

MONITORING INDUSTRIAL ENERGY AND CARBON FLOWS

Neelis, M.L.

Monitoring industrial energy and carbon flows

Thesis Utrecht University, Copernicus Institute for Sustainable Development and Innovation,
Section Science, Technology and Society

ISBN 978-90-8672-027-9

Copyright © 2008, Maarten Neelis

Printed by Ponsen & Looijen, Wageningen

MONITORING INDUSTRIAL ENERGY AND CARBON FLOWS

Het monitoren van industriële energie- en koolstofstromen

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof. dr. J.C. Stoof, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op 25 juni 2008 des middags te 4.15 uur

door

Maarten Lambertus Neelis

geboren op 4 februari 1977 te Rotterdam

Promotor: Prof. Dr. K. Blok
Co-promotor: Dr. M.K. Patel

Het begin van alle kennis is ontzag voor de Heer

Spreuken 1:7

Voor Elise

Contents

1	Introduction	1
1.1	Energy and climate policy – the need for monitoring energy use, energy efficiency and CO ₂ emissions	1
1.2	Monitoring energy use, CO ₂ emissions and energy efficiency in the industrial sector.....	4
1.3	Scope and outline of this thesis.....	9
	References.....	12
2	Modelling CO₂ emissions from non-energy use with the non-energy emission accounting tables (NEAT) model	15
	Abstract	15
2.1	Introduction.....	16
2.2	Overview of emission source categories and system boundaries in the NEAT model approach.....	19
2.3	Emissions from solvent and other product use	21
2.4	Industrial process emissions	28
2.5	Total non-energy use, carbon storage, storage fractions and total fossil CO ₂ emissions.....	34
2.6	Comparisons with the official GHG inventory	37
2.7	Discussion.....	38
2.8	Conclusions.....	40
	Acknowledgements.....	41
	References.....	42
3	CO₂ emissions and carbon storage resulting from the non-energy use of fossil fuels in the Netherlands, NEAT results for 1993 – 1999....	45
	Abstract	45
3.1	Introduction.....	46
3.2	Data sources for the NEAT Netherlands model.....	48
3.3	CO ₂ emissions from non-energy use.....	48
3.4	Total non-energy use in CO ₂ equivalents, carbon storage and storage fractions	54
3.5	Comparison with the National Inventory Report.....	57
3.6	Conclusions.....	66
	Acknowledgements.....	68
	References.....	69

4 Towards consistent and reliable Dutch and international energy statistics for chemical industry..... 71

Abstract	71
4.1 Introduction.....	72
4.2 Energy statistics for the chemical industry – why is it so difficult	73
4.3 Dutch energy statistics for the chemical industry – structure of the survey	77
4.4 Dutch energy statistics for the chemical industry – main findings of the in-depth analysis of company surveys.....	81
4.5 Changes implemented in the oil statistics survey	92
4.6 Similar problems in international energy statistics	97
4.7 Conclusions.....	103
Acknowledgements	103
References	104

5 Energy efficiency developments in the Dutch energy-intensive manufacturing industry, 1980 – 2003 107

Abstract	107
5.1 Introduction.....	108
5.2 Methodology and data collection	111
5.3 Results and discussion	122
5.4 Overall conclusions, policy relevance and recommendations	133
Acknowledgements	136
Appendix A: Detailed results	137
References	142

6 Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes .. 147

Abstract	147
6.1 Introduction.....	148
6.2 Research approach, input data, and basic assumptions.....	150
6.3 Results.....	154
6.4 General directions for energy savings based on our findings	162
6.5 Discussion	165
6.6 Conclusions.....	170
Acknowledgements	171
Appendix A: Detailed results	172
References	183

Summary and conclusions	187
Samenvatting en conclusies	195
Dankwoord.....	205
Curriculum vitae	207

CHAPTER 1

Introduction

1.1 Energy and climate policy – the need for monitoring energy use, energy efficiency and CO₂ emissions

The last couple of decades have been a period of growing concern about the sustainability of the continuously increasing demand for energy. Many of the energy resources used in the global economy are available only in limited amounts and are distributed in an unequal way geographically, resulting in concerns related to the security of energy supply. The current energy system also has significant negative impacts on the local, regional and global environment. Examples of these negative impacts that reached the newspapers in the weeks of writing this introduction include the expected air quality problems during the 2008 Olympics in Beijing (local environment) and deforestation that might partly be due to increasing land-use for bio-fuels (regional environment). On the global level, the enhanced greenhouse effect caused by anthropogenic greenhouse gas emissions is nowadays the major energy related environmental issue. Although by no means the only source, fossil fuel use is the major source of these anthropogenic greenhouse gas (GHG) emissions. In 2004, fossil fuel use resulted in GHG emissions of 31 Gt carbon dioxide (CO₂) equivalent, 63% of the total anthropogenic GHG emissions (IPCC, 2007)¹.

Following the increasing concerns among meteorologists about humankind's impact on the climate in the eighties, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 to assess the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change. The IPCC published up to now four assessment reports discussing the state-of-the-art knowledge related to climate change (IPCC, 1990/1995/2001/2007). The scientific activities resulted in increasing attention from policy makers. In 1992, the United Nations Framework Convention on Climate Change

¹ Other sources of GHG emissions are CO₂ emissions from deforestation, decay of biomass and industrial processes (20%), methane (CH₄) emissions from e.g. agriculture and waste (9%), nitrous oxide (N₂O) emissions from e.g. agriculture (7%) and emissions of fluorinated gases (1%) (IPCC, 2007).

(UNFCCC) was established (UN, 1992) and at the third Conference of Parties of this convention in 1997, the Kyoto Protocol was signed with specified targets on the reduction of GHG emissions in developed countries in 2008 – 2012 compared to 1990 levels (UN, 1997). The protocol entered into force in February 2005.

Four general strategies are suggested to directly² reduce anthropogenic GHG emissions related to the global energy system:

1. Reducing the demand for and thereby the level of energy intensive activities.
2. Improving the efficiency of energy use, i.e. reducing the amount of energy required per unit of activity.
3. Reducing the share of GHG-intensive energy resources and increasing the share of renewable energy resources.
4. Capture and sequestration of the CO₂ emitted during fossil fuel use.

The links between these mitigation options become clear from the following formula³:

$$GHG\ emissions = activity(\alpha) * \sum_i \frac{activity_i}{activity}(\beta) * \frac{energy\ use_i}{activity_i}(\gamma) * \frac{GHG\ emissions_i}{energy\ use_i}(\delta)$$

Equation 1.1

GHG emissions can be reduced by changing the mix of individual activities i to include more activities with lower energy intensity (i.e. the structure of the economy, factor β , mitigation option 1), by reducing the energy use for the individual activities (factor γ , mitigation option 2) and by reducing the GHG emission intensity of the energy used (factor δ , mitigation option 3 and 4).

In response to the global concern about climate change, governments at various levels developed often unprecedented policies targeted at reducing GHG emissions related to the energy system via the four mitigation strategies. The Kyoto protocol, for example, enables countries to reduce emissions cost-effectively in other countries via Emissions Trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI). Emission trading has also been introduced in the European Union in 2005 for large industrial CO₂ emitting

² A fifth indirect strategy reducing atmospheric CO₂ concentrations rather than GHG emissions is to increase the capacity of natural CO₂ sinks, e.g. by forestation.

