacted. After the preparatory steps, the sowing process takes place, most of the time in August. Fertilizers are spread over the field during the growing process of the rapeseed plant. The main fertilizers include nitrogen, phosphor, potassium and lime. The need for nitrogen fertilizer depends strongly on the soil conditions, previous cultivated crop and application of manure (Schmidt, 2007). Weeds are removed by spraying herbicides and/or insecticides, and if necessary, by means of inter-row tillage. In general, two rounds of fertilizer spreading and three rounds of pesticides spraying are required (Dreier, 1999). In July, the rapeseed is harvested from the field. The residue rape straw can be removed from the field and be used as a by-product (e.g. as a fuel). However, most of the time, rape straw is ploughed back into the soil (Reinhardt, 2007). The incorporation of the rape straw enhances the soil organic content, which is beneficial for the next crop. The harvested rapeseed is transferred from the harvesting machine into a tractor-trailer and transported to the storage facilities. Subsequently, the rapeseed is dried for over ten days in order to reduce the water content to a level of 9% (Schmidt, 2007). Next to rape straw, several other by-products can be harvested - such as honey, bee wax and propolis - during the blossoming of the rapeseed. So far, these additional by-products have not been used yet on a commercial scale in Germany (Gärtner & Reinhardt, 2003). More detailed information on the agricultural process is given by Schmidt (2007). The distribution of the agricultural fields used for rapeseed cultivation in Germany can be found in appendix B-V.

2.1.2 Industrial processes

The industrial processing of rapeseed into RME occurs in two steps: the oil production and the esterification. The oil production takes place in an oil mill and can be split into two sub-processes: oil extraction and oil refinement. The esterification process takes place in an esterification or biodiesel plant. Sometimes, the oil mill facility and esterification plant are integrated. Each of the processes is described shortly in the following.

After the delivery of the rapeseed grains, the seeds are minced and subsequently conditioned by adjusting the temperature and water content. Next, around 75% of the oil is extracted from the seeds by means of mechanical pressing (Dreier, 1999). All dirt particles are subsequently filtered from the rape oil. In addition to the rape oil, rape meal emerges as a second product from the oil pressing process and contains approximately 10% of the oil. The remaining oil is extracted chemically by using a solvent (usually hexane). Subsequently, the mixture of oil and hexane is distilled in order to recover the crude oil. The rape meal contains around 1% of the oil after the chemical extraction process (Borken *et al*, 1999). Rape meal can be used for several purposes outside the biodiesel industry (e.g. as animal fodder, fuel or raw material for biogas winning) (Gärtner & Reinhardt, 2003). The oil extraction step is shown in the left part of figure 2.

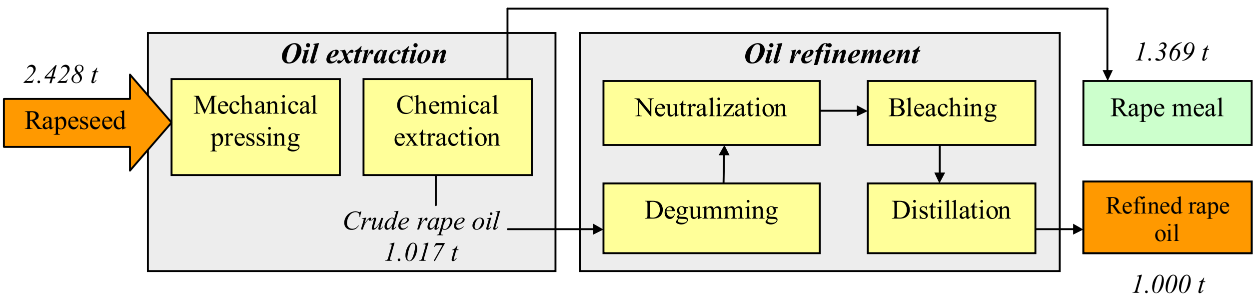

Figure 2: *Simplified overview of the rape oil production process. The mass flows are given per tonne (t); energy intensive processes are indicated with a blue dot (Data source: Schmidt, 2007).*

After the extraction process, the rape oil is not yet ready to be converted into an ester due to unwanted accompanying particles affecting the esterification process. Either a chemical or physical refining process is required to make the oil suitable for further use. The physical refinement is preferable over the chemical refinement as fewer costs, process chemicals and losses are associated with this process. Therefore, the physical refinement process is assumed in this study. Four refining steps are distinguished: degumming, neutralization, bleaching, and distillation (see figure 2). In the degumming step, all kinds of particles are removed from the oil, such as phospholipids, minerals, phosphoric acid, etc. Subsequently, the crude oil is neutralized by removing the free fatty acids using an alkali. Furthermore, the heavy metals are also taken away in this process. After the neutralization, bleaching earth is added to remove the color pigments, trace metals soaps and oxidation products (Northeast biofuels, 2007). Finally, smell- and taste materials are removed by means of distillation. The four refining steps can be combined in numerous ways. For instance, the neutralization and distillation of the crude oil may occur simultaneously. Similarly, the degumming process is often combined with the bleaching process. During the refining process, around 98% of the crude oil is converted into refined oil (Dreier, 1999). Nowadays, the oil production step has already achieved an almost optimal technological state (Wörgetter, 2007).

Refined rape oil can be used directly in specially adapted engines, but has to be converted to an ester for consumption in conventional diesel engines (see figure 3). In the esterification process, the refined rape oil reacts with large excesses of alcohols (usually methanol) to produce Rape Methyl Ester (RME) and glycerin. A catalyst is used to speed up the reaction. Today, a variety of catalysts are available - alkaline and acid, hetero- and homogeneous, enzymes. Nonetheless, most modern, commercial biodiesel plants utilize homogeneous, alkaline catalysts (Bacovsky *et al*, 2007). Several innovative catalysts are currently being tested in laboratories and pilot plants. In recent years, especially heterogeneous and biocatalysts have been attested as a way to further optimize the esterification process (Bacovsky *et al*, 2007).

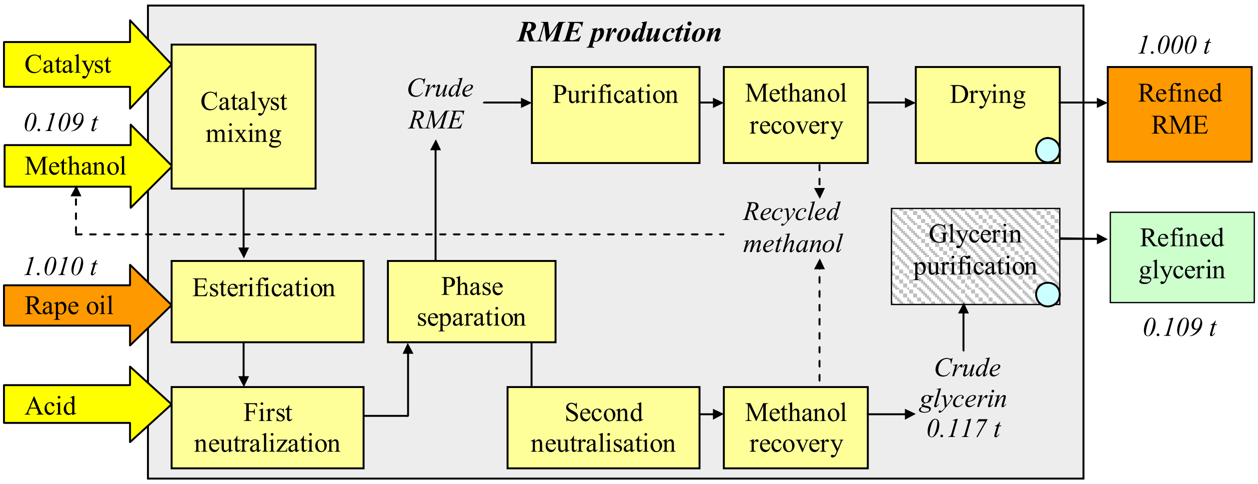

Figure 3: *Simplified overview of the Rape Methyl Ester (RME) production process. The glycerin purification step is optional. The mass flows are given per tonne (t). (Data sources: Borken et al, 1999; Northeast biofuels, 2007).*

The esterification process can be carried out in a batch or continuous mode and with a single- or multi-feedstock processing technology. Batch systems process a certain amount of rape oil and alcohol, after which a new batch is put into the reactor, whereas continuous systems operate with continuous flows of rape oil, alcohol and RME (Northeast biofuels, 2007). Furthermore, single-feedstock technologies can only process vegetable oils with a low amount of free fatty acids, whereas state-of-the-art multi-feedstock technologies are able to process multiple feedstock, because of an additional pre-esterification step and the possibility to adjust the reaction conditions to a specific feedstock. The latter features of the multi-feedstock technologies enable the processing of feedstock with a higher amount of free fatty acids (e.g. animal fat and high acidic palm oil) (Bacovsky *et al*, 2007). After the esterification, the glycerin and RME are neutralized and separated. The latter process may occur either in a settling tank or by means of centrifugation. The residual catalysts and soap in the RME and glycerin are neutralized with acids or washed out (purification), whereas the excess alcohol is recovered by means of distillation. The salt is sometimes recovered and sold for fertilizer usage (Jungmeier, 2007). The by-product glycerin is sold directly in crude form (80-88% purity) or distilled first and sold in pure form (99-100% purity) (Borken *et al*, 1999). The RME and glycerin are dried, stored in tanks and transported to storage facilities or the gas station. Each technology providers offers slightly different processing technologies, by which the circumstances determine the most optimal technology. For more detailed information on (state-of-the-art) processing technologies, see Bacovsky *et al* (2007). The locations of the industrial biodiesel plants in Germany can be found in appendix B-V.

2.2 Political framework and market

This section describes the development of the political framework and market situation in which the German biodiesel industry is embedded. Policy has been a decisive factor in the fast development of the biodiesel industry in Germany (ABI, 2001). The market situation is determined on the one hand by the political framework and on the other hand by several economic, legal and social factors. The political framework and market situation are strongly connected to each other and are therefore jointly described in one section.

2.2.1 Agricultural policy and market

Economic policy

1962-1992
The Common Agricultural Policy (CAP) (1962-today) was implemented to provide the European Community with the political and legal tools to intervene on the European agricultural markets. The overarching political framework allows free trade among member states, impairs market access for outside countries, secures and sets prices of commodity goods and provides financial security for crop farmers. As for many other food crops, German farmers received subsidies for rapeseed production, which varied for each year (Arnold *et al*, 2005; European Navigator, 2007). Also German oil mills enjoyed financial support from the European Union (EU) for the processing of rapeseed into rape oil. The financial support was to compensate for the difference between domestic and world market rapeseed prices. The stimulating EU system resulted in a considerable increase of rapeseed production over the period 1962-1992 in Germany (Folkers, 1999).

1992-2000
With the Agricultural Reform in 1992, the EU decommissioned a percentage of agricultural land to be set aside in order to dampen the food surpluses. This percentage was adapted every year according to the market situation. Non-food crops were allowed to be cultivated on this so-called *set-aside land* without losing the subsidy granted to German farmers for decommissioning their land. As a result, the cultivation of non-food crops became interesting for German farmers as an alternative income (WWI, 2006). In addition, Europe and the U.S. implemented the Blair House Agreement (1992-today) in which the oil seed production within the EU is limited to 5.128 million hectares (Folkers, 1999). Excess production volumes are not to be used in the food and fodder industry. Non-food crops were therefore excluded from the agreement. Nonetheless, as the agreement limits the production of oilseed meal by-products cultivated on set-aside land within the EU (one million tonnes of soybean equivalents), non-food crop production is indirectly also limited (Concawe, 2007). The German government has been stimulating this new non-food market for agricultural products by splitting the rapeseed market in two separate markets: the food- and the non-food rapeseed market. Since then, food rapeseed is to be cultivated on regular agricultural fields and is free to be traded on either the food market or the non-food rapeseed market. However, as food rapeseed fetches higher prices on the food market, it is rarely sold on the non-food market.

Non-food rapeseed is allowed to be cultivated on both regular agricultural fields and set-aside land. However, farmers are forbidden to sell set-aside rapeseed on the food market. Serious financial penalties are inflicted on farmers who try to circumvent these regulations. Food rapeseed prices are higher than non-food rapeseed prices mainly because of different market conditions and subsidies granted by the EU. The subsidies for non-food rapeseed cultivation make it more profitable to cultivate rapeseed on set-aside land than to leave the set-aside land uncultivated (Folkers, 1999). The German government aims at optimizing the cultivation of non-food crops on set-aside land in order to reduce the need for direct subsidies on energy crops (WWI, 2006). The usage of rapeseed (oil) changed tremendously since the beginning of the biodiesel industry in 1991 (see figure 4). The main shift in rapeseed (oil) usage has been the substitution of exported rapeseed to rapeseed designated for RME production.

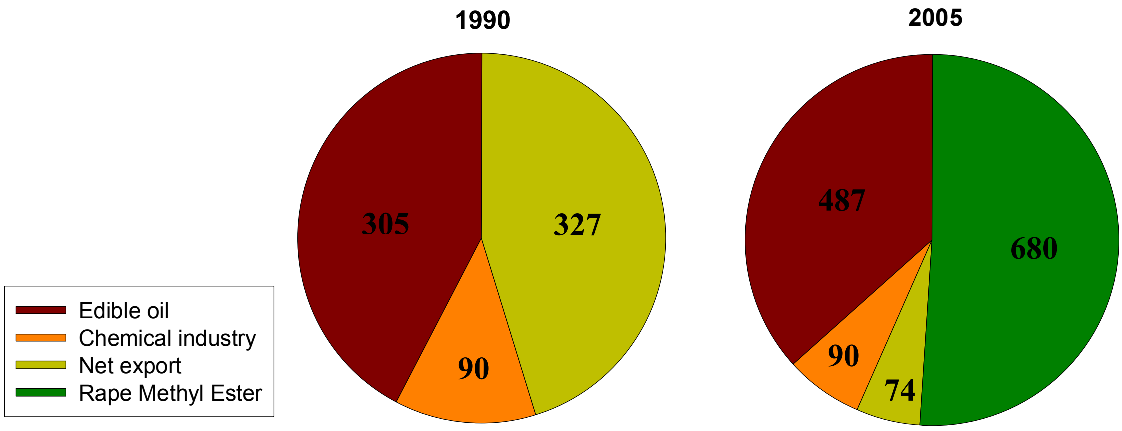

Figure 4*: Rapeseed (oil) usage in 1990 and 2005 expressed in thousand hectares of harvested rapeseed area (Data source: Specht, 2005).*

2000-2012

In the wake of the Uruguay round (1994), the Agenda 2000 (1999) and CAP reform (2003) were agreed upon in order to realize a further liberalization of the EU agricultural market. Prices for agricultural goods were lowered and the set-aside rate was fixed at 10% for every year, regardless of the market developments[2]. Finally, agricultural production was decoupled from subsidies by granting a standard subsidy to each farm, regardless of its size (Single Payment Scheme). The rationale behind the shift from the crop-specific subsidies to land payments was to base agricultural production on market driven forces and harmonize prices of agricultural goods to world market level (Arnold *et al*, 2005). In Germany, an average premium of €301/ha of agricultural land and of €79/ha of grassland was granted after the year 2005. For the years 2009-2013, a standard agricultural premium of €301/ha will be granted, which will differ slightly for each region in Germany. An extra fee of €45/ha is made available for the cultivation of energy crops, provided that the maximum level of 1.5 million hectare is not exceeded. The introduction of the extra fee and non-discriminating land premiums resulted in a comparable profitability for the production of energy and food crops (Arnold *et al*, 2005). Nonetheless, it is not expected that these extra payments for energy crops will have an increasing effect on the production volumes of energy crops in the future (Thrän *et al*, 2004). More strongly yet, as beef and dairy production have become economically more attractive over the season 2007/2008 and outlooks project a favorable

[2] An exception was made for the season 2003/2004 in which the set-aside rate was reduced to 5%.

market situation until the year 2014 (European Commission, 2007a and 2008a), it is likely that less grassland will become available in the future for the cultivation of energy crops.

After 2012
In the long term, the EU will most likely be urged to further liberalize its agricultural markets. The globalization will lead to many uncertainties regarding land availability and rapeseed prices. On the other hand, the future shift in land use enlarges the potential for biomass production, which might be amplified by the EU enlargement to Eastern Europe countries (Arnold *et al*, 2005; Fischer *et al*, 2007; Thrän *et al*, 2004). Agricultural premiums for rapeseed cultivation are expected to decrease in the future due to the admission of East European countries to the EU (UFOP, 2006a).

Environmental policy

The initial philosophy of the CAP was to stimulate the agricultural production in the EU, regardless of the environmental and ecological consequences. Over time, environmental pollution has become more important and focus was laid on sustainable agricultural practices. The increasing interest in the environment was reflected for the first time in the Agenda 2000, which imposed limits on the amount of pesticide and nitrogen fertilizer usage. Farmers may forfeit their subsidy in case of non-compliance. In Germany, the maximum amount of fertilizer usage has been determined for each state separately (Gärtner, 2008). Nonetheless, until then, no clear regulations with respect to environmental issues - GHG reductions, biodiversity, etc. - were incorporated in the German law of good farming practice. In 2007, Unilever and UFOP developed several guidelines to support sustainable management practices for winter rapeseed production (UFOP, 2007c). The guidelines comprise a set of practices regarding soil conditions, nutrients and pest management and biodiversity to alleviate the environmental burden of rapeseed production. In parallel, the German government issued the Biomass Sustainability Ordinance, which prescribes several criteria for the sustainable cultivation of feedstock for biofuels. Biofuels have to fulfill these criteria in order to be eligible for tax relief (cf. section 2.2.2). The criteria on agricultural practices forbid, among other things, any significant increase in emissions of acidic, eutrophic, ozone-depleting or toxic substances and obligate the environmentally safe usage of fertilizers, pesticides and herbicides. Furthermore, several requirements regarding the protection of natural habitats have to be met during the cultivation process of biomass (German government, 2007). Unfortunately, the ordinance does not mention any quantitative specifications.

2.2.2 Biodiesel policy and market

Mineral Oil Tax (1991-2006)

Biodiesel was completely exempted from the Mineral Oil Tax from the very beginning of the German biodiesel industry in 1991. However, it was not until the late nineties before an official legal foundation was created for the production of biodiesel. The exemption of biodiesel from the mineral oil tax made it possible for biodiesel to find a market and become an economically competitive fuel (Karus, 2007).

The initial philosophy of the German government was to launch biodiesel as a 100% substitute (B100) for fossil diesel in order to enjoy full environmental benefits. In the beginning, several public transport organizations switched to biodiesel to set the example. However, the low quality biodiesel and the lack of warranties from car manufactures hampered the break-through of biodiesel on a large scale. The introduction of the DIN quality standards (DIN V 51.606 (1994) and DIN E 51.606 (1997)) created confidence among customers and car manufacturers. As a result, the car manufacturers issued warranties for the safe usage of biodiesel in diesel engines. The reassurance of high quality biodiesel and suitable diesel engines provided the necessary conditions for the biodiesel market to grow. The rather steady growth rate in biodiesel production became negative in 1998 due to an extreme low crude oil price, high rape oil price and a set-aside rate of merely 5% (ABI, 2001) (see also appendix B-IV).

<u>Ecological Taxation (1999 onwards)</u>

In 1999, the social government introduced an additional tax on fossil fuels. This ecological tax (Öko-Steuer) levies an additional 6 DM/100 liter (= ± €3/100 liter) in order to shift the costs of GHG emissions reduction to the polluters. The ecological tax increased with 6 DM per year, resulting in a total increase of 30 DM/100 liter (= ± €15/100 liter) in 2003 (ABI, 2001). In parallel, the first preparations were made to implement a legal framework for biofuels (Karus, 2007). As biodiesel was exempted from the ecological tax, the economic competitiveness of biodiesel improved compared to fossil diesel. This effect was amplified by the high crude oil price in 1999. As a result, both biodiesel production and investments in biodiesel plants surged from the year 2000 onwards. The high concentration of biodiesel plants in the former East German states has been a result of the investment subsidies in these areas (FNR, 2006) (see appendix B-V). At the same time, a steady increase in biodiesel imports can be discerned from 2001 onwards, with a small decrease for the year 2006 (Gärtner & Reinhardt, 2005; UFOP, 2006b).

<u>Amendment of Mineral Oil Tax (2004)</u>

The tax privileges for biofuels were finally made legally binding by the amendment of the Mineral Oil Tax in 2004. With the legal registration of tax exemption for biofuels, two important EU directives, regarding the promotion of biofuels (directive 2003/30/EG) and Energy Taxation (directive 2003/96/EG), were officially adopted in the German law. Furthermore, the EU Commission officially allowed the German government to exempt biofuels from the Mineral Oil Tax until 2009 (UFOP, 2006b). At the same time, the EU Commission stated that the tax exemption should be restricted to the difference between the production costs of the biofuel and the conventional fossil fuel. An annual review is performed in order to revise a possible overcompensation. As the crude oil price reached an all-time high in 2005, the economic competitiveness of biodiesel compared to fossil diesel improved and led to an overcompensation of biodiesel. The overcompensation and the rapidly growing biodiesel industry had resulted in substantial financial tax losses for the German government. As a result, the impending financial revenue shortfall of the federal government triggered initiatives to implement a new, less expensive, federal policy framework. This new framework had to meet two targets at the same time. On the one hand, tax losses had to be reduced in a relatively short period of time. On the other hand, the government had to keep stimulating the biodiesel industry in order to achieve the targets set by the European Union (UFOP, 2006b).

<u>Energy Tax Act (2006) and Biofuel Quota Act (2007)</u>

A trade-off was made between the two targets by implementing the Energy Tax Act in 2006 and the Biofuel Quota Act in 2007. The Energy Tax Act, which replaced the Mineral Oil Tax, defined an annual increase of the tax rate on biodiesel until the year 2012. The tax rate increases every year with € 0.06/liter until 2011 and with € 0.12/liter from 2011 to 2012.

After 2012, the tax rate remains at a constant level of € 0.45/liter. Prerequisite for the tax exemption and quota system is the compliance of biodiesel with the quality standard (cf. section 2.2.3). In parallel, the Biofuel Quota Act was introduced to safeguard the achievement of the quantity targets set by the European Union for the year 2010. Fuel producers and traders are obliged to blend biofuels with mineral fossil fuels according to the quotas of the EU. The fixed mandatory blending percentage for diesel is 4.4% (UFOP, 2006b). Table 1 gives an overview of the development of tax rates until 2015.

Year	Tax rate biodiesel	Year	Tax rate biodiesel
Aug. - Dec. 2006	€ 0.09 / liter	2010	€ 0.27 / liter
2007	€ 0.09 / liter	2011	€ 0.33 / liter
2008	€ 0.15 / liter	2012 onwards	€ 0.45 / liter
2009	€ 0.21 / liter		

Table 1: *Tax rate for biodiesel in Germany for the period 2006-2015 (Data source: UFOP, 2006b).*

In case (bio)fuel producers and/or traders do not comply with the diesel quota, a fine of €16/GJ, i.e. € 0.50/ liter biodiesel, has to be paid (UFOP, 2006b). However, the biodiesel price level determines whether it is more cost efficient to blend the legal amount of biodiesel or to pay a fine for non-compliance.

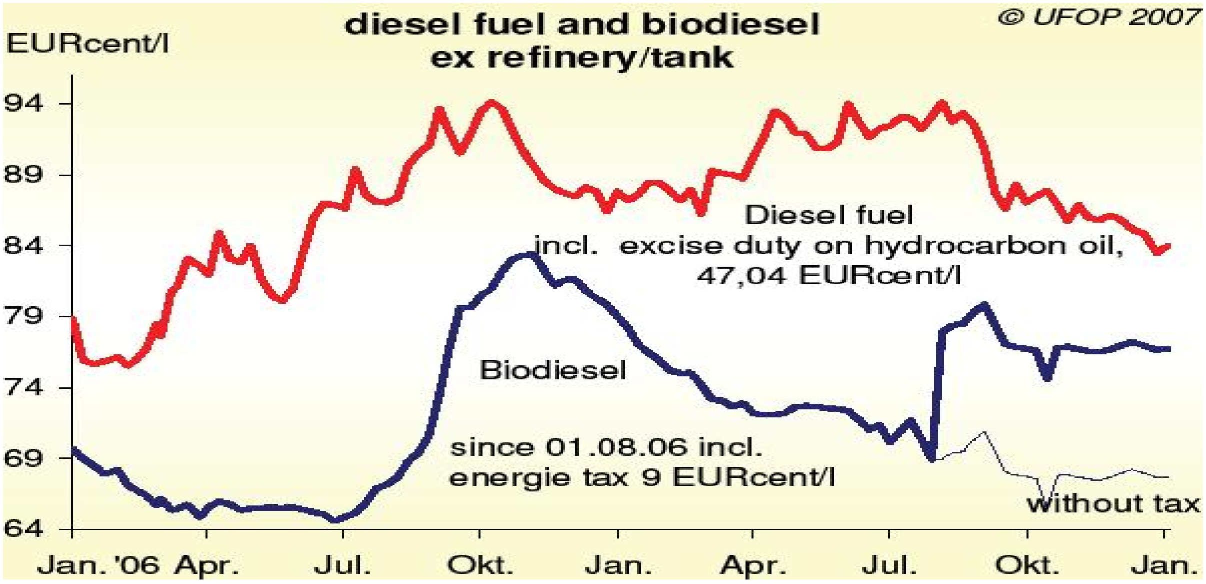

Figure 5*: Development of prices for fossil diesel ex refinery (duty on hydrocarbon oil included) and biodiesel ex tank over the period January 2005-January 2007 with explanatory notes (Data source: UFOP, 2007c).*

The effect of the introduced tax rate on the biodiesel price is shown in figure 5. The raising tax rate has already deteriorated the economic performance of biodiesel compared to fossil diesel. The UFOP (2006b) fears that B100 will become unprofitable in the year 2008/2009. Demand for biodiesel has already declined in the beginning of 2007, whereas the biodiesel capacity is still growing. As a result, the biodiesel overcapacity is increasing rapidly (UFOP, 2006b). The German government acknowledged this problem and incorporated a stipulation in the Biofuel Quota Act to revise tax rates annually to ensure that biodiesel will remain economically competitive over time. The additional costs of biodiesel due to differences in energy content compared to fossil diesel are accounted for in this regulation. These additional costs apply only to pure biodiesel (B100), not to the blended form (B05). The adjustments of tax rates will depend heavily upon crude oil prices and the production costs of biodiesel itself. The latter will fluctuate as well due to changing prices of input products for biodiesel, e.g.

methanol, energy and vegetable oil prices. The market share of B100 has decreased considerably over the years, whereas B05 has gained in importance. In 2005, biodiesel was used as B100 in captive fleets (busses and trucks) (45%), sold at filling stations (10%) and sold to farmers (5%); the remaining biodiesel was blended with fossil diesel to B05 (40%) (Retzlaff, 2006). In contrast to the commercial vehicle sector, the agriculture and forestry sector are still exempted from taxation. Hence, these sectors will become an important market for the biodiesel industry, especially if crude oil price will continue to increase (UFOP, 2006b). Nevertheless, this effect is outweighed by the decrease in biodiesel demand from the commercial vehicle sector.

<u>Biomass Sustainability Ordinance (2007) and proposal EU directive (2008)</u>

The Biofuel Quota Act sets forth several obligatory sustainability requirements, such as the sustainable production of feedstock for biofuels, the protection of natural habitats and a minimum reduction potential of GHG emissions. Nonetheless, no specifications were present within the quota law regarding the requirements and procedures. As a result, the German government issued a draft for the Biomass Sustainability Ordinance in 2007. The ordinance specifies the above-mentioned criteria that have to be fulfilled in order to receive the tax relief as stated in the Energy Tax Act. Furthermore, it states that the GHG emission reduction potential of a biofuel should be at least 30 percent compared to their fossil counterparts (40 percent per 1 January 2011) (German government, 2007). The reduction potential of each biofuel is computed by means of a corresponding emission factor for each step in the life cycle of the biofuel. Biofuels with a high GHG emission reduction potential also enjoy a high amount of energy credits for the biofuel quota. By introducing the ordinance, the German government shifts focus from pre-defined biofuel quantities to the promotion of specific GHG efficient biofuels. To the knowledge of the author and Gärtner (2008), no environmental policy and/or regulations with regard to energy use and/or emission caps associated with the industrial processes were in force before the introduction of the ordinance.

In January 2008, the European Commission presented a proposal for a renewable energy legislative framework. This proposal aims to establish a 10% binding minimum target for the share of renewable energy for biofuels in the transportation sector for the year 2020. In addition, it was proposed to set new targets for national GHG emission targets (European Commission, 2008b). Similar to the German ordinance, the proposal states that biofuels have to fulfill several criteria regarding the feedstock in order to be eligible for the 10% biofuel quota. For instance, biomass for biofuels is not allowed to be cultivated on wetlands, undisturbed forestland, permanent grasslands and areas designated for nature protection purposes. The GHG emission reduction potential of biofuels are obtained by using either a specified computation method or a set of default values, both incorporated in the proposal, for each step in the life cycle of the biofuel.

Expectations are that biofuels' reduction potentials, which according to the German ordinance have to be proven in the form of a certificate, will significantly influence the price of biofuels in the future (IE, 2007). The ordinance gives therefore impetus to German biofuel producers to introduce innovative biofuel concepts with high reduction potentials. Especially biofuels imported from Latin America and South East Asia are highly credited, provided that certain sustainability criteria concerning direct land use change are respected. As an increasing demand can be expected for biofuels with a high reduction potential, a growing displacement of domestic biofuels, amongst which RME, is likely for the medium and long-term (IE, 2008).

3. Methodology

3.1 General theories

3.1.1 Experience curve theory

Many products and services become technologically and economically more efficient as more experience is gained by the industry. More experience leads generally to lower costs and higher qualitative performance in each of the consecutive stages and aspects of the production process of the product or service. In the process of experience accumulation, several learning mechanisms play an important role. Learning mechanisms have been defined and described in different ways by multiple authors. Based on literature, an overview can be made of five learning mechanisms, which are often seen as the mechanisms behind experience accumulation and the concomitant cost reductions:

- *Learning-by-searching*; i.e. improvements of the product due to RD&D (Junginger, 2005)
- *Learning-by-doing*; i.e. improvements in the production process as a result of experience gained during the manufacturing of a product (Arrow, 1962)
- *Learning-by-using*; improvements in the product as a result of the experience gained from the usage of the technology (Rosenberg, 1982)
- *Learning-by-interacting*; i.e. increasing diffusion of knowledge and technology as a result of improved network interactions between the different actors (Lundvall, 1992)
- *Learning-by-upscaling* of production plants (Junginger, 2005)

Often, the contribution of each learning mechanism to the total cost reductions differs for each stage of the industry (Junginger, 2005). Learning-by-searching applies predominantly to the stages of invention, product development, and diffusion of the product on the market. Learning-by-doing and learning-by-using apply mostly to the respective stages of the actual production and the market introduction of the product. In practice, it is challenging to allocate the cost reductions to the separate learning mechanisms quantitatively, since quantitative effects of learning are often unknown. Moreover, overlap between learning mechanisms makes this even more difficult. An exception exists for learning-by-upscaling, which can be examined rather easily in a quantitative way by means of scaling factors.

Despite the difficulty to allocate the cost reductions to the separate learning mechanisms, it is however possible to give a quantitative expression for the relation between total cost reductions and cumulative experience. This quantitative relation was described for the first time by the Boston Consultancy Group (BCG) in 1968. The BCG (1968) devised the concept of the experience curve, which relates the costs of a product with the cumulative quantity produced. The cumulative production can be seen as a measure for the accumulated experience within the industry. Although not proven, empirical data confirms the existence of a relationship between costs and cumulative production for a wide variety of products and services (BCG, 1968). A specific empirical observation is that production costs tend to decline with a fixed rate with every doubling of the cumulative production due to technological learning. A power function can be used to describe the relation between cumulative production and production costs (see equation 1-3).

$C_{cum} = C_0\ Cum^b$ (1)
$\log C_{cum} = \log C_0 + b \log Cum$ (2)
$PR = 2^b$ (3)

C_{cum} : Cost per unit
C_0 : Cost of the first unit produced
Cum : Cumulative (unit) production
b : Experience index (<0)
PR : Progress ratio

The equations show that the unit costs decline with a constant factor, the *progress ratio*, with each doubling of the cumulative production. Sometimes, the term *learning rate* is used instead and can be defined as 1-PR. A learning rate of 30%, i.e. a progress ratio of 70%, implies a 30% cost reduction for each cumulative doubling. Production costs need to be corrected for inflation by expressing them in real terms. The R^2 ($0 \geq R^2 \geq 1$) of the trend line represents the correlation between the cumulative production and production costs. Finally, a standard error (σ_{PR}) is calculated for the progress ratio (see equation 4). The standard error in the experience index (b) is denoted by σ_b.

$\sigma_{PR} = \ln 2 \cdot PR \cdot \sigma_b$ (4)

Experience curves are often presented as straight lines in double-logarithmic diagrams, which show how the costs evolve over multiple orders of magnitude. In addition, a straight line gives a better impression of the relation between cumulative production and production costs. The steepness of the slope indicates the pace with which experience is gained by the industry. A cumulative doubling in the initial technology deployment stage entails higher absolute cost reductions than the cumulative doublings in the following stages. Furthermore, as the technology deployment becomes more advanced, progressively more production is required to realize a cumulative doubling.

The experience curve shows the quantitative relationship between the empirically observed cost reductions and the cumulative production. This relationship can be used to extrapolate the experience curve and project future cost reductions. These assessments do however not forecast the *moment* at which the cost level will be achieved, but merely at which *value of the cumulative production*. The moment in time depends on the deployment rate of the technology, which is in turn determined by the market situation and the policy set out by the government. Furthermore, these assessments provide information about the learning investments necessary to achieve these goals (IEA, 2000). Learning investments can be made by the government or by companies, which in the latter case can be triggered by implementing effective policies. Learning investments focus primarily at stimulating the technological development once the technology has become mature. Public RD&D expenditures precede the learning investments and aim to initiate and stimulate the development stages of a technology (IEA, 2000).

Many studies have shown that the experience curve method is applicable for several renewable energy technologies (e.g. Neij, 1999; Wene, 2000). Furthermore, several scientists have used experience curves to quantify cost reductions for biofuels, such as Goldemberg (1996) and McDonald and Schrattenholzer (2001). Similar to this research, two studies were carried out for the cases of cane-ethanol production in Brazil (Wall Bake, 2006) and corn-ethanol production in the United States (Hettinga, 2007). In the Brazilian case, a PR of 0.81

was calculated for the industrial processing costs (investment costs included) over the period 1975-2004; in the US case, a PR of 0.87 was calculated for the industrial processing costs (investment costs excluded) over the period 1983-2005. The results of this study and previous studies can be used to discern patterns in technological development, cost reductions and efficiencies of different policy measures of first generation biofuels.

3.1.2 Life Cycle Assessment

The Life Cycle Assessment (LCA) is a methodological tool to assess the environmental impact over the entire life cycle of a product, i.e. from the initial step of resource extraction (cradle) to the final step of disposal (grave). The environmental performance of the product is related to the function of the product, which allows the comparison with analogue products or services. The LCA procedure comprises the following consecutive stages: goal and scope definition, inventory analysis and impact assessment (Baumann & Tillman, 2004). A series of international standards were issued (ISO 14040-14043, 1997-2000) to set guidelines on how to conduct an LCA for each of these stages. Each of these stages will be described shortly.

In the stage of the *goal and scope definition*, the system boundaries are defined, i.e. the system is confined with respect to the natural system, geographical location, time horizon and technical system. Another important part of this stage is the definition of the functional unit. The functional unit corresponds to a reference flow to which all other modeled flows of the system are related (Baumann & Tillman, 2004). Finally, the impact categories (e.g. global warming, acidification, etc) and method of impact assessment are chosen.

After the goal and scope definition, a flow chart is constructed in the *inventory analysis*. The flow chart represents the consecutive sub-processes, and the associated relevant energy and mass flows, of the life cycle of the product. Subsequently, data on mass and energy flows are collected for all the sub-processes in the flow chart. Afterwards, the collected data have to be processed and recalculated. First of all, the data are normalized by converting them to the units of the activity they are related to. Then, both the flows linking the activities in the flow chart and the flows crossing the system boundaries have to be related to the functional unit. Finally, the mass and energy flows crossing the system boundaries have to be summed up in order to get the total net sum of mass and energy associated with the life cycle of the product or service.

Next to the main product, one or several by-products may emerge that can substitute other products or services. In that case, the mass and energy flows associated with these processes have to be accounted for by allocating the flows between the main product and by-product. The allocation of mass and energy flows can be done in several ways. According to the ISO standard (ISO 14041, 1998), system expansion is preferable over allocation principles based on physical or economic characteristics (Baumann & Tillman, 2004). System expansion means that the life cycle of the examined product is credited with the environmental load from the life cycle of the substituted product that is avoided by the usage of the by-product.

In the *impact assessment*, the quantitative energy and mass flows, as calculated in the inventory analysis, are translated to environmental impacts and classified into several impact categories. After the classification, the energy and mass flows are multiplied with their corresponding contribution factors (characterization stage). Subsequently, all contributions are aggregated to one indicator for the impact category. Finally, it is possible to attribute weighting factors to the impact categories and sum them up in order to obtain a onedimensional index of the environmental performance of the product. However, the weighting process is excluded from this research.

3.2 Applied methodology

3.2.1 Definition learning system

A learning system is a demarcated set of interrelated components in which technological learning mechanisms are active. The interrelated components comprise farmers, biodiesel producers, biodiesel consumers, research institutes, the government and several other stakeholders. The interaction between the components triggers the five learning mechanisms as mentioned in section 3.1.1. Ideally, one would consider the *whole world* as one learning system, since technological learning in rapeseed and RME production has most likely taken place all over the world. However, this study confines the learning system to the Federal Republic of Germany over the period 1970-2007 for several practical reasons (e.g. data availability, time limitations, etc.). The choice for the *national* system boundaries is considered justified given the fact that Germany has a long world's leading position in biodiesel production and processing technologies, what seems to make a significant "import" of technological knowledge from other countries over the years unlikely[3]. Furthermore, the Federal Republic of Germany can be regarded as a homogeneous system of interrelated components embedded in one economic, political and legal framework. Nonetheless, it could be alleged that technological learning took place on a higher level for both rapeseed and biodiesel production, thereby demanding a larger learning system. Furthermore, the worldwide operating German technology providers have most likely also experienced technological learning outside Germany. Yet, it was decided to adhere to the learning system of the Federal Republic of Germany and exclude the (possible) technological learning "import" (and/or export) in the analysis for practical reasons. More attention will be given to these issues in the discussion (see chapter 7).

Another, *methodological* problem arises with the definition of the learning system, since the system boundaries have changed over time. The accession of the German Democratic Republic (GDR) to the former Federal Republic of Germany (West Germany) in 1991 resulted in the fusion of two separate learning systems. Ideally, the feedstock system should be investigated for both West Germany and the GDR to enable a sound analysis of the technological learning processes over the period 1971-2007. However, the lack of data on rapeseed production costs in the GDR made it impossible to examine the past technological learning processes in this system (cf. section 4.1). West Germany is therefore considered to be the only learning system before 1991. In order to examine the relationship between technological learning and feedstock costs on a long timescale, West Germany and the current Federal Republic of Germany are regarded as the same learning system. This methodological issue will be discussed in further detail in the sensitivity analysis (chapter 6). The learning system can be split into several sub-learning systems in order to gain insight in the contribution of each specific area to the overall experience accumulation (Junginger, 2005). Similar to this study, Hettinga (2007) attempted to quantify technological learning as reductions in production costs and energy requirements for the case of corn-ethanol production in the United States. Hettinga (2007) devised a compound learning system, which was split into two sub-learning systems: the feedstock production and the industrial

[3] The "import" of technological knowledge from outside the learning system could distort the calculated progress ratio and suggest a higher pace of technological learning than is actually the case.

processing. This differentiation was justified since the agricultural feedstock production and industrial processing are two separate, independently operating systems (Hettinga, 2007). The strict separation between agro-industrial and industrial systems also holds for the case of RME production in Germany. The main structure of the compound learning system is therefore adopted from Hettinga (2007) (see figure 6). Furthermore, the CO_2-equivalents associated with the three most important GHG emissions (CO_2, CH_4 and N_2O) were added as a performance indicator for technological learning.