³ This equation is a specified and shorter version of the more general “master-equation” formulated for the first time by Ehrlich and Holdren (1971). The “master-equation” gives environmental impact as the product of population, Gross Domestic Product (GDP) per capita and environmental impact per unit of GDP.

installations (EU, 2003). The EU emission-trading scheme (EU-ETS) aims to contribute to Europe's emission abatement commitments in an efficient way with least possible diminution of economic development and employment. Other policy instruments in the European Union include the Energy Service Directive (EU, 2006), aiming to enhance the cost-effective improvement of energy end use efficiency in the European Union in the non EU-ETS sectors and the proposed directive on the promotion of the use of energy from renewable resources (EC, 2008). This proposed directive is part of the integrated proposal for Climate Action put forth by the European Commission in January 2008.

For a proper assessment of the past, current and future impacts of global energy use on the climate system and for the design and evaluation of policies aiming to reduce this impact, reliable monitoring of energy use, energy related GHG emissions and energy efficiency developments is of vital importance. This becomes clear from the following examples related to some of the policy instruments mentioned above:

- The Kyoto protocol has binding national targets for GHG emission reductions compared to 1990 levels. Compliance or non-compliance with the protocol can only be assessed if countries monitor and report GHG emissions in a consistent manner via internationally harmonized methodologies such as those published by the IPCC (1997, 2006).
- For an efficient and well-functioning emission allowance market, emissions of the installations included in the market should be reported and monitored in accordance with legally binding rules. For the EU-ETS scheme, guidelines for reporting and monitoring of GHG emissions, pursuant to the directive, have been published in 2004 and 2007 (EC, 2004/2007).
- The Energy Service Directive sets goals for energy efficiency improvements. The Directive requires Member States of the European Union to develop Energy Efficiency Action Plans (EEAP's). These EEAP's shall describe the measures planned to reach the Directive's targets and include results with regard to the fulfilment of these targets. The latter is only possible if the realized energy efficiency improvements are monitored. Annex IV of the Directive gives a general framework, for this monitoring, including guidelines on methodologies and the type of data that may be applied (EU, 2006).

The insight that consistent and reliable monitoring of energy use, GHG emissions and energy efficiency developments is of vital importance for the design and evaluation of climate policy forms the starting point of this thesis in which the focus is on the industrial sector.

1.2 Monitoring energy use, CO₂ emissions and energy efficiency in the industrial sector

Globally, the industrial sector is responsible for approximately 1/3rd of the primary energy use and CO₂ emissions⁴. A few energy intensive sectors, especially those that produce basic materials, dominate energy use and CO₂ emissions. The chemical and petrochemical, iron and steel, non-metallic minerals, paper and pulp and non-ferrous metals industry together accounted for a share of 67% of the industrial energy use in 2004 (OECD/IEA, 2007).

1.2.1 Energy statistics for the industrial sector

Both for the evaluation of energy efficiency (factor γ in Equation 1.1) and GHG-intensity (factor δ in Equation 1.1), reliable and consistent information on energy use is of key importance. Despite this importance, the availability of good quality energy statistics is by no means a matter of course. There are even indications that the coverage and timeliness of energy statistics is declining over the last years as a result of e.g. the liberalization of the energy market, budget cuts and diminishing expertise (OECD/IEA, 2004). As such, there is clear need for ongoing (scientific) efforts aiming to improve the methodologies used for the compilation of energy statistics and for checking their quality. Energy statistics can be gathered at different levels of aggregation. The lowest possible level of aggregation is the level of unit operations, directly related to end uses of energy. Unit operations can in this context be defined as separately distinguishable operations where energy is used to provide a specific clearly distinguishable service. For the industrial sector, examples of unit operations are reactors, separation equipment, but also space heating and lighting. Various of these energy end uses make up the energy use at higher aggregation levels such as the energy use of a production line in the chemical industry, the energy use of a company and the energy use of a total industrial sector. Normally, the company level is the lowest aggregation level for which energy use data is collected and the sector level is typically the lowest level for which comprehensive energy statistics published at regular time intervals are publicly available. Examples are the international energy statistics published annually by the International Energy Agency (IEA, 2007) and national statistics such as those published annually for the Netherlands (Statistics Netherlands, 2008) and quadrennial for the United States (EIA, 2002).

Two principle statistical systems of collecting data by industrial sector can be distinguished. Either industrial energy consumers are directly surveyed or energy-supplying sectors (e.g. oil refineries) are surveyed in which these suppliers classify deliveries according to economic activity or type of customer (OECD/IEA, 2004). Combinations of the two systems are also

⁴ Fossil fuel use results not only in CO₂ emissions, but also in other GHG emissions such as CH₄ and N₂O. In view of the scope of this thesis, we further focus on CO₂.

possible. A problem of the second methodology of collecting data is that information on the use of less conventional fuels can be missed. An example is the use of recovered solid fuels in the cement and iron and steel sector. A second problem is that via surveys to energy suppliers no information is collected on the way energy is used within the industrial sectors and that information on energy conversions (e.g. the production of steam in steam boilers) is thus missing. Also in direct surveys to industrial consumers, often no questions are included on end use by unit operation and on energy conversions within the sector⁵.

A classical example of an industrial sector where many energy conversions take place is the iron and steel industry. In coke ovens, coking coal is converted to cokes, co-producing coke oven gas. The cokes are used as reducing agent in blast furnaces, thereby producing blast furnace gas. Both residual gases are partly used as fuel within the iron and steel sector but are also used in dedicated power plants to produce electricity. The importance of these coal transformation processes is acknowledged in the international energy statistics where coke ovens and blast furnaces are included as energy transformation processes. Farla and Blok (2001) discussed the quality of national and international energy statistics for the iron and steel industry from various sources and concluded that quite some mistakes are made in reported energy use data, including double counting and non-reporting of energy use. Another industrial sector where complex energy conversions take place is the chemical industry. Similar data problems as in the iron and steel sector may therefore be expected in this sector. Moreover, in the chemical industry, energy commodities are not only used for energy purposes, but also as feedstock for the production of chemicals. Various types of conversions take place between energy commodities, but also between energy commodities and chemical products. In the course of these conversions, the boundary between energy commodities on the one hand and chemical products on the other hand is crossed in both directions. In addition, the production of basic chemicals in the petrochemical industry is linked to the refinery sector with flows of energy commodities in both directions. These aspects make the chemical industry a complex industry for the compilation of consistent and reliable energy statistics. Although no comprehensive overview on the quality of energy statistics for the chemical industry is yet available, there are indications from studies on energy efficiency and CO₂ emission monitoring (see below) that there are severe quality and consistency problems related to national and international energy statistics for the chemical industry. For example, Worrell et al. (1994) concluded that the quality of international statistics for the petrochemical industry was insufficient to draw robust conclusions about energy efficiency developments in this industry and Patel et al. (1999) found considerable differences in definition between feedstock energy use data in Italian, German and Dutch energy statistics. Therefore, there is clear need for further analyses on the quality of energy statistics for this industrial sector and

⁵ An exception is often made for the auto-production of power and heat within the industrial sector.

ways to improve this quality. This is especially the case, because the chemical sector is a key sector from an energy point of view with a final worldwide energy use of 34 EJ in 2004, approximately 1/3rd of the final energy use of the total industrial sector and more than any other single sector of industry (OECD/IEA, 2007).

1.2.2 CO₂ emission monitoring in the industrial sector

The link between fossil energy use and energy related CO₂ emissions (factor δ in equation 1.1) is in essence very simple. Via specific CO₂ emission factors, fuel use in a specific process or industrial sector can be converted into the equivalent amount of CO₂ emissions. In the reporting format for national GHG inventories (UNFCCC, 2008), industrial fuel combustion emissions should be reported by industrial sector, following the sector division that is used in the international energy statistics. Default values for fuel emission factors can be found in the guidelines for national GHG inventories (IPCC, 1997, 2006). The accuracy of CO₂ emission calculations from fuel combustion can be further improved, e.g. by using more specific national emission factors (e.g. SenterNovem, 2007). In the reporting and monitoring guidelines for the EU-ETS, various tiers are distinguished for establishing emission factors for fuels with the highest tier involving laboratory tests to determine the carbon content of the specific fuel used (EC, 2004/2007). Although conceptually rather straightforward, various problem areas related to CO₂ emission accounting from fossil fuel use can be distinguished. An example is the risk of double counting or omission of CO₂ emissions if data from various sources is combined.

A sector for which CO₂ emission accounting from fossil fuel use is not straightforward is the petrochemical industry where, as said before, energy commodities are used not only for energy, but also as feedstock. The share of feedstock use in the total primary energy supply of countries is for many countries limited (typically around 5%), but there are exceptions such as the Netherlands and the Republic of Korea where feedstock use makes up more than 10% of the total domestic energy use (IEA, 2007). The use of energy commodities as feedstock imposes, as was shown above, challenges for the compilation of energy statistics, but also for the accounting of CO₂ emissions. A significant part of the carbon embodied in fuels used as feedstock is stored in chemical products having life-times ranging from weeks to several decades or even longer. These chemicals can result in GHG emissions either during product use (e.g. solvents) or during the post-consumer phase (e.g. waste incineration) and often in a different country than the one where the feedstock is first consumed due to trade in organic chemicals and intermediates. The same holds for products of energy industries that are directly used for their non-energy properties such as bitumen and lubricants. In the national emission inventory guidelines (IPCC, 1997) used within the framework of the Kyoto protocol, a methodology is provided to calculate the storage of carbon in synthetic organic chemicals. The methodology is based on the multiplication of the energy commodities that are used as

feedstock or directly for non-energy purposes with carbon storage fractions. The default storage fractions are based on a publication by Marland and Rotty (1984). Various authors (e.g. Patel et al., 1999; Gielen, 1999) pointed at weaknesses in relation to the methodology such as the inconsistencies between the way the storage fractions are used and the way they have been determined, the failure to take adequately into account the trade in synthetic organic chemicals and the failure to account for different definitions that are used for feedstock and other non-energy use in the energy statistics. Given these fundamental weaknesses in the methodology, there is clear need for independent checks of national GHG inventories in relation to the accounting of emissions from the feedstock and other non-energy use of fossil fuels⁶.

1.2.3 Energy efficiency monitoring and energy efficiency potentials in the industrial sector

GHG emissions can also be mitigated by increasing energy efficiency or by reducing the demand for energy intensive activities. For both mitigations options, a clear view on the amount of energy that is needed for a certain activity is required (factor γ in Equation 1.1). Energy efficiency improvement can be defined as using less energy for producing the same amount of service or useful output without affecting the level of the service or useful output itself. The most obvious link between energy use and services provided is the link at the unit operation level. In a distillation column, the service provided is e.g. the separation of product A and B from a mixture of both. If a new design of the distillation column enables the separation of product A and B from the mixture using less energy, the column is more energy efficient compared to the previous one⁷. At higher levels of aggregation (e.g. an industrial company or an industrial sector), the link between energy use and the service provided becomes more complex, because multiple services are produced that relate to the total energy use of the company or sector. As a result, also monitoring the energy efficiency (defined as above) becomes more complex. For energy efficiency monitoring at these higher aggregation levels, economic indicators such as turnover, production value or value added are often used for defining the service or useful output level. Without doubt, changes in the ratio of energy use to these economic indicators tell us something about changes in the way energy is used in a certain sector. But what do they tell exactly? Has there been a shift from energy intensive products with a low value added to less energy intensive products with a high value added,

⁶ In 2006, new guidelines for national GHG inventories were published (IPCC, 2006). These new guidelines are, however, not yet used within the framework of the Kyoto protocol, which runs until 2012. In these new guidelines, the problems related to emission accounting for the non-energy use of fossil fuels are partly solved. Parts of this thesis (Chapter 2 and 3) formed an important input into the revision of the guidelines.

⁷ For a fair comparison, also the difference in energy use for producing the two distillation columns should be taken into account, so-called third-order energy analysis. For equipment using significant amounts of energy during the lifetime, this upstream contribution is normally small (Blok, 2007).

e.g. the shift from basic chemical production to fine chemicals? Did the prices of capital, labour, energy and materials change resulting in a different cost structure for the industry? Or has there been a real change in the energy efficiency and did the sector produce exactly the same output using less energy per unit of this output?

It is widely accepted that for the industrial sector, the use of physical rather than economic indicators of activity offers a better understanding of energy efficiency developments (e.g. Freeman et al., 1997; Boonekamp, 2005). Physical indicators of activity are more closely linked to the ‘technical efficiency’ of an industrial sector, they are not affected by variations in prices of commodities and they allow more easily to take into account differences in product mix over time and between countries (OECD/IEA, 2007). Examples of studies using physical indicators for the energy intensive industry (often characterized by a limited amount of products that consume the vast majority of energy) are quite numerous (e.g. Phylipsen et al., 1998; Persson et al., 2006; ODYSSEE, 2008). In non-energy intensive sectors of industry, the total energy use is spread over a large group of products. As a result of the larger data requirements, physical indicators are therefore less often used for non-energy intensive industries. Recently, Ramírez-Ramírez (2005) provided an important addition to the research field by developing and applying physical activity indicators also for a non-energy intensive sector of industry: the food, beverage and tobacco industry. Several of the studies mentioned stress the need for further development and application of methodologies for monitoring energy efficiency developments using physical indicators of activity, exploring issues such as (public) data availability, data quality and cross-country comparisons.

Climatic change is a long-term problem with current emissions resulting in changes in the atmospheric CO₂ concentration in this, but also in following generations. Given these long-term scope, a clear view not only on short-term energy efficiency improvement potentials is necessary, but also on medium and longer-term potentials. Worrell (1994) distinguishes theoretical, technical, economic and market potentials for energy efficiency improvements. Market, economic and technical potentials refer to potentials that are in principle achievable using currently available technologies. The market potential can be defined as the potential that is likely to be reached in practice, the economic potential as the potential that can be achieved at a net positive economic effect and the technical potential as the achievable energy efficiency improvement resulting from the most effective combination of measures available. A large body of work deals with the cost-effectiveness of various energy saving measures and quantifies technical, economic and market potentials for various sectors (e.g. Ecofys, 2001; OECD/IEA, 2006). For medium and long-term assessments of energy efficiency potentials, also reflections on theoretical energy saving potentials are important. The theoretical energy efficiency potential of a certain activity is determined by thermodynamic laws and can be defined as the difference between the minimum energy use required for a certain activity