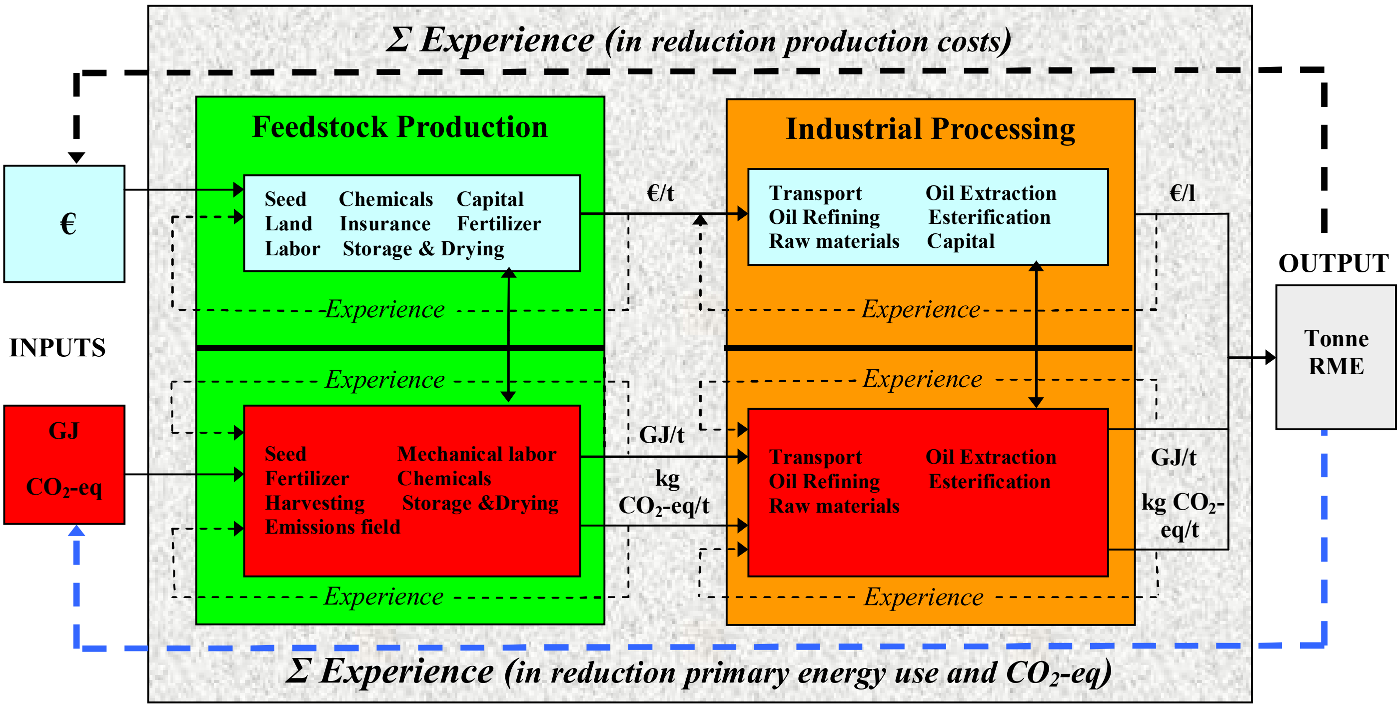

Figure 6: *Compound learning system for rapeseed-RME production in Germany. The performance indicator production costs is represented by the blue boxes; the performance indicators energy use and CO_2-equivalents are represented by the red boxes. The flows are given per tonne (t) and per liter (l).*

Ramirez & Worrel (2006) and Hettinga (2007) explored whether energy requirements could be used as an alternative measure for technological learning. Although both studies found strong correlations between cumulative production and energy requirements, provided that energy expenses account for a major share in the total costs, more research is needed in this area. Next to the incentive to reduce production costs, several other drivers to reduce energy use and GHG emissions might be present, such as laws on production methods or emission caps. However, it should be noted that objectives to reduce costs might conflict with objectives to reduce energy use and GHG emissions. For example, higher fertilizer usage might lead to higher yields, and thus, lower total production costs, but might also involve higher primary energy use and GHG emissions. Before the year 2000, it is assumed that no clear regulations existed with respect to the energy use and GHG emissions of rapeseed production, since literature does not refer to any such regulations. From 2000 onwards, several limits were imposed on the maximum amount of fertilizer and/or chemical usage, which could have indirectly driven reductions in primary energy use and/or GHG emissions (cf. section 2.2.1). As for the industrial processes, no indications were found in literature of any environmental policy and/or regulations regarding energy use and/or emission caps were in force before the introduction of the Biomass Sustainability Ordinance in 2007 (cf. section 2.2.2). It is therefore assumed that no such regulations existed and cost reductions have been the only driver for lower energy use and concomitant GHG emissions over time for the industrial processes. The postulated relationship between technological learning, represented by cumulative production, and environmental performance is denoted by the blue dashed line in figure 6. The performance indicators energy use and CO_2-equivalents are represented together in one box because of their strong correlation. An overview of the research structure, performance indicators and the related sections in this report are given in table 2. The coming about of the performance indicators is elaborated in section 3.2.2.

Performance indicator → System	Production costs *[€$_{2007}$]*	Primary energy use *[GJ_p]*	Global Warming *[CO_2-eq]*
Rapeseed production	Section 5.2.1	Section 5.3.1	
Cumulative rapeseed production [t]	*[€$_{2007}$/t]*	*[GJ_p/t]*	*[CO_2-eq/t]*
Industrial processing	Section 5.2.2	Section 5.3.2	
Cumulative RME production [t]	*[€$_{2007}$/l]*	*[GJ_p/t]*	*[CO_2-eq/t]*
Total RME production	Section 5.2.4	Section 5.3.3	
Cumulative RME production [t]	*[€$_{2007}$/l]*	*[GJ_p/t]*	*[CO_2-eq/t]*

Table 2: *Overview of research structure and related sections in this report. The performance indicators are given per tonne (t) and per liter (l).*

3.2.2 Applied method of experience curve

The experience curve method is used to quantify technological learning as reductions in production costs, primary energy use and CO_2-equivalents. The differentiation of the compound learning system into two sub-learning systems (feedstock and industrial processing system) makes it possible to construct an experience curve for each system. Furthermore, efforts are made to construct an experience curve for the total production costs of RME. A questionnaire was devised that will be sent to all German industrial esterification plants (36) and technology providers (5) in order to collect data for the industrial processing costs. The questionnaire can be found in appendix A-III. The computer program Sigmaplot (version 10.0) is used to calculate the progress ratios, standard errors and the degree of correlation (R^2). All production costs are corrected for inflation and, if necessary, converted from Deutsche Mark to Euro. The values for the primary energy use and GHG emissions have to be accorded first by recalculating and transforming the available data to a standard LCA methodology (cf. section 3.2.3). Afterwards, efforts can be made to plot the values against the cumulative rapeseed production. An overview of the research structure for the construction of the experience curves is given in appendix A-I. The main methodological issues associated with the experience curves are discussed for each sub-system.

Feedstock production

The feedstock system is analyzed over the period 1971-2007. The demarcation of the learning system by the national boundaries is considered justified for the feedstock system as technological learning exchange between West Germany, the GDR and other countries is expected to have been marginal. All the consecutive steps of the rapeseed cultivation, as described in section 2.1.1, are incorporated in the analysis. However, the transport step to the storage facilities is not included in the analysis, but considered in the industrial system. The mechanization of the agricultural practices, and thus technological learning, took primarily place after the Second World War (Handler, 2007). The annual production volumes are therefore summed up over the period 1950-1970 to obtain the value for the initial cumulative production.

The *feedstock costs* are differentiated into the following cost categories: seed, fertilizer, chemicals, storage & drying, insurance & analysis, labor, land and variable and fixed capital costs. EU subsidies for energy crop cultivation on set-aside land are excluded from the cost calculations. A cost breakdown will be given to gain insight in the development of the cost categories over time. The total production costs are given per hectare and per tonne rapeseed.

The *primary energy use and CO_2 equivalents* are differentiated into the following categories: mechanical labor, harvesting, storage & drying, seed, fertilizers, chemicals and emissions field. A breakdown will be given to gain insight in the development of the sub-processes over time. The total primary energy use and CO_2 equivalents are expressed per tonne rapeseed.

Industrial processing

The industrial processing system is analyzed over the period 1991-2007 in the Federal Republic of Germany. The choice of the geographical system boundaries is considered justified given the national framework conditions (e.g. tax regulations, obligatory blending quotas, etc.) in which the German biodiesel industry is embedded. The possible import and export of technological learning from other countries is ignored in the standard analysis. The leading position of Germany with regard to annual production volumes and plant technology seem to legitimate this choice. The industrial system comprises all the consecutive steps of the *industrial* oil milling and esterification processes (cf. section 2.1.2). The value for the initial cumulative production was set equal to the total RME production in 1991, since no RME was produced in Germany before the biodiesel era[4].

The *industrial processing costs* are differentiated into several cost categories: transport, oil extraction, oil refining, esterification, glycerin processing and distribution. Subsidies for biodiesel plants and costs for feedstock and tax are excluded from the analysis. Depreciation costs for investment are incorporated in the processing costs. All processing costs have to be corrected for plant size by using scaling factors. Credits for by-products (rape meal and glycerin) are accounted for in the total production costs. A cost breakdown will be given to gain insight in the development of the costs over time. The industrial processing costs are given per liter RME.

The *investment costs* are examined in further detail to find out whether a quantitative relation can be found between specific investment costs[5] and the cumulative installed production capacity of biodiesel plants in Germany. The cumulative installed *capacity* is taken as the measure for accumulated experience, since it is deemed to reflect technological learning of plant building better than the cumulative *production*. Investment costs are determined by several factors: depreciation period, interest rate, inflation index, technological equipment, plant structure, ancillary facilities, etc. The specific investment costs will be corrected for as many of these factors as possible to make a sound comparison possible.

As mentioned in section 3.1.1, it is often difficult to allocate cost reductions to the separate learning mechanisms quantitatively, since quantitative effects of learning are often unknown. Nonetheless, an exception exists for learning-by-upscaling, which can be examined rather easily in a quantitative way by using scaling factors. The effect of plant size on the specific

[4] The assumption of almost zero initial cumulative production is rather pessimistic, considering the accumulated experience of the chemical industry with vegetable oil production and esterification before the biodiesel era. However, as it was very difficult to quantify this experience it was decided to assume no experience at all.
[5] The specific investment costs are the investment costs per tonne production capacity.

investment costs (upscaling effect) will be examined by using the following power function (Junginger, 2005):

$$\frac{Cost\ plant\ x}{Cost\ reference\ plant} = \left(\frac{Capacity\ plant\ x}{Capacity\ reference\ plant}\right)^R \qquad (5)$$

R = scaling factor

The *primary energy use and CO_2 equivalents* are differentiated into the following categories: oil refining, oil extraction, transport, indirect compounds of oil production, esterification, methanol and other chemicals. A breakdown will be given to gain insight in the development of the sub-processes over time. The total primary energy use and CO_2 equivalents are expressed per tonne RME.

Total production chain

The total production chain is analyzed over the period 1991-2007 for the Federal Republic of Germany. The total production chain comprises the feedstock production and the industrial processing. The total costs, primary energy use and CO_2 equivalents are plotted against the total RME production to examine technological learning throughout the production chain. Again, the value for the initial cumulative production was set equal to the total RME production in 1991.

The *total production costs* can be defined in two different ways: the *hypothetical* and the *actual* production costs. The *hypothetical* production costs are the sum of the feedstock and industrial processing costs minus the financial revenues for by-products. The *hypothetical* production costs are plotted against the cumulative German biodiesel production to examine the total cost reductions, and thus technological learning, for the entire rapeseed-RME system over the period 1991-2007. The *actual* production costs are, however, determined by the *rapeseed price* (for stand-alone plants) or *rape oil price* (for annex plants[6]) instead of rapeseed (oil) *costs*. Usually, a large difference exists between costs and prices, due to agricultural subsidies, profit margins and market dynamics. Consequently, the methodological choice to use *costs* instead of *prices* has a significant influence on the total production costs. The *actual* production costs are not plotted against the cumulative German biodiesel production, since these costs do not reflect technological learning over time as a result of rapeseed price fluctuations. Both the *hypothetical* and *actual* production costs are given per liter RME.

The *total primary energy use and CO_2 equivalents* are differentiated into the following categories: direct processes, indirect processes and RME distribution. The primary energy use and GHG emissions associated with the combustion phase and by-products are incorporated. The *total primary energy use and CO_2 equivalents* are expressed both per tonne and per 100 km driven over the New European Driving Cycle (NEDC) with a reference car (cf. section 3.2.3). The NEDC is considered to represent the typical driving cycle of a car in Europe and is often used to assess the average fuel usage and GHG emissions of car engines. This study assumes that the NEDC represents the German case as well. The key characteristics of the

[6] An annex biodiesel plant has an integrated oil mill and purchases *rapeseed*, whereas a conventional stand-alone biodiesel plant purchases *rape oil*.

reference vehicle, which is driven by a 1.9 L turbo-charged direct injection compression ignition engine (74 kW), are given in appendix B-II.

Extrapolation of the experience curves

In case experience curves can be constructed for the above-mentioned performance indicators, a quantitative projection will be made for the future production costs, primary energy use and CO_2 equivalents. Projections on future production volumes will be used to extrapolate the experience curves and forecast the production costs and/or environmental performance for the year 2020. The standard deviation of the most recent data points is used to account for uncertainties in the underlying data and assumptions made. Furthermore, two future scenarios - each with different production growth rates - will be devised for both sub-systems.

3.2.3 Applied methodological framework LCA

The special methodological feature of this research is the comparison of the environmental performance over time. A cradle-to-grave analysis is carried out for all years over the period 1991-2007. The first direct sub-process (cradle) in the life cycle is the cultivation process. The *biogenic* energy stored in the rapeseed is not considered, since the focus of the LCA lies merely on the amount of expended *fossil* energy. The final sub-process (grave) is the combustion phase of the RME. This study investigates the primary energy flows and the three most relevant GHG emissions associated with the life cycle of RME, viz. CO_2, N_2O and CH_4. In order to make a sound comparison possible, all energy and GHG emissions have to be recalculated and transformed to a standard methodological framework. The international ISO standards state clear regulations on this methodological framework (cf. section 3.1.2). Nonetheless, several methodological decisions have to be made by the practitioner himself, e.g. regarding the definition of the functional unit and system boundaries and how to account for the mass and energy flows associated with by-products. Many LCA practitioners have concurred with each other on what the most preferable decisions are regarding the above-mentioned methodological issues when performing an LCA on biofuels. The corresponding LCA methodology, based on these most preferable methodological decisions, was applied in the Concawe study (2007) (Jungmeier, 2007). Therefore, the LCA methodology, as applied in the Concawe study (2007), was adopted as the methodological framework for this study as well. Subsequently, a flow chart was constructed with all sub-processes of the life cycle of RME (see appendix A-II).

The sub-processes of the life cycle are distinguished in direct and indirect processes. The *direct processes* refer to the actual production chain of RME (mechanical labor, oil extraction, esterification, etc); the corresponding *direct energy and CO_2-equivalents* are related to the energy (electricity, natural gas, fossil diesel, etc.) necessary to perform these processes. The *indirect processes* refer to the production chains of the so-called indirect compounds (fertilizers, chemicals, methanol, etc.), i.e. input products required for the direct processes. Accordingly, the *indirect energy and CO_2-equivalents* are related to the production chains of these indirect compounds. The energy and GHG emissions associated with the production and maintenance of capital (e.g. tractors, harvesting machines, sheds, etc.) are excluded from the indirect processes. The dashed box II in the flow chart (see appendix A-II) represents the division between direct and indirect processes.

The energy and CO_2 equivalents associated with the sub-learning systems (feedstock and industrial system) are expressed per tonne rapeseed and per tonne RME. The functional unit of the total energy and GHG emissions is related to a distance driven of 100 km over the New European Driving Cycle (NEDC) (Concawe, 2007).

The by-products rape meal and glycerine are accounted for by using the principle of system expansion. According to the ISO standard (ISO 14041, 1998), system expansion is preferable over allocation methods based on physical or economic characteristics. Furthermore, the majority of LCA practitioners favor the principle of system expansion over other allocation methods (Jungmeier, 2007). The by-product rape meal is mainly used as animal fodder by substituting soybean meal from the U.S. Glycerine substitutes primarily synthetic glycerine produced in the chemical industry. Also here, the specific primary energy use to produce these substituted products is kept constant over time to examine the sole technological learning effect.

Two impact categories are defined to obtain aggregated scores for the environmental performance: *primary energy use* and *global warming*. The calculated energy flows can be attributed directly to the impact category *Primary Energy use*. The three GHG emissions are multiplied with their corresponding global warming potentials to obtain the CO_2 equivalents, which are subsequently summed up to a total score for the *Global Warming*. Finally, it will be attempted to plot the scores from different years against the cumulative RME production in order to construct an experience curve.

3.2.4 Explanation of past developments and future outlook

The possible reductions in production costs, primary energy use and CO_2 equivalents have most likely been a result of technological learning. Biodiesel producers, technology providers[7] and experts from the biodiesel field were consulted to find out which learning mechanisms and underlying factors have driven these reductions and at what particular time. Examples of underlying factors are policy, tax regime, exogenous price developments, legislation, etc. Finally, an outlook will be made based on the extrapolated experience curves, literature studies, market analyses and expert opinions.

[7] The biodiesel producers and technology providers will be inquired by means of a questionnaire.

4. Data collection and processing

4.1 Data collection

Production volumes and inflation index

The production volumes of rapeseed (1950-2006) were taken from the Federal Statistical Office in Germany (2007). For the period 1950-1990, production volumes apply to the former Federal Republic of Germany (West Germany), since no data were found for the German Democratic Republic (GDR). For the period 1991-2005, production volumes apply to the (current) Federal Republic of Germany. Unfortunately, the lack of data on RME production volumes necessitated the use of aggregated data on total biodiesel production. The fixed exchange rate to convert from Deutsche Mark (DM) to Euro (€) was taken from the German Federal Bank (2001). The consumer price index was taken from the Federal Statistical Office of Germany (2007) (see also appendix B-I).

Production costs

Data on rapeseed production costs were collected for the years 1971-2006 and mainly taken from two datasets: the *KTBL Taschenbuch Landwirtschaft* (1976-2002) and the *KTBL Betriebsplanung* (1985-2006). Again, no data were found for the GDR. Data for the period 1971-1990 applies to West Germany; data for the period 1991-2006 applies to the (current) Federal Republic of Germany. Due to a lack of data on rapeseed production costs for the years before 1976, data were taken for oil fruit production costs instead (1971 and 1975). The KTBL datasets describe costs for seed, fertilizer, chemicals, storage/drying, weather insurance, analysis costs, labor requirements and partly also the land, labor and variable and fixed capital costs. Unfortunately, no single dataset was available for land costs. Therefore, several sources had to be used: 1971-1977 (Klare *et al*, 1979), 1975-1983 (Federal Statistical Office Germany, multiple years *a*), 1981-1995 (Federal Statistical Office Germany, multiple years *b*) and 1993-1999 (Doll, 2002). For the years 1987, 1993 and 1996, the fixed and variable capital costs were calculated by using data from a Swiss agricultural research institute (ART, 2007; FAT, 1993). Rapeseed prices were collected at the ZMP (Schenck, 2007); agricultural subsidies were taken from the Statistical Office in Germany (2007). Figures for the average rapeseed yields (1957-2006) were taken from the ministry of agriculture, nutrition and forest (Hauser, 2007) and the Federal Statistical Office in Germany (2007).

Data on the industrial processing costs (oil extraction and esterification) were very difficult to collect. Ideally, the industrial processing costs would be acquired at the esterification plants directly as these are the most accurate and reliable data available. Therefore, a questionnaire was devised and sent to all industrial esterification plants (36) and technology providers (5) in Germany (see appendix A-III). Unfortunately, only a few biodiesel producers responded due to the extremely competitive biodiesel market. Next to the questionnaire, numerous stakeholders associated with the German biodiesel market, were consulted for data about production costs (see appendix A-IV). Again, hardly any data were found. Therefore, it was necessary to extract cost data for the period 1991-2006 from literature sources only.

Both the biodiesel producers and the technology providers were reluctant to relinquish data on investment costs. Therefore, turnkey investment costs were taken from several press releases (see appendix C-IV). Furthermore, scaling factors were taken from the Desmet Ballestra Group (Kock, 2006) and Leifert (1996).

Energy flows and GHG emissions

No data sources were available about the environmental performance of rapeseed before the introduction of RME in 1991 (Reinhardt, 2007). After 1991, a multitude of German LCA studies about RME have been published. Most studies used an array of data sources, all originating from different years and different countries. The majority of German LCA publications, the underlying datasets and salient features are shown in table 3.

German Publication	**Reference place**	**Reference year**	**Underlying dataset[8]**
Reinhardt, 1993	Germany	Early nineties	*Own data*
Ministry of Environment, 1993	Germany	Early nineties	Reinhardt, 1993
Stelzer, 1998	Germany	Mid nineties	Various sources
Borken *et al*, 1999	Germany	2000	*Own data*
Ministry of Environment, 1999	Germany	Late nineties	Reinhardt, 1993; Borken *et al*, 1999
Dreier, 1999	Germany	1997	Various sources
Dreier & Tzscheutschler, 2000	Germany	1999	Dreier, 1999; various sources
IFEU, 2000	Germany	2003-2010	Borken *et al*, 1999
Gärtner & Reinhardt, 2001	Germany	Unknown	Borken *et al*, 1999
Gärtner & Reinhardt, 2003	Germany	2000-2005	Borken *et al*, 1999; Gärtner & Reinhardt, 2001
Non-German Publication	**Reference place**	**Reference year**	**Underlying dataset[8]**
General Motors, 2002	Europe	2010	E^2 – database
Groves, 2002	England	2002	Own data
Ademe, 2002	France	2009	Own data
Mortimer, 2003	Everywhere	Unknown	Previous studies up to 2003
Quirin *et al*, 2004	Europe	2010	Previous studies up to 2003
Larson, 2005	Everywhere	2005-2010	Previous studies up to 2005
Varela *et al*, 2006	Everywhere	2010-2030	Previous studies up to 2006
Concawe, 2007	Europe	± 2002	Ademe, 2002; Groves, 2002
Schmidt, 2007	Denmark	± 2000	Eco-invent 2004; own data

Table 3: *Overview of majority of examined LCA publications, the reference place and year, and the underlying datasets.*

Table 3 shows that the multitude of LCA studies pertaining to Germany were based on the only two German datasets available, both composed by the IFEU (1993 and 1999). These datasets were used for this study as well. This study used the first dataset (Reinhardt, 1993) for the year 1993 and the second dataset (Borken *et al*, 1999) for the year 2000. The latter dataset was published in 1999, but applies to the reference year 2000. The datasets contain data originating from several years and pertain to a period rather than a particular year. However, the datasets were preferable over the individual studies because a considerable share of the data was produced by the IFEU itself. For the year 2007, the most recent LCA studies with original underlying datasets were used (see table 3). The Danish LCA study by Schmidt (2007) was used for the *direct* processes of the rapeseed production and oil production. Schmidt (2007) used Danish and Swiss data for the agricultural stage. The Swiss and Danish agricultural conditions were assumed to resemble the German conditions due to the geographical vicinity. For the *direct* processes of the esterification, an English (Groves, 2002) and a French LCA study (Ademe, 2002) were used. Unfortunately, no more recent data could be found for this sub-process. Borken *et al* (1999) was the only dataset containing data about other impact categories (e.g. acidification). It was therefore not possible to investigate the development of other impact categories over time. The specific energy use – and concomitant GHG emissions – of each transport mode were taken from Borken *et al* (1999).

[8] Only the most important datasets are mentioned; often multiple data sources were used.

Transport was assumed to take place with a 40 tonne truck, an average diesel engine transport train and an average diesel engine inland ship (Borken *et al*, 1999). The energy and mass flows associated with the combustion stage of RME were taken from the Concawe study (2007). The Concawe study uses an average passenger car with a direct injection diesel engine, which is driven 100 km over the New European Driving Cycle (NEDC) (see appendix B-II). The conversion efficiencies and GHG emissions related to the heat production from natural gas (industrial furnace, 100 kW) and heavy fuel oil (industrial furnace, 1 MW) were taken from the Eco-invent database (2004). The Eco-invent database (2004) was also used for the German electricity mix from the year 2000. The conversion efficiency and GHG emissions related to steam production were taken from the Concawe study (2007). Reinhardt (1993) was used for the primary energy use and GHG emissions associated with the life cycle of fossil diesel. Global Warming Potentials (GWP) were taken from the IPCC (2001) and measured over a period of 100 years. For conversion factors, specific GHG emissions and GWP, see appendix B-II.

4.2 Data processing

Production volumes

The rapeseed production volumes were added up over the period 1950-1971 to get the initial cumulative production for the year 1971 (1.75 million tonnes). The initial RME production in 1991 amounted up to 200 tonnes. Despite the fact that vegetable esters were produced before the biodiesel era, the initial cumulative production was set at 200 tonnes. More attention will be given to this subject in the sensitivity analysis (chapter 6) and discussion (chapter 7).

Production costs

Production and investment costs originating from years before 2002 were converted from the old German currency (Deutsche Mark) into Euros. Furthermore, all production and investment costs were corrected for inflation.

The feedstock costs have been calculated both per tonne rapeseed and per hectare. The costs per hectare were obtained by dividing the costs per tonne by the average rapeseed yield. The average rapeseed yield was calculated by taking the average of the yield of three years in a row in order to correct for seasonal variations. Several assumptions were made to fill the gaps in the datasets and to be able to compare the feedstock costs over the years. For the years 1971 and 1975, the amounts of fertilizer requirements and prices were taken from 1976. Due to a lack of data, the analysis costs and the amounts of lime and water required for the rapeseed production were assumed to remain constant over time and were taken from the year 2004 and 2006. A five-year average was calculated for the data omissions in the fixed capital costs (1971, 1975, 1985 and 1989). Also for the agricultural wages, a five-year average was used for the data omissions (1985, 1991, 1996, 1997, 2000 and 2002).

The analysis of the industrial processing costs was rather difficult due to the high variety in data sources. The differences between the studies regarding the cost structures and aggregation levels of the data made it very difficult to compare the figures in a sound way. Therefore, several assumptions had to be made, especially concerning the different transport steps. It was not always clear whether the transport of rapeseed (oil) to the esterification plant was included in the costs or not. These transportation costs were excluded from the analysis in case the author mentioned them explicitly. Assumptions were made for Kleinhanß *et al* (1992), Leifert (1994), Schiele (1996), Schöpe (2006), Keymer (2000), IFO (2002) and

Chacón (2004) regarding the costs associated with the distribution, storage and sale of RME. Three-year averages were used to fill these data gaps (see also section 5.2.2). The study commissioned by the German parliament (Deutscher Bundestag, 2004) did not present any data on oil milling costs. Therefore, oil-milling costs from Chacón (2004) were used. It was not possible to correct the production costs for scaling, as plant sizes were often not mentioned.

Energy and GHG emissions

Borken *et al* (1999) was the only dataset containing all data necessary for the recalculations to the methodological framework. Furthermore, Borken *et al* was also the most recent and detailed *German* dataset. Therefore, data from Borken *et al* (1999) was used for the data omissions in 1993 and 2007. For the year 1993, data from Borken *et al* was used for the amounts of bleaching earth, sodium hydroxide and soybean meal per tonne RME. For 2007, data from Borken *et al* (1999) were used for the distances of rapeseed transport and the amounts of lime, phosphoric acid, sodium hydroxide, methanol and “other chemicals” per tonne RME. The energy and mass flows associated with the distribution of RME were used for both 1993 and 2007.

The primary energy flows and GHG emissions of the *direct processes* were recalculated by using the same conversion efficiencies for heat, steam, fossil diesel and electricity for all years. The CO_2-equivalents were calculated by multiplying the amounts of emitted GHG per tonne RME with their corresponding Global Warming Potentials. The datasets did not provide enough information on the composition of energy carriers comprising the *indirect energy flows*. As a result, the primary energy use and GHG emissions could not be recalculated using the conversion efficiencies mentioned above. In order to avoid *observed* changes in energy and mass flows due to different conversion factors used by the different datasets, the same specific primary energy use, i.e. the primary energy necessary to produce one unit of a particular indirect compound, was used for all three years (1993, 2000 and 2007). This specific primary energy use was multiplied by the amount of indirect compound. The same was done for the GHG emissions. The specific primary energy use - and associated GHG emissions - of all indirect compounds were taken from Borken *et al* (1999). An exception was made for *nitrogen* fertilizer production, since this exogenous factor may have contributed to significant further reductions in the environmental performance of RME over time. Three different values for the specific primary energy use of *nitrogen* fertilizer production (1993, 2000 and 2007) were calculated by using data from Ramirez (2005). The experience curve, as constructed by Ramirez (2005), for the specific primary energy consumption of ammonia production by means of *average* technologies, was extrapolated to obtain values for the years 2000 and 2007. The global production volumes of ammonia, necessary for the extrapolation of the experience curve, were taken from the International Fertilizer Industry Association (IFA, 2007a). The values associated with the extrapolation of the experience curve are given in section 5.3. The specific primary energy uses - and concomitant GHG emissions - of rapeseed transport were multiplied with the transport distances per transport mode. It was not always clear whether the energy and mass flows, associated with the transport of indirect compounds, were already accounted for in the life cycles of the indirect compounds. More attention will be given to this subject in the discussion (chapter 7). The specific primary energy use of the by-products was also kept constant and taken from Borken *et al* (1999).

5. Results

5.1 Specific observed developments

Before quantifying technological learning in detail, several qualitative developments in agriculture and industry are described, which have influenced, and/or will most likely influence, the developments in production costs and environmental performance of rapeseed and RME over time.

5.1.1 Rapeseed production

Rapeseed varieties

The introduction of the “0-rapeseed” and “00-rapeseed” in the seasons 1974/1975 and 1986/1987 has been the major trigger in the first development growth of rapeseed. The lower contents of bitter oil acids and glucosinolates made the new varieties better edible than previous rapeseed varieties (ABI, 2001). The advantages of the new varieties were twofold. First, the sales potential and consumption possibilities of rapeseed were extended. Second, rapeseed would become a suitable feedstock for biodiesel production, as from that moment on the emerging by-product rape meal could be used as animal fodder due to the low content of bitter oil acids and glucosinolates (Roesch, 1997). The advent of hybrid varieties in the late nineties led to an increase in average rapeseed yields of around 5% compared to conventional rapeseed varieties. At the same time, new varieties were made with a higher resistance against insect infestations and plant diseases, which resulted in a lower use of herbicides, pesticides and fungicides, and thus, in lower production costs and environmental pollution (Roesch, 1997). Nowadays, both quality improvements and yield increases are considered important in new rapeseed varieties.

In the future, breeding programs will continue to exist, as the demand for tailored rapeseed varieties will remain. Genetically modified (GM) rapeseed will come to the fore as a promising, yet highly disputed, alternative variety to achieve further improvements. GM rapeseed may be used to enhance oil quality, increase yields and reduce the need for fertilizers and chemicals, but may also entail numerous environmental dangers to human health, wildlife and other organic species (IEA, 2004; WWI, 2006). The environmental dangers have already evoked resistance among several stakeholders in the German society (GAC, 2003). To date, the cultivation of GM rapeseed has been forbidden by the EU (BBF, 2006). In March 2007, the European Commission authorized the import of three GM rapeseed varieties on the EU market. These varieties are only allowed to be used for animal fodder or industrial purposes (European Commission, 2007b).

The pursuit for rape oil quality optimization, either by conventional, hybrid or GM varieties, is relevant for the further development of biodiesel in Germany. Especially the fatty acid profile needs further optimization to enhance the suitability of biodiesel for the diesel engine. For the ideal biodiesel, a proper trade-off has to be made between short-chain and long-chain fatty acids to optimize the positive and minimize the negative traits of both chains. More ideal mixtures of short and long-chain fatty acids can be obtained by improving rapeseed varieties, but especially by mixing several vegetable oils together. The future biodiesel will therefore likely be produced from an array of different feedstock (Hansen, 2007; Körbitz, 2007). Relevant traits of biodiesel are the winter operability, smoothness of the combustion process, ignition behavior, combustion emissions, fuel stability and the energy content (ABI, 2007a). As climate conditions differ per region, the optimal fatty acid profile will differ as well since each climate requires a different pattern of biodiesel characteristics. For example, winter operability will be less of an issue in tropical areas than in colder areas. So far, no optimal fatty acid profile has been found (yet) for Germany. Despite the rise of alternative feedstock crops for biodiesel, a continuous demand will exist for new, improved rapeseed varieties. Close communication and cooperation with oil seed breeders and the automotive industry are imperative to realize these new varieties. In the end, the diesel engine dictates the necessary characteristics of biodiesel, and thus, of the rapeseed varieties – as well as other feedstock varieties – required for the most optimal biodiesel (Körbitz, 2007).

Rapeseed yield

The rapeseed yield tends to differ for each year and for each location in Germany, due to the varying environmental conditions, incidence of diseases and crop rotation (see figure 7). The yield fluctuations pose a serious risk for (investors in) biodiesel plants, which have to deal with varying prices and supply quantities of rapeseed. Despite the yield fluctuations over time, an increasing trend can be discerned in the *average* rapeseed yield in Germany over the period 1957-2006 (see figure XXX). An average annual yield increase was calculated of 2% since the 1950s (Kaltschmitt *et al*, 2005). The increase in average rapeseed yield has mainly been a result of new rapeseed varieties (Gärtner, 2008). The past has shown a long-term tendency towards higher yields, but it is not sure whether this trend will continue in the future. In literature, only rough estimations are made about future rapeseed yields. Some studies project yields to increase slowly, but steadily in the future with average annual yield rates of around 1-2% (Thrän *et al*, 2004; Zeddies, 2006). The development of new rapeseed varieties will most likely continue to play the main role in yield increases (IEA, 2004). As noted before, the deployment of GM rapeseed varieties could contribute significantly to higher rapeseed yields. However, public resistance has impeded the realization of this development so far.

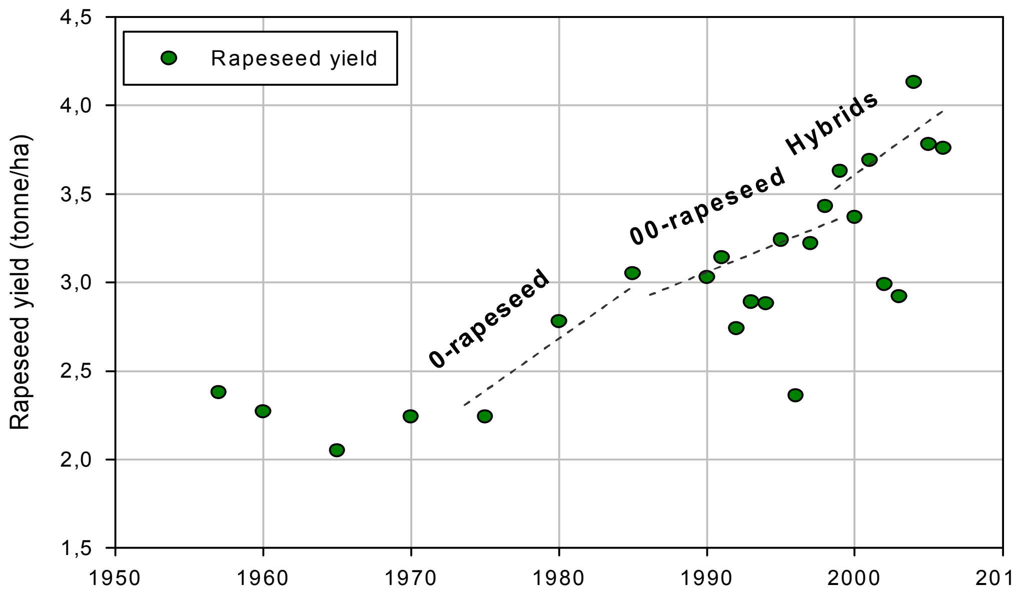

Figure 7: *Rapeseed yields in Germany over the period 1957-2006. Rapeseed varieties related with yields are indicated in the figure (Data sources: ABI, 2001; Federal Statistical Office Germany, 2007).*

Agricultural land prices

Non-food rapeseed is predominantly cultivated on agricultural lands, which are set aside according to the Common Agricultural Policy. Nowadays, the majority of agricultural land is leased instead of owned by farmers (Doll, 2002). Furthermore, around 60% of the non-food rapeseed is cultivated in the eastern states (ABI, 2001) (see also appendix B-V). Land lease prices vary along with the soil conditions, natural yield rate, climate conditions and the site-related political framework (Doll, 2002). In addition, different land market structures in West Germany and the GDR, later remaining as an inheritance in the Federal Republic of Germany, have been another reason for the large variety in land lease prices all over Germany. The fierce competition on the agricultural land markets in West Germany stood in stark contrast to the quasi-monopolistic market in the GDR. At the moment, the land markets in the eastern states are being privatized and restructured to match prices with the actual market value of the agricultural lands (Doll, 2002).

In the period 1971-1989, average land lease prices in West Germany remained rather constant at a level of around €200/ha (Doll, 2002; Klare, 1979) (see figure 8). The huge discrepancy in land lease prices between western and eastern states remained after the accession of the GDR; the average land lease price was €254/ha in the western states and €90/ha in the eastern states in 1993 (Federal Statistical Office Germany, 1993). However, the land lease prices also varied among the western states; the average land lease price was €91/ha in Saarland and €314/ha in Nordrhein-Westfalen in 1991 (Federal Statistical Office Germany, 1991). Over the period 1993-1999, land lease prices in the eastern states recovered as a result of the restructuring processes. Nonetheless, this increase was offset by the decrease in land lease prices in the western states, resulting in a slight decrease in the *average* land lease price in the Federal Republic of Germany. From 2002 onwards, average land lease prices have increased both in the western and eastern states. Despite the convergence in land lease prices between eastern and western states after the accession of the GDR, a significant gap still remains (Doll, 2002).

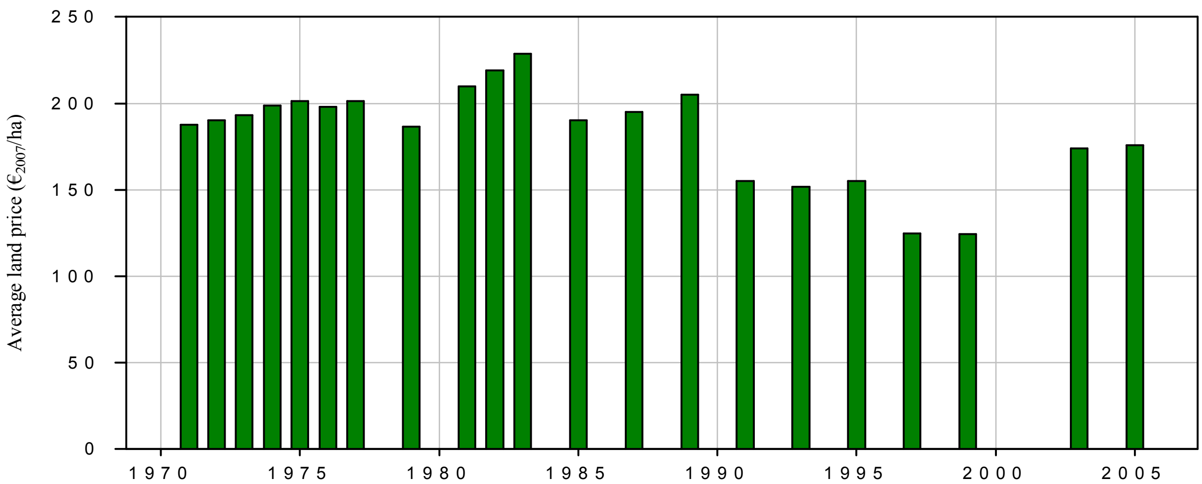

Figure 8: *Average agricultural land lease price for greenlands in West Germany (1971-1989) and the Federal Republic of Germany (1991-2005) (Data source: Klare, 1979, 1984, 1996; Doll, 2002).*

The multitude of price-determining factors makes it difficult to give an outlook on future land lease prices in the Federal Republic of Germany. Nonetheless, two relevant trends are expected to take place in the future (Doll, 2002). First, the convergence trend in land lease prices between the western and eastern states will continue. Second, future land lease prices will be increasingly influenced by international markets and prices due to ongoing liberalization and globalization processes on the agricultural markets.

Fertilizer

A broad array of studies stress the major share of fertilizers in the total costs, primary energy use and GHG emissions associated with rapeseed production (e.g. Dreier, 1999; Chacón, 2004; Quirin *et al*, 2004). The amount of fertilizers used by farmers has decreased over time mainly due to learning-by-doing, whereas environmental laws on fertilizer usage are not expected to have contributed to this regress (Gärtner, 2008). The energy efficiency of the nitrogen fertilizer production process has improved significantly since the 1960s, mainly due to energy efficiency gains in the production process of ammonia (Ramirez, 2005). As natural gas accounts for 70-90% of the ammonia production costs and 70-75% of the urea[9] production costs, changes in natural gas prices have a considerable influence on nitrogen fertilizer prices, and thus, on the production costs of RME. Despite strong fluctuations in the nitrogen, phosphor and potassium fertilizer prices, a clear downward trend can be discerned from the 1980s to the beginning of the 21st century (see figure 9). From 2002 onwards, prices of triple super phosphate, potash and in particular urea have been increasing (FAO, 2007).

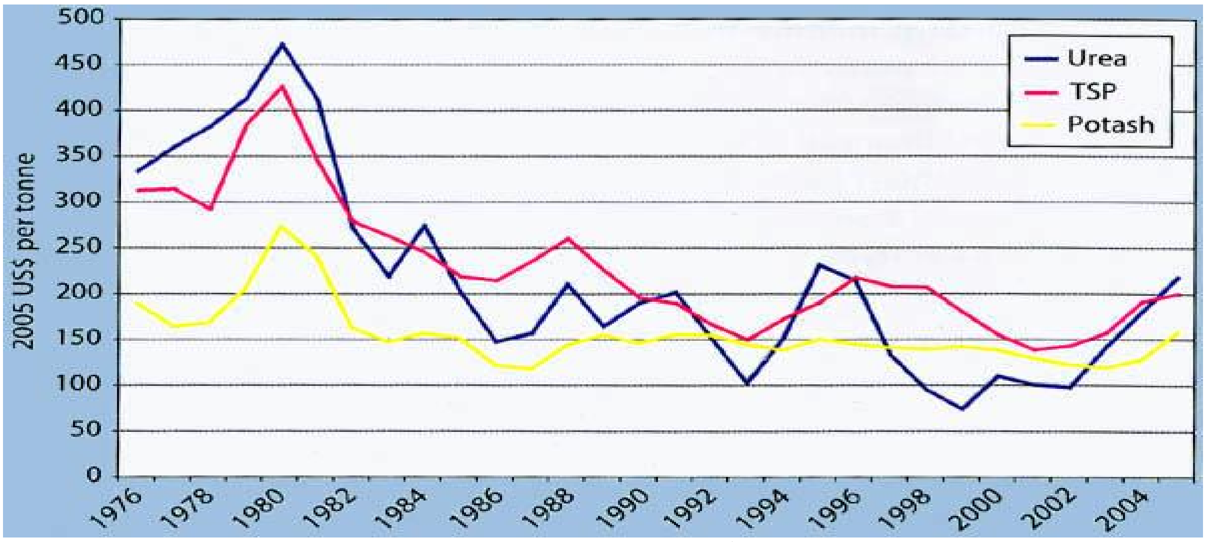

Figure 9: *Prices for urea, triple super phosphate and potash (in US$) over the period 1976-2006 (Data source: FAO, 2007).*

The potential for energy savings in the ammonia production process are still significant, although limited to a thermodynamic minimum of energy necessary to produce the ammonia (Ramirez, 2005). The European Commission (2006) issued a list of different technologies to reduce N_2O emissions associated with the production process of the raw material nitric acid. These technologies can reduce N_2O emissions from 30-50% up to 98-99% (Schmidt, 2007) and could have positive implications for the environmental performance of RME. Also in the future, nitrogen fertilizer prices will depend strongly upon energy efficiency improvements and natural gas prices. Only little potential is left for further energy savings in the production processes of phosphorous fertilizers due to the simplicity of these processes. As energy plays a relatively minor role in the production process of phosphorous fertilizers, prices will be less affected by fluctuating energy prices. Expert opinions differ whether the usage of nitrogen

[9] Ammonia and urea are two of the five most important nitrogen fertilizers used today in the world (Ramirez, 2005).

fertilizer in agriculture will increase or decrease in the future. The introduction of GM rapeseed varieties may lower the need for fertilizers (IEA, 2004). More consensus exists on the expected regress in phosphorous fertilizer usage (IFA, 2007b; Quirin *et al*, 2004).