compared to the current energy use. There are various studies that discuss theoretical energy efficiency potentials at the level of unit operations and processes (e.g. Szargut et al, 1988), but comprehensive overview studies on theoretical potentials for total sectors of industry are not widespread. One exception is De Beer (1998) who discusses long-term energy savings potentials for the pulp and paper, iron and steel and nitrogen fertilizer industry, including also explicitly an assessment of theoretical energy requirements. For sectors where chemical conversions between raw materials and products take place, the energy effects of reaction are an important part of the energy balance and are therefore of key importance for understanding the way energy is used in the sector and for determining (theoretical) energy efficiency potentials. A clear example is the iron and steel industry. For the conversion of iron ore (the natural resource) to iron and steel, a minimum amount of energy is required, which can be calculated based on the basic thermodynamic laws. Also in the chemical industry, raw materials and chemical intermediates are converted into other chemical products via reactions that can either be exothermic or endothermic. In detailed studies on energy-saving potentials of individual processes and in more theoretical studies on potential energy savings in chemical processes, the energy effects of reaction are always regarded a key element in understanding the structure of energy use in a process and in defining areas for potential improvement (e.g. Leites et al., 2003). In overview studies on the energy use and energy efficiency potentials of the chemical sector as a whole, the energy effects of reaction are, however, often not explicitly dealt with, calling for a systematic, sector-wide analysis.

1.3 Scope and outline of this thesis

The central research question for this thesis is:

How can the monitoring of energy use, CO₂ emissions and energy efficiency for the industrial sector be improved?

We focus on the research needs identified in the previous section. The specific goals of this thesis are:

- To contribute to improved energy statistics for the chemical industry by studying in detail historical energy statistics for the Netherlands at the company level and to draw lessons for improvement of the Dutch and the international energy statistics for this industry.
- To develop and apply a methodology to account for CO₂ emissions resulting from the feedstock use and other non-energy use of fossil fuels that can be used as crosscheck for national GHG emission inventories.

- To develop and apply a methodology to study energy efficiency trends in the industrial sector based on publicly available physical production and energy use data.
- To develop a bottom-up energy model for the petrochemical sector and to assess theoretical energy saving potentials in the Dutch, European and global petrochemical industry at the level of individual production processes.

The content of the various chapters is discussed in more detail below.

In Chapter 2 and 3, we first focus on the national CO₂ emission accounting methodologies for the feedstock and other non-energy use of energy commodities. In Chapter 2 we develop a model to account for these CO₂ emissions. The model aims to track the final fate of the carbon embodied in the fossil fuels used for non-energy purposes using a carbon flow analysis. The model estimates are to a large extent made independently from the energy statistics of the country. We assess whether the results obtained with the model can be used as a crosscheck for the CO₂ emissions from non-energy use according to the national GHG inventory of the country. In Chapter 3, the model developed in Chapter 2 is applied to Netherlands for the period 1993 – 1999. Based on production and trade data, estimates are made for the CO₂ emissions related to non-energy use, storage of carbon in synthetic organic chemicals and for the total non-energy use in the Netherlands. The results are compared with the Dutch GHG inventory. Based on the comparison, conclusions are drawn on the use of the Dutch energy statistics for the calculation of GHG emissions and recommendations are given to improve the Dutch GHG emission inventory based on the outcome of the analysis.

In the study on non-energy use in the Netherlands described in Chapter 3 and in the preparation of Chapter 5 of this thesis, irregularities were discovered in the Dutch energy statistics for the chemical industry. In the study described in Chapter 4, we therefore zoom in on these statistics. We study the company data that form the basis of the energy statistics for the chemical industry in the Netherlands in detail to find causes for the observed irregularities. The outcome of this detailed analysis was used for improving the survey that is used for the compilation of the statistics. We describe which changes are made to the survey. We use the Dutch experience to critically assess the survey used to compile the international energy statistics as they are published by the International Energy Agency and give suggestions for improvement of this international survey.

In Chapter 5, we develop a methodology to study energy efficiency trends in the industrial sector based on publicly available physical production and specific energy consumption data. We apply the methodology to the Netherlands for the period 1995 – 2003. We combine the results with a similar study for the period 1980 – 1995, allowing analyses over the full time period 1980 – 2003. We compare the results with the monitoring reports prepared as part of

the Long Term Agreements between the Dutch government and the Dutch industry, quantitatively assess the effect of data uncertainties on the observed energy efficiency trends and explore the feasibility of using the methodology in other countries also.

Chapter 6 deals with theoretical energy saving potentials in the petrochemical industry. A bottom-up energy model for 68 production processes in the petrochemical industry is developed. For these processes, we quantify the sum of all energy inputs that do not end up in the useful products of the process. These losses can be regarded as a good approximation of theoretical energy saving potentials. Losses resulting from non-selectivity, energy conversions losses and the excess final energy defined as the difference between actual process energy use and the theoretical minimal energy requirements based on the reaction equation are separately quantified. The quantification is made in relative terms (i.e. per tonne of product) and in absolute terms for the Netherlands, Western Europe and the World by combining specific process data (i.e. per unit of output) with production volumes.

References

- de Beer, J, 1998. Potential for industrial energy efficiency improvement in the long term, PhD thesis, Utrecht University, Utrecht.
- Blok, K, 2007. Introduction to energy analysis, Techne Press, Delft.
- Boonekamp, PGM, 2005. Improved methods to evaluate realized energy savings, PhD thesis, Utrecht University, Utrecht.
- EC, 2004. Commission Decision 2004/156/EC of 29 January 2004 establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council. Official Journal of the European Union, 26.02.2004.
- EC, 2007. Commission Decision 2007/589/EC of 18 July 2007 establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council. Official Journal of the European Union, 31.08.2007.
- EC, 2008. COM(2008) 19 final of 23.01.2008. Proposal presented by the Commission for a directive of the European Parliament and of the council on the promotion of the use of energy from renewable resources.
- Ecofys, AEA Technology, National Technical University of Athens, 2001. Economic evaluation of sectoral emission reduction options for climate change. Project for the European Commission. Reports available online via:
http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm
- Ehrlich, PR and Holdren, JP, 1971. Impact of population growth, Science, Vol. 171, pp. 1212-1217.
- EIA, 2002. Manufacturing Energy Consumption Survey 2002, Energy Information Administration, available online via www.eia.doe.gov/emeu/mecs/.
- EU, 2003. Directive 2003/87/EC of the European Parliament and of the Council of 13.10.2003 establishing a scheme for greenhouse gas emission allowance trading within the community and amending Council Directive 96/61/EC, Official Journal of the European Union, 25.10.2003.
- EU, 2006. Directive 2006/32/EC of the European Parliament and of the Council of 05.04.2006 on energy end use efficiency and energy services and repealing Council Directive 93/76/EEC, Official Journal of the European Union, 27.04.2006.
- Farla, JCM and Blok, K, 2001. The quality of energy intensity indicators for international comparison in the iron and steel industry, Energy Policy, Vol. 29, pp. 523-543.
- Freeman, SL, Niefer, MJ and Roop, JM, 1997. Measuring industrial energy efficiency: practical issues and problems, Energy Policy, Vol. 25, pp. 703-714.
- IEA, 2007. Energy Balances and Energy Statistics for OECD and non-OECD countries 2004 – 2005, four publications, International Energy Agency, Paris.

- IPCC, 1990. Intergovernmental Panel on Climate Change: First Assessment Report. Published in three volumes, detailed bibliographical information available online via <http://www.ipcc.ch/ipccreports/assessments-reports.htm>.
- IPCC, 1995. Intergovernmental Panel on Climate Change: Second Assessment Report. Published in three volumes and a synthesis report, detailed bibliographical information available online via <http://www.ipcc.ch/ipccreports/assessments-reports.htm>.
- IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Volumes 1, 2 and 3, Houghton, JT, Meira Filho, LG, Lim, B, Treanton, K, Mamaty, I, Bonduki, Y, Griggs, DJ and Callander, BA (Eds). Intergovernmental Panel on Climate Change, Organization for Economic Cooperation and Development (OECD), International Energy Agency (IEA), Paris.
- IPCC, 2001. Intergovernmental Panel on Climate Change: Third Assessment Report. Published in three volumes and a synthesis report, detailed bibliographical information available online via <http://www.ipcc.ch/ipccreports/assessments-reports.htm>.
- IPCC 2006. 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K (eds). Published: IGES, Japan.
- IPCC, 2007. Intergovernmental Panel on Climate Change: Third Assessment Report. Published in three volumes and a synthesis report, detailed bibliographical information available online via <http://www.ipcc.ch/ipccreports/assessments-reports.htm>.
- Leites, IL, Sama, DA and Lior, N. The theory and practice of energy saving in the chemical industry: some methods for reducing thermodynamic irreversibility in chemical technology processes, *Energy*, Vol. 28, pp. 55-97.
- Marland, G and Rotty, RM, 1984. Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950 – 1982. *Tellus*, Vol. 36B, pp. 232-261.
- ODYSSEE, 2008. ODYSSEE project by Ademe, the European Commission and energy efficiency agencies in the EU countries, more information available via <http://www.odyssee-indicators.org>.
- OECD/IEA, 2004. Energy statistics manual, Organization for Economic Cooperation and Development, International Energy Agency, Paris.
- OECD/IEA, 2006. Energy Technology Perspectives, Organization for Economic Cooperation and Development, International Energy Agency, Paris.
- OECD/IEA, 2007. Tracking industrial energy efficiency and CO₂ emissions, Organization for Economic Cooperation and Development, International Energy Agency, Paris.
- Patel, M, Jochem, E and Marscheider-Weideman, F, 1999. CO₂ emissions from non-energy use – Methodological aspects and case study for Germany, *Ambio*, Vol. 28, pp. 175-181.

- Persson, TA, Claeson Colpier, U and Azar, C, 2006. Adoption of carbon dioxide efficient technologies and practices: an analysis of sector-specific convergence trends among twelve nations. *Energy Policy*, Vol. 35 (5), pp. 2869-2878.
- Phylipsen, GJM, Blok, K and Worrell, E, 1998. Handbook on international comparisons of energy efficiency in the manufacturing industry, Utrecht University, Department of Science, Technology and Society, Utrecht.
- Ramírez-Ramírez, A, 2005. Monitoring Energy Efficiency in the Food Industry, PhD thesis, Utrecht University, Utrecht.
- SenterNovem, 2006. Nederlandse lijst van energiedragers en standaard CO₂ emissiefactoren, SenterNovem, Utrecht.
- Statistics Netherlands, 2008. Energiebalans Nederland, available online via <http://www.statline.cbs.nl>.
- Szargut, J, Morris, DR and Steward, FR, 1988. Exergy analysis of thermal, chemical and metallurgical processes, Springer Verlag, Berlin.
- UN, 1992. United Nations Framework Convention on Climate Change, United Nations, New York.
- UN, 1997. Kyoto Protocol to the Convention, United Nations, Geneva.
- UFCCC, 2008. Common Reporting Format developed by the Secretariat of the United Nations Framework Convention on Climate Change, available online via <http://unfccc.int>.
- Worrell, E, 1994. Potentials for improved use of industrial energy and materials, PhD thesis, Utrecht University, Utrecht.
- Worrell, E, Cuelenaere, RFA, Blok, K and Turkenburg, WC, 1994. Energy consumption by industrial processes in the European Union, *Energy*, Vol. 19, pp. 1113-1129.

CHAPTER 2

Modelling CO₂ emissions from non-energy use with the Non-energy use Emission Accounting Tables (NEAT model)*

Abstract

To contribute to a more accurate accounting of CO₂ emissions originating from the non-energy use of fossil fuels, the NEAT (Non-energy use Emission Accounting Tables) model has been developed. The model tracks the final fate of the carbon embodied in this non-energy use by means of a carbon flow analysis for the relevant sectors. The model generates estimates for total non-energy use, carbon storage in synthetic organic chemicals and CO₂ emissions resulting from non-energy use that are independent from energy statistics. This paper describes the basic methodology of the NEAT model. It is shown that the results obtained with the model can be used as an important addition to and crosscheck for the non-energy use emission accounting in official GHG emission inventories prepared according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC). The model can help to identify which definitions of non-energy use are applied in the energy statistics employed in national emission inventories and can help to improve national inventory methodologies based on this insight.

* Published in Resources, Conservation and Recycling, Vol. 45 (2005), pp. 226-250. Co-authors are M. Patel, D.J. Gielen and K. Blok.

2.1 Introduction

In the context of greenhouse gas (GHG) emission inventories, so far most attention has been paid to CO₂ emissions resulting from the combustion of fossil fuels. A significant fraction of fossil fuels is not directly used in combustion processes, however, but is consumed for non-energy use purposes. The non-energy use of fossil fuels consists of two parts:

- The consumption of fossil fuels as feedstock in the chemical industry. Examples are the use of naphtha for the production of olefins and the use of natural gas for the production of ammonia¹.
- A limited number of non-energy refinery and coke oven products that are consumed in various economic sectors and the use of solid carbon for the production of metals and inorganic chemicals. Examples are the use of bitumen in the building industry, lubricants for transportation and the use of cokes for the production of metals².

Worldwide, the non-energy use of fossil fuels represented 5.3% of the Total Primary Energy Supply (TPES) in 2000. This share differs from country to country, depending on the relative importance of refineries and basic chemical industries. In the Netherlands for example, with its large petrochemical industry, the non-energy use share was 13.5% in 2000 and in Korea, the share was 14.1 % in 2000 (IEA, 2002). Estimating CO₂ emissions resulting from the non-energy use of fossil fuels is not straightforward, because part of the carbon embodied in these fossil fuels is first stored in chemicals that have lifetimes ranging from days to decades. These chemicals lead to emissions during the use phase (e.g. solvents) or in the waste treatment phase. In other cases (e.g. asphalt and land filled plastics), these chemicals do not lead to emissions at all within a time span relevant for emission accounting. Apart from the emissions originating from the carbon embodied in synthetic organic chemicals, non-energy use may lead to industrial process emissions during the production of certain chemicals such as ammonia. In some processes, the hydrocarbon input is used both as fuel and as feedstock. Depending on the definition of non-energy use applied in the energy statistics, part of the carbon embodied in the non-energy use might therefore also lead to CO₂ emissions from fuel combustion. In Section 2.2 of this paper, the various emission source categories will further be defined and discussed.

¹ In energy statistics published by the International Energy Agency (IEA), this feedstock use is reported as a memo item under the final energy consumption of the chemical industry.

² In energy statistics published by the International Energy Agency (IEA), the use of these refinery, coal and coke oven products is reported as non-energy use in i) Industry / Transformation / Energy, ii) Transport and iii) Other sectors.