5.1.2 Industrial processing

Technological changes

Batch → Continuous
The process innovation from batch systems to continuous systems has been the most important technological change in the esterification step (Dallos, 2007). Batch systems are usually found in small-scale biodiesel plants and continuous processing systems in large-scale biodiesel plants. The main advantages of batch systems are the low investment costs and the ability to adapt to several raw materials and small processing quantities, while guaranteeing sufficient product quantity. The main disadvantages are the inconsistency of the production process, safety issues and the high variable costs (Connemann, 1998). The introduction of the so-called CD process was the first processing technology that could produce with a higher biodiesel throughput per time unit, smaller processing equipments and at low variable costs (Connemann, 1998; Dallos, 2007). This process innovation was often accompanied by the implementation of automatic control systems, which enabled the control and measurement of the production process in a less labor intensive way (Wörgetter, 2007). Lower production costs have been the main driver for the shift from batch to the continuous and automated processing technologies (Dallos, 2007). Connemann (2007) and Starke (2007) consider technological improvements (learning-by-searching) to be the second most important factor that has contributed to the reductions in *relative* production costs[10] over time.

Single feedstock → Multi feedstock
Another technological change in the esterification step is the shift from single-feedstock to multi-feedstock technology (Hansen & Vaals, 2005). At the outset of the biodiesel industry, the majority of biodiesel plants were driven by single-feedstock technologies capable of processing merely one feedstock, predominantly rape oil. Over time, both existing and newly built biodiesel plants were increasingly retrofitted and equipped with multi-feedstock technologies. Multi-feedstock technologies are capable of processing feedstock with higher free fatty acids contents - e.g. palm oil, waste oils and animal fats - whereas single-feedstock technologies can only process half or fully refined vegetable oils with low free fatty acids contents (Bacovsky *et al*, 2007). Multi-feedstock technologies have additional reaction steps, such as a pre-esterification step that converts, directly or indirectly, the free fatty acids into biodiesel. Despite the differences between both technologies, the plant yields (efficiencies) are quite similar for single and multi-feedstock plants, viz. nearly 100% (Bacovsky *et al*, 2007). However, multi-feedstock plants can achieve lower variable production costs due to the possibility of selecting the feedstock with the lowest prices (ABI, 2007b).

Plant yield
The yields of both the oil extraction and esterification stage have increased over time due to efficiency improvements in the production processes. Especially the exploitation and

[10] The term *relative* production costs is used here to stress the decline in production costs as a result of technological learning. The *absolute* production costs have risen over the last years due to higher raw material prices.

recovery rates of input products during the esterification process have improved considerably (Gärtner & Reinhardt, 2005). Furthermore, anecdotal reports indicate a slight decline in the energy use up to the year 2000, after which the energy use has most likely stabilized (Alfort, 2007; Reinhardt, 2007; anonymous, 2008). However, it should be mentioned that the energy use per tonne RME differs considerably for each biodiesel plant due to the varying processing technologies. For example, the separation of RME and glycerine may occur either in a settling tank (low energy use) or by means of centrifugation (high energy use) (cf. section 2.1.2). As mentioned above, nowadays, plant yields are nearly 100% for both single-feedstock and multi-feedstock plants. The efficiency improvements of the esterification process were vital as the plant yield is the second most important factor determining the profitability of the plant (see figure 12). In the nineties, plant yields of around 85-95% were normal; today, a plant yield of 95% is considered moderate and a plant yield of 90% catastrophic (Körbitz, 2007). In the beginning of the biodiesel industry, cost reductions were mainly a result of improved plant practices and the achievement of full plant capacity. Learning-by-doing is therefore considered to be the most important learning mechanism during this period, whereas upscaling has been the main reason for cost reductions in recent years (Wörgetter, 2007). According to several biodiesel producers[11], learning-by-doing was considered to be the second or third most important factor in the past relative cost reductions *over the entire period* of the biodiesel industry. A striking development in the German biodiesel industry has been the stark separation in the developments of plant technologies, due to a lack of communication among the technology providers. All technology providers learned separately from each other and devised their own proprietary processing systems (Dallos, 2007). Consequently, each technology provider offers another plant technology with different yields, feedstock processing abilities and range of plant sizes. The most optimal plant technology depends on the objective of the biodiesel producer and differs for each individual and complex investment (ABI, 2007). As the processes of oil milling and esterification are fairly straightforward and yields of nearly 100% are already achieved, no further improvements are expected to occur in the future (Dallos, 2007; Gärtner, 2008). The processing of biodiesel and the recovery of excess input products are already nearly technically and economically optimal. However, a further optimization of the by-product processing is likely to occur, provided that the by-product revenues will outweigh the necessary investments (Dallos, 2007).

<u>Biodiesel plants</u>

Number of plants

The number of industrial biodiesel plants in Germany has increased rapidly over the period 1991-2007 (see figure 10). Unfortunately, not enough data were available to determine the technological nature (single or multi-feedstock) of all the industrial plants. Nonetheless, some clear trends can be observed in figure 10 regarding the market developments over time. Until 2000, the biodiesel industry was mainly driven by single-feedstock plants, using rape oil as feedstock. From 2000 onwards, the number and share of multi-feedstock plants increased rapidly (Hansen, 2007). In parallel, the average plant capacity increased faster for multi-feedstock plants than for single-feedstock plants, resulting in a growing share of multi-feedstock plants in the total production capacity. The low variable costs and the improved fatty acid profile of multi-feedstock biodiesel will probably lead to a further continuation of this trend. As of the year 2000, a similar trend can be observed for the so-called "annex plants", i.e. biodiesel plants with an integrated oil mill. As the minimization of transport costs

[11] Biodiesel producers inquired by means of questionnaire and/or telephone: Groos (2007), Rosengarten (2007), Schweiger (2007) and Starke (2007).

gained in importance, the number and share of annex plants increased as well. The available data on biodiesel plants indicate that annex plants have already exceeded stand-alone plants in number. Additional information and figures on the development of the number of biodiesel plants can be found in appendix D-I.

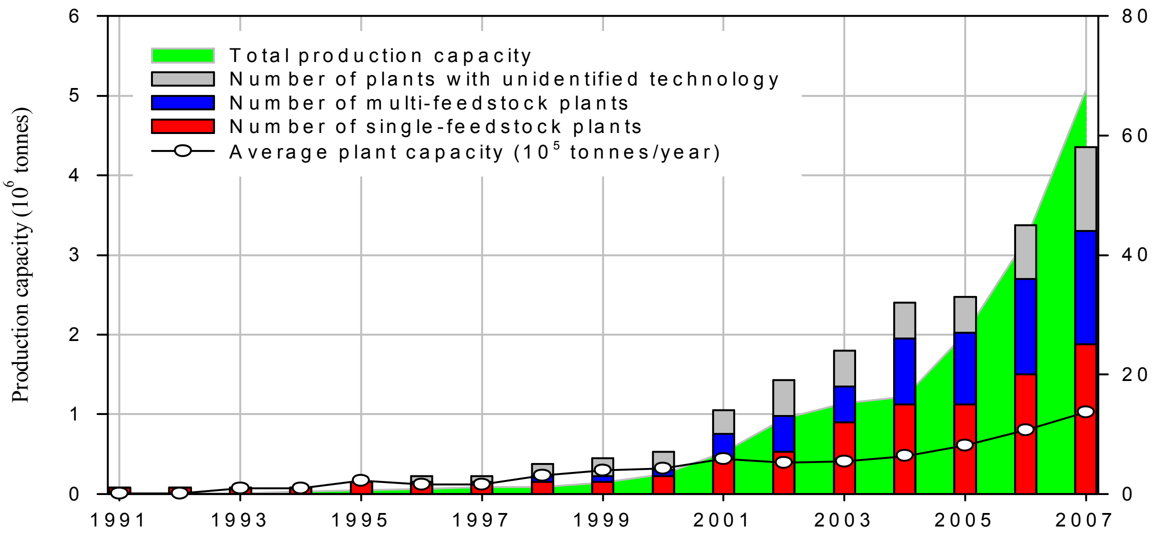

Figure 10: *Number of biodiesel plants, total biodiesel production capacity and average plant capacity over the period 1991-2007 (Data sources: ABI, 2001; VDB, 2006; FNR, 2007; multitude of press releases[12]).*

Production capacity and upscaling

A second observed development is the increase in the average plant capacity over time (Hansen, 2007). The reason for this development is twofold. First, the production capacities of newly built biodiesel plants have increased tremendously (Alfort, 2007). In the nineties, production capacities of modern plants did not exceed the 100 ktonnes per year; nowadays, production capacities of modern plants are usually above the 200 ktonnes per year. Second, the production capacities of existing plants were augmented on a large scale. Several biodiesel plants extended their production capacities in the years 2004-2007, ranging from 0.3 ktonnes/year to over 100 ktonnes/year (see appendix D-I).

Until 2004, the steady increase in the total production capacity was mainly realized by the building of new plants. From 2004 onwards, the total production capacity experienced a boom due to an investment wave in the biodiesel industry, which was triggered by the amendment of the law on the mineral oil tax in 2004 (Bockey, 2005). The surge in production capacity was on the one hand realized by a sharp increase in the number of newly installed high-capacity plants, and on the other hand by the upscaling of existing plants. Despite the significant contribution of the upscaling of existing plants on the total capacity expansion in the last four years, this process has played only a minor role over the entire period 1991-2007. Over this period, a percentage of 22.1% (1.36 mln. tonnes/year) of the total production capacity expansion can be attributed to the upgrading of existing plants, whereas 77.9% (4.82 mln. tonnes/year) can be attributed to building of new plants. As can be seen in figure 10, both developments had a substantial effect on the average plant capacity, which more than doubled in three years time from 47.6 ktonnes/year (2004) to 102.7 ktonnes/year (2007). As mentioned above, the upscaling process took place for single-feedstock as well as for multi-feedstock plants; the average plant capacity of single and multi-feedstock plants was

[12] See appendix C-IV.

respectively over six and 23 times higher in 2007 compared to 1999. Additional information and figures on the development of the production capacities can be found in appendix D-I. Connemann (2007) and several biodiesel producers (Groos, 2007; Rosengarten, 2007; Schweiger, 2007) consider the increased biodiesel production, but above all the upscaling of biodiesel plants (learning-by-upscaling), to be the primary reasons for the decrease in *relative* production costs. Upscaling and the further increase in average plant capacity are expected to become the major technological learning mechanism in the future (Gaede, 2008).

The introduction of the Energy Tax Act in 2006 caused a legitimate fear that the annually increasing tax rates will make pure biodiesel (B100) unprofitable in the coming years. The huge production capacity and the drop in biodiesel demand in early 2007 have already resulted in several biodiesel plants to employ less than full capacity (Bockey, 2006). The overcapacity has severely sharpened the competition on the market and stresses the importance of producing at low costs. A low crude oil price or high vegetable oil prices could seriously jeopardize the existence of the production plants (Bockey, 2006). Already several small biodiesel producers were forced to exit the biodiesel market as a result of high methanol, energy and vegetable oil prices (Richter, 2007). The revision of the annually increasing tax rates is therefore imperative for the survival of the biodiesel industry in the future (cf. section 2.2.2).

Investment costs

The technological and plant developments, as described above, had large impacts on the investment costs of biodiesel plants. In general, the new generation biodiesel plants have high production capacities, integrated oil mills and are equipped with continuous, multi-feedstock process technologies with high exploitation and recovery rates of input products and by-products. It is extremely difficult, not to say impossible, to compare the specific investment costs of different plants, due to different characteristics such as plants building materials, site characteristics, infrastructure, annex buildings, by-product processing installations and the large variety of processing technologies (Dallos, 2007; Hilber, 2007). In addition, investment costs are strongly influenced by the market situation. The exploding demand for new plants in recent years exceeded the supply and resulted in much higher charged prices than before the large capacity expansion (Körbitz, 2007). In general, one might say that the specific investment costs have risen, mainly as a result of the shift from single to multi-feedstock plants, but above all because of improved by-product processing facilities (Dallos, 2007). In addition, higher stainless steel prices have also contributed to higher specific investment costs (Alfort, 2007). The above-mentioned developments in technology and plants entail higher total investments costs, but lower variable processing costs. Especially the large-scale investments in by-product processing facilities have increased financial revenues for biodiesel producers, and thus, reduced variable production costs (Dallos, 2007). The higher production capacities of modern plants have been the main factor with a decreasing effect on the specific investment costs (learning-by-upscaling); the second most important factor has been the accumulation of experience with the construction of plants (learning-by-doing) (Dallos, 2007). Finally, the technological innovation from batch to continuous processes has reduced the specific investment costs, because relatively large equipment, machinery and vessels were no longer necessary and replaced by smaller units (Dallos, 2007).

In the *future*, upscaling is expected to remain the most important learning mechanism for further reductions in the *relative* specific investment costs, although the potential for cost reductions is fairly limited (anonymous, 2008). However, the specific investment costs might also increase due to the implementation of more sophisticated by-product processing facilities. However, the market situation will most likely have a larger influence on the future investment costs than the actual plant building costs.

Site selection and shift in transport mode

The fierce competition on the German biodiesel market compels biodiesel producers to further reduce production costs. Low transport costs and a critical site selection have therefore become crucial for the profitability of a biodiesel plant in recent years (ABI, 2007b). Since 2001, the number of biodiesel plants with an integrated oil mill - annex plants - has been increasing rapidly (see appendix D-I). Furthermore, biodiesel plants are more and more built on locations where they can enjoy optimal synergy advantages. Industrial areas for instance provide ample space - also for a potential future plant expansion or glycerin refinery - and the possibility to share (transport) infrastructure, utilities and personnel and maintenance costs. Moreover, industrial areas are often in close proximity of oil mills, oil refineries, feedstock suppliers and methanol producers to minimize transport costs (ABI, 2007b; Kock, 2006). Other suitable locations to erect biodiesel plants are at sea or river harbors and at active freight rail systems.

The need for higher transport efficiencies became even more compelling as a result of increasing specific transport costs over time (ABI, 2007b). Next to a more optimal site selection, higher transport efficiencies were mainly achieved by a shift towards cheaper transport modes. The supply of feedstock was increasingly done by means of train and ship instead of truck (Körbitz, 2007). Figure 11 indicates that transport by water has the lowest and transport by truck the highest specific costs, although Hamelinck (2004) has shown that specific transport costs may range considerably for each transport mode. Furthermore, Hamelinck (2004) indicates that transports distances and costs are scale-dependent, i.e. transport costs tend to increase with the upscaling of production capacities. After all, upscaling and centralization of production facilities often go hand in hand. However, as production facilities are increasingly built at logistically optimal sites, the exact economic effects for the transportation step are ambivalent.

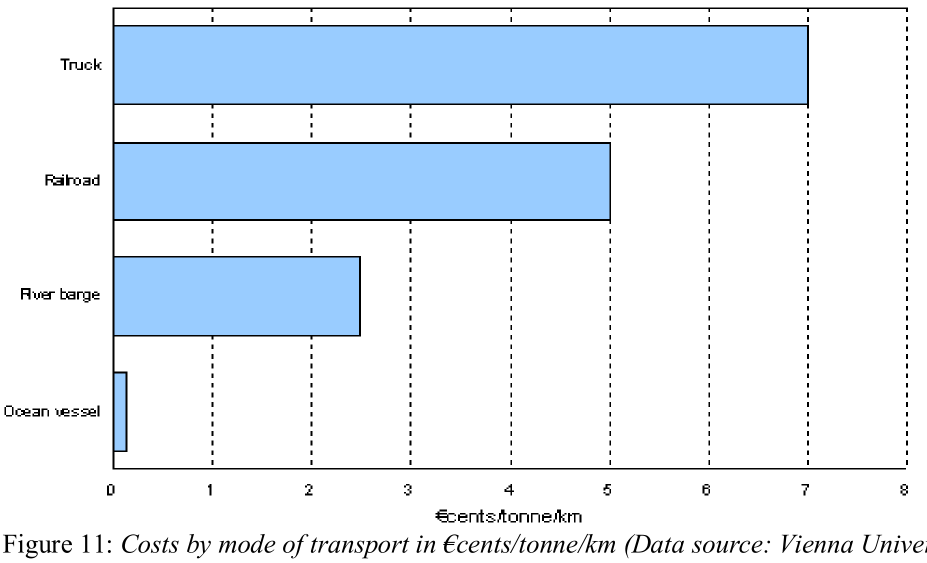

Figure 11: *Costs by mode of transport in €cents/tonne/km (Data source: Vienna University of Economics, 2007).*

The lower specific costs for transport by rail and ships have made the locations nearby harbors and active freight rail systems more interesting for biodiesel producers. Next to the shift in transport modes for the supply of feedstock and oils, more industrial biodiesel plants have changed to the use of pipelines for the transport of biodiesel towards oil refineries.

Pipelines are very cheap and provide a good alternative for transport by truck (Stockinger, 2007). Despite the relatively high share of transport in the total production costs, it plays only a minor role in the energy and GHG emission balance (Jungmeier, 2007).

Expectations are that the specific transport costs will increase substantially for all transport modes in Europe in the nearby future (ABI, 2007b). Transport costs by rail are projected to increase with 20%, whereas transport costs by truck are projected to increase with 40% for the year 2015 compared to 2005. As a further shift from truck to train and ship is likely to occur in the future, the selection of optimal plant locations will increase in importance as well. Locations that provide optimal logistics will lower transport distances and have access to cheap transport modes.

Change in exogenous price levels

The profitability of a biodiesel plant is determined by the processing technology, plant size, depreciation costs, location and several exogenous factors. Figure 12 shows the most important factors influencing the plant profitability and their relative effect with a ten percent change in factor size. As can be seen, over 30% of the plant profitability is determined by the exogenous biodiesel sales price. The plant technology influences the second, and also partly the third, key criteria for the plant profitability, namely the plant yield and feedstock (oil) price. After all, sophisticated multi-feedstock technologies can achieve high yields and influence the feedstock costs by deploying the cheapest feedstock. Apart from the investment costs and labor costs, the remaining factors are exogenous and cannot be controlled by the producer.

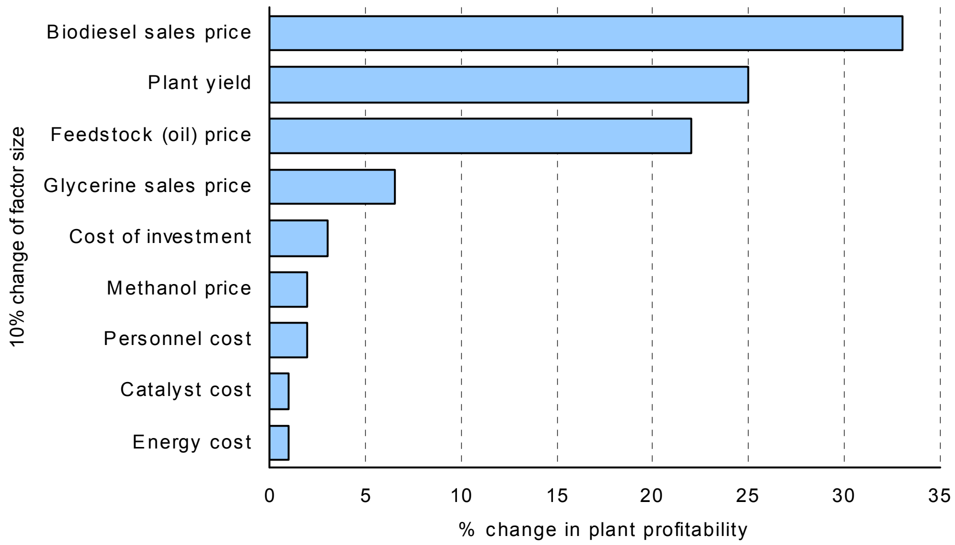

Figure 12: *Factors influencing the biodiesel plant profitability (Data source: ABI, 2007b).*

Feedstock (oil) costs account for 75-90% of the total production costs of biodiesel (Connemann, 2007). Despite the possibility of multi-feedstock plants to use the cheapest feedstock for production, developments in feedstock (oil) prices still have a substantial influence on the plant profitability. Moreover, as prices of different vegetable oils are rather connected in the long term, price increases cannot be completely averted by using alternative feedstock. The substantial influence and the volatile character of rape oil prices were demonstrated in 1997 and 1998 when a high rape oil price and low crude oil price seriously deteriorated the economic performance of biodiesel (ABI, 2001). At the same time, rape oil prices are also affected by the biodiesel production as biodiesel is a strong demand driver for rapeseed. The rapidly growing biodiesel production and the shortage of oil crushing capacity in the last years have already resulted in a large price premium for rapeseed and rape oil since the year 2000. In the summer of 2007, the rape oil price surpassed the biodiesel price (without tax) (see figure 13). The projected growth of the European biodiesel production is expected to impact the feedstock prices even more in the nearby future. Higher rape oil prices and the expected shortfall in domestic rapeseed supply will have biodiesel producers to resort more and more to alternative and imported feedstock (Hansen, 2007).

After the feedstock (oil) prices, glycerin, methanol and energy prices are the largest cost components (Matzen, 2007). The glycerin market and prices will be discussed in the next section. Methanol prices are rather instable and show a strong increase over the last seven years. Together with the increase in energy prices, high methanol and rapeseed (oil) prices have already lowered the profitability of biodiesel production and forced several small biodiesel producers to exit the biodiesel market over the last years (Richter, 2007) (see also figure 13). The growing European biodiesel market will have serious repercussions on the raw material prices and stresses the importance of high efficient biodiesel plants for long-term survival on the market.

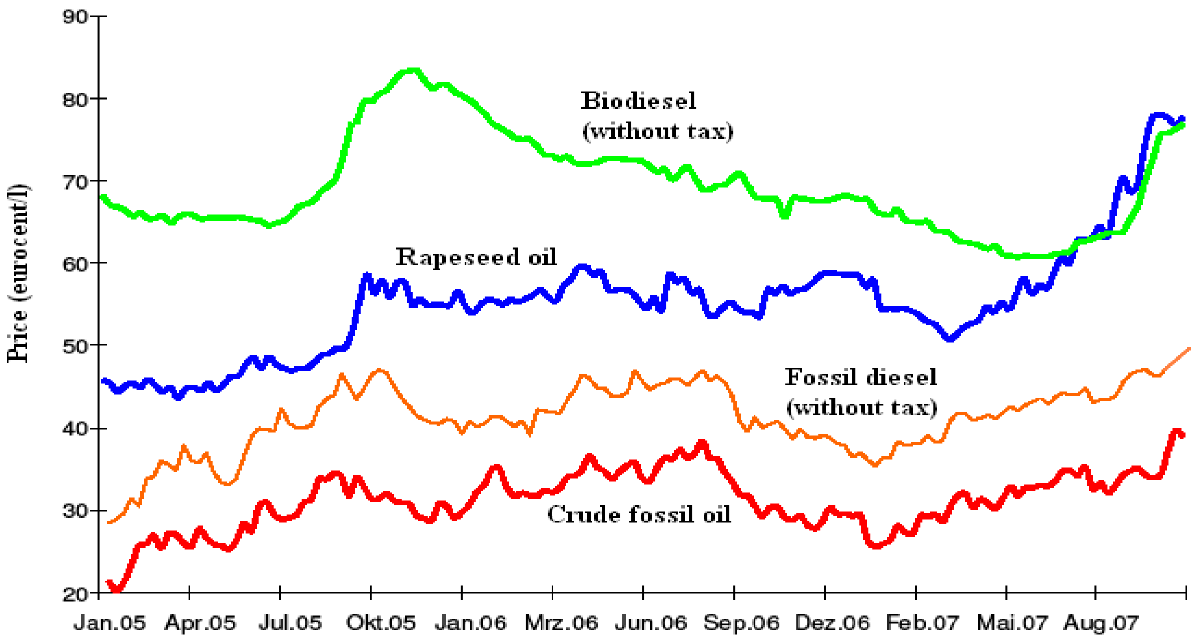

Figure 13: *Development of prices for crude fossil oil, fossil diesel (without tax), rape oil and biodiesel (without tax) over the period January 2005-August 2007 (Data source: UFOP, 2007c).*

By-product markets

The economic and environmental performance of RME is substantially influenced by the prices and usages of the by-products. The by-product rape meal can be used for several purposes. Until now, rape meal has mainly been used as a high-protein substitute for animal fodder made from soybeans (soy meal) (Gärtner & Reinhardt, 2003). In 1997, rape meal already constituted around 29% of the German fodder market (Agra-Europe, 1997). A further replacement of soy meal can be expected in the future, as rape meal prices are lower than soy meal prices. The replacement rate will most likely be amplified by a further decrease in rape meal prices (see also appendix B-VII). After all, the expanding biofuel market will entail excessive amounts of rape meal, which in turn might result in a market glut and, subsequently, in lower rape meal prices. Eventually, the declining trend in rape meal prices will most likely be impaired by the maximum amount of oilseed-meal by-products allowed to be sold on the food market, which is stated in the Blair House Agreement (Arnold *et al*, 2005) (cf. section 2.2.1). The levels of rape meal inclusion in the animal feed industry also depend heavily upon its price discrepancy with soy meal. Rape meal displays structurally lower prices than soy meal. However, as soy meal might become cheaper in the future, the outlet possibilities of rape meal might reduce significantly (Hansen & Vaals, 2005). In the future, the restrained outlet possibilities of rape meal in the fodder market will limit the further expansion of RME production (Wörgetter, 2007). After all, the financial revenues for rape meal are vital for the economic viability of RME.

The political and market conditions necessitate the usage of rape meal in alternative ways, e.g. as fertilizer or fuel for electricity and heat production. In the latter case, rape meal is fermented into biogas first and subsequently combusted in a biogas facility. The alternative usage of rape meal as a fuel results in slightly higher by-product credits for primary energy use and GHG emissions compared to the scenario in which rape meal is used as animal fodder (Gärtner & Reinhardt, 2003). The usage of rape meal as a fertilizer is the least efficient option (Gärtner, 2008).

The by-product glycerin can be sold directly in crude form (80-88% purity) or distilled first and sold in pure form (99-100% purity). As the disposal of raw glycerin achieves merely 30-50% of the refined glycerin prices, it is economically beneficial for large-scale biodiesel plants to refine the crude glycerin themselves (Arnold *et al*, 2005). In 1997, average glycerin prices were affected for the first time by the glycerin supply originating from biodiesel production. Europe, formerly importing crude glycerin from Asia, became self-sufficient due to increasing domestic glycerin supplies. In 2004, glycerin markets were no longer able to accommodate the crude glycerin gluts from the booming biodiesel industry, resulting in a collapse of glycerin prices (Lavers, 2004). Consequently, several major European technology providers (ADM, Cargill, etc.) have been investing in glycerin refining capacities over the last years to enhance the profitability of biodiesel. This capacity expansion has led to a refined glycerin surplus in Europe, which could be exported to the U.S. However, the expected growth of the U.S. biodiesel industry will limit the future outlet possibilities for European glycerin in the U.S (Kotrba, 2007).

At the moment, synthetically produced glycerin is the only eligible form of glycerin that can be replaced by glycerin emerging from biodiesel production. In the nearby future, glycerin prices might depress even further due to the excessive supplies of glycerin emerging from the rapidly growing biodiesel markets. Especially the market for refined glycerin is small and will most likely not be able to accommodate the huge amount of produced RME-glycerin (Arnold *et al*, 2005). On the other hand, many possible new applications for RME-glycerin are already available today, which may counterbalance a further decline in glycerin price.

In the long term, low crude glycerin prices will probably open new markets and facilitate the usage of crude glycerin in alternative ways, e.g. as a process chemical or animal fodder (Arnold *et al*, 2005; Hansen & Vaals, 2005). The shift in glycerin by-product usage will most likely influence the economic and environmental performance of RME; the financial revenues of glycerin for biodiesel producers will decrease considerably due to lower glycerin prices. It is expected that glycerin supply will eventually stabilize as a result of the limited amount of agricultural fields available for RME-rapeseed production. In the long term, expectations are that the stabilization in supply and the opening of new markets for glycerin will result in constant glycerin price levels (Arnold *et al*, 2005; Concawe, 2007).

5.2 Production costs

5.2.1 Rapeseed production costs

The lack of data on the production costs and rapeseed production volumes in the GDR made it sheer impossible to construct an experience curve for this learning system over the period 1971-1990. West Germany is therefore considered to be the only learning system before 1991 (cf. section 3.2.1). The production costs of West Germany were therefore considered to be representative for the GDR, whereas the production volumes were dealt with as if it were *total* production volumes of West Germany and the GDR together. This methodological issue will be discussed in further detail in the sensitivity analysis (chapter 6).

The rapeseed production costs were calculated over the period 1971-2006, both per hectare and per tonne rapeseed[13]. A breakdown of the costs is given in figure 14. Subsidies for energy crop cultivation on set-aside land were excluded from the cost calculations. The two striped, dark gray striped, dark gray bars - the years 1971 and 1975 - denote the average production costs of oil crops in general, not specifically for rapeseed[14]. Over the period 1971-2006, production costs have declined by 70.3% per tonne (1971: €845/tonne; 2006: €251/tonne) and with 49.9% per hectare (1971: €1893/ha; 2006: €947/ha). The difference in cost reduction percentages is mainly due to the increasing yield over time. The increase in rapeseed yield, improved rapeseed varieties and the decrease in fertilizer prices and usage have been the most important factors contributing to the reduction in production costs. Furthermore, the increase in agricultural land price in recent years is reflected in the increasing land costs over this period (cf. section 5.1.1).

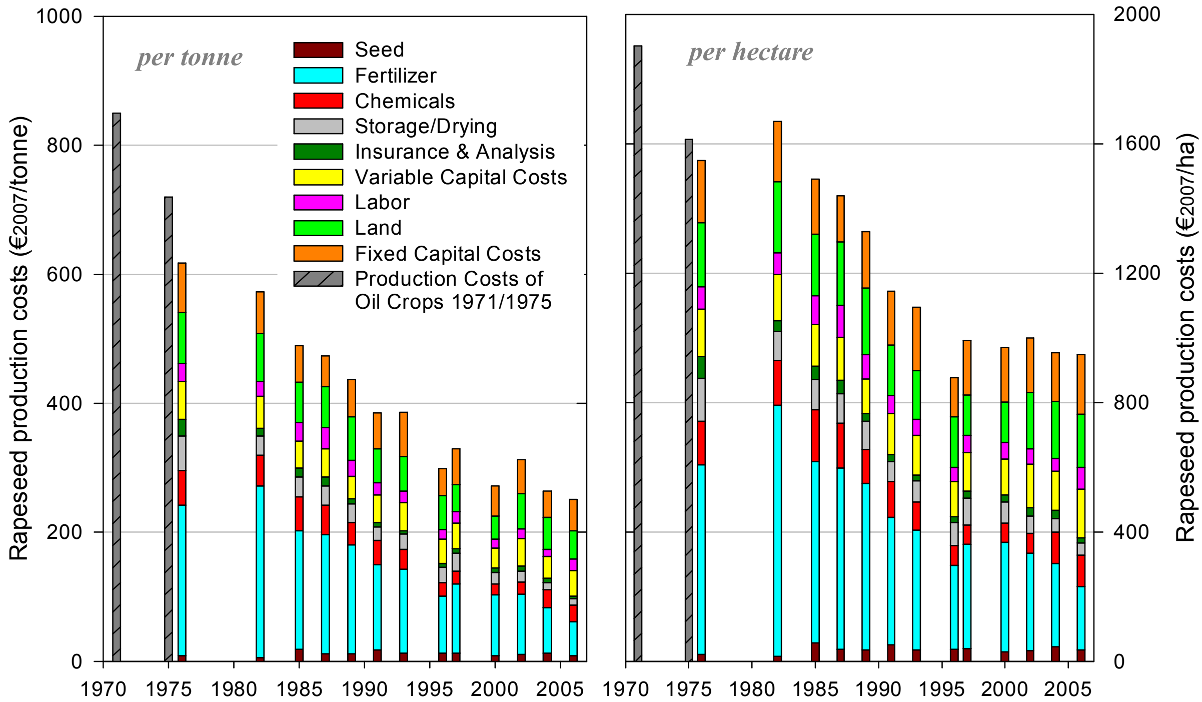

Figure 14: *Breakdown of rapeseed production costs per tonne and per hectare over the period 1971-2006*

[13] The rapeseed production costs per tonne were calculated by dividing the costs per hectare with the rapeseed yield. For the rapeseed yield, a three-year average was used in order to correct for seasonal influences.
[14] Unfortunately, no specific data for rapeseed production costs were available for these years. The production costs of oil crops were an average of the production costs of rapeseed and sunflower (Handler, 2007)

The increase in production costs per hectare in 1982 compared to 1976, and also in 1997 compared to 1996, was a result of an increase in the average fertilizer price and fertilizer usage (see also appendix B-VII). This increasing effect is less visible for the production costs per tonne as it was (partly) offset by the rapeseed yield increase over these periods.

Table 5 presents for each cost category the share in total costs, the absolute and relative production cost change and the share in the total production costs decline over the period 1971-2006. The costs categories fertilizer, chemicals, storage and drying, insurance and analysis, labor and fixed capital costs have decreased over time. Striking is the change in the contribution of fertilizer costs, which was two times less in 2006 compared to 1971. The contribution of the variable capital costs and all the fixed costs categories (labor, land, fixed capital costs) increased in relative terms over the period 1971-2006. The substantial decline in fertilizer costs contributes by far the most to the total cost reductions, viz. 62% per hectare and 50% per tonne. Despite the decline in the share of fertilizer costs in the total costs, fertilizer remains the largest cost component over time.

Cost Category	**Share in total costs**		**Absolute and relative change in production costs 1971-2006**				**Share in total cost decline (%)**	
	1971	**2006**	**€$_{2007}$/ha**	**%**	**€$_{2007}$/tonne**	**%**	**ha**	**tonne**
Seed	1.1	3.7	13.2	61.2	-0.4	-4.2	1.4	-0.1
Fertilizer	41.2	20.8	-583.5	-74.8	-296.2	-85.0	-61.7	-49.9
Chemicals	9.4	10.1	-81.8	-46.0	-53.9	-67.9	-8.7	-9.1
Storage & Drying	8.1	4.1	-114.1	-74.6	-58.0	-84.9	-12.1	-9.8
Insurance & Analysis	3.7	1.5	-56.3	-79.4	-27.8	-87.8	-6.0	-4.7
Variable capital costs	6.1	16.0	36.3	31.5	-11.2	-21.8	3.8	-1.9
Labor	4.9	7.1	-25.6	-27.6	-23.6	-57.0	-2.7	-4.0
Land	10.0	17.4	-25.4	-13.4	-41.2	-48.5	-2.7	-6.9
Fixed capital costs	15.4	19.3	-108.3	-37.2	-81.4	-62.7	-11.5	-13.7
Total	**100**	**100**	**-945.3**	**-49.9**	**-593.7**	**-70.3**	**-100**	**-100**

Table 5: *Overview of development and structure of the cost categories of the rapeseed production costs, and their contribution to the change in the total production costs over the period 1971-2006.*

The relation between the cumulative production and rapeseed production costs can be shown by means of two experience curves (see figure 15). The upper curve represents the production costs per hectare and the lower graph represents the production costs per tonne. The initial value for the cumulative production in 1971 is 1.75 million tonnes of rapeseed, which is the sum of the rapeseed production volumes over the period 1950-1971. Over the period 1971-2006, the cumulative production doubled over five times, whereas the production costs declined by 70.3% per tonne and 49.9% per hectare. As a result, the progress ratios of 87.5% ± 1% (R^2=0.92) and 80.4% ± 1% (R^2=0.97) were calculated for respectively the production costs per hectare and per tonne. The high R^2's indicate a strong relationship between the cumulative production and the production costs. However, the initial value of the cumulative production has considerable influence on the progress ratio and R^2 of the experience curve (see sensitivity analysis).

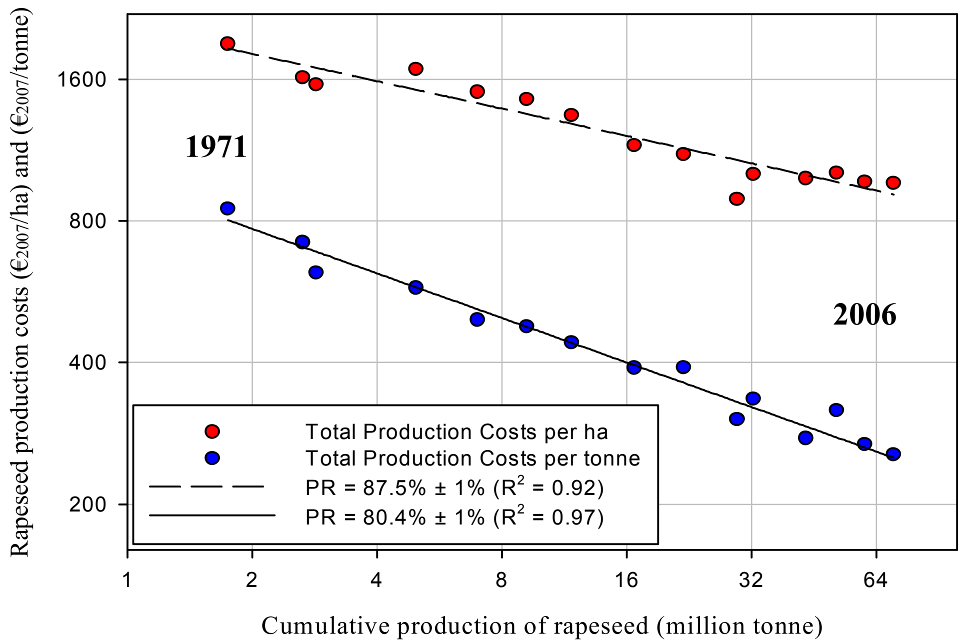

Fig 15: *Experience curve of rapeseed production costs over the period 1971-2006*

5.2.2 Industrial processing costs

The highly competitive German biodiesel market made the technology providers and biodiesel producers extremely reluctant to relinquish any data on production costs. Only a few, small biodiesel producers responded to the questionnaire. Therefore, less qualitative data originating from literature studies were used instead. Unfortunately, the industrial processing costs were structured differently in each study, making it difficult to quantify and compare the costs over time. In addition, several studies failed to specify the cost components, particularly for transport, distribution and glycerin processing. Assumptions and recalculations were necessary to make a sound comparison possible between the different literature studies (see next page). Furthermore, most studies indicated aggregated figures for the cost categories, thereby making it impossible to correct for influential price effects. Finally, frequently missing information on plant size, assumed processing technology (batch or continuous) and incorporation of investment depreciation costs made it difficult to compare the costs over time.

Figure 16 shows a breakdown of the processing costs over the years. The black lines represent the original value of the *total* industrial processing costs as presented in the underlying literature studies. The colored bars represent the industrial processing costs after assumptions and recalculations were made (see footnotes next page). These values were used as input values for the experience curves in this study.

The esterification process experienced the largest cost reductions over the years, whereas the oil production costs remained constant over time. The main factors causing the cost reductions in the esterification step were higher plant yields, the shift to continuous, automated processing technologies and the accompanying reduction in labor costs (cf. section 5.1.2). The constant oil production costs can be explained by the fact that oil milling is already a very mature industry, which has hardly any potential for further improvements. The costs for the transportation steps are very erratic; no clear pattern can be discerned here, despite the decrease in transportation distances as described before (cf. section 5.1.2). However, it should be mentioned that the industry-wide shift to more favorable plant sites and more optimal logistics have become particularly important in recent years. As there were data on industrial processing costs available after 2004, this development cannot be observed in figure 16. The costs for the category “distribution, storage and sale” seem to decline gradually over time. However, this gradual decline is partly a result of the many assumptions made for the distribution of biodiesel (see footnote 17). In general, the costs have declined as a result of larger plant sizes and upscaling. The *relative* industrial processing costs might have declined even more in recent years as a result of the booming production capacity expansion (cf. section 5.1.2). Furthermore, several biodiesel plants have shifted to optimal processing technologies, implying less labor and therefore lower processing costs (Wörgetter, 2007).