In their emission inventory guidelines (IPCC, 1997), the Intergovernmental Panel on Climate Change (IPCC) recommends two principal methods of calculating national GHG emissions, the Reference Approach (IPCC-RA) and Sectoral Approach (IPCC-SA). The IPCC-RA only calculates fossil CO₂ emissions and is supposed to be applied as a crosscheck for the IPCC-SA and for countries with limited data availability. The principal idea behind the IPCC-RA is to subtract the amount of fossil carbon stored from the total CO₂ emissions calculated on basis of the Total Primary Energy Supply (TPES) of a country. The carbon storage is calculated by multiplying the non-energy use of a certain fuel with a storage fraction for this fuel:

$$\text{carbon storage} = \text{non-energy use} * \text{emission factor} * \text{storage fraction}$$

$$(t \text{ carbon}) \quad (J) \quad (t \text{ carbon} / J) \quad (\%)$$

Equation 2.1

The IPCC provides default values for the storage fractions (100% for bitumen; 80% for naphtha, LPG and ethane; 75% for coal oils and tars from coking oil; 50% for lubricants and gas/diesel oil and 33% for natural gas; IPCC, 1997, Volume 2, pp. I-37). The resulting emission estimate (TPES in carbon equivalents minus the carbon storage) is nowadays generally regarded as an estimate for national fossil CO₂ emissions from ‘Fuel combustion’ only (see Section 2.6 for a further discussion on the scope of the IPCC-RA). In the more detailed IPCC-SA, instead of taking the national fossil fuel supply as the basis for the calculations, data on energy use by sector are used to calculate fossil CO₂ emissions from fuel combustion per sector. In the ‘Tier 1 and 2 methods’ described in the guidelines, the carbon storage is still calculated using formula 1. Only in more complex ‘Tier 3’ methods, which are not explicitly described in the guidelines, CO₂ emissions from fuel combustion are estimated using data other than those from the energy statistics³. In addition to CO₂ emissions from fuel combustion, GHG emissions in the IPCC-SA are also reported in other emission source categories. These include ‘Industrial Process Emissions’, ‘Solvent and other product use’ and ‘Waste’. Various disadvantages exist with regard to the current IPCC methods for non-energy use CO₂ emission accounting such as:

- The failure of methods based on only the energy statistics to take into account the variety of downstream non-energy carbon flows through the economy (e.g. trade in synthetic organic chemicals). These flows might differ substantially between countries.

³ An example of a country applying such a method is the Netherlands in which emissions reported by individual firms are combined with emission estimates based on the energy statistics. For more details, we refer to Neelis et al., 2005.

- The unclear scope of the IPCC-RA, either as a method to calculate CO₂ emissions from fuel combustion only or as a tool to calculate total fossil CO₂ emissions (further discussed in Section 2.6).
- The lack of proper definitions of non-energy use in the energy statistics for important processes such as steam cracking, leading to possible overestimation or underestimation of emissions in both the IPCC-RA and IPCC-SA (further discussed in Sections 2.4 and 2.6).

For these reasons, emissions resulting from the non-energy use of fossil fuels contribute considerably to the overall uncertainty in many national GHG emission inventories, especially in countries with a large share of non-energy use relative to the TPES. In the Netherlands, emissions from oil feedstocks are, for example, among the top 10 of *key sources* contributing to both *level* and *trend* uncertainty according to Olivier and Peters (2005)⁴.

To contribute to a more accurate accounting of GHG emissions resulting from the non-energy use of fossil fuels, we developed the NEAT (Non-Energy use Emission Accounting Tables) model. The model, developed as an Excel spreadsheet tool, is based on a bottom-up carbon flow analysis. The model tracks the final fate of the carbon embodied in the fuels used for non-energy use purposes using primarily production and trade statistics. The first version of the model has been described by Gielen and Patel (1999) and was with minor adaptations used by Gielen and Yagita (2002) to study Japanese carbon storage in 1996. The main focus of the first model version was on the correct calculation of the carbon storage in the economy. Since the first version, the model has further been refined and extended by a module to calculate direct industrial process emissions resulting from non-energy use (e.g. from ammonia production). The extended model now systematically deals with all carbon flows related to the non-energy use of fossil fuels and can be used to generate estimates for total non-energy use, carbon storage and non-energy use emissions that are independent from the energy statistics. The aim of this paper is to investigate whether the results obtained with the extended NEAT model (version 2.0) can be used as a crosscheck for the non-energy use emission accounting in official GHG emission inventories. We start with an overall overview of the NEAT methodology (Section 2.2), followed by 3 sections in which the various model calculations are described. In Section 2.6, the comparison with the official GHG inventory is discussed. We end with a discussion and some main conclusions and recommendations for future work. The application of the model for country studies of Korea, Italy and the Netherlands is described elsewhere (Park, 2005; La Motta et al., 2005; Neelis et al., 2005).

⁴ Definitions of the terms ‘key source’, ‘level uncertainty’ and ‘trend uncertainty’ can be found in the IPCC Good Practice Guidance (IPCC, 2000).

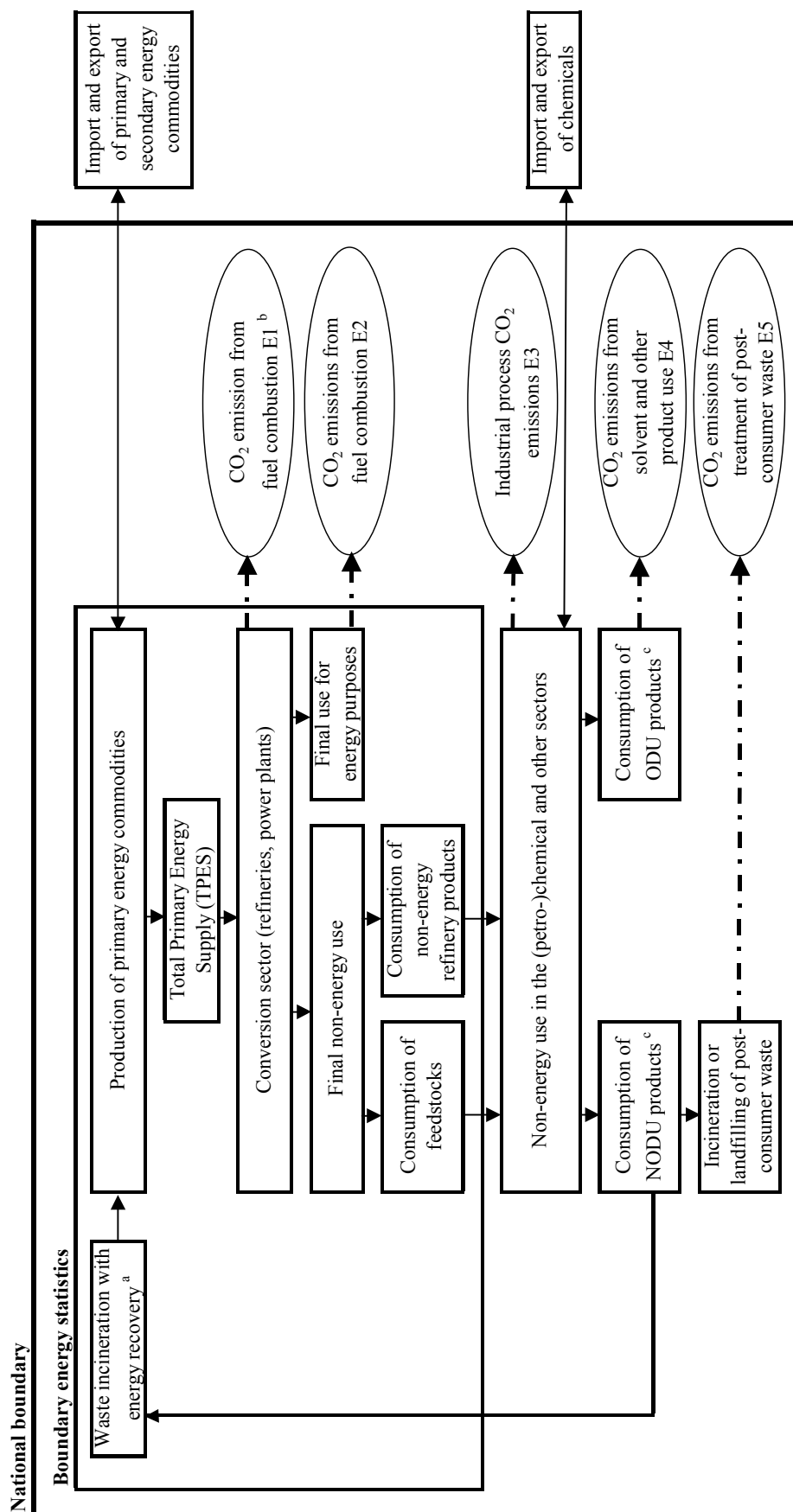
2.2 Overview of emission source categories and system boundaries in the NEAT model approach

As mentioned in the introduction, the four IPCC emission source categories that are relevant for non-energy use emission accounting are:

1. Fuel combustion
2. Industrial processes
3. Solvent and other product use
4. Waste

In the NEAT model, we also distinguish these source categories. We convert all flows into CO₂ equivalents based on the carbon content of the flows under consideration. We then calculate the CO₂ emissions in the various source categories⁵. Figure 2.1 shows how the NEAT emission categories relate to the overall national energy and carbon flows. The figure shows all activities, which add up to a country's TPES as it can be found in energy statistics. Primary energy commodities (crude oil, natural gas) are converted to secondary commodities. The conversions result in CO₂ emissions from 'Fuel combustion' in the conversion sector (E1)⁶. The secondary energy commodities produced in the conversion sector (fuels, electricity) are available for final consumption. The majority of the energy commodities are consumed for energy purposes in all economic sectors, leading to CO₂ emissions from 'Fuel combustion (E2)'. The remainder is used for the two types of non-energy use described in the introduction. Part of the carbon embodied in this non-energy use is already oxidised to CO₂ during the production phase of certain chemicals of which ammonia is the most important example in terms of total worldwide CO₂ emissions. These emissions have been defined by the IPCC as CO₂ emissions from 'Industrial processes (E3)'. As we will show in Section 2.4, various possible definitions can be applied to divided the total hydrocarbon input over final energy use and final non-energy use for a number of these processes and the allocation between emissions from 'Fuel combustion (E2)' and emissions from 'Industrial processes (E3)' is therefore not always straightforward. The remainder of carbon embodied in the fossil fuels used for non-energy use purposes is first stored in chemicals. Some of these products only lead to GHG emissions during incineration of post-consumer waste. In the NEAT model, we refer to these products as products that are not oxidised during use (NODU). According to the emission inventory guidelines (IPCC, 1997), waste that is incinerated with energy recovery is considered as fuel and is hence defined to lead to emissions from 'Fuel combustion (E1)'. Emissions from incineration without energy recovery are assigned to the emission category 'Waste (E5)'. Another group of chemicals (e.g. detergents and

⁵ For fuel combustion, incomplete combustion is neglected.



^a In line with the international energy balance (IEA, 2000), It is assumed that the waste used for energy recovery is in the energy balance reported as a produced energy commodity. The energy recovery (to e.g. electricity) is subsequently covered in the conversion sector and the CO₂ emissions are part of the emissions from fuel combustion (E1).

^b Including emissions from waste incineration with energy recovery.

^c ODU = oxidised during use, NODU = not oxidised during use

Figure 2.1 Overview of national energy flows and fossil CO₂ emissions in the NEAT model approach (the solid lines indicate energy and/or material flows, the dotted lines indicated emission flows, the overall are the relevant IPCC source categories)

solvents) is already released into the atmosphere during or directly after use (fully or at least partially). In NEAT, these products are referred to as products that are oxidised during use (ODU). The emissions from the use of these ODU products are assigned to the IPCC emission source category of ‘Solvent and other product use (E4)’⁶. In the NEAT model, we count these emissions as CO₂ emissions. In the official emission inventories according to the IPCC-SA, these emissions might also be reported as non-methane volatile organic compounds (NMVOC) emissions from ‘Solvent and other product use’ or as methane emissions in the category ‘Waste’.

We discuss the NEAT model calculation of CO₂ emissions from ‘Solvent and other product use (E4)’ in Section 2.3 and of CO₂ emissions from ‘Industrial processes (E3)’ in Section 2.4. In Section 2.4, we also discuss possible definitions for non-energy use applied in the energy statistics for a number of processes and the resulting difficulties in allocating emissions to either ‘Industrial processes (E2)’ and ‘Fuel combustion (E3)’. Emissions from waste incineration of NODU products (E1 and E5) are not calculated in the NEAT model. We assume that these emissions are correctly calculated in the official emission inventories. The model can be used to generate independent estimates for the total non-energy use in CO₂ equivalents and for the carbon storage. Based on this, storage fractions for use in the IPCC-RA can be calculated and the total fossil CO₂ emissions can be estimated. These elements are discussed in Section 2.5. The comparison with the energy statistics and the official GHG emission inventory is discussed in Section 2.6.

2.3 Emissions from solvent and other product use

To develop an estimate of the emissions from the use of ODU products (‘solvent and other product use’), the petrochemical industry is modelled by means of a national carbon balance, covering (in the current model version), 77 of the most important organic chemical commodities in terms of production volume⁷. The carbon balance contains the conversion

⁶ In the current IPCC Guidelines (IPCC, 1997, Vol 3, pp. 1.25) and in previous descriptions of the NEAT model (Gielen and Patel, 1999 and Gielen and Yagita, 2002), a distinction was made between ‘long-life’ and ‘short-life’ products. We consider this nomenclature to be confusing, because certain products called long-life (e.g. polyethylene bags) are consumed and oxidised (during waste incineration) very shortly after their production. The current nomenclature (ODU versus NODU) better reflects the type of oxidation in line with CO₂ emission categories (‘Solvent and product use’ versus ‘Waste’ or ‘Fuel combustion’). For a more detailed discussion, reference is made to Patel et al. (2005).

⁷ The selection has been made based on own insight. The list contains all organic chemicals listed in the top 50 of chemicals produced in the US (DOE/OIT, 2000) with the exception of methylchloride.

routes from 22 basic chemicals to 55 intermediate and final products (Table 2.1). The method will be explained by use of the simplified example of ethylene use as shown in Figure 2.2.