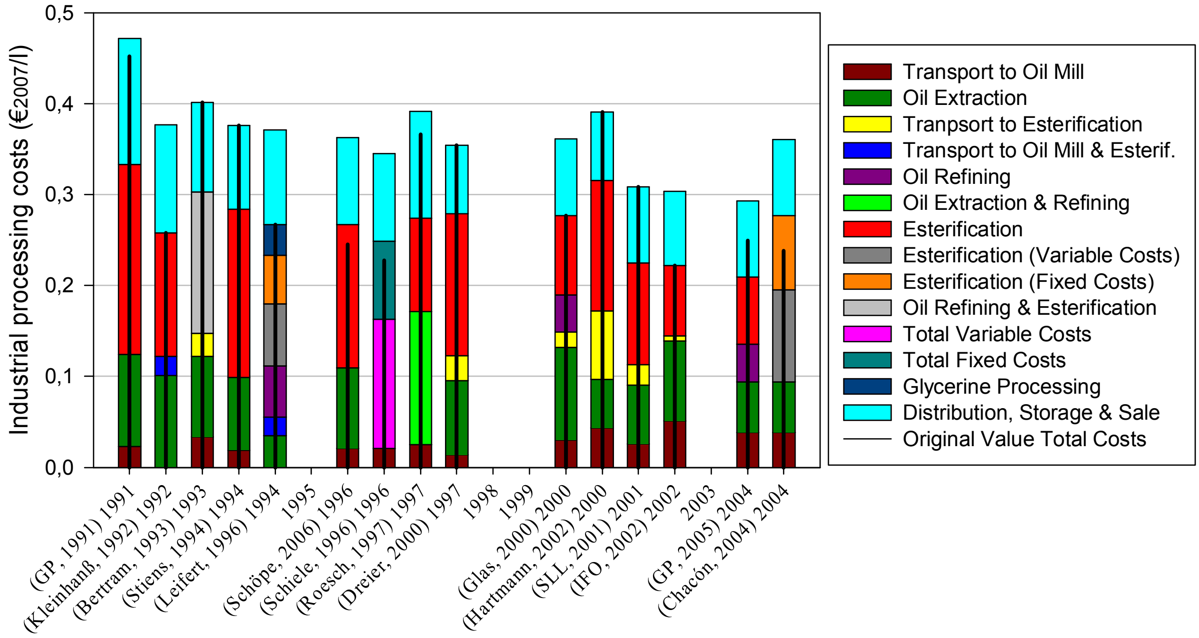

Figure 16: *Breakdown of industrial processing costs per liter RME over the period 1991-2004.*[15,16,17,18]

The relation between the cumulative production and total production costs can be shown by means of an experience curve (see figure 17). RME was produced for the first time in 1991, with an annual production of 200 tonnes, which was also assumed to be the initial value for

[15] For several studies, only one author is referred to for the sake of shortness. The co-authors can be found in the reference list at the end of this study.

[16] The industrial processing costs are not corrected for price dynamics and plant size, since most studies failed to indicate this information.

[17] Several literature studies lacked to specify whether costs of the following categories were included in the analysis: **Transport to oil mill** (German Parliament, 1991: Schiele, 1996; Roesch, 1997; German Parliament, 2004; Chacón, 2004; Schöpe, 2006) and **Distribution, Storage & Sale** (Kleinhanß, 1992; Leifert, 1996; Schiele, 1996; Keymer, 2000; IFO, 2002; German Parliament, 2004; Chacón, 2004; Schöpe, 2006). It was assumed that these costs were not incorporated in respectively the cost categories **Oil production costs** and **Esterification**. Seven-year averages were calculated by using data from the other studies (three years before and after the reference year) to fill these data voids. The observed gradual decline in the category **Distribution, Storage & Sale** is partly due to the many seven-year average values used for this category.

[18] Only a few studies specified whether costs for **investment depreciation** (Schiele, 1996; Chacón, 2004), **labor** (Leifert, 1996; Schiele, 1996; Hadler, 1997; Chacón, 2004), **glycerin processing** (Leifert, 1996) and **insurance and taxes** (Schiele, 1996) were included in the analysis. It was assumed that the remaining studies included these costs in the category **Esterification**.

the cumulative production in 1991, despite the experience already accumulated in the chemical industry and in other countries (e.g. France and Austria). The cumulative production doubled nearly 14 times and decreased with 31.2% in the period 1991-2004. This results in a progress ratio of 97.4% ± 1% (R^2=0.65). The low value of the R^2 indicates that there is no clear correlation between the cumulative production and the industrial processing costs of RME. Technological learning exchange with other countries might have distorted the experience curve for the industrial processing costs. More attention will be paid to this issue in the sensitivity analysis (chapter 6).

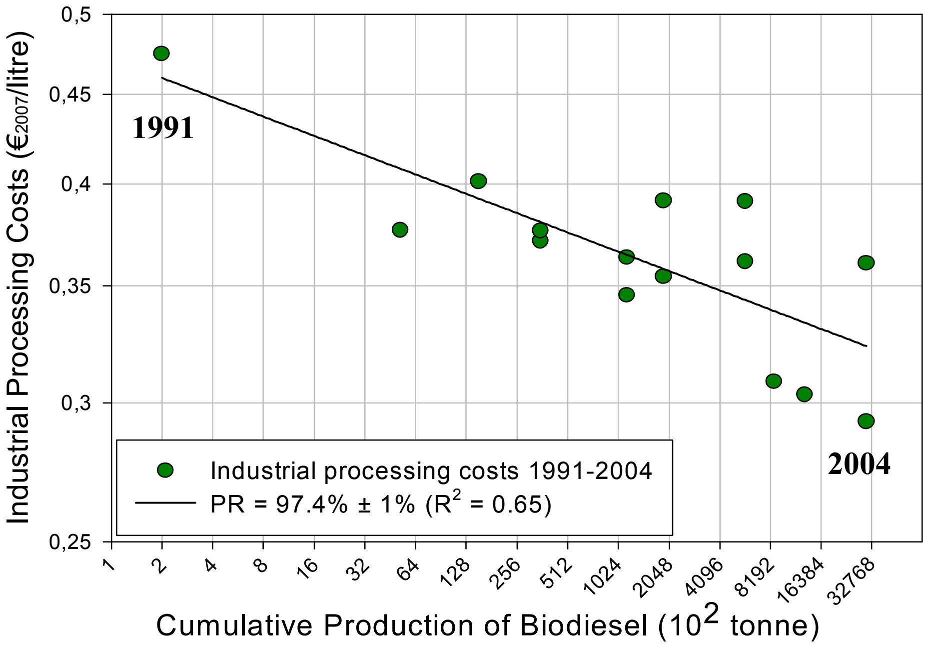

Fig 17: *Experience curve of the industrial processing costs of RME production over the period 1991-2004*

5.2.3 Investment costs

The investment costs were examined in further detail to find out whether a quantitative relation can be found between specific investment costs and the cumulative installed production capacity of biodiesel plants in Germany. Again, biodiesel producers and technology providers were extremely reluctant to relinquish data on investment costs. Therefore, turnkey investment costs were taken from a multitude of press releases (see appendix C-IV).

The collected data were analyzed and efforts were made to construct an experience curve. However, no correlation was found at all between the specific investment costs and the cumulative installed capacity. The data limitations are expected to give at least a partial explanation for this result. After all, influential scale effects and the high variety in biodiesel plant characteristics (feedstock technology, ancillary facilities, oil mill, etc.) make a comparison between turnkey investment costs almost impossible. Furthermore, the turnkey investment costs reflect the *prices* paid by biodiesel producers, which were considerably influenced by the strong demand for new biodiesel capacity in recent years (cf. section 5.1.2). Therefore, efforts were made to find a quantitative relation by comparing plants with similar characteristics. Nonetheless, no significantly higher R^2's were calculated. The experience curve with the highest fit (R^2=0.52) was constructed for single-feedstock (rapeseed) biodiesel plants with an integrated oil mill. Finally, the sole influence of scale was examined for plants with similar characteristics and building year[19]. Again, none of the constructed experience curves yielded a high fit. Therefore, scaling factors were taken from literature and experts from the field (anonymous, 2008).

The specific investment costs tend to decline with higher scales due to the fact that costs for materials and design rise less than proportionally to capacity increases. Despite the limited amount of data available in literature, two scaling factors for stand-alone plants were calculated for the years 1994 and 2006 (see figure 18). However, whereas the scaling factor of 1994 pertains to a single-feedstock (rapeseed) plant, this specification is unknown for the scaling factor of 2006. This might explain the intersection of the individual curves, since multi-feedstock plants are likely to have higher specific investment costs at low plant capacities due to higher standard costs associated with the more advanced multi-feedstock processing technology. Both scaling factors are based on merely three data points, implying a high uncertainty in the results[20].

The calculated scaling factors differ considerably for the years 1994 (0.77) and 2006 (0.50). Anecdotal information[21] (anonymous, 2008) indicates a scaling factor of around 0.6 for the year 2000 and a scaling factor range of 0.4-0.6 for recent years, depending on the stepwise increase in machinery and ancillary facilities involved with the upscaling of plants. The range for recent years corresponds with the calculated scaling factor of 0.5 for the year 2006. Furthermore, as the indicated scaling factor for the year 2000 (0.6) lies in between the calculated values for the years 1994 and 2006, a gradually decreasing scaling factor can be observed over time.

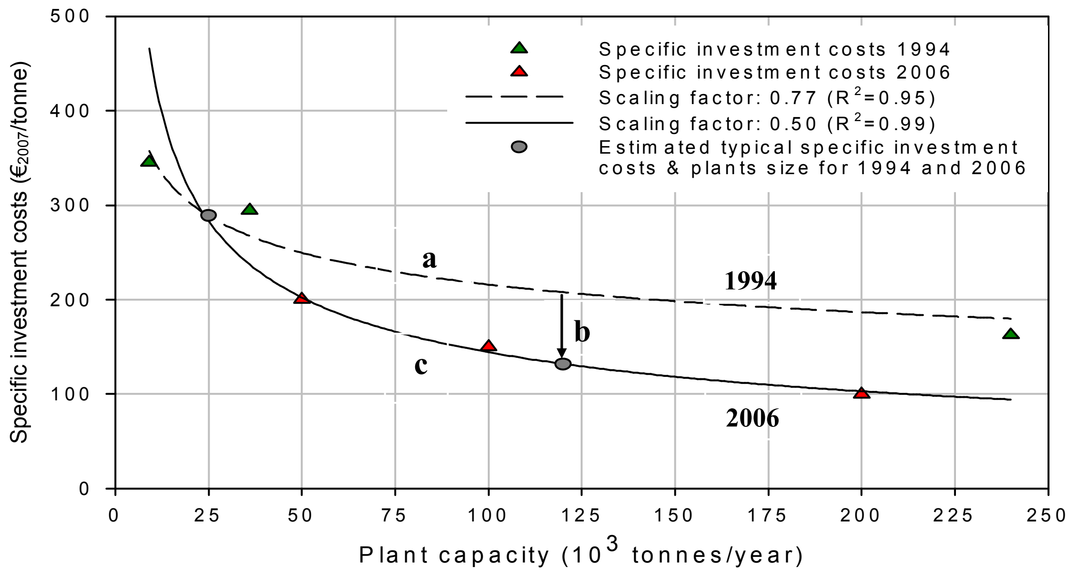

Figure 18: *Influence of scaling factors on the specific investment costs of a stand-alone biodiesel plants for the years 1994 and 2006. The characters a and c indicate upscaling; the character b indicates scale-independent learning (Data sources: Kock, 2006; Leifert, 1994).*

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19 A power function ($y=ax^{-b}$) was used to investigate the relationship between plant capacity (x-axis) and specific investment costs (y-axis).

20 The reliable fit (high R^2) of both curves is at least partly due to the low amount of data points used.

21 Anecdotal information stems from a technology provider who whishes to remain anonymous.

The individual curves in figure 18 reflect the effect of scale on the specific investment costs, whereas the vertical distance between the curves reflects the reductions in the specific investment costs due to technological learning (scale-independent learning). Unfortunately, a quantitative analysis into the contribution of both factors in the reductions of the specific investment costs was not useful given the uncertainty involved with the scaling factors. However, some general, qualitative considerations can be made to obtain insight in the technological learning processes accumulated by technology providers. In 1994, the average plant capacity of a stand-alone plant was 25 ktonnes per year (ABI, 2001); for the year 2006, an average stand-alone plant capacity of around 120 ktonnes per year was calculated based on the collected data on plant capacities in appendix C-IV. The corresponding estimated specific investment costs of 1994 and 2006 are indicated with gray dots by following the individual curves[22]. The effect of upscaling and scale-independent learning can be assessed in two different ways. First, one might argue that the estimated specific investment costs of 1994 can be extrapolated to the average plant capacity of 2006 (120 ktonnes per year) by using the scaling factor of 1994 (a). The associated reductions in specific investment costs are due to upscaling. The vertical distance between the specific investment costs at the plant capacity of 120 ktonnes per year is caused by scale-independent learning (b). When following this line of reasoning, upscaling has contributed slightly more to the reductions in specific investment costs than the factor of scale-independent learning. The second line of reasoning is the other way around. The estimated specific investment costs of 2006 can be extrapolated to the average plant capacity of 1994 by using the scaling factor of 2006 (c). In this case, all reductions in specific investment costs over time can be attributed to upscaling, whereas no scale-independent learning has taken place at all. The latter result is rather unlikely given the plausibility that upscaling is always accompanied by at least some scale-independent learning. Nonetheless, both lines of reasoning are in accordance with anecdotal information (Dallos, 2008), which indicates learning-by-upscaling to be the primary and learning-by-doing the secondary driver behind reductions in specific investment costs over time (cf. section 5.1.2). However, more detailed and accurate data are required to obtain more insight in the contribution of both factors on the reductions in the specific investment costs over time (see chapter 7).

5.2.4 Total production costs

The total production costs can be defined in two different ways: the total *hypothetical* and the total *actual* production costs. The total *hypothetical* production costs are the sum of the feedstock and industrial processing costs minus the financial revenues for by-products (cf. section 3.2.2). Unfortunately, it was not possible to obtain total *hypothetical* production costs for all years due to data scarcity. Furthermore, the required feedstock and industrial processing costs were not always calculated for the same years, whereas for other years multiple figures were available. Therefore, several assumptions had to be made to obtain total *hypothetical* production costs for as many years as possible. First of all, as the rapeseed production costs were not available for the years 1992, 1994 and 2001, the respective production costs of 1991, the average of 1993 and 1995, and 2000 were assumed to represent the rapeseed production costs for these years. Second of all, for the industrial processing costs several numbers about industrial processing costs were available (cf. section 5.2.2). These costs were averaged and assumed to represent the industrial processing costs for that

[22] The overlap between the gray dot (estimated specific investment costs) for the year 1994 and the intersection of the individual curves is coincidence.

reference year. The development of the feedstock costs, industrial processing costs and *hypothetical* production costs are presented in figure 19.

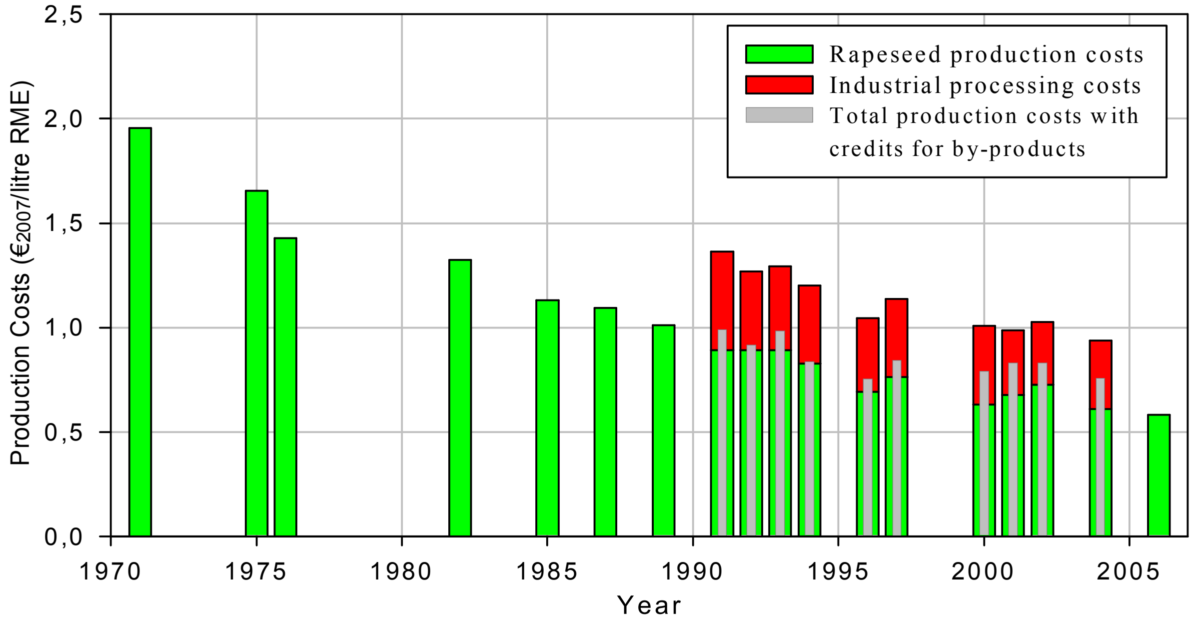


Figure 19: *Development of the feedstock costs, industrial processing costs and hypothetical production costs over the period 1971-2006.*

The total *hypothetical* production costs (by-product credits included) have decreased with 23.3%, starting with a value of € 0.99/l RME in 1991 and ending with a value of € 0.76/l RME in 2004. Figure 19 shows that the rapeseed production costs have declined much more than the industrial processing costs. The substantial decrease in rapeseed production costs has mainly been a result of increasing rapeseed yields, lower fertilizer usage and improved rapeseed varieties. The much smaller decline in industrial processing costs was mainly due to the relative simplicity of the oil milling and esterification processes (Dallos, 2007; Gärtner, 2008). Table 6 presents the development and structure of the production costs of the rapeseed cultivation and industrial processing and their contribution to the reductions in the total production costs.

	Absolute and relative change in production costs (1991-2004)		**Share in total production costs (%)**		**Share in change of total production costs (1991-2004)**
	€/liter RME	**%**	**1991**	**2004**	**%**
Rapeseed cultivation	-0.28	-31.4	65.2	65.1	-65.4
Industrial processing	-0.15	-31.2	34.8	34.9	-34.6
Total prod. costs (without credit for by-products)	-0.43	-31.3	100.0	100.0	-100.0
Credits for by-products[23]	-0.20	-52.8	38.0	23.6	
Total prod. costs (with credits for by-products)	**-0.23**	**-23.3**	**100.0**	**100.0**	

Table 6: *Overview of development and structure of rapeseed production costs and industrial processing of RME, and their contribution to the change in the total production costs of RME over the period 1991-2004.*

[23] The underlying literature studies indicated different by-product yields; no clear pattern was observed over time. The by-product yields were therefore assumed to remain constant over time. Assumed average rape meal yield: 600 kg/tonne rapeseed; assumed average glycerine yield: 115 kg/tonne rapeseed oil.

The production costs of rapeseed cultivation and industrial processing decreased respectively with 31.4% and 31.2% over the period 1991-2004. As the relative change in production costs of both categories was about the same, the share of these categories in the total production costs remained constant over time. Furthermore, the decrease in rapeseed production costs contributed twice as much to the total cost reductions due to its larger share in the total production costs. It should be noted that the majority of learning effects, and concomitant cost reductions, in the rapeseed production already took place before the biodiesel industry started in 1991. The main cost reductions associated with the industrial processing occurred in the early nineties. The by-product credits decreased significantly (52.8%) over time as a result of lower rape meal and glycerin prices. Especially the glycerin prices dropped tremendously in 1997 and from 2004 onwards as a result of the glycerin gluts emanating from the booming biodiesel industry (cf. section 5.1.2). The decrease in by-product credits (€0.20/l RME) has partly counterbalanced the cost reductions achieved in the rapeseed cultivation and industrial processing (€0.43/l RME). The large impact of the by-product credits emphasizes the importance of by-product markets.

The *actual* production costs are, however, determined by the *rapeseed price* (for stand-alone plants) or *rape oil price* (for annex plants)[24] instead of rapeseed (oil) *costs*. As the majority of identified German biodiesel plants have an integrated oil mill (see appendix D-I), this study uses *rapeseed* prices for the *actual* production costs instead of *rape oil* prices. Rapeseed *prices* are generally lower than rapeseed production *costs* due to agricultural subsidies granted to farmers. However, the increasing rapeseed prices have led to a smaller difference between rapeseed *costs* and *prices* over time. The total *actual* production costs display an erratic pattern over time, although a clear increase can be observed from 2000 onwards, partly as a result of the price premium on rapeseed (cf. section 5.1.2 and see appendix B-VI). As the *actual* total production costs do not fully reflect the accumulated experience in the RME production, no further attention is paid to this issue.

The relation between cumulative production and total *hypothetical* production costs can be shown by means of an experience curve (see figure 20). The experience curve was plotted against the cumulative biodiesel production. Biodiesel was produced for the first time in 1991, with an annual production of 200 tonnes, which was also the initial value for the cumulative production in 1991. The fluctuating rape meal and glycerin prices were kept constant over time to avoid distortion of the production costs and examine technological learning. The total *hypothetical* production costs decreased with 23.3% over nearly 14 cumulative doublings during the period 1991-2004. This results in a progress ratio of 96.7% ± 1% (R^2=0.84). The progress ratio is rather high, i.e. unfavorable, given the considerable cost reductions of 23.3%. This is mainly due to the high number of cumulative doublings over the period 1991-2004, which in turn is a result of the low value for the initial cumulative biodiesel production (200 tonnes). In addition, the experience curve below plots the rapeseed production costs against the cumulative production of RME instead of rapeseed. Rapeseed production volumes doubled only twice during the period 1991-2004 where RME production volumes doubled nearly 14 times. This implies that in the experience curve below, the cost reductions in rapeseed production are spread out over a much higher number of cumulative doublings. Therefore, the learning rate of the rapeseed production costs will be much higher for the case of the total production costs. Several specific observed developments (section

[24] An annex biodiesel plant has an integrated oil mill and purchases *rapeseed*, whereas a conventional stand-alone biodiesel plant purchases *rape oil*.

5.1) indicate that the potential for cost reductions in rapeseed production is still significant, but relatively small for industrial processing. Although the experience curves of the rapeseed production and industrial processes already seem to be in an advanced stage, both still offer potential for further cost reductions. Hence, it is likely that the total *hypothetical* production costs of RME also have potential left for further improvements. An outlook on the future *hypothetical* production costs of RME will be given in section 5.4.

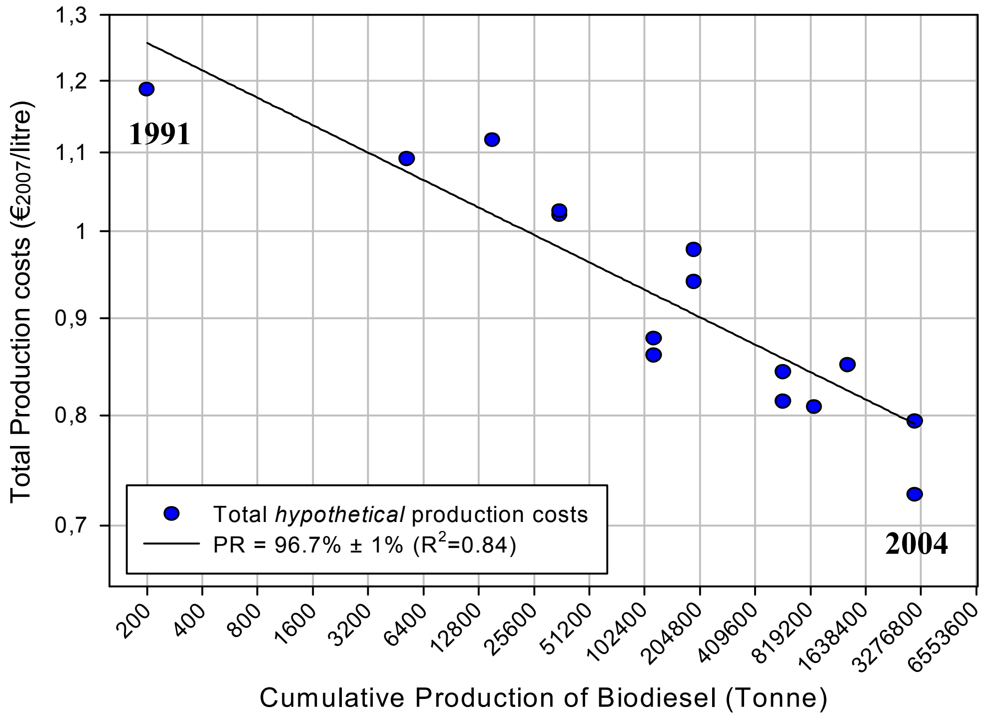


Figure 20: *Experience curve of the total hypothetical production costs of RME over the period 1991-2004 (used constant rape meal price: €150/tonne; used constant glycerin price: €250/tonne).*

5.3 Environmental performance

This study aims to investigate the development of the primary energy use and GHG emissions associated with the life cycle of RME over time. As noted in section 4.1, only a limited amount of eligible datasets was available. Furthermore, the datasets in question contain data originating from several years, thereby pertaining to a period rather than a particular year. It was therefore impossible to construct experience curves. Although data scarcity impedes the deduction of a (possible) mathematical relationship between cumulative production and primary energy use / CO_2 equivalents, a comparison was made for three years (1993, 2000 and 2007) to examine the development of the environmental performance over time. Table 7 gives an overview of the available LCA datasets with their corresponding reference years used for the analysis. The German datasets for the years 1993 and 2000 were compiled by the German research agency IFEU and are considered to be of exemplary quality. For the year 2007, three different datasets were used originating from Switzerland, England and France. The Swiss Eco-invent dataset is regarded to be of high quality and represent the German case rather well (Jungbluth, 2007). Data originating from the English and French dataset are assumed to represent the German case rather well, since the industrial processes are similar all over Europe due to worldwide operating technology providers (Jungmeier, 2007). Nonetheless, as these datasets concern rather old data and pertain to other countries, they will most likely not fully reflect the current situation in Germany.

	1993	2000	2007	
Rapeseed production	Reinhardt, 1993	Borken *et al,* 1999	Eco-invent, 2004	
Reference place	Germany	Germany	Switzerland	
Industrial processes	Reinhardt, 1993	Borken *et al,* 1999	Groves, 2002	Ademe, 2002
Reference place	Germany	Germany	England	France

Table 7: *Overview of datasets with their reference place and year used for this study.*

The lack of information on the composition of energy carriers comprising the *indirect energy flows*, caused difficulties with the recalculation of the energy use and GHG emissions to the standard methodological framework (cf. chapter 4). Consequently, the same specific primary energy use, i.e. the primary energy necessary to produce one unit of a particular indirect compound, had to be used for all three years. This implies that the *observed* reductions in primary energy use and GHG emissions do not reflect the *actual* reductions, since the developments of the exogenous factors were excluded from the research. However, as *nitrogen* fertilizer contributes significantly to the environmental load of RME, different values were used for the specific primary energy use (1993: 40.3 GJ/ tonne N; 2000: 38.6 GJ/ tonne N; 2007: 37.3 GJ/ tonne N) and corresponding GHG emissions (cf. section 4.2). Finally, the primary energy use and GHG emissions associated with the waste flows were excluded from the analysis due to data scarcity. However, as indicated by Schmidt (2007), the contribution of these flows to the total results was negligible.

5.3.1 Rapeseed production

The primary energy use and GHG emissions associated with the rapeseed production were calculated per tonne RME for the years 1993, 2000 and 2007 (see figure 21 and table 8). The values of the three investigated GHG emissions were multiplied with the corresponding global warming potentials and summed up to obtain the total values of the impact category "Global Warming". Appendix C-III gives an overview of all energy flows and GHG emissions for all three years.

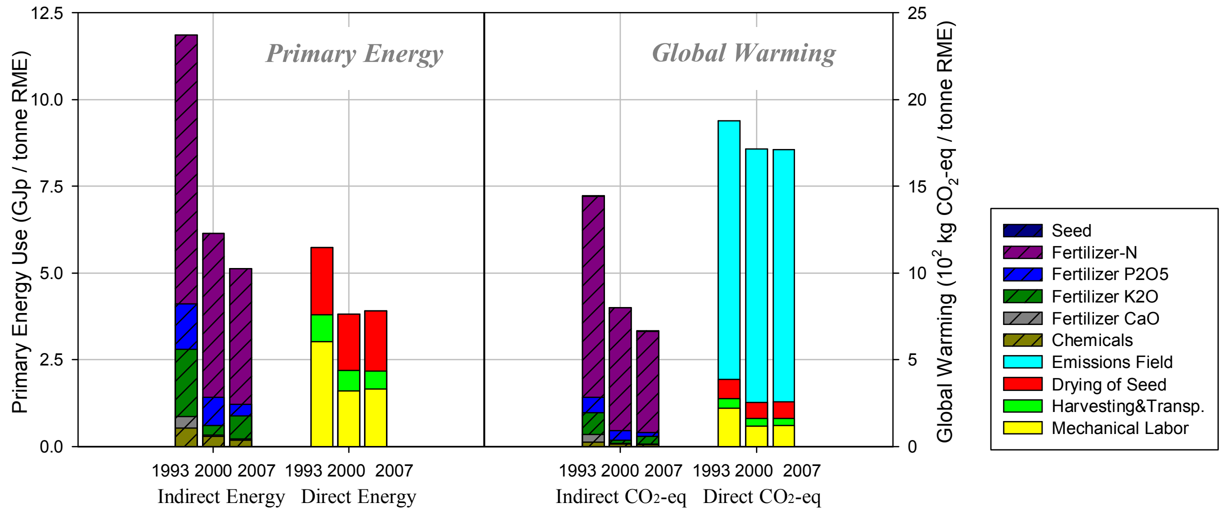


Figure 21: *Primary energy use and GHG emissions associated with the rapeseed cultivation given per tonne RME over the years 1993, 2000 and 2007*

	Absolute value			Relative change (%)		
	1993	2000	2007	1993-2000	2000-2007	1993-2007
Primary Energy (GJ_p/tonne RME)	17.6	9.5	9.0	-46.0	-5.3	-48.9
GHG emissions (10^2 kg CO_2-eq/tonne RME)	33.2	25.1	23.8	-24.4	-5.2	-28.3

Table 8: *Overview of the absolute values and the relative change of the total primary energy use and GHG emissions associated with the rapeseed cultivation for the years 1993, 2000 and 2007*[25,26,27].

The *total* primary energy use and concomitant CO_2-equivalents per tonne RME (sum of direct and indirect processes) associated with the rapeseed production have decreased by 48.9% and 28.3% respectively over the period 1993-2007 (see table 8). As can be seen in figure 21 and table 8, the largest reductions in primary energy use and GHG emissions took place over the period 1993-2000.

The *indirect compounds* comprise the major share in the *total* primary energy use and GHG emissions, although its share has diminished over time as a result of lower amounts of indirect compounds used per tonne RME produced (see appendix C-III). Despite this diminishing share, the indirect compounds still exceed the contribution of the direct processes

[25] The category **mechanical labor** comprises the following agricultural practices: tillage & sowing, fertilizing and spraying of chemicals.
[26] Data from Reinhardt (1993) and Eco-invent (2004) were given per hectare and converted in order to obtain values per tonne RME. Conversion factors were also taken from Reinhardt (1993) and Eco-invent (2004), respectively for the **years 1993** (**1.17 tonne RME/ha**) **and 2007** (**1.34 tonne RME/ha**). The increase in conversion factors is most likely due to obtained improvements made in the production chain over time. Data from Borken *et al* (1999) were given per GJ RME and recalculated with conversion factor (**1.19 tonne RME/GJ$_{RME}$**) for the **year 2000** (Borken *et al*, 1999) to obtain values per tonne RME.
[27] Indicated amounts of **nitrogen fertilizer** were multiplied with **changing** values for the specific primary energy use and GHG emissions over time. These values were based on Ramirez (2005) (see previous page). The indicated amounts of the other indirect compounds were multiplied with **constant** values for the specific primary energy use and GHG emissions, taken from Borken *et al* (1999). For the **drying** process, indicated amounts of electricity and heating oil were multiplied with conversion factors (see appendix XXX). The primary energy use and GHG emissions associated with the **transport of an indirect compound** is included in the category for the production of that particular indirect compound.

in 2007. Table 9 shows that the energy and GHG emissions associated with the production of the indirect compounds have been reduced by 56.8% and 53.9% respectively. Especially the primary energy necessary for the production of fertilizers (indirect process) was reduced significantly as a result of the smaller amounts of fertilizer required for the production of one tonne RME. Lower fertilizer usage per tonne rapeseed, which in turn is a result of improved rapeseed varieties, higher rapeseed yields and efficiency improvements in the production chain of RME, is the main reasons for the decline in fertilizer *usage* (direct process) over time (cf. section 5.1.1 and 5.1.2). The lower chemical and fertilizer usage is most likely driven by the incentive for farmers to reduce costs rather than as a result of environmental policy or regulations (Gärtner, 2008). The large share and reduction in the *total* energy use and emitted GHG emissions of fertilizers resulted in a contribution of almost 75% in the *total* energy and CO_2-equivalents reductions. Nitrogen fertilizer has been by far the prime contributor, as it accounts for 44.8% in the *total* primary energy reduction and 60.8% in the *total* CO_2-equivalents reduction. The high contribution of the fertilizers in the *total* reduced CO_2-equivalents is mainly a result of the high number of N_2O and CH_4 emissions avoided.

Category	Share in Total Prim. Energy (%)		Share in Tot GHG emissions (%)		Relative change over the period 1993-2007 (%)		Share in Prim. Energy/ GHG Change (%)	
	1993	2007	1993	2007	MJ_p	kg CO_2-eq	MJ_p	kg CO_2-eq
Seed	0.1	0.2	0.1	0.1	-12.4	-12.4	0.0	0.0
Fertilizer-N	43.9	43.2	34.8	24.6	-49.6	-49.6	44.8	60.8
Other fertilizers	20.4	11.5	7.8	3.0	-71.0	-72.7	29.7	19.9
Chemicals	3.0	1.9	0.7	0.3	-66.5	-66.5	4.1	1.7
Sum indirect processes	*67.4*	*56.8*	*43.5*	*28.0*	*-56.8*	*-53.9*	*78.6*	*82.4*
Mechanical Labor	17.1	18.2	6.6	5.1	-45.2	-44.9	15.9	10.3
Harvesting & Transport	4.5	5.9	1.7	1.6	-32.4	-31.7	3.0	1.9
Drying of Seed	11.0	19.1	3.4	4.2	-11.4	-11.0	2.6	1.3
Emissions Field	0.0	0.0	44.8	61.6	0.0	-2.6	0.0	4.0
Sum direct processes	*32.6*	*43.2*	*56.5*	*72.0*	*-32.0*	*-8.9*	*21.4*	*17.6*
Total	**100**	**100**	**100**	**100**	**-48.7**	**-28.5**	**100**	**100**

Table 9: *Overview of development and structure of the primary energy and GHG emissions associated with the rapeseed cultivation, and their contribution to the change in the total primary energy and GHG emissions of rapeseed cultivation over the period 1993-2007.*

The primary energy use and concomitant GHG emissions of all the *direct processes* have decreased over the period 1993-2007. Striking is the slight increase in primary energy use over the period 2000-2007 due to the increase in steam usage for the drying process and the energy fossil diesel usage for mechanical labor. The higher indicated energy usage by the Swiss dataset is expected to be a result of rough estimations and/or data uncertainty. The ratio between the necessary electricity and heating oil consumption seems to be completely different for all three years, implying an uncertainty involved with this parameter. The slightly higher fossil diesel usage can be explained by the fact that agricultural practices are less efficient in Switzerland due to the mountainous landscape and the lack of large-scale farming advantages (Jungbluth, 2007). As can be seen in table 9, mechanical labor has the largest share in the total primary energy use for the direct processes for both 1993 and 2007 and has had the largest reductions in primary energy use and GHG emissions over this period (-45.2%). Consequently, mechanical labor is the main contributor (of the direct processes) in the reductions of the *total* primary energy (15.9%) and GHG emissions (10.3%). The energy reductions associated with the mechanical labor were mainly a result of higher mechanical labor efficiencies per hectare. While rapeseed yield increased over time, the number of fieldwork processes per hectare, and thus diesel consumption per hectare, remained around the same level. As a result, the diesel consumption per tonne RME produced decreased over time, especially for the tillage and sowing processes (see appendix C-III). Over the period 1993-2007, there has been a decrease of 48.7% in *total* primary energy use and a decrease of 28.5% in emitted GHG emissions.

The *net* N_2O emissions (emissions from the field) are the N_2O emissions emanating from the rapeseed production minus the *avoided* N_2O emissions from the reference field (set-aside land). The *net* N_2O emissions were taken from Smeets *et al* (2008) and corrected for the amount of fertilizer usage by using the model of Bouwman *et al* (2006). An overview of the N_2O emissions is given in table 10 for the years 1993, 2000 and 2007.

	Year			Change 1993-2007 (%)
	1993	**2000**	**2007**	
N-fertilizer usage (kg N/tonne RME)	192	122	105	-45.3
Fertilizer N_2O (g)	455	349	327	-28.1
Other N_2O (g)	4,579	4,579	4,579	0
Total *net* N_2O (g)	5,034	4,928	4,906	-2.6
Total CO_2-eq (kg)	1,490	1,459	1,452	-2.6

Table 10: *Overview of the structure, absolute values and relative change of the net N_2O emissions for the years 1993, 2000 and 2007. (Data sources: Reinhardt (1993); Borken et al (1999), Eco-invent (2004); Smeets et al (2008)).*

Despite the significant reductions in fertilizer N_2O emissions (-28.1%), the total *net* N_2O emissions have declined only marginally (-2.6%). This result is in accordance with Smeets *et al* (2008), which indicated that the amount of fertilizer usage has only a minor influence on the *net* N_2O emissions compared to the chosen reference land and uncertainties involved with the N_2O emissions. This study assumes constant N_2O emissions from the reference field (set-aside land[28]) as no indications were found on land use change and/or emissions change over time. However, as the GHG emission reduction of RME may vary from -72% to 69% (Smeets *et al*, 2008), depending on the chosen reference land, large uncertainty is involved with the total *net* N_2O emissions. In addition, the utilization of state-of-the-art agricultural technologies combined with an optimized fertilizer regime can also have a significant influence on the amount of N_2O emissions, thereby causing additional uncertainty (Smeets *et al*, 2008). More attention will be paid to this issue in the discussion (chapter 7).

5.3.2 Industrial processing

The primary energy use and GHG emissions associated with the industrial processes of oil production and esterification into RME were calculated for the years 1993, 2000 and 2007 (see figure 22 and table 11). The values of the three investigated GHG emissions were multiplied with the corresponding global warming potentials and summed up to obtain the total values of the impact category "Global Warming". Appendix C-III gives an overview of all energy flows and GHG emissions for all three years.

[28] Set-aside land was used as the reference field in this study (cf. section 2.1.1).

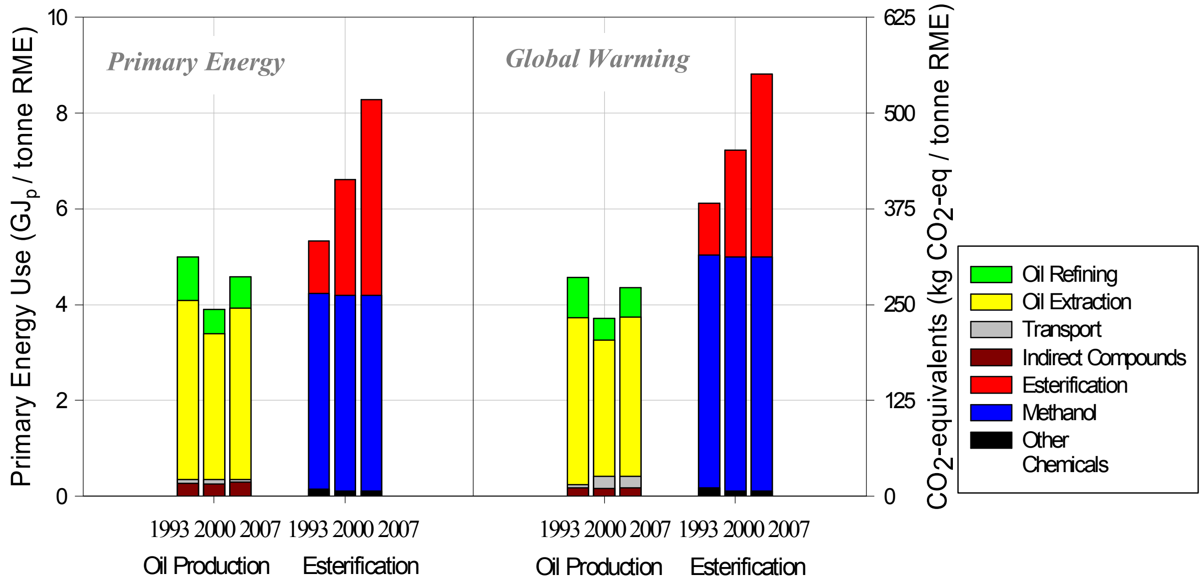


Figure 22: *Primary energy flows and GHG emissions associated with the oil production and esterification for the years 1993, 2000 and 2007.*

	Absolute value			Relative change (%)		
	1993	2000	2007	1993-2000	2000-2007	1993-2007
Primary energy oil production (GJ$_p$/tonne RME)	5.26	4.16	4.87	-21.0	17.2	-7.4
Primary energy esterification (GJ$_p$/tonne RME)	5.34	6.61	8.28	23.9	25.3	55.2
GHG emissions oil production (kg CO_2-eq/tonne RME)	296	242	283	-18.2	16.9	-4.4
GHG emissions esterification (kg CO_2-eq/tonne RME)	382	452	551	18.1	22.0	44.1

Table 11: *Overview of the absolute values and the relative change of the total primary energy use and GHG emissions associated with the industrial processes of oil production and esterification for the years 1993, 2000 and 2007.*[29,30,31]

Oil production

The oil extraction holds the major share in the *total* primary energy use and GHG emissions for all three years (around 75%), followed by the oil refinery process (between 11-18% for all three years). The indirect compounds comprise only a minor share in the *total* primary energy use and CO_2-equivalents and remained rather constant over time. The reduction in *total* primary energy use over the period 1993-2000 was therefore mainly a result of the lower total

[29] The category **Esterification** includes glycerin processing.

[30] Data from Reinhardt (1993) were given per hectare and data from Borken *et al* (1999) per GJ RME. Conversion factors were respectively taken from Reinhardt (1993) and Borken *et al* (1999) for the **years 1993** (**1.17 tonne RME/ha**) **and 2000** (**1.19 tonne RME/GJ$_{RME}$**). Data from Ademe (2002) and Groves (2002) were given per tonne crude rape oil, tonne refined oil and ton RME for respectively the stages oil extraction, oil refinement and esterification. The values for the **year 2007** associated with the extraction and oil refinement were recalculated by using the respective conversion factors of (**1.02 tonne RME/tonne crude rape oil)** and (**1.00 tonne RME/tonne refined rape oil)** (Concawe, 2007).

[31] Indicated amounts of electricity and heating oil were multiplied with conversion factors (see appendix XXX). The primary energy use and GHG emissions associated with the transport of an indirect compound are included in the category for the production of that particular indirect compound. The indicated amounts of the indirect compounds were multiplied with **constant values for the specific primary energy use and GHG emissions**, taken from Borken *et al* (1999).

electricity and natural gas use, necessary for the oil extraction and refining processes. Consequently, the concomitant CO_2 and CH_4 emissions - and thus CO_2-equivalents - declined as well. The primary energy use and emitted GHG emissions associated with the transport of rapeseed were kept constant over time as the specific energy consumption and distances for each transport mode were unknown. Contrary to expectation, the *total* primary energy use and CO_2-equivalents increased over the period 2000-2007, mainly due to the increase in electricity and natural gas use in the oil extraction and refining processes. Possible explanations for the unexpected increase might be data uncertainty and/or the use of plant specific (instead of industrial average) data (Gärtner, 2008). The use of Danish data for the year 2007 is not expected to explain the increase in electricity and natural gas use as the industrial processes are similar all over Europe. More attention will be paid to this issue in the discussion (see chapter 7). Despite the increase over the period 2000-2007, a *net* decrease of 7.4% in *total* primary energy use and of 4.4% in CO_2-equivalents is observed over the period 1993-2007.

Esterification
The electricity and natural gas requirements, and concomitant CO_2 and CH_4 emissions, associated with the actual esterification process (represented by the red bars in figure 22) increased substantially over the years. The observed increase contrasts anecdotal reports, which assert that energy requirements have declined over the period 1993-2000 and remained constant over the period 2000-2007 (cf. section 5.1.2). The observed increase over the period 1993-2000 was much more likely due to the revision of the 1993 dataset than because of an actual increase in the electricity and natural gas use (Gärtner, 2008; Reinhardt, 2007). Unfortunately, the results could not be corrected for the revision, since no specific information and data were available. An explanation for the increase over the period 2000-2007 is most likely the use of plant specific instead of industrial average data (Gärtner, 2008; Groves, 2008). After all, the electricity and natural gas requirements can vary considerably for each biodiesel plant due to different building years, plant sizes and processing technologies (cf. section 5.1.2). As the industrial processes are similar all over Europe (Jungmeier, 2007), the use of French and English data for the actual esterification process is not expected to explain the increase in electricity and natural gas use. Special attention will be given to this subject in the discussion (chapter 7).

The primary energy and CO_2-equivalents associated with the production of indirect compounds (represented by the blue bars) decreased slightly over the period 1993-2000 due to lower amounts of "other chemicals" necessary for the production of RME. As the same data were used for the years 2000 and 2007, no changes are observed in the environmental performance of the indirect compounds over this period. Overall, the share of the direct processes in the *total* primary energy use and CO_2-equivalents decreased over time. Over the period 1993-2007, the esterification step experienced a net increase of 55.2% in *total* primary energy use and an increase of 44.1% in CO_2-equivalents over the period 1993-2007.

5.3.3 Total environmental performance

Figure 23 and table 12 give an overview of the structure and development of the primary energy flows associated with the rapeseed cultivation, oil production, esterification process and total life cycle of RME for the years 1993, 2000 and 2007 (see also appendix C-III). The gray bars represent the total *net* primary energy use, i.e. the total primary energy use minus credits for the by-products rape meal and glycerin. Table 12 presents the energy flows both per tonne RME and per 100 km driven with an average car according to the New European Driving Cycle (see section 3.2.3 and appendix B-II).

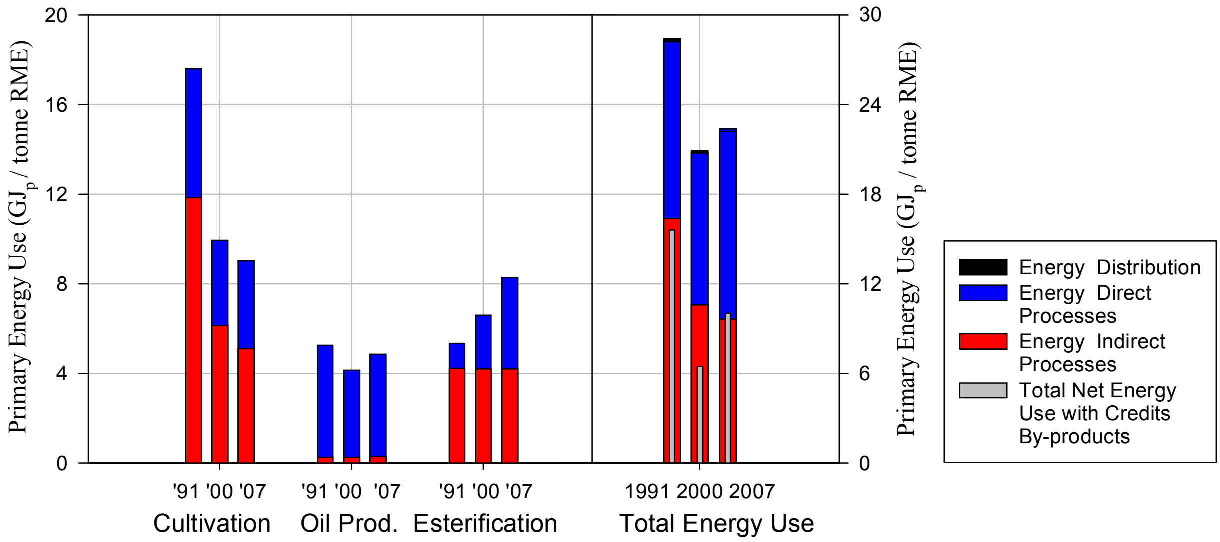


Figure 23: *Primary Energy flows associated with the rapeseed cultivation, oil production, esterification process and total life cycle of RME for the years 1993, 2000 and 2007.*

	Absolute value			Relative change (%)		
	1993	2000	2007	1993-2000	2000-2007	1993-2007
Primary energy (credits by-products excluded) (GJ_p/tonne RME)	28.4	20.9	22.4	-26.4	7.1	-21.2
Primary energy (credits by-products included) (GJ_p/tonne RME)	15.6	6.5	10.0	-58.3	54.7	-35.6
Primary energy (credits by-products excluded) (GJ_p/100 km driven)	139.5	102.7	109.9	-26.4	7.1	-21.2
Primary energy (credits by-products included) (GJ_p/100 km driven)	76.6	31.9	49.3	-58.3	54.7	-35.6

Table 12: *Overview of the absolute values and the relative change of the total primary energy use and GHG emissions associated with the life cycle of RME for the years 1993, 2000 and 2007.*[32,33,34]

The primary energy use was also expressed per 100 km driven in order to make a comparison with other biofuels easier. Appendix D-III shows a bar chart like figure 23, for the values per 100 km driven. As mentioned in section 5.3.1, the primary energy use of the rapeseed cultivation decreased for the periods 1993-2000 and 2000-2007, mainly as a result of lower fertilizer usage, which in turn is a result of higher yields and improved rapeseed varieties. Despite the decrease in primary energy use (in particular for the period 1993-2000), rapeseed

[32] The primary energy use associated with the stages of rapeseed production, industrial processing and distribution of RME were also calculated per **100 km driven with a reference car**. The corresponding conversion factors can be found in appendix B-II.

[33] The primary energy use associated with the **distribution of RME** was only given by Borken *et al* (1999). These values were assumed to remain constant for all three years. This assumption was considered justified as no indications were found of significantly higher distribution distances or different distribution modes over time.

[34] The **credits for by-products** comprise avoided primary energy use associated with soy meal production, synthetic glycerin production and the maintenance of the reference field (set-aside land). The indicated amounts of by-products were multiplied with **constant values for the specific primary energy use and GHG emissions**, taken from Borken *et al* (1999).

cultivation keeps the largest share in the *total* primary energy consumption over the years (1993: 62.0%; 2007: 40.4%) (see table 13). Nonetheless, the share decreases considerably, not only because of lower primary energy use of the agricultural processes, but also as a result of increasing primary energy use of the esterification process. The decrease in primary energy use for the rapeseed cultivation has the largest contribution in the *total* primary energy reduction over the period 1993-2000. The small decrease in primary energy use over the period 2000-2007 was counterbalanced by the increase in primary energy use for the industrial processes.

The industrial processes of oil production and esterification have the smallest share (respectively 18.5% and 18.8%) in the *total* primary energy use in 1993 (see table 13). However, as mentioned above, the shares increased over time. The increase in the primary energy use for the industrial processes outweighed the decrease in the agricultural energy use over the period 2000-2007. Consequently, the *total* energy use of RME increased over the period 2000-2007. The share of the *total indirect energy* decreased over time, mainly as a result of the decrease in indirect energy necessary for the rapeseed cultivation. Despite the decrease in direct energy of the rapeseed cultivation and oil production over time, there has been an unexpected *net* increase in the *total direct energy* over time due to the strong increase in the indicated direct energy use of the esterification process. The distribution of RME is kept constant over time and holds only a minor share in the *total* primary energy use.

	Share Total Primary Energy use (%)		**Share Total GHG emissions (%)**		**Relative change over the period 1993-2007 (%)**	
	1993	***2007***	***1993***	***2007***	***MJ_p***	***kg CO_2-eq***
Rapeseed cultivation	62.0	40.4	82.8	73.7	-48.7	-28.5
Oil production	18.5	21.8	7.4	8.8	-7.4	-4.4
Esterification	18.8	37.0	9.5	17.1	55.2	44.1
Distribution	0.7	0.8	0.4	0.4	0	0
Total RME (credits by-products excluded)	**100**	**100**	**100**	**100**	**-21.2**	**-19.7**
Credits by-products	45.1	55.1	23.8	28.5	-3.6	-3.8
Total RME (credits by-products included)	**54.9**	**44.9**	**76.2**	**71.5**	**-35.6**	**-24.7**

Table 13: *Overview of development and structure of the primary energy use and GHG emissions associated with the life cycle of RME, and their contribution to the change in the total primary energy and GHG emissions of RME over the period 1993-2007.*

The credits for by-products increased over the period 1993-2000 due to a higher glycerin yield per tonne RME (see appendix C-III). As a result, the decrease in *total* energy use was amplified by this increase in credits and resulted in a substantial decrease in *total net* energy use. For the period 2000-2007, credits for by-products decreased due to lower indicated rape meal and glycerin yields per tonne RME. Again, the effect of the change in *total* energy use was amplified by the decrease in credits, resulting in a higher *total net* energy use than the *total* primary energy use without credits. The use of plant specific instead of industrial average data could be an explanation for the decrease in rape meal and glycerin yields over the period 2000-2007.

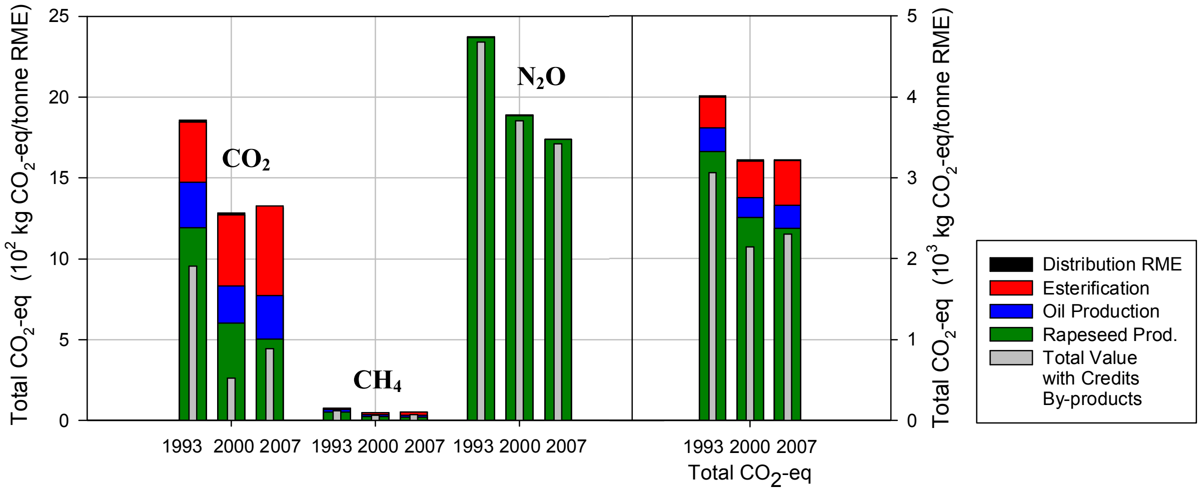


Figure 24: *GHG emissions associated with the rapeseed cultivation, oil production esterification process and total life cycle of RME for the years 1993, 2000 and 2007*

Figure 24 and table 14 show the structure, change and contribution of CO_2, CH_4 and N_2O in the *total* CO_2-equivalents change over time. As can be seen, the N_2O emissions have the largest share in the total CO_2-equivalents decrease (52.7%), followed by the CO_2 emissions (45.2%)[35]. The contribution of CH_4 in the total CO_2-equivalents decrease is only marginal (2.1%). Especially the lower fertilizer usage (especially nitrogen fertilizer) has resulted in strong reductions in CO_2, CH_4 and N_2O emissions, and has, together with the reductions in CO_2 emissions due to lower fossil diesel use, caused the rapeseed production to have the largest contribution in the total GHG emissions decrease. Appendix D-III shows a bar chart like figure 24, for the values per 100 km driven.

	Relative change 1993-2007 (%)			Share in CO_2-equivalents change (%)		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Rapeseed cultivation	-57.9	-61.6	-26.7	51.0	2.3	46.7
Oil production	-4.3	-9.2	28.8	93.2	10.2	-3.4
Esterification	43.4	80.1	-35.8	95.5	4.7	-0.3
Distribution	0.0	0.0	0.0	0.0	0.0	0.0
Total RME (credits by-products excluded)	**-29.2**	**-33.2**	**-26.6**	**45.2**	**2.1**	**52.7**
Credits by-products	-3.4	-4.6	-13.0	-	-	-
Total RME (credits by-products included)	-53.6	-40.0	-26.8	-	-	-

Table 14: *Overview of development and structure of the GHG emissions associated with the life cycle of RME, and their contribution to the change in the total CO_2-equivalents of RME over the period 1993-2007.*[36]

[35] The relatively small contribution of CO_2 emissions in the total CO_2-equivalents decrease is due to the *observed increase* in CO_2 emissions for the *esterification process*. In reality, CO_2 emissions will most likely comprise a larger share in the total CO_2-equivalents decrease.

[36] The assumptions made for the GHG emissions were the same as for the primary energy use (see footnotes table 12).

The decrease in GHG emissions associated with the oil production stage was mainly a result of the lower electricity and natural gas usage, necessary for the direct processes of oil extraction and oil refining. However, as the decrease in GHG emissions was relatively small for this stage, so was the contribution to the decrease in total GHG emissions. Despite the slight decrease in GHG emissions of the indirect compounds, the esterification is the only stage that shows a total increase in GHG emissions. The higher indicated electricity and natural gas usage for the actual esterification process increased the CO_2 and CH_4 emissions over time.

Table 13 and the figures 23 and 24 show that reductions in primary energy use and GHG emissions have been achieved throughout the entire production chain of RME. These reductions have most likely been driven by the incentive for farmers and biofuel producers to reduce costs rather than by any environmental policy or regulations (cf. section 3.2.1). For the year 2007, the total CO_2-equivalents associated with the life cycle of RME were calculated to be 65% lower than for the life cycle of fossil diesel (see appendix D-III). The GHG reduction potential of RME is thereby enough to meet the targets (30-40%) as set by the German Biomass Sustainability Ordinance (cf. section 2.2.2).

5.4 Outlook

This chapter gives an outlook on future production costs of rapeseed cultivation and industrial processing. This outlook is based on the extrapolation of the experience curves and the specific observed developments as described in section 5.1. Projections on the future rapeseed and RME production volumes are made in order to be able to extrapolate the experience curves.

5.4.1 Future production volumes

The trend in the growing annual non-food rapeseed and RME production volumes is constrained due to the limited availability of agricultural land dedicated for energy crop cultivation (Arnold *et al*, 2005). Theoretically, RME is not limited to the maximum amount of domestic non-food rapeseed production in Germany as it can also be produced from imported rapeseed. Nonetheless, as high rape (oil) prices have already resulted in a shift to alternative feedstock, it can be expected that the import of rapeseed will be limited.

Unfortunately, no data were found about anticipated rapeseed, RME or biodiesel production volumes. Hence, several calculations had to be made by using past average annual growth rates, future agricultural land potentials and biofuel targets set by the German government. An average land potential was obtained by employing three studies (Fritsche *et al*, 2004, Nitsch *et al*, 2004 and Thrän *et al*, 2006) and used to calculate the additional domestic non-food rapeseed production potential. It was assumed that the full domestic production potential of non-food rapeseed will be reached in 2020. Two different rapeseed production growth rates (3% and 7%) were applied to account for the uncertainty in the projected future rapeseed production volumes caused by several factors, e.g. food consumption per capita, possible yield increase, re-designation of land, etc (Thrän *et al*, 2006). Projections on future *biodiesel* production were based upon the future diesel demand and biofuel targets set by the German government for the years 2010 and 2020. The calculations are not discussed here in further detail for the sake of brevity. The annual production volumes and an elaboration of the assumptions and calculations can be found in appendix D-II.

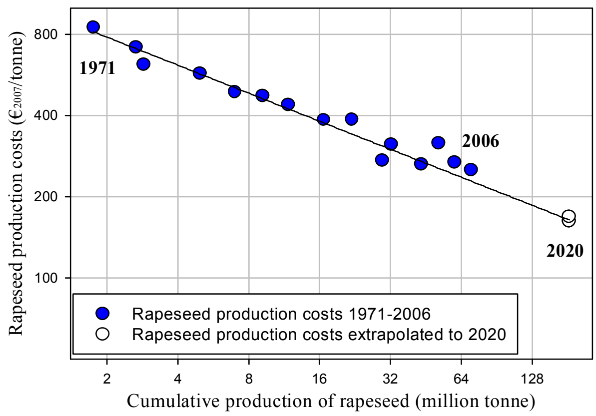
5.4.2 Extrapolation of the experience curves

The future production volumes were used to extrapolate the experience curves. For the rapeseed production, the projected production costs are given for both the low growth and high growth scenario (see table 15 and figure 25). The projected production costs amount to 162-169 €/tonne for both scenarios (the range in production costs is due to the standard error in the progress ratio). Thus, rapeseed production costs are estimated to decrease with another 33-35% due to an increase in cumulative production of 2.6 times. The range in production costs is relatively small and similar for both the low growth and high growth scenario. The reason for this is twofold. First, the low standard error in the progress ratio leads to a rather small divergence of the future cost range when extrapolating the experience curve. Second, the huge value of the cumulative rapeseed production is barely affected by the difference in rapeseed growth of the two scenarios. Moreover, as the experience curve is already in an advanced stage, sizeable amounts of extra rapeseed production are required to bring about a similar cost reduction as in the early stages of the experience curve. The relatively small difference in cumulative rapeseed production will not suffice to cause such an effect.

Rapeseed cultivation	Low growth rate (3%/year)	High growth rate (7%/year)
Production costs 2006 (€$_{2007}$/tonne)	251	251
Projected cum. production 2020 (mln. tonnes)	183.1	183.5
Projected production costs 2020 (€$_{2007}$/tonne)	162-169	162-169
Industrial processing	**Biodiesel share of 10%**	**Biodiesel share of 20%**
Production costs 2004 (€$_{2007}$/litre)	0.30-0.35	0.30-0.35
Projected cum. production 2020 (mln. tonnes)	3.78	7.57
Projected production costs 2020 (€$_{2007}$/litre)	0.27-0.32	0.26-0.31
Total *hypothetical* production costs	**Biodiesel share of 10%**	**Biodiesel share of 20%**
Production costs 2004 (€$_{2007}$/litre)	0.73-0.79	0.73-0.79
Projected cum. production 2020 (mln. tonnes)	3.78	7.57
Projected production costs 2020 (€$_{2007}$/litre)	0.66-0.73	0.65-0.72

Table 15: *Projected production costs of rapeseed cultivation and industrial processing for the year 2020*

The industrial processing costs were projected for both the scenarios of a ten and twenty percent biodiesel share in 2020 (see table 15 and figure 25). Although the scenario of a twenty percent biodiesel share in 2020 is considered to be rather unlikely, it shows the potential for industrial processing costs when achieving the corresponding amount of cumulative production. A range of 0.27-0.32 €/liter was calculated for the ten percent scenario and a range of 0.26-0.31 €/liter for the twenty percent scenario. Thus, industrial processing costs are estimated to decrease with another 9-10% for the former scenario and with 11-13% for the latter scenario. In these scenarios, the costs reductions will be triggered by the increase of more than respectively three and four doublings in the cumulative production. The wide ranges in projected processing costs in 2020 were due to the large difference between the two data points in 2004. The experience curve for the industrial costs shows relatively little potential for further cost reductions; the twenty percent scenario achieves an average additional cost reduction of merely one eurocent more than the ten percent scenario.



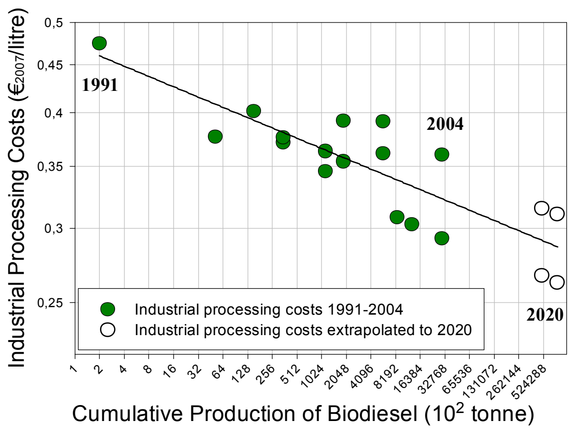


Figure 25: *Experience curves of rapeseed cultivation and industrial processing extrapolated to the year 2020 for two scenarios*

The total *hypothetical* production costs were for both the scenarios of a ten and twenty percent biodiesel share in 2020 (see table 15 and figure 26). It should be born in mind that the future *RME* production expansion is limited by the restrained outlet possibilities of rape meal in the fodder market (cf. section 5.1.2). The introduction of new rape meal by-product usages is therefore vital for RME to remain economically viable. Although the precise economic implications of new rape meal by-product usages for the *absolute* production costs, and thus economic viability, of RME are unknown, this study assumes a further *RME* production expansion for the year 2020 (see also discussion chapter). A range of 0.66-0.73 €/liter was calculated for the ten percent scenario and a range of 0.65-0.72 €/liter for the twenty percent scenario. Thus, total *hypothetical* production costs are estimated to decrease with another 9% from €0.76/l RME in 2004 to an average value of €0.69/l RME in the year 2020. In these scenarios, the costs reductions will be triggered by the increase of more than respectively three and four cumulative doublings. The wide ranges in projected processing costs in 2020 were due to the large difference between the two data points in 2004. The experience curve for the total *hypothetical* production costs show relatively little potential for further cost reductions. However, it should be mentioned that the high amount of cumulative doublings in biodiesel production partly explains the high, i.e. unfavorable, calculated progress ratio for the experience curve, which in turn has resulted in the low projected cost reductions for the year 2020 (see also chapter 7).

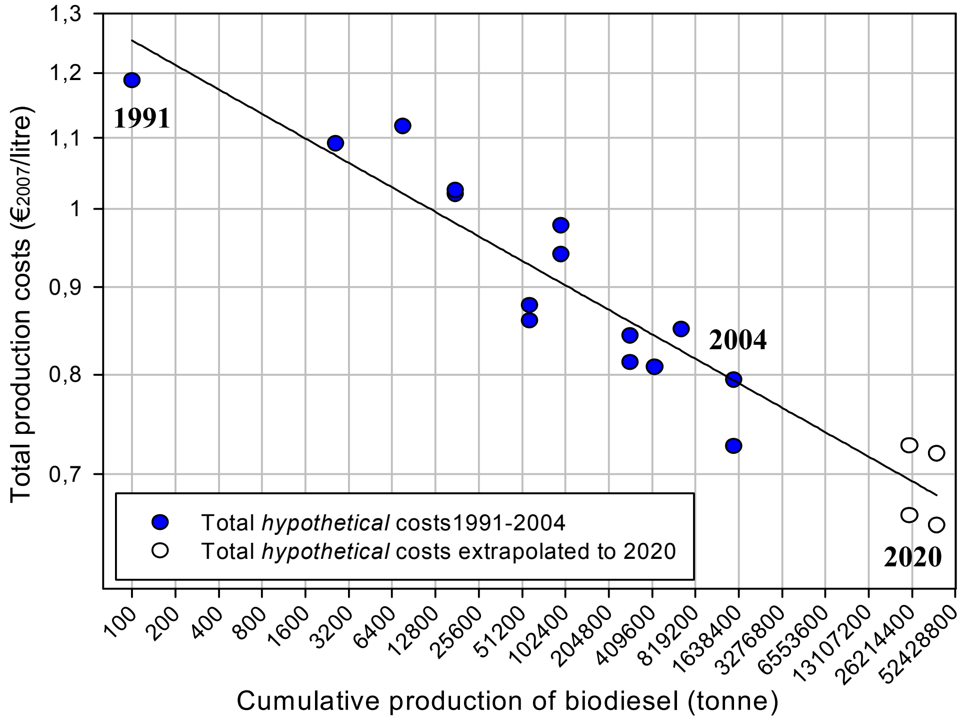


Figure 26: *Experience curves of total hypothetical production costs extrapolated to the year 2020 for a ten and twenty percent biodiesel share in 2020.*

5.4.3 Comprehensive outlook

The extrapolation of the experience curves provides a quantitative top-down projection on future production costs. In addition, a qualitative outlook can be given in order to explain the projected cost reductions and supplement the quantitative results of both the production costs and environmental performance. This qualitative outlook is based on expert opinions and the specific observed developments as described in section 5.1.

Rapeseed production

An average annual growth rate of rapeseed production was calculated of around 5% over the past 16 years. Two scenarios (three and seven percent growth rate) were devised to account for the relative unpredictability of the future annual growth rate, and thus, projected rapeseed production costs. As both scenarios yielded the same range in rapeseed production costs (162-169 €/tonne), the experience curve indicates a certain likeliness that future production costs will be within this range. Unfortunately, no bottom-up (engineering) studies on future production costs were available to compare the cost projections with. Nonetheless, the projected cost reductions of the experience curve are in accordance with several forecasted developments.

Fertilizers are expected to play an important role in future reductions of both the cost, primary energy and GHG emission reductions. Expected efficiency gains in the production processes of fertilizers - especially nitrogen fertilizer - and the possible regress in fertilizer usage can considerably influence the production costs and environmental performance of rapeseed (cf. section 5.1.1). Furthermore, improved rapeseed varieties, especially GM rapeseed, are expected to increase yields and lower the need for fertilizers and chemicals (cf. section 5.1.1). The mechanical labor is already sophisticated, but ongoing field trials indicate further improvement possibilities for the tillage step (Gärtner, 2008). Also Smeets *et al* (2008) indicate that the utilization of state-of-the-art agricultural technologies combined with an optimized fertilizer regime can significantly reduce N_2O emissions from the field. The introduction of GM rapeseed could possibly lead to a change in the PR of the experience curve and reveal new possibilities for technological learning. However, it should be noted that the future production costs and environmental performance of rapeseed are not merely determined by future technological learning processes, but also by exogenous price levels and efficiency improvements in production processes of indirect compounds. As rape oil accounts for 75-90% of the total production costs of RME, a calculated cost reduction in rapeseed cultivation of 33-35% in 2020 (cf. section 5.4.2) will have serious implications for the economic performance of RME. Unfortunately, it is very difficult to give a quantitative projection for the energy and GHG emission performance of rapeseed in 2020 (Gärtner, 2008). The Biomass Sustainability Ordinance stimulates biodiesel producers to enhance the GHG emission reduction potential of RME. Additionally, several sustainability criteria, such as the environmentally safe usage of fertilizers and chemicals, have to be met during the rapeseed cultivation in order for RME to be eligible for tax relief (cf. section 2.2.1). Together with the incentive to reduce production costs, the ordinance will most likely be the main driver behind future improvements in the environmental performance of rapeseed production. The future by-product usage of rape straw is possible, but the ecological implications - e.g. disruption of carbon balance of the soil and high particle emissions associated with the rape straw incineration - are still strongly disputed.

Industrial processing

The projected industrial processing costs entail high uncertainty and have thereby a relatively higher cost range for the year 2020 than the projected rapeseed costs. Considering both scenarios, industrial processing costs are expected to be within the range of 0.27-0.32 €/liter. Again, no bottom-up studies on future production costs were available to gauge whether the projected cost reductions are feasible. Nonetheless, the projected cost reductions are plausible given the fact that the highly competitive biodiesel market urges producers to curtail production costs. Several forecasted developments are described shortly below to assess the feasibility of the quantitative projection.

The further upscaling of biodiesel plants and the shift to a higher percentage of multi-feedstock and annex plants are expected to continue in the future. Furthermore, despite the lack of potential to further optimize the actual oil milling and esterification processes from both an economic and environmental point of view, more sophisticated by-product processing is expected to be implemented in the future (cf. section 5.1.2). All these forecasted changes entail higher specific investment costs and lower variable costs. However, the cost savings in the variable costs are likely to outweigh the extra investment costs due to the large annual production volumes of biodiesel today. It should be said that the shift from single to multi-feedstock plants affects merely the production costs of biodiesel in general, not of RME. After all, most single-feedstock plants are already capable of processing rape oil and do not benefit from investments in multi-feedstock technologies. The construction of biodiesel plants at sites with more favorable logistics is another cost component with reduction potential, since transportation distances will be lowered. Considering all forecasted developments, there is still potential left for further cost reductions and it is therefore deemed possible that a 9-13% cost reduction in industrial processing costs (cf. section 5.4.2) will be achieved in 2020. Also for the industrial processes, it is very difficult to give a quantitative projection for the environmental performance in 2020. The factors behind further improvements in environmental performance will most likely be improved by-product processing and more optimal site selection and logistics.

Total RME production

The projected total *hypothetical* production costs involve high uncertainty, mainly as a result of the high cost range for the year 2004. The cost range for the year 2020 is projected to be within the range of 0.65-0.73 €/liter, implying a meager decrease of 9% compared to the year 2004. The projected cost reductions are rather small considering the large reduction potential for rapeseed production costs. Furthermore, it could be questioned to what extent the *RME* production expansion to the ten percent target for the year 2020 is likely given the restrained outlet possibilities of rape meal in the fodder market (cf. section 5.4.2). Nonetheless, this study assumes that new by-product applications will become available over time.

The *actual* total RME production costs are determined by the rape (oil) price, industrial processing costs and financial revenues for by-products sale. As rape oil accounts for 75-90% of the total production costs, the future rapeseed oil price levels are decisive for the profitability of RME. The projected cost reductions in rapeseed cultivation will have a lowering effect on the rapeseed (oil) prices, whereas the increasing competition on the rapeseed market will have a rising effect on the rapeseed (oil) prices. Moreover, the uncertainty regarding the future European Union subsidy scheme makes it even more difficult to give an outlook on future rapeseed (oil) prices. The considerable range in the industrial processing costs (10-25%) also implies large uncertainty in regard to the improvement potential for the total RME production costs. The biodiesel industry should find the most optimal processing technologies to dampen both industrial processing and investment costs. The shift in by-product usages, due to the oversupply on the markets, will be detrimental for biodiesel producers as by-products are expected to fetch lower prices on other markets. The alternative usages of rape meal will slightly improve the environmental performance of RME; the effect on the primary energy use and GHG emissions caused by a shift in the glycerin usage is unknown.

6. Sensitivity and uncertainty analysis

This chapter aims to investigate the effects of several methodological issues and assumptions on the final results. A selection was made regarding the most influential factors affecting the progress ratio of the experience curves, viz. the production volumes and value for the initial cumulative production. Furthermore, price effects were excluded from production costs to assess technological learning in rapeseed and RME production.

6.1 Production volumes

The experience curve theory states that production costs reduce with a constant factor with each doubling in the cumulative production due to technological learning. Hence, the initial cumulative production represents the amount of technological learning accumulated before the first data point. Furthermore, the value for the initial cumulative production determines the amount of cumulative doublings - over the period for which data are available - and thereby the calculated progress ratio. The impact of this value was examined for both the rapeseed and RME production. Also, two separate experience curves were constructed for the learning systems West Germany and the Federal Republic of Germany to examine the (possible) technology exchange between the western and eastern states after the accession.

Rapeseed production
Three scenarios were devised with different values for the initial cumulative rapeseed production, each based upon the production volumes associated with a different period prior to the first data point in the experience curve (see table 16). In scenario I, the production volumes over the period 1950-1970 were taken as the initial cumulative production. As most technological progress took place after the Second World War (Handler, 2007), this scenario was used as the base case in this study. The initial cumulative productions of scenario II and III were calculated by adding up the production volumes over a longer and shorter period, viz. 1900-1970 and 1971 respectively. The available rapeseed production volumes (1950-2006) were extrapolated to the year 1900 to obtain a rough estimate of the initial cumulative rapeseed production for scenario II. The extrapolation of the rapeseed production volumes and the coming about of the scenarios are described in appendix E-I.

The large differences in the initial cumulative production are reflected in the differing calculated progress ratios (see table 16). Despite the diverging progress ratios, all three scenarios yielded an experience curve with a reliable fit. As the amount of initial cumulative production decreases, the progress ratio becomes higher, i.e. less favorable, due to the fact that more doublings are necessary to realize the same cost reductions. The difference between the progress ratios of scenario I and II is relatively small because of the rather low (estimated) rapeseed production volumes in the beginning of the 20th century. The progress ratios of scenario I and III on the other hand differ much more due to larger annual production volumes, and thus, technological learning accumulated over this period. The different progress ratios emphasize the importance of the assumptions made on the initial cumulative production.

As described in chapter 3, one compound experience curve was constructed for the period 1971-2006, although the available data pertained to West Germany for the period 1971-1989 and to the Federal Republic of Germany for the period 1991-2006. The accession of the GDR in 1990 could have led to either a sudden fall in the *average* rapeseed production costs or have no effect at all on the level of *average* production costs, depending on the technological progress of the rapeseed cultivation in the GDR. The former case would imply an adoption by the western states of technology and experience previously developed and accumulated in the GDR; the latter case would imply the other way around. In case the eastern states adopted experience from the western states, a slight increase in production costs might be observed as *average* rapeseed production costs increased due to inefficient agricultural practices in the former GDR. As no discontinuity can be seen in the compound experience curve in the years after 1990, the difference in technological progress between the western and eastern states is considered to have been insignificant, based on the experience curve. However, the sudden increase in annual rapeseed production after the accession could have (partly) counterbalanced a decrease in *average* production costs. After all, relatively more cumulative doublings occurred in these years resulting in less cost reductions per doubling. However, this effect is expected to have been rather small. Hence, it is considered justified that only one instead of two separate experience curves were constructed over the period 1971-2006.

	Scenario I: Base case	**Scenario II: Long time frame**	**Scenario III: Short time frame**
Initial cumulative production	1950-1970	1900-1970	1971
Initial value (10^6 tonnes)	1.75	2.38	0.0
Progress ratio (%)	80.4	77.8	87.1
R^2	0.97	0.96	0.95
	Base case (1971-2006)	**West Germany (1971-1990)**	**FRG (1991-2006)**
Initial cumulative production	1950-1970	1950-1970	1950-1970
Initial value (10^6 tonnes)	1.55	1.55	1.55
Progress ratio (%)	80.4	78.7	87.1
R^2	0.97	0.95	0.95

Table 16: *Effects of initial cumulative production values and decomposition of rapeseed experience curve on the calculated progress ratio*

Nonetheless, it is worthwhile to investigate whether separate experience curves can be constructed for West Germany and the Federal Republic of Germany (FRG) in order to see if different progress ratios and more reliable fits can be calculated (see table 16). A considerably lower progress ratio was calculated for West Germany (78.7%) than for the Federal Republic of Germany (87.1%); a reliable fit[37] was calculated for both experience curves. The increase in progress ratio has been, at least partly, a result of the increase in annual rapeseed production, whereby cost reductions are spread over more cumulative doublings. However, the technological learning rate might have also partly increased as a result of the accession of the GDR, which could have had a higher, i.e. less favorable, learning rate than West Germany.

Industrial processing

Three scenarios were devised for the industrial processing cost to examine the effect on the calculated progress ratio and R^2 (see table 17). As no RME production volumes were available, total biodiesel production volumes (1991-2004) were used for the base case scenario (cf. section 4.1). In scenario II, production costs were plotted against the cumulative global fatty acid and biodiesel production over the period 1950-1990. The reasoning behind this scenario is that technological learning has to some extent taken place with the production

[37] The reliable fit (high R^2 value) of both experience curves is partly due to the low amount of data points used to plot the experience curves.

and esterification of fatty acids in the chemical industry and with biodiesel production and plant construction outside Germany (cf. section 3.2). Unfortunately, it is impossible to say to what extent these technological learning processes have occurred, and thus, to quantify the amount of initial cumulative production. The sole aim of this scenario is therefore to demonstrate the effect of the higher initial cumulative production on the calculated progress ratio when assuming that technological learning took place in all global fatty acid[38] and biodiesel production in the past. In scenario III, cost data before 1994 were excluded from the experience curve as the incorporation of these data points is controversial[39]. After all, biodiesel was produced in a non-commercial fashion before 1994. The production volumes over the years 1991-1993 were summed up and used for the initial cumulative production. The coming about of the scenarios is described in appendix E-I.

	Scenario I: Base case	**Scenario II: All**	**Scenario III: Commercial**
Initial cumulative production	German biodiesel 1991	Global fatty acid & biodiesel production 1950-1990	German biodiesel 1990-1993
Initial value (10^3 tonnes)	0	43,572	35
Progress ratio (%)	97.4	69.7	97.7
R^2	0.65	0.53	0.32

Table 17: *Effects of excluding non-commercial processing costs, initial cumulative production values and annual production volumes of industrial processing to RME on the calculated progress ratio*

The base case reflects the worst-case scenario, since the zero initial cumulative production causes a maximum amount of 14 cumulative doublings over which the cost reductions are spread (cf. section 5.2.2). In scenario II, cost reductions are spread over just nearly one cumulative doubling, due to the much higher initial cumulative production. As expected, a much lower progress ratio (69.7%) was calculated, demonstrating the high sensitivity of the progress ratio on the chosen value for the initial cumulative production. The lower R^2 (0.53) does not confirm the speculation that a better experience curve can be constructed when considering the global chemical and biodiesel industry as one overarching learning system. Since scenario II reflects the most optimistic scenario with respect to the pace of technological learning, the actual progress ratio will likely be somewhere in between the values calculated in scenario I and II. In scenario III, cost reductions took place over merely six cumulative doublings, while the progress ratio (97.7%) is higher than in the base case scenario. This seemingly contradiction is due to the fact that the high amount of cumulative doublings in the years before 1994 took place simultaneously with the largest cost reductions. Table 17 shows the relatively small effect of the value for the initial cumulative production on the calculated progress ratio.

6.2 Excluding price effects

The production costs are influenced by the quantities and exogenous prices of the raw materials necessary to produce rapeseed and RME (cf. section 3.2.2). Cost reductions due to the usage of fewer raw materials (fertilizer, tractor fuel, methanol, etc.) are a result of

[38] No figures were found for the amount of fatty acids used for esterification in the past. Therefore, figures on the total global fatty acid production were used instead and extrapolated back to 1950.
[39] Several biodiesel experts and producers argued that early biodiesel pilot plants are not representative for commercial biodiesel production. Therefore, it is sometimes advocated that cost data stemming from early years in the industry should not be incorporated in the experience curve.

technological learning; changes in production costs due to fluctuating prices are not. This section aims to quantify the contribution of the exogenous prices on the total production costs by keeping the prices at a constant level.

Rapeseed production
The prices of indirect compounds necessary for the rapeseed cultivation have changed constantly over the period 1971-2006. The *absolute* production costs can be corrected for the price effect, i.e. *relative* production costs, by using similar prices (2006) for all years. Table 18 shows the price effect for the four largest cost categories and the total production costs for the years 1971 and 2006. As can be seen, the cost reductions were partly due to changing exogenous prices. The *absolute* cost reduction of the category fertilizer is almost two times higher than the *relative* cost reduction. As reductions in total fertilizer costs account for nearly 50% in the total rapeseed cost reductions (cf. section 5.2.1), the decline in fertilizer prices accounts for 25% in the total rapeseed cost reduction. In total, 20% of the overall cost reduction is due to the price effect, whereas 80% of the overall cost reduction is as result of the reduction in raw material quantities and thereby of technological learning. The calculated progress ratio of the *relative* production costs (87.3%) is higher than the progress ratio of the *absolute* production cost (80.4%). The higher progress ratio implies less cost reductions with each cumulative doubling. Contrary to expectation, a lower, although still high, R^2 (0.95) was calculated for the *relative* production costs. The experience curve for the *relative* production costs and the price effect of the other cost categories can be found in appendix E-II.

	1971	2006	Change
Absolute production costs (€$_{2007}$ / t rape)	**845**	**251**	**-70%**
Fertilizer	348	52	-93%
Chemicals	79	25	-68%
Land	85	44	-48%
Total capital costs	181	89	-51%
Relative production costs (price effect excluded) (€$_{2007}$ / t rape)	**565**	**251**	**-56%**
Fertilizer	101	52	-49%
Chemicals	80	25	-69%
Land	74	44	-41%
Total capital costs	183	89	-51%

	Technological learning	Price changes
Contribution total cost reductions 1971-2006	80%	20%
	Absolute production costs	**Relative production costs**
Progress ratio (%)	80.4	87.3
R^2	0.97	0.95

Table 18: *The effect of the changing prices of indirect compounds on the four largest cost components, total production costs and progress ratio of rapeseed production over the period 1971-2006.*

Industrial processing
The majority of available studies on industrial processing costs did not distinguish between quantities and prices in the cost categories. Unfortunately, it was therefore not possible to examine the price effect on the industrial processing costs. Especially in recent years, changing price levels have seriously affected industrial processing costs (cf. section 5.2.2). The multitude of price factors and the lack of commodity price series impede any further analysis on the price effects for the industrial processing costs.

6.3 Excluding fertilizer effect

Similar to the production costs, the environmental performance of RME is influenced by exogenous developments in the production of indirect compounds. This study uses constant values for the specific primary energy use and GHG emissions for all three years (1993, 2000 and 2007) (cf. section 4.2). Nonetheless, the development of the specific primary energy use of *nitrogen* fertilizer production was taken into account by using different values from Ramirez (2005). As *nitrogen* fertilizer has been by far the prime contributor in the *overall* reduction of primary energy use (44.8%) and CO_2-equivalents (60.8%) in the rapeseed production step (cf. section 5.3.1), it is worthwhile to examine to what extent the exogenous developments in *nitrogen* fertilizer production have contributed to the *overall* reductions over time.

The figures on the environmental performance of RME can be corrected for the developments in nitrogen fertilizer production by using similar values[40] for the specific primary energy use and emitted GHG emissions for all years. Table 19 shows the effect of the exogenous developments on the category "nitrogen fertilizer" and the total environmental performance for the years 1993, 2000 and 2007. As can be seen, the reductions in primary energy use and CO_2-equivalents were only slightly higher (4%) as a result of the improvements made in nitrogen fertilizer production. Nonetheless, as *nitrogen* fertilizer has been by far the prime contributor to the *overall* reductions in the *rapeseed* production step (cf. section 5.3.1), the exogenous fertilizer developments still account for 2% in both the *overall* primary energy use and CO_2-equivalents reductions of *RME* production over time. In total, the *overall* reductions were mainly due to lower amounts of fertilizer usage (technological learning) for both primary energy use (93%) and CO_2-equivalents (91%), whereas only a minor share has been a result of improvements made in nitrogen fertilizer production (energy use: 7%; CO_2-eq: 9%).

Absolute environmental performance RME		**1993**	**2000**	**2007**	**Change 1993-2007**
Category "Nitrogen fertilizer"	GJ_p/tonne RME	7.7	4.7	3.9	*-50%*
	kg CO_2-eq/tonne RME	11.6	7.1	5.9	*-50%*
Total *absolute* performance	GJ_p/tonne RME	17.6	10.0	9.0	*-49%*
	kg CO_2-eq/tonne RME	33.3	25.1	23.8	*-29%*
Relative environmental performance RME (nitrogen fertilizer developments excluded)		**1993**	**2000**	**2007**	**Change 1993-2007**
Category "Nitrogen fertilizer"	GJ_p/tonne RME	7.2	4.5	3.9	*-46%*
	kg CO_2-eq/tonne RME	10.7	6.8	5.9	*-46%*
Total *relative* performance	GJ_p/tonne RME	17.0	9.7	9.0	*-47%*
	kg CO_2-eq/tonne RME	32.4	24.9	23.8	*-27%*

	Technological learning	**Nitrogen fertilizer production**
Primary Energy Use	93%	7%
Global Warming	91%	9%

Table 19: *The effect of exogenous developments in nitrogen fertilizer production on the category "Nitrogen fertilizer" and total environmental performance of RME over the period 1993-2007.*

[40] The specific primary energy use and GHG emissions of the year 2007 (37.3 GJ_p/tonne N; 5.6 kg CO_2-eq/tonne N) were taken for all three years (1993, 2000 and 2007).

7. Discussion

Chapter 5 has shown substantial improvements in the production cost and environmental performance of RME over time. This chapter considers the results in a broader context and evaluates the research by assessing the underlying data and applied methodology. Furthermore, a comparison will be made with the production costs of first generation bio-ethanol in Brazil and the United States and future generation biofuels.

7.1 Context of the results

Costs versus prices and frame conditions

The economic competitiveness of RME is determined by *frame conditions* and *prices* instead of production *costs*. The large influence of a change in tax regime and the price level of raw materials, by-products and crude oil prices on the economic competitiveness of RME, have been demonstrated several times in the past (see also figures 5 and 13). Especially rapeseed displays a stark contrast in the development of *costs* and *prices* over time. In the early nineties, the rapeseed *price* was generally much lower than rapeseed production *costs*, whereas in recent years the *price* exceeded the production *costs* due to market dynamics. Similarly, despite efficiency improvements in by-product processing achieved over time, financial credits for the sale of by-products have declined due to lower rape meal and glycerin *prices*. Evidently, production *costs* and *prices* do not necessarily develop in close concordance with each other. Hence, the projected *cost reductions* in this study should be put into perspective considering the large influence of *prices* and *frame conditions* and the lack of a clear correlation between *costs* and *prices*. Moreover, a further increase in rapeseed (oil) price (Hansen, 2007) and decrease in glycerin and rape meal price (cf. section 5.1.2) are likely to occur in the short term, thereby deteriorating the economic competitiveness of RME. Nonetheless, as prices are determined by a multitude of factors - e.g. feedstock potential, subsidies, market dynamics, other vegetable oils prices, etc. - the future development of the economic competitiveness of RME remains to be seen.

Internationalization

An important current development is the ongoing internationalization of biomass and biofuel markets. Especially in recent years, technology providers are reducing their dependency on domestic markets by installing production capacities all over the world. In parallel, a significant increase in the global trade of both feedstock and biofuels can be observed. In the future, this global trade is expected to become even stronger, also because of the current liberalization trend of agricultural markets. For Germany, an increasing import of rapeseed (oil) is expected for the future (Reca & Hansen, 2007). Also the ongoing establishment of foreign biodiesel industries will most likely lead to a further distribution and export of German state-of-the-art processing technologies, and subsequently, to more market competition on a global level (Hansen & Vaals, 2005). These internationalization trends will increasingly result in a worldwide accumulation and exchange of technological learning, thereby leading to faster cost reductions and improvements in environmental performance of German rapeseed and RME production. Although the demarcation of Germany as a learning system seems justified for the analysis of past developments in costs and environmental performance of RME (cf. section 3.2.1), an international approach is required for future analyses. The calculated results in this study concerning the future cost reductions should therefore be put into perspective. Despite the advantage of possible technological learning “import” in the future, German rapeseed farmers and biodiesel producers will also have to deal with sharp international price levels. Future competitive disadvantages are conceivable for German biofuel producers; a situation that might be amplified by unequal financial support granted to the production and/or export of biofuels in other countries (e.g. the United States which grant subsidies for the export of domestic biodiesel to Europe and Asia) (IE, 2008).

7.2 Data limitations and methodological issues

The main strength of this study has been the extensive and laborious data research, especially for production costs over time. A broad range of literature sources, press releases, experts, technology providers and biodiesel producers was examined at length. However, the available data involved several limitations that have to be considered in closer detail. Also, the methodological implications of these limitations are discussed in the following.

Production volumes and inflation index
The lack of data on RME production volumes necessitated the use of aggregated data on total biodiesel production. The aggregated figures causes uncertainty with respect to the experience accumulated over time. As aggregated production volumes of biodiesel are higher, more cumulative doublings took place, and thereby, a higher progress ratio was calculated. Although RME production accounts for most technological learning, a minor share has to be attributed to alternative biodiesel production. Another point of discussion is the data on EU production volumes, which also involve uncertainty, since these figures were not very accurate and had to be extrapolated to the year 1985. Also the forecasted production volumes for the year 2020 entail uncertainty as it concerns estimates, although it should be mentioned that projected rapeseed costs seem to be hardly influenced by a change in the production volumes. Data on the consumer price index are considered to be reliable, albeit previous research (Hettinga, 2007) has shown the substantial impact of different inflation indices on the calculated progress ratio and R^2. Further research on the specific impact for the rapeseed-RME system is desirable.

Feedstock costs
Unfortunately, cost data could only be traced for West Germany (1971-1990) and the Federal Republic of Germany (1991-2006). The incorporation of cost data from the GDR might have influenced the average cost level and thereby the calculated progress ratio (see section 7.2). Despite the use of two high quality datasets (KTBL), several small assumptions had to be made which have influenced the overall cost level. First, farmers were assumed to choose the adequate chemicals and fertilizers with the lowest prices, which is favorable for the total costs. This uncertainty is amplified by the varying fertilizer quantities applied across Germany due to the current irregular, sub-optimal fertilizer regime. Second, the few data omissions in the datasets required the use of ten-year average values instead. Third, quantities of rather negligible cost components, such as weather insurance and water usage, were sometimes assumed constant over time due to a lack of data. Fourth, production costs for oil crops in general were used for the years 1971 and 1975, because no data on rapeseed costs were available. The relatively high production costs for oil crops might suggest an additional cost reduction than is actually the case. Finally, rape straw was excluded from the analysis, which lowers the financial revenues, but simultaneously lowers the financial expenditure on fertilizer. As no data were found on the alternative usage of rape straw, the effect on the overall results is unknown. Despite several small assumptions, the overall cost data are deemed to be reliable and of high quality as the cost calculations were straightforward.

Consequently, the experience curve of the feedstock system is considered to be reliable since data seem to be of high quality. Nonetheless, the sensitivity analysis has shown that the value for the initial cumulative production has a large influence on the progress ratio (cf. section 6.1). Despite the plausible argument to sum up production volumes after the Second World War, it is demonstrated that alternative assumptions on the time span influence the results considerably. It can be alleged that the EU-wide regulations and markets for rapeseed production demands for the enlargement of the system boundaries to EU or world level. Furthermore, the increasing trade of rapeseed across Europe requires for more research into technological learning in rapeseed production at a higher level (cf. section 7.1). Contrary to expectation, the correction for price effects resulted in a slightly lower calculated R^2 for the experience curve. However, as this might seem contradictory from a methodological point of view, it has barely any implications for the investigated relationship between production costs and cumulative production.

Industrial processing costs
The strength of the data collection on the industrial processing costs was the huge amount of examined sources. A questionnaire was devised and sent to all esterification plants and technology providers in Germany. Unfortunately, only a few biodiesel producers responded as a result of confidentiality issues. Therefore, data originating from literature studies were used instead. These cost data involve considerable uncertainty due to data obscurities and insufficient specification of the cost components, particularly for transport, distribution and glycerin processing. The differently structured cost studies made several assumptions and recalculations necessary, resulting in large discrepancies between the original and calculated cost values. Furthermore, most studies failed to distinguish between quantities and prices, making it impossible to correct for influential energy and methanol prices. Finally, frequently missing information on plant size, reference year, assumed processing technology (batch or continuous) and incorporation of annuities made it difficult to compare the costs over time.

The above-mentioned data uncertainties influence the calculated progress ratio and R^2 a great deal and might explain the erratic pattern in the industrial processing costs over time. Both qualitative and quantitative data indicate that cost reductions have taken place over time, although more accurate and detailed data are required to construct a more reliable experience curve. A future relaxation of the biodiesel market might persuade biodiesel producers to provide more reliable data, which are nowadays still out of reach. Another important discussion point is the chosen value for the initial cumulative biodiesel production. The assumption of almost zero initial cumulative production is rather pessimistic considering the experience accumulated by the chemical, oil milling and biodiesel industry with respectively fatty acid, rape oil and biodiesel production. Unfortunately, it is impossible to say to what extent these technological learning processes have occurred. As demonstrated in the sensitivity analysis, a significantly lower progress ratio was calculated when incorporating global fatty acid and biodiesel production (cf. section 6.1). The progress ratio depends strongly on the value for the initial cumulative production. Another discussion point is the sharp difference between the cost reduction in the non-commercial and commercial phase, which could have been a result of an increase in the progress ratio. Nonetheless, the sensitivity analysis has shown that an almost similar progress ratio was calculated when considering cost data from the commercial phase only (cf. section 6.1). Furthermore, experience curves are usually applied on mature industries. Germany has been producing biodiesel for only 17 years, of which merely 14 years commercially. On the other hand, the high number of cumulative doublings in biodiesel production and the considerable cost reductions over time seem to justify the utilization of the experience curve tool. The extrapolation of the experience curve is questionable as the future *RME* production expansion is limited by the restrained outlet possibilities of rape meal in the fodder market. This study assumes that RME production will continue to grow by shifting to alternative rape meal by-product usages generating sufficient financial revenues for RME to remain an economically viable transport fuel. However, more research on the possibilities and financial and ecological implications of alternative rape meal (and glycerin) usages is required.

Investment costs and total hypothetical production costs
The turnkey investment costs were taken from a multitude of press releases. The data limitations and strong market influences are expected to give at least a partial explanation for the fact that no trends were observed over time. The accumulated experience by the German technology providers outside Germany has further clouded a possible relationship between investment costs and cumulative installed capacity (cf. section 7.1). Research on a global level is imperative to ensure the incorporation of all accumulated experience. Although the analysis on scaling factors has shown the substantial contribution of upscaling on the specific investment costs, more detailed and accurate data are required to gain insight in the precise quantitative development of investment costs, and contribution of upscaling, over time. As for the total *hypothetical* production costs, the low chosen value for the initial cumulative biodiesel production is rather pessimistic and (partly) explains the high calculated progress ratio (96.7% ± 1%). Also, the assumption of constant by-product yields does not reflect reality as by-product processing improved over time. Nonetheless, it is expected that this choice has been of minor influence on the results.

Environmental performance
The thorough search for data on the environmental performance has shown that only two German datasets (1993 and 2000) were originally available, despite the multitude of published LCA studies over time using data from these datasets. The compilation of an up-to-date German database would be welcome to examine the current environmental performance, although anecdotal information indicates that no further changes were realized in recent years (Reinhardt, 2007). Although data scarcity impeded the verification of energy requirements and CO_2-equivalents as alternative performance indicators for technological learning, it is expected that for the agricultural stage these performance indicators might have developed in concordance with the learning curve model. After all, as lower fertilizer usage was the main cost reducer over time, energy requirements, which are strongly linked to fertilizer production costs, have likely been driven by a cost incentive. As for the industrial processes, possible improvements in energy use have likely not been driven by a cost incentive, given the minor influence of energy expenses on the economic competitiveness of RME (see figure 12).

As mentioned in the results chapter, several data limitations might explain the unexpected increase in primary energy use and GHG emissions over the period 2000-2007. The Swiss data used by Schmidt (2007) could explain the slight increase for the direct processes of the agricultural stage. Although Swiss data were considered to resemble the German situation rather well, agricultural practices are less efficient in Switzerland due to the mountainous landscape and lack of large-scale farming advantages (Jungbluth, 2007). Furthermore, data uncertainty is expected to be the cause for the higher energy usage associated with the rapeseed drying process. The use of *non-German* LCA studies for the industrial processes in 2007 is not expected to be the underlying reason for the increase in energy use and GHG emissions, since the environmental performance of this stage should be quite similar for all European countries (Jungmeier, 2007). The increase is most likely due to the use of plant specific instead of industrial average data (Gärtner, 2008; Groves, 2008). Furthermore, the

English and French LCA studies originated from the year 2002, implying that these studies do not represent the current state-of-the-art technologies. The most likely explanation for the preceding increase over the period 1993-2000 is the revision of the IFEU 1993 dataset and the use of plant specific data (Gärtner, 2008; Reinhardt, 2007).

In addition to the above-mentioned data limitations, several other data (processing) issues might have affected the total results. First, the specific primary energy use and GHG emissions associated with the indirect processes were, aside from fertilizers, kept constant over time. The *actual* decline in primary energy use and GHG emissions might have been even higher due to efficiency improvements in the indirect processes. Second, although all three datasets were structured similarly, several underlying assumptions were unknown, for instance regarding the tractor types and transport modes and distances. However, these uncertainties were considered to be of minor importance. Another very important discussion point is the decision to use set-aside land as the reference field and the assumption of constant N_2O emissions from the reference field, both having a large influence on the total N_2O emissions, and thus, CO_2-equivalents. In addition, large uncertainties are involved with the values used for N_2O emissions (Smeets *et al*, 2008). Gärtner & Reinhardt (2003) indicate that no scientifically reliable value can be derived for N_2O emissions from the reference land in Germany. As the overall GHG emission reduction of RME compared to fossil diesel may vary from -72% to 69% (Smeets *et al*, 2008), depending on the above-mentioned factors, the category “*net* N_2O emissions” is decisive for the overall GHG balance of RME. Finally, the sole use of mineral fertilizers was assumed, whereas in reality, manure might also hold a share in the fertilizing process. Furthermore, as rape straw is commonly ploughed back into the soil, the energetic utilization of rape straw was not considered in spite of the fact that it more than doubles the net energy winnings in the agricultural stage (Roesch, 1997). The data limitations and methodological decisions entail large uncertainties in the results. A sophisticated sensitivity analysis could provide more insight into the effect of varying parameters on the results for the long-term developments of primary energy use and GHG emissions. Nonetheless, such an analysis was considered not to be within the reach of this study.

Stakeholders and expert opinions
The quantitative results of the experience curves and LCA research were supported by qualitative data originating from literature and opinions from biodiesel producers, technology providers and rapeseed and biodiesel experts. The reliability of the information retrieved by means of the questionnaire is questionable given the few biodiesel producers and technology providers that responded. Furthermore, anecdotal reports and expert opinions are biased and may not fully reflect reality.

7.3 Comparison first and future generation biofuels

7.3.1 First generation biofuels

First generation biofuels are generally considered to include ethanol derived from sugar or starch crops and biodiesel (methyl or ethyl) derived from vegetable oils or fats. The vast majority of liquid biofuels produced today are first generation ethanol and biodiesel. Although biodiesel production has shown an impressive growth in recent years, ethanol still accounted for more than 90% of the world biofuel production in 2005 (WWI, 2006). Brazil and the United States have a long history of ethanol production and are by far the largest biofuel producers in the world. Similar to this research, two studies were carried out for the cases of cane-ethanol production in Brazil (Wall Bake, 2006) and corn-ethanol production in the United States (Hettinga, 2007). Despite the differences in feedstock, industrial processes and framework conditions, a comparison is made to examine whether similar developments can be discerned for all three cases. Table 20 gives an overview of the results for all three cases.

	Brazil	**United States**	**Germany**
Agricultural yield (2005)	75-82 T_{cane}/ha	9-10 T_{corn}/ha	3.5-4 T_{rape}/ha
Biofuel yield (2005)	82 L/T_{cane}	400 L/T_{corn}	434 L/T_{rape}
Fuel energy yield per hectare[41] (2005)	162-178 GJ/ha	95-106 GJ/ha	57-65 GJ/ha
Feedstock production	**1975-2005**	**1975-2005**	**1971-2006**
Cost reduction	60%	63%	70%
Number of cumulative doublings	3	1.9	5.3
Progress ratio	68.0% ± 3%	55.0% ± 2%	80.0% ± 1%
Production costs 2004[42]	€ 11.7/T_{cane}	€ 60/T_{corn}	€ 264/T_{rape}
Industrial processing	**1975-2005**	**1983-2005**	**1991-2004**
Cumulative biofuel production (2005)	240 mln. T_{eth}	99 mln. T_{eth}	4.5 mln. T_{RME}
Cost reduction	70%	49%	31%
Number of cumulative doublings	5	7.2	13.9
Progress ratio	81.0% ± 2%	87.0% ± 1%	97.5% ± 2%
Production costs 2004	€ 160/T_{eth}	€ 146/T_{eth}	€ 368/T_{RME}[43]
Total *hypothetical* costs (2004)[44]	**~ € 13.1/GJ**	**~ € 12.7/GJ**	**~ € 27.3/GJ**

Table 20: *Comparison of results with the cases for cane-ethanol (Brazil) and corn-ethanol (United States). (Data sources: Wall Bake, 2006; Hettinga, 2007).*

All three feedstock systems show substantial cost reductions over time. The rapeseed production has experienced the largest cost reductions (70%), although it should be noted that this system was analyzed over a slightly longer period (1971-2006) than the other two cases (1975-2005). Furthermore, the cost reductions of Brazil and the U.S. strongly depend on the chosen currency exchange rates. However, the rapeseed cost reductions still amount up to 64% when analyzed over the period 1975-2005. Similar drivers behind feedstock cost reductions were agricultural yield increases and improved crop varieties. Furthermore, upscaling of farms was a significant driver in Brazil and the U.S., whereas lower fertilizer usage has been an important contributor in Germany. The number of cumulative doublings is considerably lower for Brazil and the U.S, due to the much higher values for the initial cumulative production[45]. The lower number of cumulative doublings has (partly) contributed to the lower, i.e. more favorable, progress ratios for the sugar cane and corn systems. Nonetheless, the results indicate a significantly higher technological learning rate for cane production and particularly for corn production. In 2005, cane production showed by far the cheapest production costs, mainly due to the agricultural yields, which in turn are a result of the favorable climate conditions in Brazil (WWI, 2006).

[41] Ethanol: LHV = 26.4 MJ/L, density = 0.791 kg/L; RME: LHV = 37.3 MJ/L, density = 0.900 kg/L (Hamelinck, 2004).
[42] Used currency exchange rates: Brazil 2.55 R$/€; United States 1.53 US$/€
[43] The average value for industrial processing costs was taken for the year 2004
[44] Credits for by-products are included
[45] The period over which the initial cumulative production was summed up was quite similar for all three cases. The diverging values for the initial cumulative production were rather due to the much higher annual production volumes for Brazil, and especially the U.S., over this period.

The long history of ethanol production in Brazil and the U.S. is reflected in the high amounts of cumulative ethanol production. In contrast, Germany has only been producing biodiesel on a commercial scale from 1994 onwards. Moreover, the annual production volumes in Brazil and the U.S. are larger as a result of the enormous country size. The cost reductions diverge considerably for each case, but are measured over totally different timeframes. Again, the three cases display similar underlying cost reduction factors (increasing plant yields, plant upscaling, process innovations and automated processing technologies), although per case different weights were assigned to each driver. The number of cumulative doublings is much higher for the German RME case, resulting in a markedly higher progress ratio than for the other two cases. However, the chosen low value for the initial cumulative production and the use of biodiesel instead of RME production volumes gives at least an (partial) explanation for this higher progress ratio (cf. section 7.2). Furthermore, the relative simplicity of the RME esterification process, which shows only limited improvement potential, seems to give an additional explanation for the low learning rate. In 2005, the industrial processing costs are highest for German RME, whereas the U.S. displays the lowest processing costs in spite of the longer Brazilian experience with ethanol production. However, anecdotal information indicates that further cost reductions have likely been achieved over the last years, due to the booming German biodiesel industry (Wörgetter, 2007). Unfortunately, data scarcity impeded the further analysis of these possible cost reductions.

In conclusion, the calculated total *hypothetical* production costs (feedstock *price* effect excluded) for RME are over two times higher (~ € 27.3/GJ) than for ethanol (~ € 12.7-13.1/GJ). The main reasons for this large difference are the higher fuel energy yield per hectare for ethanol, particularly for Brazil as a result of the favorable climate conditions, and the lower production costs per GJ produced biofuel in the United States.

7.3.2 Future generation biofuels

In general, first generation biodiesel has several disadvantages with respect to the feedstock, such as high production costs, low net energy yield, meager GHG emission reduction potential, limited land potential and competitiveness with traditional food crops. Future generation biofuels show promising prospects in terms of production costs, environmental performance and fuel yield per hectare. Hydrocarbon diesel and Fischer Tropsch diesel are considered to be the most important biodiesel varieties to replace first generation biodiesel in the long term.

Hydrocarbon diesel is often coined the 1.5 generation biofuel as it will most likely be the transitional biodiesel variant before entering the commercial phase of 2nd generation biodiesel. The advantages of hydrocarbon diesel are limited because of the low product yield, high capital costs and similar feedstock constraints as first generation biodiesel (vegetable oils and fats) ((S&T)^2, 2006). Future capital and industrial processing costs will most likely decline with increasing experience and upscaling of plants. Furthermore, the GHG emission profile should be better than for first generation biodiesel, but depends strongly on the way the required hydrogen is produced ((S&T)^2, 2006). The company Neste Oil has already developed a proprietary conversion process (NExBTL) in which GHG emissions are claimed to be reduced by 40-60% throughout the entire life cycle compared to fossil diesel (Neste Oil, 2008).

Fischer Tropsch diesel (FT-diesel) can be produced from a broad array of feedstock, implying a much larger production potential than for first generation biodiesel. Several studies indicate capital costs to be a magnitude of order higher than the capital costs for first generation biodiesel plants of comparable size, whereas variable costs are expected to be much lower (e.g. Hamelinck, 2004; $(S\&T)^2$, 2006). Production costs of FT-diesel are less dominated by feedstock costs, but more by the depreciation costs. The investment conditions (e.g. lifetime plant, interest rate, etc.) are therefore expected to mark the overall production costs ($(S\&T)^2$, 2006). Indications for production costs vary considerably in literature. For recent years, Hamelinck (2004) calculated production costs to be around $€_{2004}$ 18/GJ for a 400 MW_{HHV} plant, whereas Varela *et al* (2006) estimated a value of around $€_{2004}$ 32/GJ[46]. Different underlying assumptions, e.g. regarding plant size, might explain this discrepancy. Despite the large uncertainty involved, production costs of FT-diesel will most likely be lower than for RME in the long term and will most likely be related to the biomass production step (Varela *et al*, 2006). The energy efficiency of the FT-process is rather low (35-45%) compared to fossil diesel and first generation biodiesel. Nonetheless, as almost all required energy is extracted from the lignocellulosic biomass, a much better GHG emission profile can be achieved ($(S\&T)^2$, 2006).

Although hydrocarbon diesel has only a few advantages compared to RME, FT-diesel shows promising prospects with regard to production costs and GHG balance in the long term. As the improvement potential of RME is relatively limited when considered from a top-down viewpoint, a substitution of RME by second-generation biofuels is likely to occur in the future.

[46] The production costs of RME were calculated to be around € 27.3/GJ (see table 20).

8. Conclusions and recommendations

The objective of this study was to assess technological learning by quantifying reductions in production costs, primary energy use and GHG emissions, make future prospects based on the improvement potential and identify the underlying driving factors. This chapter draws conclusions based on the research questions as described in the introduction. Furthermore, several recommendations for further research are given.

8.1 Conclusions

Reductions in production costs are observed for both the rapeseed production and the industrial processing to RME

Rapeseed production costs per tonne have declined by 70% over the period 1971-2006. The main drivers have been increasing rapeseed yields, lower fertilizer usage and improved rapeseed varieties. Industrial processing costs per liter (including capital costs, but excluding by-product credits) have declined by 31% over the period 1991-2004. The main reason behind these cost reductions seem to have been the efficiency gains in the esterification process, due to scale effects, higher plant yields and the shift from batch to continuous processing systems. The total *hypothetical* production costs, which are the sum of the rapeseed and industrial processing costs minus the financial revenues for by-products, have declined by 23% over the period 1991-2004. Improvements in rapeseed production and industrial processing account for respectively 67% and 33% in the total cost reductions. However, the *actual* total production costs, which are determined by *frame conditions* and *prices* instead of *costs*, have increased in recent years, because of the less favorable tax regime, higher raw material prices and lower by-product prices.

Reductions in primary energy use and GHG emissions are observed for the rapeseed production, whereas an increase is observed for the industrial processing to RME

The primary energy use and CO_2-equivalents associated with the rapeseed production have been reduced by respectively 49% and 28% over the period 1993-2007. The decline in the required amount of indirect compounds accounts for 79% of the primary energy reductions and for 82% of the CO_2-equivalents reductions. Efficiency improvements made in the direct processes account for the supplementary reductions. Lower fertilizer usage (especially nitrogen fertilizer) per tonne has been the main driver for the environmental performance improvements of the rapeseed production, which in turn is a result of higher yields and improved rapeseed varieties. The quantitative results for the primary energy use and CO_2-equivalents associated with the oil production show a net overall decline of respectively 3.2% and 4.4%, but increases unexpectedly over the period 2000-2007. Both changes over time were mainly due to altering indicated energy requirements. Contrary to expectation, the quantitative results for the primary energy use and CO_2-equivalents associated with the direct esterification step increased continuously with percentages of respectively 55% and 44% over the period 1993-2007. The increases were due to higher indicated electricity and natural gas requirements. However, the quantitative results contrast anecdotal reports, which assert that energy requirements have declined over the years. Nonetheless, this qualitative information is rather unclear and entails considerable uncertainty. The actual developments of the primary energy use and GHG emissions associated with the industrial processes remains therefore unclear. Overall, the improvements in environmental performance (including credits for by-products) for the rapeseed production outweighed the observed deterioration in environmental performance for the industrial processes over the period 1993-2007. A total decline of 21% was observed for the primary energy use and 36% for the CO_2-equivalents.

However, choices on by-product usage (fodder, fuel, chemical, etc.) have a large influence on the total environmental performance.

The construction of experience curves was possible for the production costs, but not for the primary energy use and GHG emissions.
The analysis has shown that the experience curve concept can be used to describe the developments in both rapeseed production and RME processing costs. A reliable experience curve was constructed for the rapeseed production with a progress ratio of 80.4% ± 1% (R^2 = 0.97). However, the progress ratio is significantly influenced by the value for the initial cumulative production. The experience curve for the industrial processing was less reliable given the low correlation found (R^2 = 0.65). Furthermore, the calculated high progress ratio of 97.4% ± 1% implies a low rate of technological learning. The progress ratio of the experience curve for the total *hypothetical* production costs is 96.7% ± 1% (R^2=0.84). The high, i.e. unfavorable, progress ratios for the industrial processing and total production chain were partly due to the low chosen value for the initial cumulative production. The construction of an experience curve for the investment costs was sheer impossible since no correlation between cumulative installed capacity and specific investment costs was found at all. Data limitations on the environmental performance hampered the construction of an experience curve for the primary energy use and CO_2-equivalents.

Despite projected reductions in production costs, primary energy use and GHG emissions, the future economic competitiveness of RME is mainly determined by other factors.
Technological learning is expected to continue throughout the entire production chain of RME. By extrapolating the experience curve, rapeseed production costs were projected to be within the range of €162-169 per tonne in the year 2020. From a top-down viewpoint, future rapeseed costs are considered likely to be within this range given the reliable experience curve and the small influence of future production volumes on the extrapolated costs. Unfortunately, it was not possible to make a quantitative projection on the primary energy use and CO_2-equivalents in 2020. Nonetheless, advanced (genetically modified) rapeseed varieties, improved agricultural practices and lower fertilizer and chemical usage are expected to become the main drivers for future cost reductions and improvements in environmental performance. The industrial processing costs were projected to be within the range of €0.26-0.32 per liter RME in the year 2020. From a top-down viewpoint, the future industrial processing costs are expected to be within this range, as the future production volumes do not significantly affect the projections. The factors behind further cost reductions will most likely be scale effects, and also for the improvements in environmental performance, improved by-product processing and more optimal site selection and logistics. The total *hypothetical* production costs were projected to be within the range of 0.65-0.73 €/liter RME for the year 2020, implying a cost reduction of 9% compared to the year 2004. However, the restrained outlet possibilities of rape meal in the fodder market might hinder the further production expansion of *RME* necessary for the achievement of the cost reductions. Furthermore, despite the projected *cost* reductions, the economic competitiveness of RME is predominantly determined by the *frame conditions* and *prices.* The marginal projected cost reductions are of minor influence considering the influential tax regime and price effects of raw materials, rapeseed (oil) and/or by-products. Also the internationalization of biomass and biofuel markets causes additional uncertainty. Although German farmers and biodiesel producers might benefit faster cost reductions due to the increasing worldwide accumulation and exchange of technological learning in RME production, they will also have to compete with foreign countries, of which some might be able to provide cheaper biomass and/or biofuels. Currently, the GHG reduction potential of RME is high enough to meet the

targets (30-40% GHG reduction) of the German Biomass Sustainability Ordinance, which makes RME eligible for tax exemption. Further reductions in GHG emissions will most likely be driven by the economic incentive to enhance the GHG reduction potential; a key feature that will play a significant role in the determination of the future RME price. After all, GHG efficient biofuels will enjoy price benefits over less efficient biofuels. As the potential for further reductions in production costs and GHG emissions of RME is limited, the economic competitiveness of RME might deteriorate in the long term. When considering the above-mentioned influential, yet unpredictable factors, the development of the future economic competitiveness of RME remains unclear.

8.2 Recommendations for further research

The experience curve for the industrial processing costs involves large uncertainty due to a lack of sufficient reliable data. The government has the disposal over reliable, industrial average production costs from biodiesel producers for the annual assessment of the possible over-compensation of biodiesel. These data are not released as a result of confidentiality issues. The author recommends the government to use these data to improve the quality of the experience curve and enhance the reliability of the future cost projections.

Although anecdotal reports indicate the stabilization of the environmental performance since the year 2000, an update of the LCA dataset would be desirable to verify these statements. Also, bottom-up studies on the improvement potential of the environmental performance of both conventional and GM-rapeseed would be useful to assess the effectiveness of RME as a way to fight climate change and improve energy security in the future. Promising results might encourage policy makers to take tentative steps towards the introduction of GM-rapeseed without losing sight for adverse side effects.

The outlook of this study is predominantly based on the extrapolation of the experience curves. Nonetheless, to assess the future economic competitiveness of RME an integrated analysis is necessary. Bottom-up studies on future production costs and a thorough analysis into the interaction of (future) prices dynamics, (imported) production volumes and by-product markets are therefore required. Another topic worth investigating is the effect of rapeseed import, particularly from Eastern Europe and Russia, on the biodiesel production potential and production costs. Rapeseed production costs could be significantly lower in these countries as a result of lower costs for capital, labor and indirect compounds. Finally, the current tendency towards globalization and free trade of agricultural products might eventually lead to the abolishment or replacement of the current EU subsidy scheme. Further research into the effects of such a change on the rapeseed production costs is recommended.

Studies by Ramirez & Worrel (2006) and Hettinga (2007) indicate that primary energy requirements can be used as an alternative performance indicator for technological learning, provided that energy expenses account for a major share in the total costs. Unfortunately, this study was not able to examine the use of energy requirements and/or CO_2-equivalents as alternative performance indicators due to data limitations. More research is required, also on other renewable energy technologies, to legitimate the use of these alternative performance indicators.

This study and previous studies (Hettinga, 2007; Wall Bake, 2006) have shown that production costs of three completely different agricultural crops (sugar crops, starch crops and oil crops) developed in close concordance with the learning curve model, showing reliable fits for all three cases. Further research is needed to examine whether the experience curve method can be applied to the broad array of feedstock available for 2nd generation biofuels. As future cost reductions of 2nd generation biofuels will most likely be related to the biomass production step (Varela *et al*, 2006), experience curves could provide insight in the quantitative cost reduction potential for feedstock, which are currently still at their infancy or not yet fully developed.

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Appendices

Contents

A Methodological background

A-I Research structure

Figure 27 gives an overview of the data necessary for the construction of the experience curves for the production costs and environmental performance of RME (cf. section 3.2.2). The upper part (green) represents the required data for the rapeseed system; the lower part (orange) represents the required data for the industrial processing system. Furthermore, the left part represents the required data for the y-axes (production costs, primary energy use and GHG emissions); the right part represents the data necessary for the x-axes, which are similar for all the experience curves.

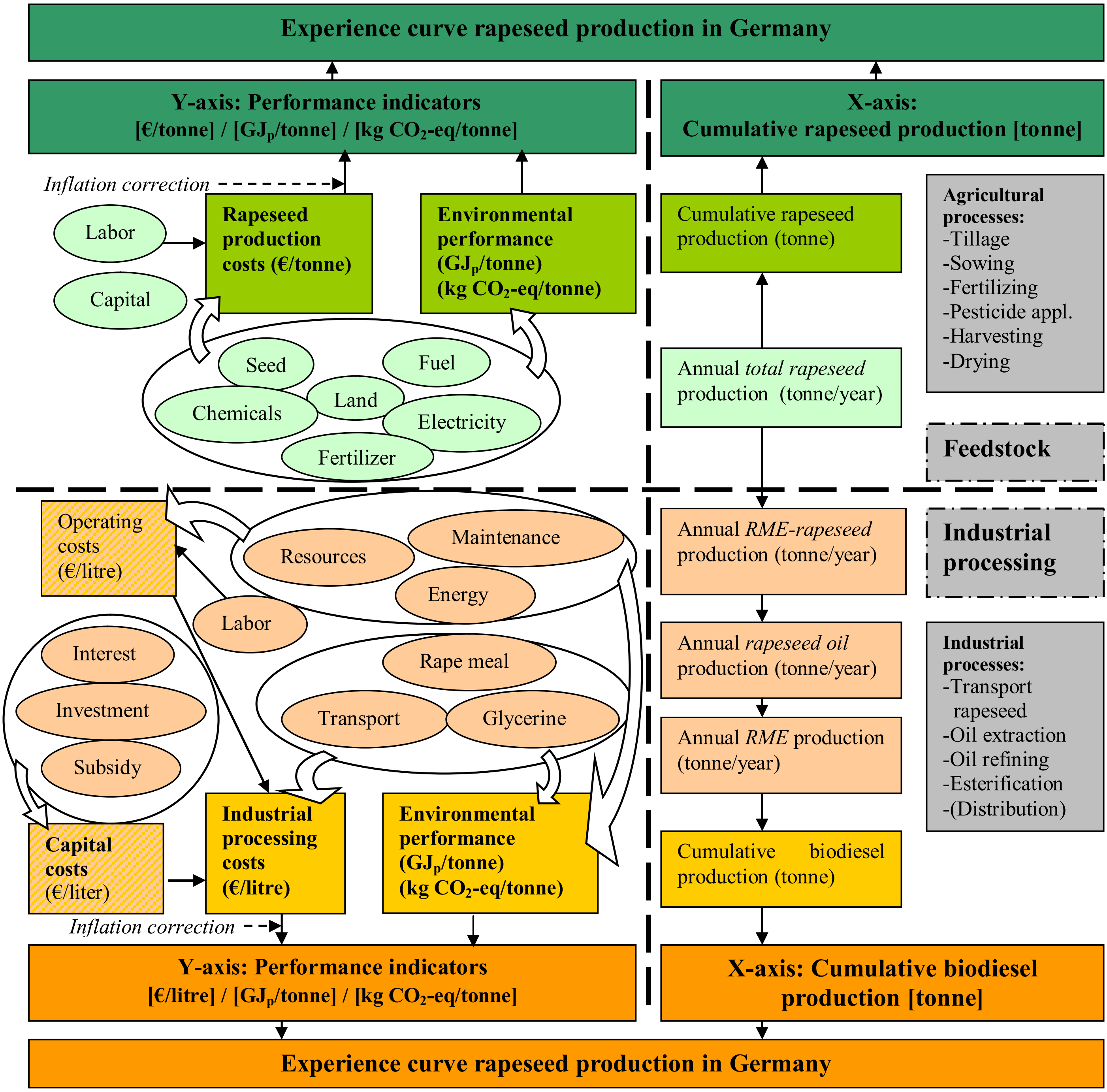

Figure 27: *Research structure*

A-II Flow chart of the life cycle of RME

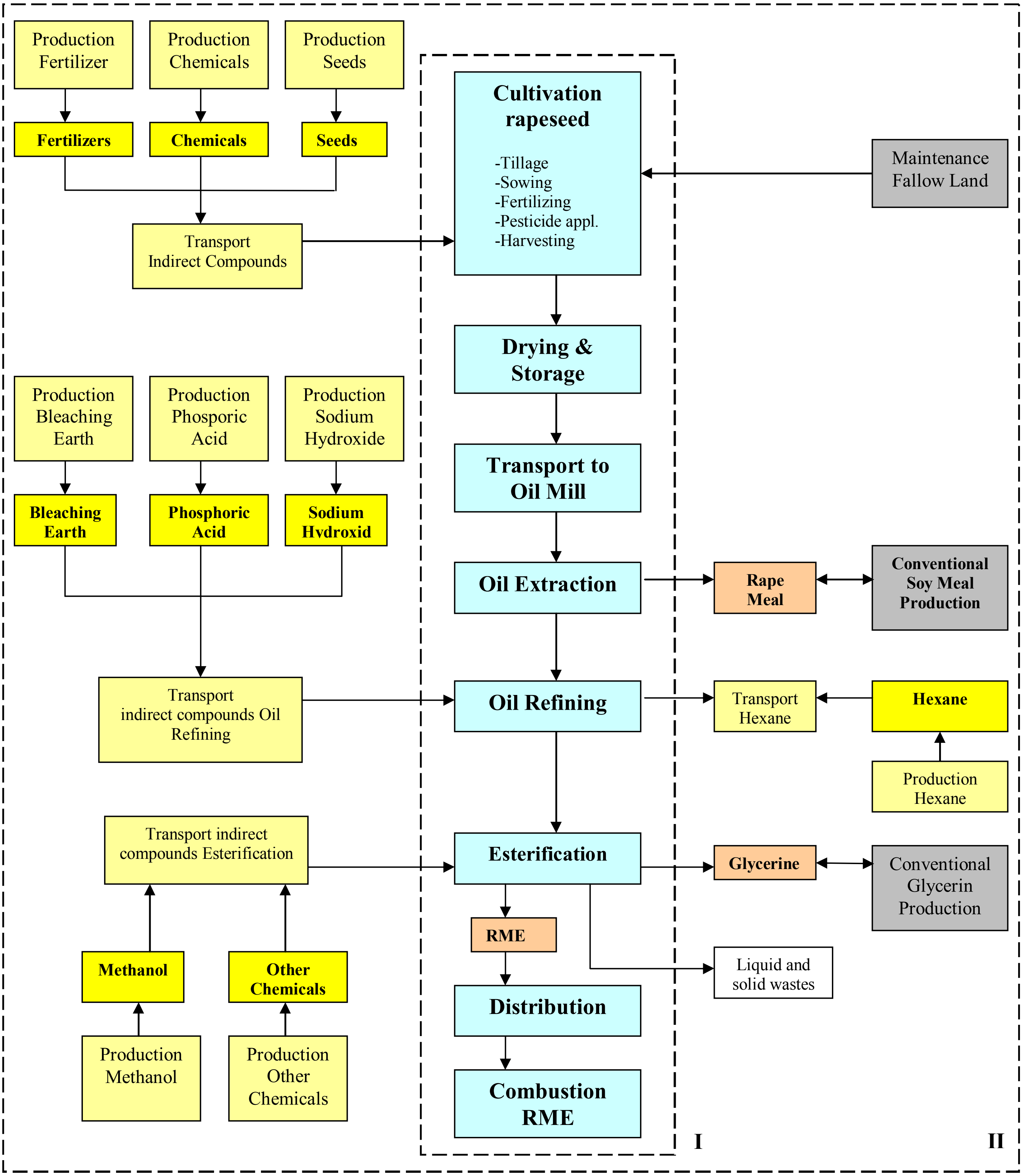

Figure 28: *flowchart of life cycle of rape methyl ester (RME). The dashed box I represents the direct processes; the dashed box II represents the system boundaries of the LCA study.*

A-III Questionnaire

A questionnaire was devised and sent to all industrial esterification plants (36) and technology providers (5) in Germany. In case of non-respondence, it was attempted several times to contact the biodiesel producers and technology providers by phone. The questionnaire was translated in German to remove the language barrier. Question four was only added to the questionnaires that were sent to the technology providers.

Fragebogen (questionnaire)

1. Die folgende Tabelle enthält Daten von Ihrer Biodieselanlagen, die in öffentlich zugänglichen Quellen gefunden werden können. Ich bitte Sie, falsche Daten zu ändern und offene Stellen in der Tabelle auszufüllen.

Standort	**Anfängliche Kapazität (t/a)**	**Jetzige Kapazität (t/a) / Jahr der Ausweitung**	**Rohstoffe***	**Erste Produktion Jahr / Jahr der Errichtung der Anlage**	**Anfängliche Investition (Mio. €)**
Erzeugung Ölmühle (t/a)	**Erzeugung Glycerin (t/a) / Reinheit Glycerin (%)**	**Abschreibungs-dauer der maschinellen Ausstattung (Jahre)**	**Jährliche Abschrei-bungskosten (€/Jahr)**	**Kosten Ölmühle (Ölerzeugung) (€ / Tonne Öl)**	**Geschätzte Betrieb & Wartungkosten (€ / Tonne Biodiesel)**
Arbeits-kosten (€ / Tonne Biodiesel)	**Elektrizitäts-verbrauch (kWh/ tonne Biodiesel)**	**Erdgas-verbrauch (m^3 / Tonne Biodiesel)**	**Rohstoff-kosten (€ / Tonne)**	**Sonstige Rohstoff-kosten (Methanol, Katalysator, usw.) (€ / Tonne Biodiesel**	**Transportkosten nach Anlage (€ / Tonne Biodiesel)**

*RO =Rapsöl JO = Jatrophaöl PO = Palmöl SBO = Sonneblumenöl
SO = Sojaöl ASF = Altspeisfett TF = Tierische Fette

2. Was sind die **durchschnittlichen Produktionskosten** von Biodiesel in Ihrer Biodieselanlagen (in Euro / Tonne biodiesel), *exklusiv der Rohstoffkosten*, aber *inklusiv der Abschreibungskosten und der Betriebs- und Unterhaltskosten*?

Für meine Forschung brauche ich Daten der Gestehungskosten verschiedener Jahre. Neben den aktuellen Produktionskosten sind für meine Arbeit vor allem auch Produktionskosten von ***vor*** 2004 wichtig. Da diese alten Daten vermutlich für die heutige Produktion nicht mehr repräsentativ sind, sind diese wahrscheinlich weniger vertraulich. Falls Daten vertraulich sind, können auch diese in der Master Thesis anonymisiert werden. Falls dies auch nicht möglich ist, können Sie mich zumindest über den Bereich der Produktionskosten oder über die Betriebs- und Unterhaltskosten von der Produktion informieren? Alle Daten der Produktionskosten aus der Vergangenheit (im Idealfall ab 1991) bis heute sind nützlich für mich.

Jahr Produk-tion	**Durchschnittlichen Produktionskosten (exklusiv Rohstoffkosten) (Euro / Tonne)**		**Jahr Produk-tion**	**Durchschnittlichen Produktionskosten (exklusiv Rohstoffkosten) (Euro / Tonne)**	
	Mit Gutschrift aus Glycerinverkauf	**hne Gutschrift aus Glycerinverkauf**		**Mit Gutschrift aus Glycerinverkauf**	**Ohne Gutschrift aus Glycerinverkauf**
1991			2000		
1992			2001		
1993			2002		
1994			2003		
1995			2004		
1996			2005		
1997			2006		
1998			2007		
1999					

3. Sind die durchschnittlichen Biodieselproduktionskosten (exklusiv Rohstoffkosten wie Rapsölkosten, Methanolkosten, Energiekosten, usw.) in den letzten Jahren / Jahrzehnten gesunken? Falls ja, was waren **die Hauptgründe** dafür? Bitte beziffern Sie in der untenstehenden Tabelle die wichtigsten Gründe dafür (zum Beispiel: Erfahrung = 1, Vermehrte Produktion = 2, usw., wobei 1 der wichtigste Grund ist).

Gründe für die Verringerung der Gestehungskosten	**Anzeigen mit Zahlen (1,2,3,etc)**
Gestiegene Erfahrung mit dem Produktionsverfahren (learning by doing)	
Gestiegene Produktion (Massenproduktion)	
Technische Erneuerungen (bessere Materialien, Automatisierung der Prozesse, verbesserte Entwürfe der Produktionsanlagen, usw.)	
Größere Produktionsanlagen (Wachstum der durchschnittlichen Produktionskapazität neuer Anlagen)	
Sonstige:………..	

Können Sie auch angeben, ob bestimmte Faktoren zu einem bestimmten Zeitpunkt in den letzten 20 Jahren am wichtigsten waren für Kostensenkungen?

…………………………………

4. Sind die **spezifischen Investitionskosten** von Biodieselanlagen (€ /Tonne jährlicher Produktionskapazität) innerhalb der letzten 20 Jahre gesunken, oder sind sie eventuell (zeitweise) auch gestiegen? Falls ja, was waren **die Hauptgründe** für die Veränderungen der spezifischen Investitionskosten? Es ist möglich, dass es mehrere Gründe für die Änderungen der spezifischen Investitionskosten gab, die entweder gestiegen oder gefallen sind. In diesem Fall, beziffern Sie bitte in der untenstehenden Tabelle die Gründe für das Ansteigen, bzw. das Fallen der spezifischen Investitionskosten. (zum Beispiel: Erfahrung = 1, Vermehrte Produktion = 2, usw., wobei 1 der wichtigste Grund ist).

Sind die spezifischen Investitionskosten gesunken oder gestiegen?	**………………………………..**
Gründe für Veränderung der Investitionskosten	**Anzeigen mit Zahlen (1,2,3, etc)**
Singlefeed-Anlagen → Multifeed-Anlagen	
Gestiegene Erfahrung mit der Konstruktion der Anlagen	
Größere Produktionsanlagen (Wachstum der durchschnittlichen Produktionskapazität neuer Anlagen)	
Technische Erneuerungen (bessere Materialien, Automatisierung der Prozesse, verbesserte Entwürfe der Produktionsanlagen, usw.)	
Sonstige:………..	

Können Sie auch angeben, ob bestimmte Faktoren zu einem bestimmten Zeitpunkt in den letzten 20 Jahren am wichtigsten waren für Kostensenkungen?

…………………………………

5. Falls Sie Bemerkungen oder weitere Kommentare haben, bitte ich Sie, diese hinzuzufügen.

…………………………..

Organisation	**Person**	**Concerning**	**Organisation**	**Person**	**Concerning**
AGQM	Mr. Dr. Haupt	E.C.	Fachagentur Nachwachsende Rohstoffe	Mr. Winkelmann	E.C.
Austrian Bioenergy Centre	Mrs. Dipl.-Ing. Bacovsky	E.C.			
	Mr. Dr. Dallos	I.C. + E.C.			
Austrian Biofuels Institute	Mr. Dipl. Ing. Körbitz	E.C. + O.P.C	Fachverband der chemischen Industrie Österreichs	Mrs. Dr. Doloszeski	E.C. + O.P.C
Autohaus Verlag	Mr. Meunzel	E.C.	Federal Statistical Office	Mrs. Weber	Price series
Bayerische Landesanstalt für Landwirtschaft	Mr. Dipl. Ing. Agr. Keymer	R.P.C. + O.P.C. + E.C.	F.O. Lichts	General email	E.C.
BLT institute	Mr. Dipl.-Ing. Handler	R.P.C.	Forschungsanstalt für Landwirtschaft	Mr. Dipl.Ing.Agr. Tietz	R.P.C. + other costs (land, labor, capital)
	Mr. Dipl.-Ing Rathbauer	O.P.C. + E.C.		Mr. Dr. Weingarten	R.P.C. + other costs (land, labor, capital)
	Mr. Dipl.-Ing. Wörgetter	O.P.C. + E.C.		Mr. Dr. Zimmer	R.P.C. + other costs (land, labor, capital)
Büro für Technikfolgenabschätzung beim Deutschen Bundestag	Mrs. Goelsdoorf	E.C.	Fraunhofer Institute (ISI)	Mr. Dr. Ragwitz	O.P.C. + E.C.
CDU Bendorf	Mr. Dr. Goerke	E.C.	Ifo Institute	Mr. Ing. Schöpe	O.P.C. + E.C.
Ciemat	Mrs. Lago	E.C.	IFEU	Mr. Gärtner	LCA data
Chemical Market Associates Inc	General email	Price series		Mr. Dr. Reinhardt	LCA methodology + data
Cognis Deutschland	Mr. Dr. Hill	E.C.	Joanneum Research Institute	Mr. Dr. Dipl-Ing. Jungmeier	LCA methodology + data
	Mr. Westfechtel	E.C.		Mr. Ing. Könighofer	LCA methodology + data
Deutscher Bauernverband	General email	R.P.C.	Joint Research Center	Mr. Christides	E.C.
European Biodiesel Board	Mrs. Ho	R.P.C. + O.P.C. + E.C.	Kuratorium für Technik und Bauwesen in der Landwirtschaft	Mr. Eckel	R.P.C.
ESU consultancy	Dr. Jungbluth	LCA data		Mr. Hartmann	R.P.C.
European Commission - Directorate-General for Transport and Energy	Mr. Dipl.-Ing. Heinz	E.C.	Landwirtschaftskammer Baden-Württemberg	General email	R.P.C. + other costs (land, labor, capital)
Energie Versorgung Niederösterreich	Mr. Dr.-Ing. Igelspacher	O.P.C. + E.C.	Landwirtschaftskammer Nordrhein-Westfalen	Mr. Dr. Uppenkamp	R.P.C. + O.P.C. + E.C.
Fachagentur Nachwachsende Rohstoffe	Mr. Kemnitz	E.C.	Landwirtschaftkammer Schleswig-Holstein	Mr. Dr. Drescher	R.P.C. + land costs
	Mr. Kerckow	R.P.C. + O.P.C. + E.C.			

Table 21: *Contacted stakeholders and organizations (I)*

A-IV Contacted stakeholders and organizations (II)

Table 21: *Contacted stakeholders and organizations (II)*

Ludwig-Bölkow-Systemtechnik	Mr. Dipl.-Kfm Schindler	E.C. + LCA data	University München	Mr. Dipl. Ing. Berenz	E.C.
MEO Consultancy	Mr. Prof Dr. Schmitz	E.C.	University Stuttgart	Mr. Dr. Eltrop	E.C.
Methanol Market Services Asia	Mr. Berggren	Price series		Mr. Dipl. Ing. König	E.C.
German Ministry of Agriculture	Mr. Hauser	Agricultural subsidies	Verband Deutscher Biodieselhersteller	Mrs. Dr. Retzlaff	E.C. + O.P.C
	Mr. Krüger	R.P.C. + other costs (land, labor, capital)		Mr. Stein	E.C. + O.P.C
	Mr. Stap	R.P.C. + O.P.C. + E.C.	VDB/VDO	Mrs. Sprick	E.C. + O.P.C
German Ministry of Finance	Mr. Nimmergut	R.P.C. + O.P.C. + E.C.	Verband Deutscher Ölmühlen	General email	O.P.C. + P.R.
Oil mill Innöl CoKG	Mr. Ing. Hasiweder	O.P.C.	Verband der Landwirtschaftskammern	Mrs. Dr. Bajorat	R.P.C.
Öko Institute	General email	R.P.C. + O.P.C. + E.C.	Wuppertal institute	Mr. Dr.-Ing Ramesohl	O.P.C. + E.C.
	Mr. Fritsche	LCA data	ZMP (Zentrale Markt- und Preisberichtstelle)	Mrs. Von Schenck	Price series
Rabobank Netherlands	Mrs. Hansen	I.C. + E.C.			
Regio und Energie Consulting	Mr. Breuer	E.C.	**Abbreviations**		
RWI Essen	Mr. Dr. Vance	E.C.	**R.P.C.**	**Rapeseed production costs**	
Shell	Mrs. Dr. Lewandowski	R.P.C.	**O.P.C.**	**Rape oil production costs**	
Shell Global Solutions	Mr. Groves	LCA data	**E.C.**	**Esterification costs**	
Technologie- und Förderzentrum	Mr. Dr. agr. Hartmann	E.C.	**I.C.**	**Investment costs**	
	Mr. Dr. Remmele	R.P.C. + O.P.C. + E.C.			
	Mr. Thuneke	R.P.C. + O.P.C. + E.C.			
	Mr. Dr. Widmann	E.C.			
Thüringer Landesanstalt für Landwirtschaft	Mr. Dr. Dipl.-Ing Graf	O.P.C.			
	Mrs. Ing. Agr. Gröber	R.P.C. + O.P.C. + E.C.			
	Mr. Dr. Reinhold	O.P.C.			
	Mr. Dr. Richter	O.P.C. + E.C.			
TÜV SÜD	Mrs. Ing Ortenburger	E.C.			
Union zur Förderung von Öl- und Proteinpflanzen UFOP	Mr. Bockey	E.C.			
	Mrs. Reder	R.P.C.			
University Bochum	Mr. Prof. Dr. Folkers	E.C.			
University Bonn	Mrs. Prof. Dr. Holm-Müller	E.C.			
University Hohenheim	Mr. Dr. Henniges	E.C.			
	Mr. Prof. Dr. Zeddies	E.C.			

B Data

B-I Consumer price index and currency converter

The consumer price index was used to correct production costs and prices for inflation. Furthermore, all production costs and prices before 2002 were converted from the old German currency (Deutsche Mark) to euros. The expression of the costs and prices in real terms was necessary to make a sound comparison possible over time. The consumer price index and currency converter are shown in table 22.

Year	Consumer price index	Year	Consumer price index
1970	34.2	1989	70.5
1971	35.9	1990	72.4
1972	37.9	1991	73.6
1973	40.6	1992	77.4
1974	43.4	1993	80.8
1975	46.0	1994	82.9
1976	47.9	1995	84.4
1977	49.7	1996	85.6
1978	51.0	1997	87.2
1979	53.2	1998	88.1
1980	54.3	1999	88.6
1981	59.6	2000	89.8
1982	62.7	2001	91.6
1983	64.7	2002	92.9
1984	66.3	2003	93.9
1985	67.7	2004	95.4
1986	67.6	2005	97.3
1987	67.7	2006	98.9
1988	68.6	2007	100.0
Deutsche Mark (DM)	**Euro (€)**		
1.000	0.5113		

Table 22*: Consumer price index for West Germany (1970-1990) and the Federal Republic of Germany (1991-2007) and the currency converter to express costs and prices in euros. The point of reference for the consumer price index is March 2007 (Data sources: German Federal Bank, 2007; Federal Statistical Office Germany, 2007).*

B-II Conversion factors

Energy carriers

Several energy carriers are necessary as input energy for the sub-processes of the life cycle of RME. Table 23 shows the primary energy requirements and GHG emissions associated with the production and consumption of each energy carrier per GJ.

Energy carrier x	MJ_p / GJ_x	kg CO_2 / GJ_x	g CH_4 / GJ_x	g N_2O / GJ_x	Conversion efficiency (%)	Reference
Heat (natural gas)	1,252	67.2	169.0	0.25	79.9	Eco-invent, 2004
Heat (heavy fuel oil)	1,421	92.6	51.5	1.9	70.4	Eco-invent, 2004
Steam (natural gas)	1,130	63.2	200.0	0.0	88.5	Concawe, 2007
Fossil diesel	1,112	8.3	13.9	0.27	89.9	Reinhardt, 1993
Electricity	3,009	172.0	369.0	5.0	33.2	Eco-invent, 2004

Table 23: *Conversion efficiencies and GHG emissions associated with the production and combustion of energy carriers used in the production process of RME*

Electricity mix

The Ecoinvent database (2004) was used for the German electricity mix from the year 2000. Unfortunately, no more recent data could be found. It is assumed that no significant changes have taken place in the conversion efficiencies and structure of the electricity mix since 2000. Table 24 shows the primary energy requirements for the production of 1000 MJ electricity and the calculated efficiencies for each energy carrier. The total calculated efficiency for electricity production is 33.2%. This implies that 10.8 MJ primary energy is used for the production of 1 kWh electricity.

	Electricity (MJ_e)	Share in German electricity mix (%)	Total Primary Energy Use (MJ_p)	Calculated efficiency (%)
Coal	246.3	24.6	851.0	28.9
Natural Gas	110.5	11.1	287.2	38.5
Nuclear	284.6	28.5	949.7	30.0
Oil	11.1	1.1	48.5	22.9
Lignite	248.5	24.9	873.1	28.5
Renewables	98.9	9.9	298.6	34.0
Total [47]	**1,000**	**100**	**3,009**	**33.2**

Table 24: *Primary energy requirements for the production of 1000 MJ electricity in Germany (Data source: Ecoinvent, 2004).*

New European Driving Cycle

The values of the *total* primary energy use and CO_2 equivalents associated with the life cycle of RME are expressed per 100 km driven over the New European Driving Cycle (NEDC) with a reference car. The NEDC is considered to represent the typical driving cycle of a car in Europe. It is used to assess the average fuel usage and GHG emissions of car engines. This study assumes that the NEDC represents the German case as well. Salient characteristics of the reference vehicle, which is driven by a 1.9 L turbo-charged direct injection compression ignition engine (74 kW), are presented in table 25. More detailed information on the reference vehicle can be found in Concawe (2007). The values of the *total* primary energy use and CO_2 equivalents associated with the agricultural stage, industrial processes, distribution and by-products were originally expressed per tonne RME. The final values were expressed per 100 km driven over the NEDC (see section 5.3.3) and obtained by dividing the original values with the density and energy content of RME (density: 1136 L/1000 kg; energy content: 32.8 MJ/L).

Vehicle characteristics		***Energy and GHG emissions associated with combustion***		
Displacement (l)	1.9		**Fossil diesel**	**Biodiesel**
Powertrain (kW)	74	Fuel consumption (MJ_{RME}/100 km)	183.1	183.1
Engine mass (kg)	145	Total GHG emissions (g CO_2-eq/100km)	137.9	142.8
Vehicle mass (kg)	1248/1276	-as CO_2 (g CO_2-eq/100km)	134.6	139.6
Top speed (km/h)	187	-as CH_4 (g CO_2-eq/100km)	0.3	0.3
Acceleration (m/s^2)	4.8	-as N_2O (g CO_2-eq/100km)	3	3

Table 25: *Salient vehicle characteristics, fuel consumption and GHG emissions associated with a reference car driven over a distance of 100 km according to the New European Driving Cycle (Data source: Concawe, 2007).*

[47] Numbers of total may differ from the sum of separate numbers due to rounding.

B-III Rapeseed production

Data on rapeseed production volumes and harvested area were available from 1950 onwards. Furthermore, the average German rapeseed yields were collected for as many years as possible (see figure 29). For the period 1950-1990, production volumes, harvested area and yields apply to the former Federal Republic of Germany (West Germany). From 1991 onwards, all data apply to the (current) Federal Republic of Germany.

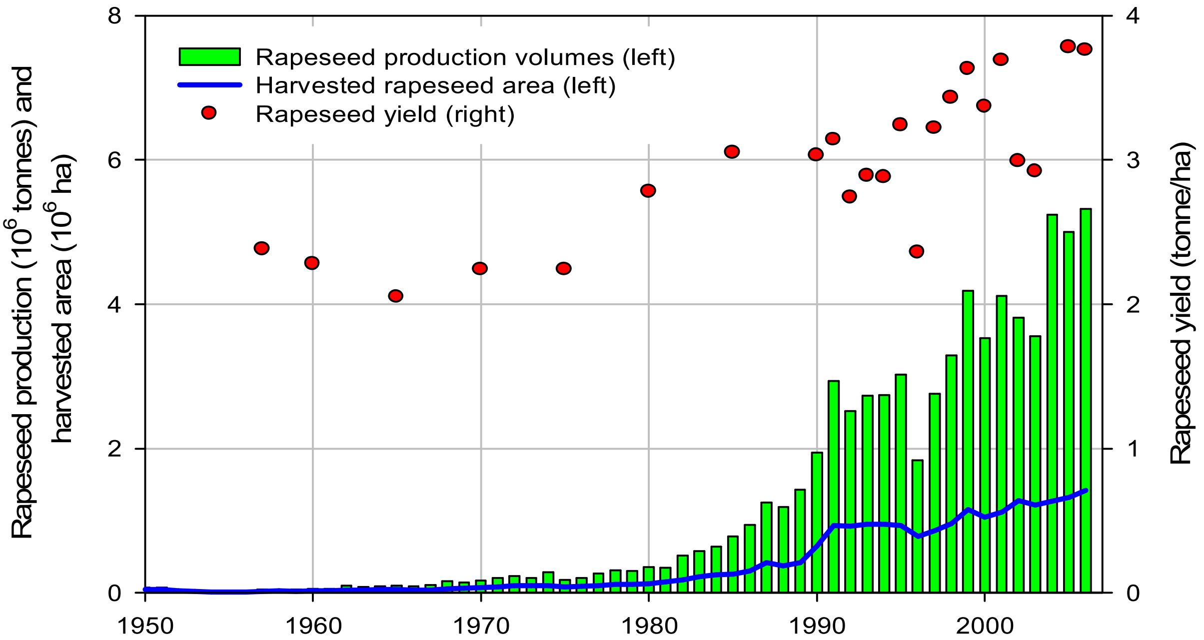

Figure 29: *Rapeseed production volumes, harvested area and yields in Germany over the period 1950-2006. (Data source: Federal Statistical Office Germany, 2007).*

Figure 29 shows a substantial increase in rapeseed production after the Second World War. The rapeseed production volumes grew faster than the harvested rapeseed area due to increasing rapeseed yields. The introduction of new rapeseed varieties ("0-rapeseed", "00-rapeseed" and hybrid varieties) has been the main reason for the increase in the average yield over time. The usage of rapeseed (oil) changed tremendously since the beginning of the biodiesel industry in 1991 (see figure 30). The main shift in rapeseed (oil) usage has been the substitution of exported rapeseed to rapeseed designated for RME production.

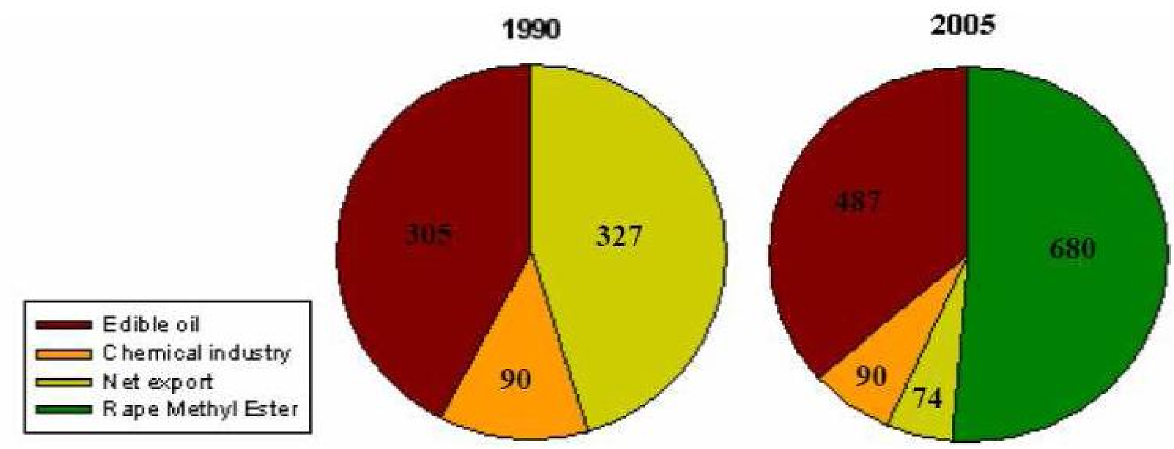

Figure 30: *Rapeseed (oil) usage in 1990 and 2005 expressed in harvested rapeseed area (Data source: Specht, 2005).*

B-IV Biodiesel production

European biodiesel was produced for the first time in Austria and France in 1985 (see figure 31). The average production growth rate was used to extrapolate the E.U. biodiesel production volumes over the period 1985-1992 (grey bars). Figure 31 shows that the E.U. biodiesel production before 1992 was insignificant compared to current production volumes. Germany started producing biodiesel production in a small pilot plant in Leer in 1991. Nowadays, Germany produces more than half of the total E.U. biodiesel production.

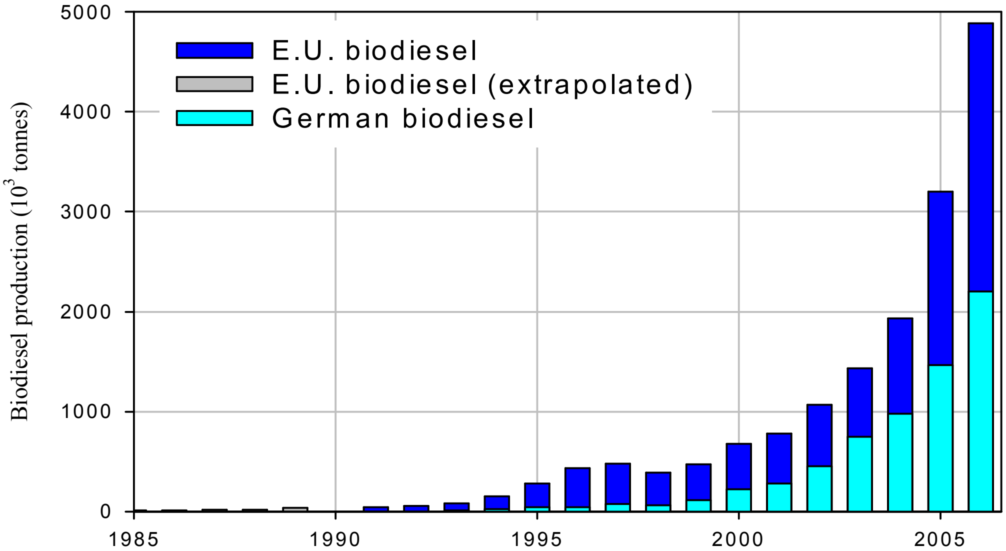

Figure 31: *Biodiesel production volumes for Germany and the European Union over the period 1985-2006. (Data source: Eurobserver, 2005; Retzlaf, 2006).*

The annual growth rate of the commercial biodiesel production in Germany is displayed in figure 32. The negative growth in 1998 was due to a combination of a low crude oil price and high vegetable oil prices. From 1998 onwards, the biodiesel production expands rapidly, involving high growth rates. As of 2001, a rather stable production growth of around 50% can be observed.

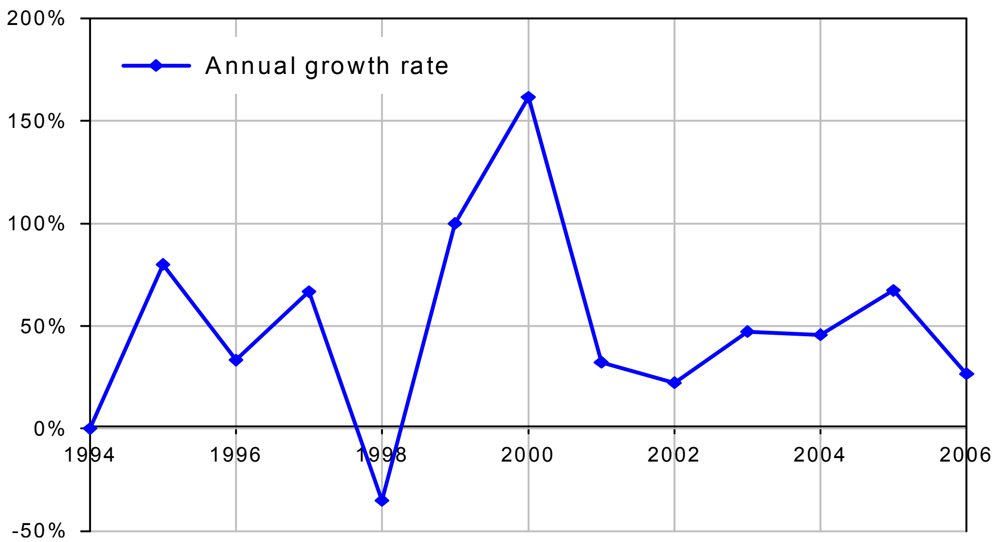

Figure 32: *Annual growth rate of commercial German biodiesel production over the period 1994-2006 (own calculations).*

B-V Production locations

The distribution of agricultural rapeseed lands in 2003 is shown on the left map in figure 33. The states with the darkest green color (Mecklenburg-Vorpommern and Bavaria) have the highest number of agricultural rapeseed lands, whereas the states with the lightest green color (Rhineland-Palatinate and Saarland) have the lowest number. The agricultural lands used for rapeseed cultivation are predominantly situated along the Baltic coast and in the eastern part of Germany. Especially Bavaria, Lower Saxony and Westphalia show potential for more rapeseed cultivation (UFOP, 2006). The industrial biodiesel plants are located all over Germany, but mainly in the northeastern states where most of the rapeseed is cultivated (see figure 33).

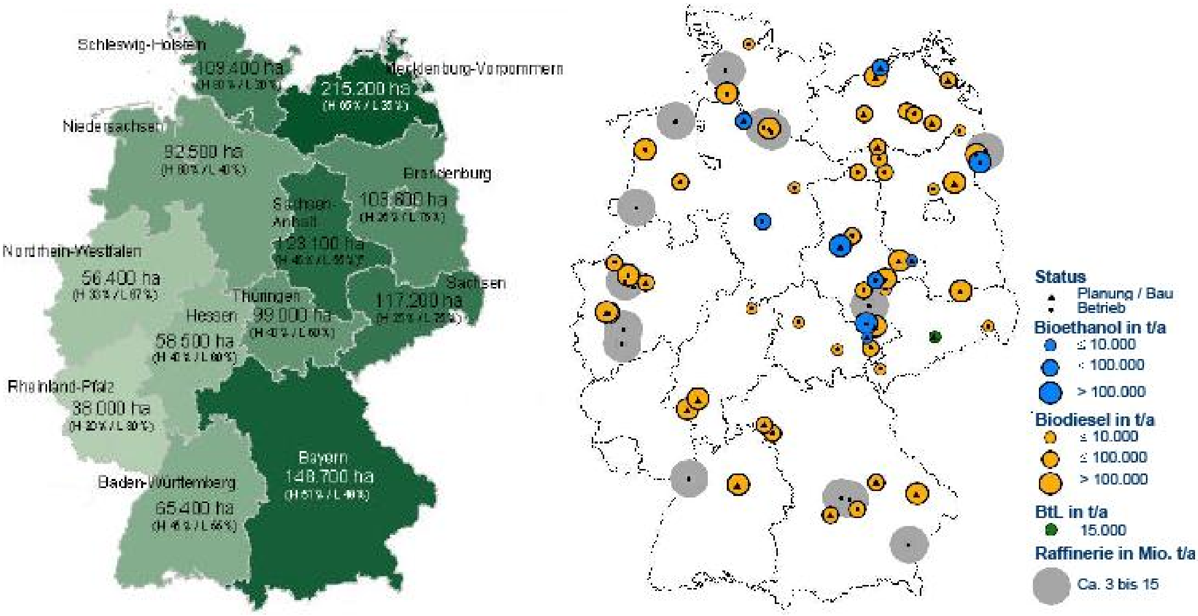

Figure 33: *Distribution of agricultural rapeseed lands in 2003 (left) and industrial biodiesel plants in 2006 (right). (Sources: KWS, 2003; Thrän & Müller-Langer, 2007)*

B-VI Rapeseed (oil) prices

Rapeseed prices tend to fluctuate heavily as a result of seasonal influences, changing subsidies and market dynamics (see figure 34). The rapeseed prices display an increasing trend over time, but collapsed in mid 1998 and mid 2004. The growing rapeseed demand for both food and non-food purposes has led to a price premium on rapeseed from the year 2000 onwards. The expected growth in biodiesel production in the next years will most likely lead to a further increase in rapeseed prices.

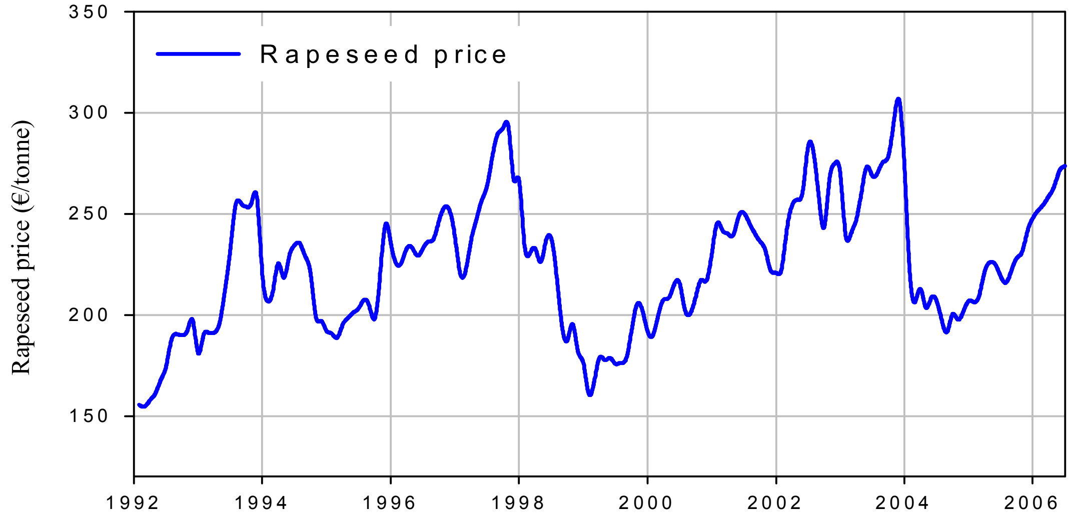

Figure 34: *Monthly nominal rapeseed prices July 1992 - December 2006 (Data source: Schenck, 2007).*

Vegetable oil prices have a substantial impact on the biodiesel plant profitability as feedstock costs account for 75-90% of the total production costs. The long-term price development of rapeseed-, sunflower- and soybean oil is shown in figure 35. A strong correlation can be observed between rapeseed and rapeseed oil prices. Furthermore, figure 35 shows that the different vegetable oil prices are rather connected in the long term, thereby limiting the possibility to completely avert price increases by using alternative feedstock oils.

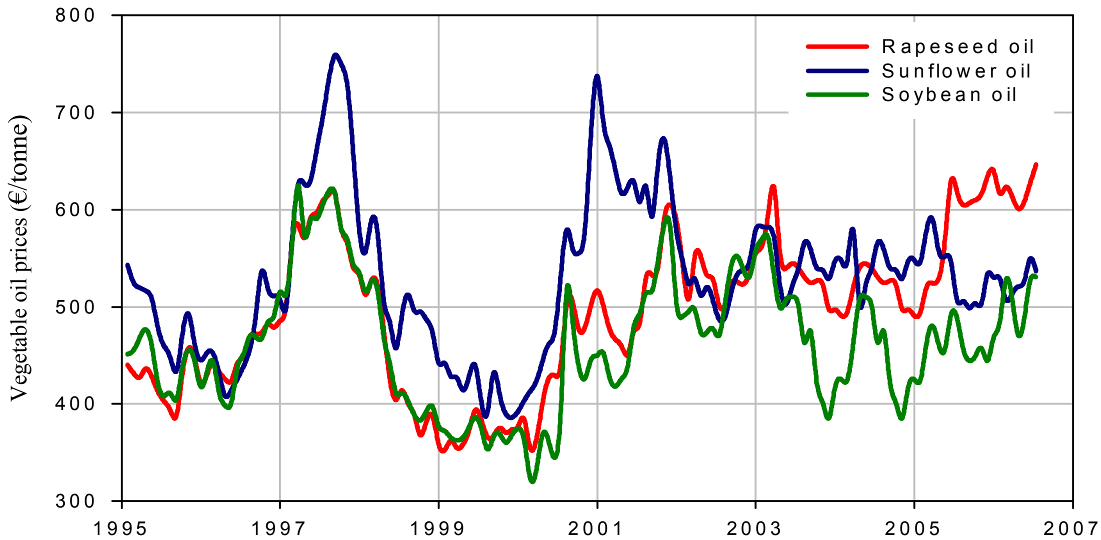

Figure 35: *Monthly nominal prices of rapeseed-, sunflower- and soybean oil from July 1995 to December 2006 (Data source: Schenck, 2007).*

B-VII By-product and fertilizer prices

Rape meal prices tend to fluctuate heavily over time (see figure 36). Rape meal prices are generally lower than soy meal prices. Expectations are that the expanding biofuel market will entail excessive amounts of rape meal, which in turn might result in lower rape meal prices for the future.

Figure 36: *Monthly nominal rape meal prices July 1996 - December 2006 (Data source: Schenck, 2007).*

The prices of urea, triple super phosphate and potash over the period 1976-2006 are shown in figure 37. Despite strong fluctuations in the nitrogen, phosphor and potassium fertilizer prices, a clear downward trend can be discerned from the 1980s to the beginning of the 21st century. From 2002 onwards, prices of triple super phosphate, potash and in particular urea show an increasing trend.

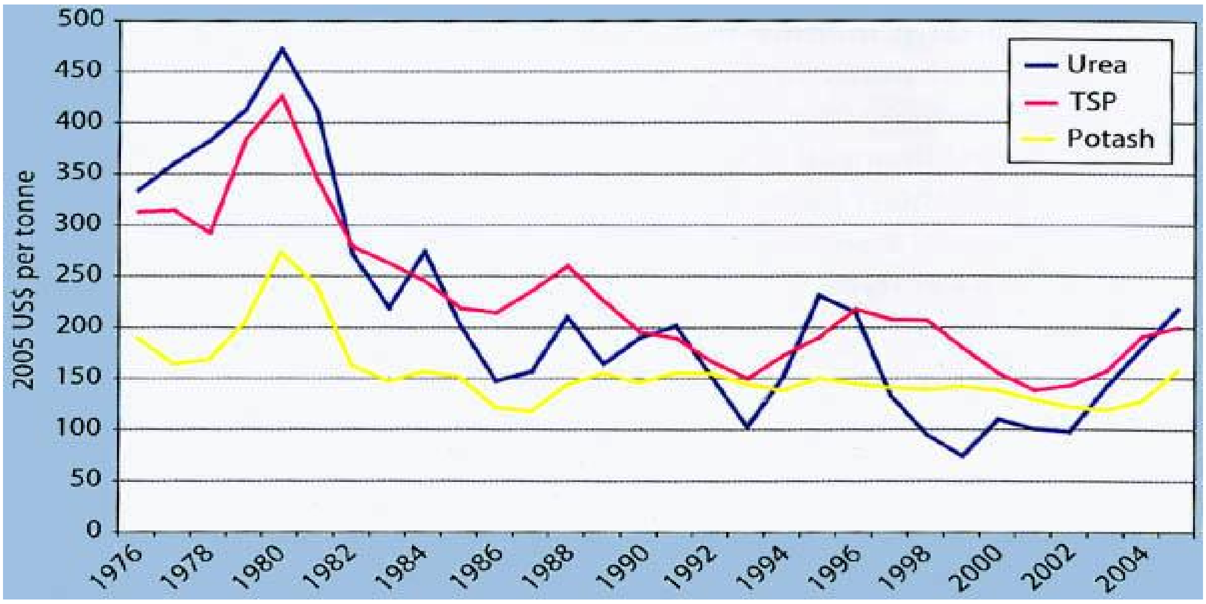

Figure 37: *Prices for urea, triple super phosphate and potash (in US$) over the period 1976-2006 (FAO, 2007).*

C Results

C-I Results sheet rapeseed production costs

Year	Rapeseed data					Production costs	
	German rapeseed production [10^4 tonne/year]	Cumulative production [10^5 tonne]	Harvested rapeseed area [10^3 ha]	Yield [tonne/ha]	Rapeseed price [€$_{2007}$/tonne]	Rapeseed production costs [€$_{2007}$/hectare]	Rapeseed production costs [€$_{2007}$/tonne]
1971	20	26	83			1893	845
1972	23	28	97				
1973	20	30	98				
1974	29	33	103				
1975	18	35	81	2.24		1603	716
1976	21	37	86			1549	617
1977	27	40	97				
1978	31	43	113				
1979	31	46	119				
1980	36	49	130	2.78			
1981	35	53	147				
1982	52	58	180			1670	573
1983	58	64	223				
1984	64	70	246				
1985	78	78	256	3.05		1491	489
1986	95	88	297				
1987	125	100	421			1438	473
1988	119	112	374				
1989	142	126	418			1329	
1990	194	146	645	3.03			
1991	293	175	933	3.14		1144	385
1992	252	200	921	2.74	162		
1993	273	228	947	2.89	196	1095	386
1994	274	255	950	2.88	235		
1995	302	285	932	3.24	204		
1996	184	303	777	2.36	224	878	299
1997	276	331	858	3.22	242	991	330
1998	329	364	959	3.43	258		
1999	418	406	1150	3.63	183		
2000	353	441	1046	3.37	199	970	272
2001	411	482	1116	3.69	228		
2002	381	520	1276	2.99	243	1000	313
2003	356	556	1218	2.92	260		
2004	524	608	1267	4.13	247	954	264
2005	501	658	1323	3.78	209		
2006	532	711	1420	3.76	247	947	251

Table 26: *Rapeseed data*

Table 27: *Biodiesel data*

	Biodiesel data		**Production costs**				
Year	German biodiesel production [tonne/year]	Cumulative production [tonne]	Industrial processing costs [$€_{2007}$/litre RME]	Total *hypothetical* production costs [a] [$€_{2007}$/litre RME]	Net rapeseed costs [b] [$€_{2007}$/litre RME]	Credits for by-products [$€_{2007}$/litre RME]	Total *actual* production costs [c] [$€_{2007}$/litre RME]
1991	200	200	0.476	0.989	0.374	0.376	0.473
1992	5000	5200	0.376	0.914	0.374	0.354	0.396
1993	10000	15200	0.401	0.982	0.453	0.312	0.543
1994	20000	35200	0.371-0.376	0.833	0.544	0.366	0.552
1995	20000	35200			0.472		
1996	40000	75200	0.346-0.363	0.754	0.518	0.270-0.314	0.580
1997	40000	115200	0.354-0.391	0.841	0.561	0.263-0.327	0.638
1998	40000	115200			0.597		
1999	75000	190200			0.423		
2000	75000	190200	0.361-0.391	0.789	0.459	0.216	0.619
2001	60000	250200	0.308	0.831	0.528	0.154	0.638
2002	110000	360200	0.303	0.829	0.562	0.198	0.667
2003	220000	580200			0.602		
2004	220000	580200	0.293-0.360	0.758	0.570	0.177-0.181	0.718
2005	277000	857200			0.482		
2006	450000	1307200			0.570		

a) Total *hypothetical* production costs = rapeseed *costs* + industrial processing costs - credits for by-products
b) Net rapeseed costs = feedstock costs per liter RME based on rapeseed *price*
c) Total *actual* costs = Net rapeseed costs + industrial processing costs - credits for by-products

C-III Results sheet environmental performance (I)

	1993			2000			2007		
(Sub)process	**Quantity per t RME**	**MJ_p/ t RME**	**kg CO_2-eq / t RME**	**Quantity per t RME**	**MJ_p/ t RME**	**kg CO_2-eq / t RME**	**Quantity per t RME**	**MJ_p/ t RME**	**kg CO_2-eq / t RME**
Rapeseed production									
Tillage & Sowing	59.7 L diesel	2389	173.1				30.6 L diesel	1214	88.7
Fertilizing	6.0 L diesel	239	17.3	40.1 L diesel	1591	116.3	4.6 L diesel	183	13.3
Spraying of Chemicals	9.6 L diesel	382	27.7				6.3 L diesel	251	18.3
Harvesting & Transport	19.6 L diesel	785	56.9	15.0 L diesel	596	43.5	13.4 L diesel	530	38.9
Drying of rapeseed	21.1 kWh+29 kg oil	1945	111.5	50,7kWh+18,25kg oil	1625	94.5	28.3kWh+23.9kg oil	1723	99.2
Emissions from field		0	1490.2		0	1458.7		0	1452.1
Sum direct processes		*5739*	*1128*		*3812*	*995*		*3902*	*1000*
Seed	4.27 kg	17	3	2.5 kg	9.7	2.0	3.74 kg	14	3
Fertilizer N	192 kg	7740	1160	122 kg	4549	682	104.6 kg	3901	585
Fertilizer P2O5	72.5 kg	1312	89	45.3 kg	820	55.6	18.7kg	338	23
Fertilizer K2O	179 kg	1940	124	25.1 kg	272	17.4	61.3 kg	664	43
Fertilizer CaO	145 kg	340	45	15.9 kg	37	4.9	15.9 kg	37	5
Chemicals production	1.88 kg	524	24	1.03kg	287	13.3	0.63kg	175	8.1
Sum indirect processes		*11871*	*1446*		*5975*	*775*		*5130*	*666*
Total rapeseed production		**17610**	**3323**		**9787**	**1771**		**9032**	**1666**
Oil extraction									
Transport to oil mill	85% ship; 10% train; 5% lorry	348	15	70% ship; 15% train; 15% lorry	348	26	70% ship;15% train;15% lorry	348	26
Oil extraction	132kWh+675kgsteam	3740	218	88kWh+717 kg steam	3050	177	120kWh+769kg steam	3575	208
Oil refining	26kWh+211 kg steam	901	52	6kWh+148 kg steam	501	29	29kWh+108 kg steam	656	38
Sum direct processes		*4989*	*285*		*3898*	*232*		*4579*	*272*
Hexane	1.2 kg	161	1.7	1.0 kg	134	1	1.2 kg	161	1.7
Other chemicals		111.8	9.0		124.8	8.8		131.6	9.3
Sum indirect processes		*273*	*11*		*259*	*10*		*293*	*11*
Total rapeseed oil prod.		**5262**	**296**		**4157**	**242**		**4871**	**283**
Esterification									
Esterification	50kWh+200kg steam	1102	68	46kWh + 647,4kgsteam	2411	139	108kWh+727kg steam	4083	239
Sum direct processes		*1102*	*68*		*2411*	*139*		*4083*	*239*
Methanol	108.7 kg	4084	304	109.1 kg	4099	305.4	109.1 kg	4099	305
Other Chemicals	9.38 kg	150	10	6.3	101	7,1	6.3	101	7
Sum indirect processes		*4233*	*315*		*4199*	*312*		*4199*	*312*
Total Esterification		**5336**	**382**		**6610**	**452**		**8283**	**551**
Distribution	150 km	186	14	150 km	186	14	150 km	186	14
Total RME (without credits)		***28394***	***4016***		***20901***	***3221***		***22372***	***3225***
Soy meal (fodder usage)	1621 kg	5477	416	1621 kg	5477	416	1369 kg	4629	351
Glycerin (synthetic)	95 kg	7324	539	117 kg	8943	658	100 kg	7709	567
Sum credits		*12801*	*954*		*15420*	*1073*		*12338*	*918*
Total RME (with) credits)		***15593***	***3061***		***6484***	***2147***		***10035***	***2307***

Table 28: *Results sheet environmental performance (I)*

Table 28: *Results sheet environmental performance (II)*

	1993			2000			2007		
(Sub)process	**kg CO_2/t RME**	**g CH_4 / t RME**	**g N_2O / t RME**	**kg CO_2/t RME**	**g CH_4 / t RME**	**g N_2O / t RME**	**kg CO_2/t RME**	**g CH_4 / t RME**	**g N_2O / t RME**
Rapeseed production									
Tillage & Sowing	171	14	6				87.7	7.4	2.8
Fertilizing	17	1	1				13.2	1.1	0.4
Spraying of Chemicals	27	2	1	114.9	9.7	3.7	18.1	1.5	0.6
Harvesting & Transport	56	5	2	43.0	3.6	1.4	38.4	3.2	1.2
Drying of rapeseed	105	260	1	89.2	212.8	1.1	93.7	229.1	0.8
Emissions from field	0	0	5034	0.0	0.0	4928	0.0	0.0	4905
Sum direct processes	***377***	***283***	***2513***	***247***	***226***	***2510***	***251***	***242***	***2510***
Seed	1	2	8	0.61	1.16	4.47	1	2	7
Fertilizer N	550	1453	2934	268	707	1428	177	468	944
Fertilizer P2O5	85	157	3	52.8	98.0	1.8	22	40	1
Fertilizer K2O	116	258	9	16.2	36.1	1.3	40	88	3
Fertilizer CaO	43	44	3	4.7	4.8	0.3	5	5	0
Chemicals production	22	50	3	12.11	27.20	1.86	7.4	16.6	1
Sum indirect processes	***816***	***1963***	***2960***	***354***	***874***	***1438***	*251*	*620*	*956*
Total Agriculture	**1194**	**2246**	**8004**	**601**	**1100**	**6372**	**503**	**862**	**5868**
Oil Extraction									
Transport to Oil Mill	15	0,4	1	25	1	3	25	1	3
Oil extraction	206	488	3	167	400	2	196	465	3
Oil Refining	49	118	1	27	67	0	36	83	1
Sum direct processes	***270***	***606***	***5***	***220***	***468***	***5***	***258***	***549***	***6***
Hexane	1.7	2.2	0.1	1.4	1.9	0.0	1.66	2.24	0.05
Other chemicals	8.5	14.8	0.3	8.3	14.5	0.3	8.9	14.6	0.4
Sum indirect processes	***10***	***17***	***0***	***10***	***16***	***0***	*11*	*17*	*0*
Total rapeseed oil prod.	**280**	**623**	**5**	**229**	**484**	**6**	**268**	**566**	**7**
Esterification									
Esterification	61	262	3	131	320	1	224	614	1
Sum direct processes	***61***	***262***	***3***	***131***	***320***	***1***	***224***	***614***	***1***
Methanol	300	148	2	302.5	149	1.8	301	149	2
Other Chemicals	10	21	0.4	6.6	13.8	0.3	7	14	0
Sum indirect processes	***310***	***169***	***2***	***308***	***163***	***2***	*308*	*163*	*2*
Total Esterification	**371**	**431**	**5**	**439**	**482**	**3**	**532**	**777**	**3**
Distribution	14	3	1	13.9	2.6	1.3	14	3	1
Total RME (without credits)	***1859***	***3300***	***8014***	***1284***	***2070***	***6382***	***1317***	***2207***	***5879***
Soy meal (fodder usage)	379	303	101	379	303	101	320	256	85
Glycerin (synthetic)	527	333	14	643	406	17	555	350	15
Sum credits	*906*	*635*	*115*	*1022*	*709*	*118*	*875*	*606*	*100*
Total RME (with) credits)	*953*	*2665*	*7899*	***262***	***1361***	***6264***	***442***	***1601***	***5779***

C-IV Results sheet plant characteristics (I)

Techno-logy Provider	Biodiesel PLant	Location	*Initial Capacity (t/year)*	Current Capacity (t/year)	Investment costs (€$_{2007}$)	Oil Mill	Feedstock	Reference
AT Agrar-Technik	Campa Biodiesel Ochsenfurt I/II	Ochsenfurt	75000	150000	10.5			Bockey, 2002 Campa-AG, 2007
	Biopetrol Industries GmbH	Schwarzheide	100000	150000	29.7	no	RO	Körbitz 2001; IWR, 2002
	Rheinische BioEster	Neuss	100000	150000		yes	RS	Bacovski *et al*, 2007 Körbitz, 2004
	Ecodasa AG	Burg	25000	50000				Ecodasa, 2007
	BDK Biodiesel GmbH Kyritz I and II	Kyritz	30000	80000	19.2	yes	RS	Bacovski *et al*, 2007 German parliament, 2006
	Marina Biodiesel	Brunsbüttel	150000	150000	15.7	no	RO	Kieler Nachrichten, 2005
	Campa-Biodiesel GmbH & Co. KG	Straubing	200000	NOY	60	yes	RS	UFOP, 2006 ZVI, 2006
	Deutsche BioDiesel	Eberswalde	250000	NOY	51.2	no	RO/SO/PO	DBD, 2007 Perpetu, 2007
	Ecodasa AG	Magdeburg	250000	NOY			RS/SB/PO	Bacovski *et al*, 2007
	Ecodasa AG	Perl (Mosel)	250000	NOY		yes	RS	Ecodasa, 2007
	Biodiesel Süd	Marbach	150000	NOY	58	yes	RS/GCO/ SB/P	IWR, 2006
BDI	Saria Bio-industries	Malchin	12000	12000	10.5	yes	RS / AF	Bacovski *et al*, 2007 Körbitz, 2004
	Thüringer Methylesterwerke	Harth-Pöllnitz	45000	45000	15.2	yes	RS / AF	Bacovski *et al*, 2007 Körbitz, 2004
	Saria-ecoMotion	Lünen	100000	100000	24.3		Plant oil /AF	Saria, 2006
CDM	Landwirtschaftliche Produkt und Verarbeitungs GmbH	Henningsleben	5000	6200			RS/SB/AF	Bacovski *et al*, 2007
	EOP ElbeOel Prignitz AZ	Falkenhagen	30000	132500	15.0	yes	RS	EOP, 2007 Körbitz, 2004
	ADM Oelmühle Leer Connemann	Leer	300	120000	10.5	yes	RS / SF	Bacovski *et al*, 2007 Körbitz, 2004

Table 29: *Results sheet environmental performance (I)*

C-IV Results sheet plant characteristics (II)

ADM	Bio-Oelwerke Magdeburg I	Magdeburg	50000	75000	21.0	yes	RS	Körbitz, 2004
	ADM Oelmühle Hamburg I und II	Hamburg	100000	500000		yes	RS / SF/ P	FNR, 2007
	Saria ecoMotion	Sternberg	100000	150000	32.3	yes	RS	Saria, 2006
	ADM Soya Mainz GmbH & Co. KG	Mainz	275000	275000				FNR, 2007
	ECANOL Lubmin GmbH & Co. Premicon Biotreibstoffe KG	Plau am See	60000	NOY	25	yes	RS	Verivox, 2006
Lurgi AG	Natural Energy West	Marl	100000	200000	12.9	no	RO	Bacovski *et al*, 2007
	Natural Energy West	Malchin	40000	40000				FNR, 2007
	Rapsveredelung Vorpommern	Malchin	37000	37000		yes	RS	Biod. Malchin, 2007 Arnold *et all*, 2005
	Biodieselanlage Halle	Halle	60000	60000	17.1	no	RO	Hafen Halle, 2007
	Biopetrol Industries GmbH	Rostock	150000	200000	22.2	no	RO	Biopetrol, 2007; Rostock, 2007
	Emerald Biodiesel GmbH	Neubrandenburg	40000	150000	30.3	yes	RS	EPC, 2006; NTR, 2005
	Cargill GmbH	Frankfurt am Main	250000	NOY	25	no	RO/plant oil	Chemietechnik, 2006
	Mannheim Biofuel GmbH	Mannheim	100000	NOY				FNR, 2007
	KL Biodiesel Lülsdorf GmbH	Niederkassel-Lülsdorf	120000	NOY		no	RO	Folio, 2007
	Südstärke GmbH	Schrobenhausen	100000	NOY	30	yes	RS	LNS, 2006 S&L, 2007
	Neckermann Renewables	Wittenberg-Piesteritz	220000	NOY	70	yes	RS	JC Neckermann, XXX
Other	MUW Mitteldeutsche UmesterungsWerke	Bitterfeld	150000	200000	26.2	no	RO	Körbitz, 2004 UFOP, 2001
	Biodiesel Wittenberge	Wittenberge	60000	85000	4.1	no		FNR, 2007 Landtag, 2006 UFOP, 2001
	Petrotec GmbH	Südlohn	35000	85000			GCO	Petrotec, 2007 UFOP, 2001
	Hallertauer Hopfen-Verwertungsgesellschaft	Mainburg	8000	18000	0.6	no	RO/SO/ GCO	UFOP, 2001

Table 29: *Results sheet environmental performance (II)*

Other	GHP Biodiesel GmbH & Co. KG - Werk Oranienburg	Oranienburg	5000	12000		no	RO/GCO	Presseportal, 2005 UFOP, 2001
	BKK Bio-diesel	Rudolstadt	4000	4000	2.8	yes	RS	BKK Rudolstadt, 2005 UFOP, 2001
	Biowerk Sohland GmbH	Sohland a.d. Spree	5000	25000				FNR, 2007 UFOP, 2001
	Delitzscher Rapsöl GmbH	Wiedemar	5000	6000		yes	RS	Arnold *et al*, 2005
	Biowerk kleisthöhe	Uckerland	5000	5300	3.6	yes	RS	Arnold *et al*, 2005
	Kartoffelverwertungsgesellschaft Schlesw.-Holstein	Schleswig	15000	15000			RS	Arnold *et al*, 2005
	BKN Biokraftstoff Nord AG	Sprakensehl-Bokel	10000	35000 (2006) 200000 (2008)			RS/MFS	IWR, 2006
	NUW Nordbrandenburg Umesterwerke	Schwedt	150000	200000	43.0	no	RO	NUW, 2007
	Nehlsen Neue Energien GmbH	Grimmen	33000	33000	6.6	no	RO/GCO	MVregio, 2007
	Ulrich Biodiesel GmbH	Kaufungen	15000	45000				Biodieselmagazine, 2007
	IFBI Hessen GmbH / Kaufungen	Kaufungen		50000				IWR, 2006
	GHP Biodiesel GmbH & Co. KG - Werk Neumarkt	Neumarkt	25000	25000				Energieportal 24, 2007
	Emerald Biodiesel GmbH	Ebeleben	100000	100000	28	yes	RS	EPC, 2006
	S.A.B.Sachsen-Anhalt. Biodwerke	Kötschlitz	113000	113000	28.3		RS/SB/ P/GCO	CIZ, 2006

NOY = Not in Operation Yet
RS = Rapeseed
SO = Sunflower oil
SF = Sunflower
SB = Soy beans
PO = Palm oil
P = Palm
J = Jatropha
GCO = Grease/cooking oil
AF = Animal fats
MFS = Multi feedstock
RO = Rape oil

Table 29: *Results sheet environmental performance (III)*

D Additional results

D-I Biodiesel plants and installed capacity

This appendix provides additional information and figures on the development of biodiesel plants and production capacity as described in section 5.1.2.

Table 30 gives an overview of the development in the number of biodiesel plants, production capacities and average plant sizes over the period 1991-2007. As can be seen, the number and production capacities of both single and multi-feedstock plants have increased, although the share of multi-feedstock plants has become larger over time. A similar, but even stronger trend can be observed for the biodiesel plants that have integrated oil mills, i.e. the so-called "annex plants". The annex plants have already exceeded the number of stand-alone plants in 2007. Unfortunately, not enough data were available to determine the technological equipment and outlay of every biodiesel plant as presented in appendix C-IV. These plants are referred to as "unidentified" plants. The average plant capacity has increased as well; the production capacity growth rate of multi-feedstock plants has been higher than for single-feedstock plants.

Number plants	**1991**	**1999**	**2007[48]**	**Percentage in total 2007[49]**
Total	***1***	***6***	***58***	***100%***
Single-feedstock	1	2	25	43.1%
Multi-feedstock	0	1	19	32.8%
Unidentified	0	3	14	24.1%
Number plants	**1991**	**1999**	**2007[50]**	**Percentage in total 2007[51]**
Total	***1***	***6***	***58***	***100%***
Stand-alone plants	0	2	14	24.1%
Annex plants	1	1	21	36.2%
Unidentified	0	3	23	39.7%
Production capacity				
Total *(ktonnes/year)*[52]	***0.3***	***175***	***5957***	***100%***
Single-feedstock	0.3	33	2642	44.4%
Multi-feedstock	0	5	2202	37.0%
Unidentified	0	137	1113	18.7%
Average plant capacity				
(ktonnes/year)	***0.3***	***29.7***	***102.7***	**-**

Table 30: *Number of biodiesel plants, production capacities and the average plant sizes over the period 1991-2007 (Data source: own calculations, based on appendix C-IV).*

Figure 38 presents the increase in biodiesel production capacity over the period 1991-2007, attributed to newly built biodiesel plants and upscaling of existing plants. The figure is based on the collected data in appendix C-IV. The total biodiesel production capacity increased from 300 tonnes per year in 1991 to 6,181,900 tonnes per year in 2007. As can be seen,

[48] The building years of five biodiesel plants were unknown; these plants were attributed to the year 2007 for each category.
[49] Percentages may not add up to 100% due to rounding
[50] The building years of five biodiesel plants were unknown; these plants were attributed to the year 2007 for each category.
[51] Percentages may not add up to 100% due to rounding
[52] The calculated installed capacities differ slightly from the numbers as indicated in section 5.1.2, which originate from the UFOP.

77.9% of the increase in total capacity was caused by newly built biodiesel plants and 22.1% was caused by the upscaling of existing plants.

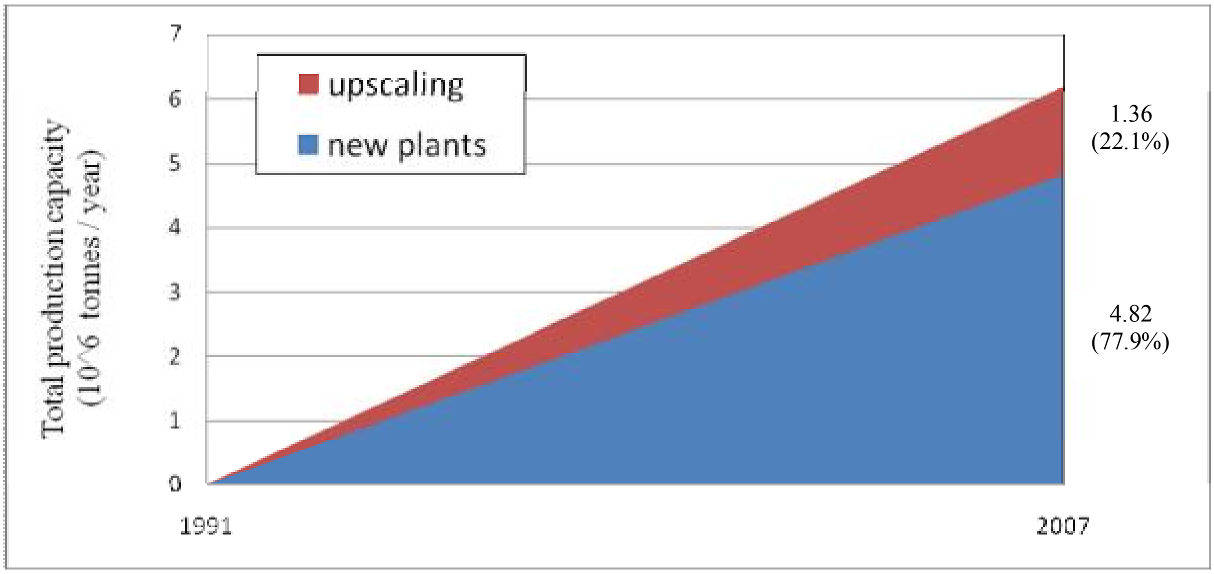

Figure 38: *The increase in the total biodiesel production capacity over the period 1991-2007, attributed to newly installed capacity and upscaling of existing plants. (Data source: multitude of press releases (see appendix C-IV)).*

D-II Outlook production volumes

Unfortunately, no data were found about future production volumes of rapeseed, RME or biodiesel. Hence, several calculations had to be made in order to be able to extrapolate the experience curves.

Rapeseed and RME production

The German rapeseed production can be divided into RME-rapeseed, i.e. rapeseed used for RME production, and rapeseed used for alternative purposes. In 2006, around 20% of the rapeseed was used for RME production and around 80% for alternative purposes (UFOP, 2007a and 2007b). The average annual growth rate of non RME-rapeseed production was calculated over the period 1990-2006. Subsequently, the future non RME-rapeseed production volumes were extrapolated over the period 2007-2020. As the future RME-rapeseed production volumes are constrained by the available agricultural land in Germany, three prominent studies (Fritsche *et al* (2004), Nitsch *et al* (2004) and Thrän *et al* (2006)) were taken to calculate the average land potential, and thus, RME-rapeseed potential. The land potentials were taken from the so-called “realistic scenarios” of all three studies. Unfortunately, only Thrän *et al* (2004) made assumptions regarding the land potential specifically for RME-rapeseed production. These assumptions were adopted to calculate the RME-rapeseed land potential for the other two studies as well. Table 31 shows the average additional RME-rapeseed potential for the year 2020.

	Thrän *et al*, 2006	Fritsche *et al*, 2004	Nitsch *et al*, 2004
Additional total biofuel potential (PJ/year)	884	350	350
Additional RME potential (PJ/year)[53]	57	22.6	22.6
Additional RME-rapeseed potential (tonnes/year)	663,400	263,032	263,032
Average additional RME-rapeseed potential (tonnes/year)	**396,488**		

Table 31: *Average additional RME-rapeseed potential for the year 2020*

It was assumed that the RME-rapeseed potential is to be completely used by the year 2020; the average and RME-rapeseed use was assumed to gradually increase over the period 2007-2020. The RME-rapeseed was added up with the non RME-rapeseed to obtain the total annual rapeseed production for each year over the period 2007-2020. Rapeseed imports were excluded from the calculations as no data were available on this issue.

Total biodiesel production

The "Fuel Strategy" of the German government aims to achieve a 6.75% biofuel share in 2010 and a 10% percent biofuel share in 2020 (BMU, 2007). It is assumed that 6.75% and 10% of the total diesel consumption will be covered by biodiesel in 2010 and 2020. The total biodiesel production will likely be a mix of first and second generation biodiesel made from several domestic and exotic feedstock (see section 5.1.1). The Mineral Oil Business Association expects a decrease in the total diesel consumption from 30.2 mln. tonnes in 2006 to 31.3 mln. tonnes in 2010 and 28.6 mln. tonnes in 2020 (MWV, 2006). Table 32 shows the necessary total biodiesel production volumes for the years 2005, 2010 and 2020.

	2005	2010	2020
Biofuel share (%)	2.00	6.75	10.00
Total diesel consumption (mln. tonnes)	29.7	31.3	28.6
Biodiesel requirement (mln. tonnes)[54]	0.79	2.80	3.78

Table 32: *Biodiesel requirements for the year 2005, 2010 and 2020 to comply with the targets according to the German fuel strategy.*

The additional required biodiesel production for the year 2010 and 2020 was assumed to increase gradually over the years. The annual growth rate until 2010 is slightly higher than the growth rate over the period 2010-2020. Figure 39 depicts the projected annual production volumes of rapeseed and *total* biodiesel over the period 2007-2020.

[53] Fritsche *et al* (2004) and Nitsch *et al* (2004) did not mention any specific value for the additional RME potential, only the additional total biofuel potential. In Thrän *et al* (2004), the additional RME potential holds a percentage of 6.45% in the additional total biofuel potential. This percentage was used for the other two studies as well.

[54] The biodiesel requirement is calculated by correcting for the difference in energy content between fossil diesel and biodiesel. The conversion factors can be found in appendix B-II.

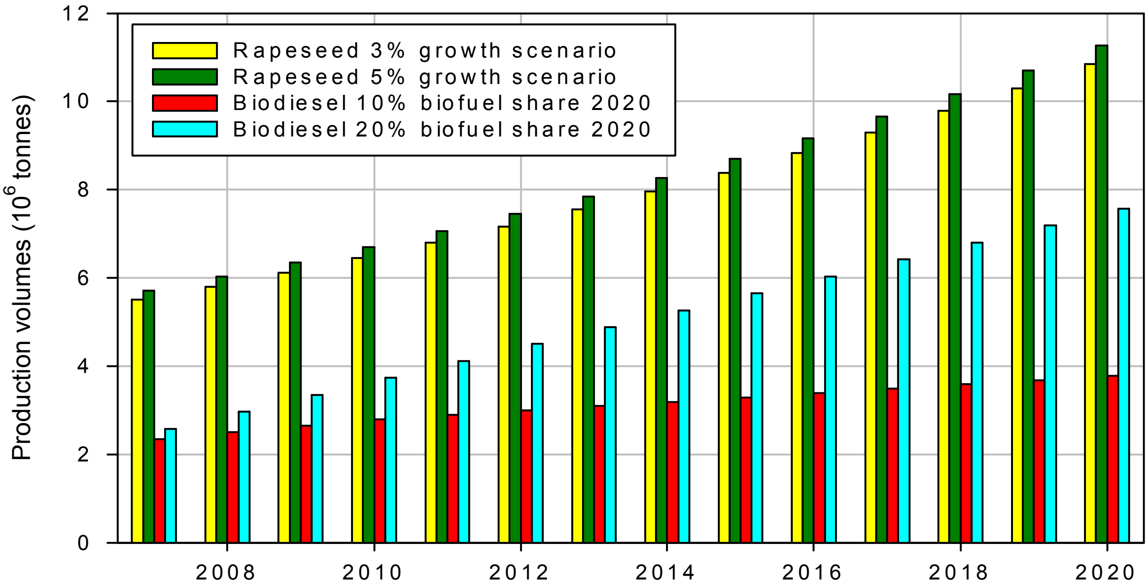

Figure 39: *Outlook future production volumes of rapeseed and biodiesel for different scenarios.*

D-III Total environmental performance

Figure 40 presents an overview of the structure and development of the primary energy flows per 100 km driven with an average car according to the New European Driving Cycle. The values are given for the rapeseed cultivation, oil production, esterification process and total life cycle of RME for the years 1993, 2000 and 2007 (see also section 5.3.3 and appendix C-III). The gray bars represent the total *net* primary energy use, i.e. the total primary energy use minus credits for the by-products rape meal and glycerin.

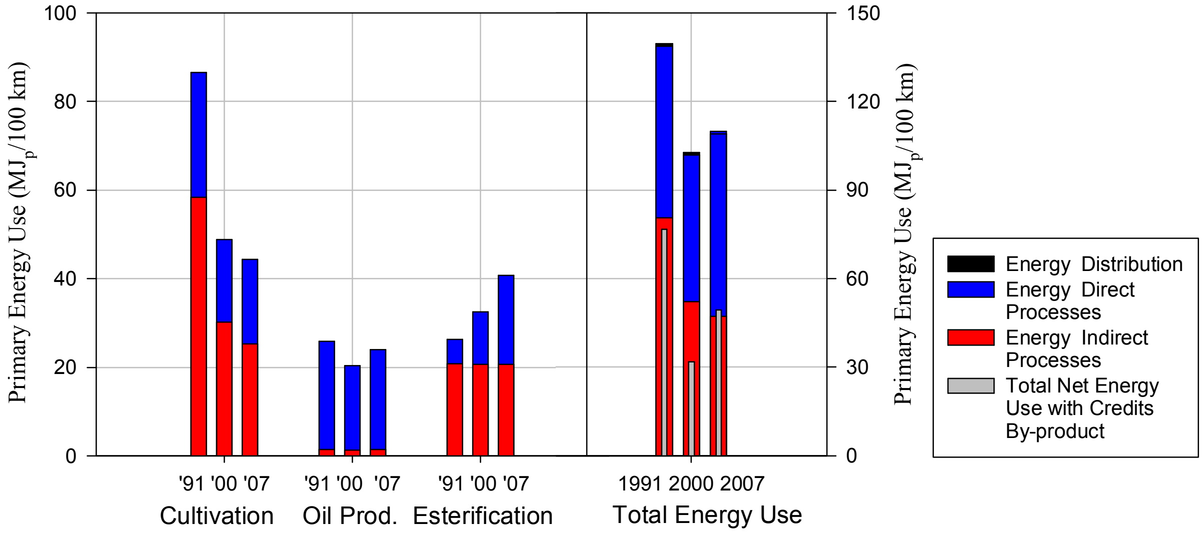

Figure 40: *Primary Energy flows associated with the rapeseed cultivation, oil production, esterification process and total life cycle of RME for the years 1993, 2000 and 2007.*

Figure 41 shows the structure, change and contribution of the GHG emissions CO_2, CH_4 and N_2O in the *total* CO_2-equivalents change over time. The values are given per 100 km driven with an average car according to the New European Driving Cycle. As can be seen, the contribution of CH_4 in the total CO_2-equivalents decrease is only marginal. Especially the lower fertilizer usage - especially nitrogen fertilizer - has resulted in strong reductions in CO_2, CH_4 and N_2O emissions, and has partly caused the rapeseed production to have the largest contribution in the total CO_2-equivalents decrease.

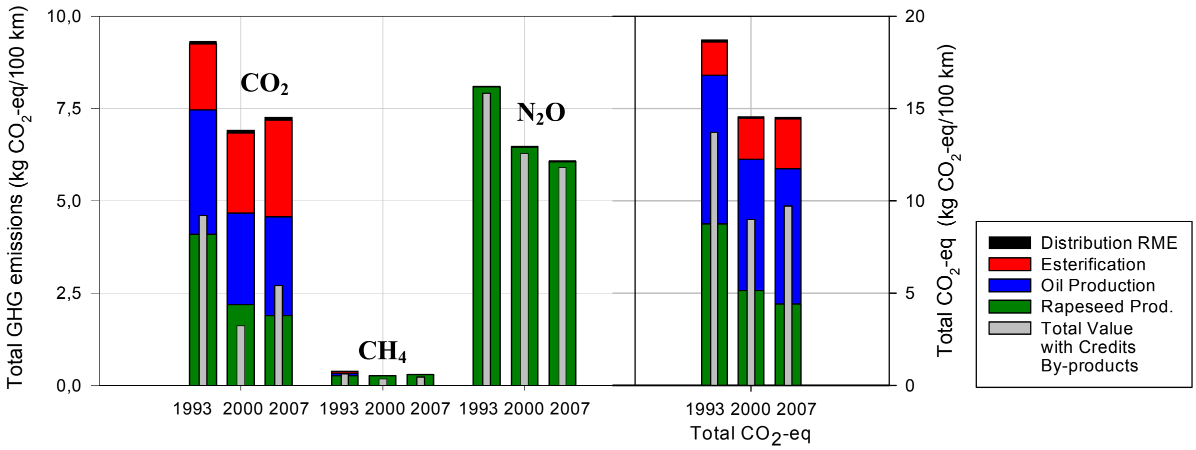

Figure 41: *CO_2-equivalents associated with the rapeseed cultivation, oil production esterification process and total life cycle of RME for the years 1993, 2000 and 2007.*

Table 33 shows a comparison between the total energy use and GHG emissions of fossil diesel and RME for the year 2007. The values are given per 100 km driven with an average car according to the New European Driving Cycle. For the RME case, two different values were used: values stemming from own calculations (RME I) and values from the Concawe study (2007) (RME II). As can be seen, the total energy use and CO_2-equivalents were calculated to be lower for RME than for fossil diesel. For the CO_2-equivalents, a range of 45.1-65.2% reduction was calculated. The GHG reduction potential of RME is therefore high enough to meet the targets (30-40%) as set by the German Biomass Sustainability Ordinance in order for RME to be eligible for tax exemption.

	Fossil diesel (Concawe)	**RME I (own values)**	**RME II (Concawe)**	**RME I % reduction**	**RME II % reduction**
Total energy use (MJ_p /100 km)	212	49.3	84.0	**-76.7**	**-60.4**
Total GHG emissions (kg CO_2-eq/100 km)	16.4	5.7	9.0	**-65.2**	**-45.1**

Table 33: *Total primary energy use and GHG emissions associated with the life cycle of fossil diesel and RME for the year 2007. Values are given per 100 km driven with an average car according to the NEDC. (Data sources fossil diesel and RME II: Concawe, 2007).*

E Sensitivity analysis

E-I Initial cumulative production

The value for the initial cumulative production determines the amount of cumulative doublings - over the period for which data are available - and thereby the calculated progress ratio. Therefore, three scenarios were devised with different values for the initial cumulative production for both the feedstock and industrial system, each based upon the production volumes associated with a different period prior to the first data point in the experience curve. The reasoning behind the coming about of the scenarios is described below.

Rapeseed production

Base case (1950-1970):
The mechanization of the agricultural practices took primarily place after the Second World War (Handler, 2007). Therefore, most of the technological learning occurred over the past sixty years. The initial cumulative production was therefore taken by adding up the rapeseed production volumes over the years 1950-1970. Rapeseed production volumes over the period 1946-1949 were not obtained via extrapolation as its contribution to the initial cumulative production is expected to be minor as it concerns a period just after the war. The cumulative rapeseed production doubled nearly ten times over the period 1971-2006. This scenario is considered to represent the accumulated technological experience in the most realistic way and is therefore taken as the base case in this study.

Long time frame (1900-1970):
Despite the rapid development in agricultural practices after the Second World War, some of the technological learning must have taken place before this period. To account for this (marginal) technological learning, the production volumes were extrapolated to the year 1900 to obtain the initial cumulative rapeseed production over the period 1900-1970. The average annual growth rate in rapeseed production over the period 1950-1990 (8.4%) was calculated and used to extrapolate the production volumes back to 1900. The years 1991-2006 were excluded from the calculation since these production volumes also concern RME-rapeseed, which perturbed the preceding annual growth rate. The incorporation of these production volumes would suggest a higher annual growth rate than is expected before 1950. The production volumes can be found in appendix D-II. The cumulative production doubled nearly 16 times over the period 1900-1970.

Short time frame (1971):
This scenario assumes no accumulation of technological learning at all and sets the value for the initial cumulative production at zero. This scenario is considered unlikely as it neglects important technological learning before 1971.

Industrial processes

Base case (1991):
Biodiesel was produced for the first time in Germany in 1991. As Germany has a long world's leading position in biodiesel production and processing technologies, it can be argued that most technological learning has taken place in Germany (cf. section 3.2.1). Although technological learning will most likely take place at a global level in the future, the "import" of technological learning into Germany in the past seems to be limited. As no biodiesel was produced in Germany before 1991, the initial cumulative production was set at zero.

All (1950-1990):
Although the methodological choice to consider cost reductions within the geographical boundaries of Germany seems justified for the past, it could be alleged that technological learning took place on a higher level within the global chemical, oil milling and biodiesel industry, both before and during the German biodiesel era. Unfortunately, it is impossible to say to what extent these technological learning processes took place. This scenario assumes that technological learning took place in all global fatty acid and biodiesel production over the period 1950-2004. The aim of this scenario is to demonstrate the high sensitivity of the progress ratio on the chosen value for the initial cumulative production rather than giving a more realistic scenario. The fatty acid production volumes - including the fatty acids used for biodiesel production - were taken from Rohmhaas (2008) and extrapolated to the year 1950 to obtain the initial cumulative fatty acid production over the period 1950-1990. An average annual growth rate of 4% was assumed; a growth rate which was observed over the past decade (Rohmhaas, 2008). The cumulative production doubled over six times over the period 1950-1990.

Commercial (1991-1993):
Biodiesel was produced in a non-commercial fashion before 1994. Several biodiesel experts and producers argued that early biodiesel pilot plants are not representative for commercial biodiesel production. Therefore, it is sometimes advocated that cost data stemming from early years in the industry should not be incorporated in the experience curve. This scenario excludes the cost data before 1994 from the experience curve. The production volumes over the years 1991-1993 were summed up and used for the initial cumulative production. The cumulative German biodiesel production doubled over seven times over the period 1991-1993.

E-II Excluding price effects

The rapeseed production costs are influenced by the quantities and exogenous prices of the required raw materials. The price effect is quantified and excluded from the production costs by using similar prices (2006) for all years. Table 34 shows the price effect on the individual cost categories and overall production costs for the years 1971 and 2006.

The price effect has been particularly strong for the following cost categories: fertilizer, storage & drying, insurance & analysis and land. For the cost category fertilizer, the *absolute* cost reduction is almost two times higher than the *relative* cost reduction. No difference can be discerned between the *actual* and *relative* cost reductions of the cost categories chemicals and capital costs, because no data were available that distinguished between quantities and prices. The *relative* cost reductions of seed and labor are even higher than the *absolute* cost reductions, because of the increase in seed prices and wages over time.

The experience curve for the *relative* rapeseed production costs is displayed in figure 42. The price correction results in a higher progress ratio (0.87) than in the base case scenario (0.80). The higher progress ratio implies less cost reductions with each doubling in the cumulative production. The lower learning rate is due to the price correction. Even after the price correction, the experience curve for rapeseed production has still a reliable fit (R^2 = 0.95).

	1971	2006	Change
Absolute production costs (€$_{2007}$ / t rape)	**845**	**251**	**-70%**
Seed	10	9	-10%
Fertilizer	348	52	-93%
Chemicals	79	25	-68%
Storage / Drying	68	10	-85%
Insurance & Analysis	32	4	-88%
Labor	41	18	-56%
Land	85	44	-48%
Total capital costs	181	89	-51%
Relative production costs (price effect excluded) (€$_{2007}$ / t rape)	**565**	**251**	**-56%**
Seed	38	9	-76%
Fertilizer	101	52	-49%
Chemicals	80	25	-69%
Storage / Drying	18	10	-44%
Insurance & Analysis	4	4	0%
Labor	66	18	-73%
Land	74	44	-41%
Total capital costs	183	89	-51%

	Technological learning	**Price changes**
Contribution total cost reductions 1971-2006	80%	20%
	Absolute production costs	**Relative production costs**
Progress ratio (%)	80.4	87.0
R^2	0.97	0.95

Table 34: *The effect of the changing prices of indirect compounds on the total production costs and progress ratio of rapeseed production over the period 1971-2006.*

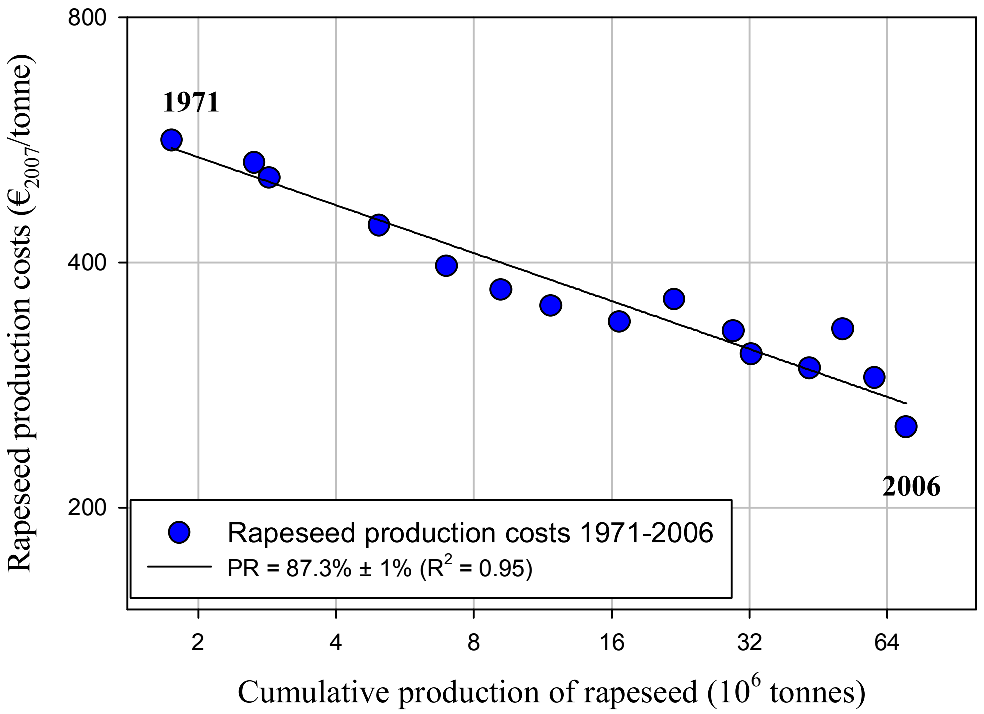

Figure 42: *Experience curve for rapeseed production costs corrected for prices over the period 1971-2006*