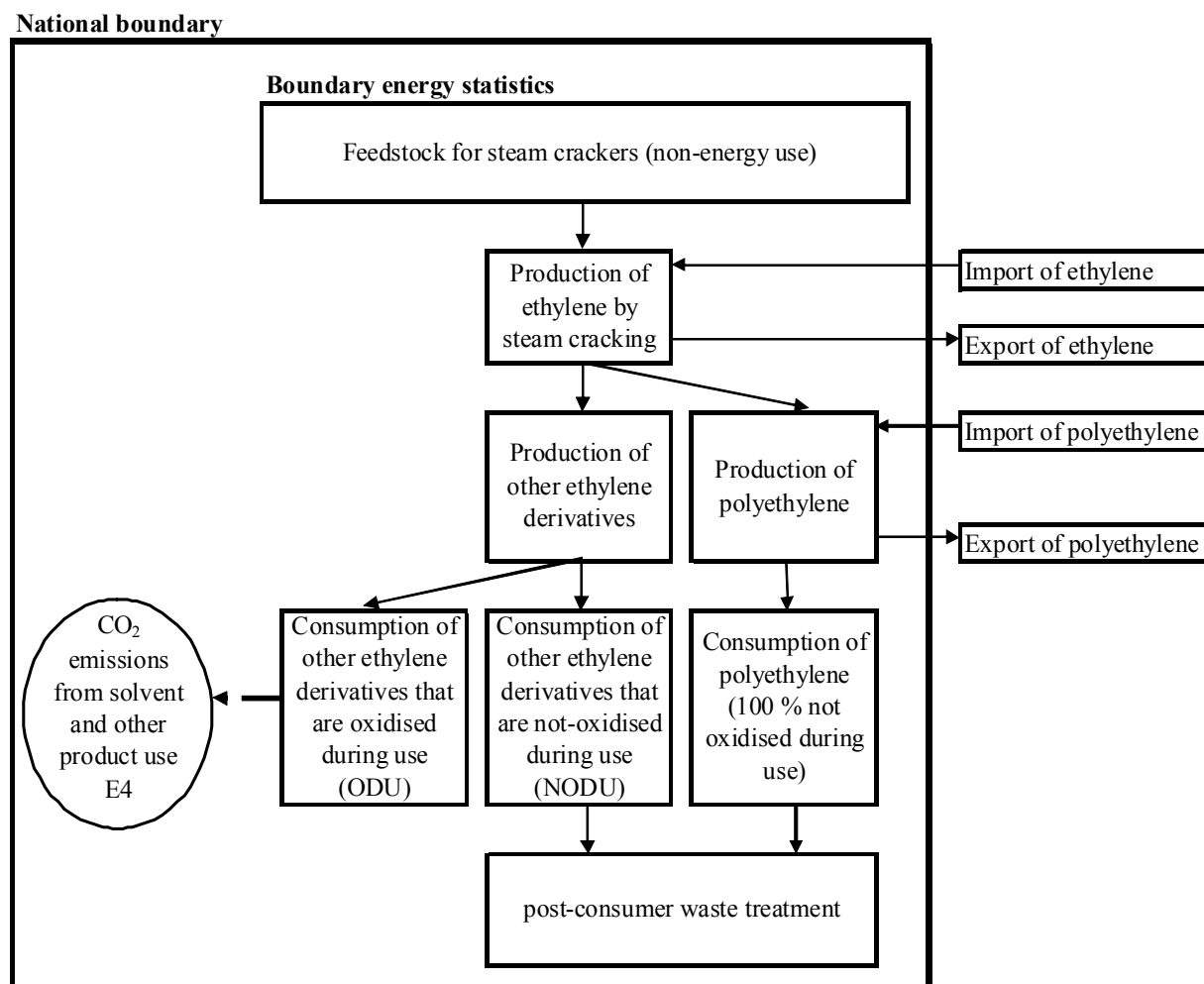


Figure 2.2 Calculation of emissions from solvents and other products use in NEAT, simplified example for ethylene (the solid lines indicate energy and/or material flows, the dotted line indicate an emissions flow, the oval is the relevant IPCC source category)

In this simplified example, ethylene is used for the production of polyethylene and for the production of other ethylene derivatives, which are not individually modelled⁸. Both the total consumption of polyethylene and the remaining ethylene consumption, which is used for the production of other ethylene derivatives, are divided into ODU and NODU applications. For some of the products, this division is clear-cut. All polymers, including the polyethylene of the example, are for example NODU products. For other products (like the total of other

⁸ In the simplified example polyethylene is the only ethylene derivative individually modelled. In the actual NEAT model, synthetic ethanol, ethylene oxide, ethylbenzene, ethylene dichloride, ethylene-propylene-diene-monomer (EPDM), epoxy resin and polyvinyl acetate are also modelled.

ethylene derivatives in the example), the fraction of ODU versus NODU products has been estimated based on the use pattern of these products found in literature (e.g. Weissermel and Arpe, 2003; Chauvel and Lefebvre, 1989). Solvents and surfactants are regarded completely ODU. An uncertainty range between ODU and NODU was determined for products for which the exact use was unknown. The fractions of ODU versus NODU applications for all 77 core commodities as well as the uncertainty ranges are given in Table 2.1. The calculation of emissions from ‘solvent and other product use’ can be summarised with the following formula:

Emissions from solvent and other product use =

$$\sum_{i=1}^{77} (P_i + I_i - E_i - C_{NEAT,i}) * \% ODU_i$$

Equation 2.2

With P_i , I_i and E_i representing production, import and export of chemical i in CO₂ equivalents and $C_{NEAT,i}$ representing the consumption of chemical i for the production of other NEAT core chemicals, also in CO₂ equivalents. For chemicals that are not used as intermediate for the production of other NEAT chemicals ($C_{NEAT,i} = 0$), the total consumption is divided into an ODU and NODU fraction. For those commodities used for the production of other NEAT commodities ($C_{NEAT,i} \neq 0$), the consumption for remaining derivatives is divided into an ODU and NODU fraction. These two cases are marked by the entries ‘total’ or ‘other’ in Table 2.1. The key simplifications in the current NEAT model carbon balance are:

- We restrict ourselves to 77 key chemicals and do not take into account imports and exports of all more downstream derivatives, which are covered as consumption for other derivatives. For countries with large net trade streams this could lead to an underestimation (net importing countries) or an overestimation (net exporting countries) of the consumption of both ODU and NODU products in the country of study. To be able to study this effect in more detail, the trade of about 450 product groups in addition to the NEAT core products is included in NEAT as an optional refinement of the model and is referred to as the additional trade module.
- We assume that all chemical conversions from basic chemicals to intermediates and end products are 100% carbon efficient. In practice, this is not the case and carbon is lost either in the form of direct CO₂ emissions or in the form of non-valuable by-products or off-specification products (non-specs), which can be burned either with or without energy recovery. As a result of the model assumption of 100% carbon efficiency, these carbon losses from incomplete conversions end up in the consumption for other derivatives. This consumption is divided into an ODU and a NODU fraction and hence might lead to an overestimation of both the consumption of

Table 2.1 Assumed fractions of ODU vs. NODU products for the 77 NEAT core products (the datasets ‘MIN release’ and ‘MAX release’ are used for the sensitivity analysis)

Chemicals	Total consumption or ‘other use’ ^a	Mean (%)		MIN release ODU ^b (%)	MAX release ODU ^b (%)
		NODU (%) ^b	ODU (%) ^b		
Basic chemicals					
Acetylene	other	50	50	10	70
Benzene	other	50	50	20	70
Bitumen	total	100	0	0	0
Butadiene	other	100	0	0	20
Other C4	other	37	63	45	100
Carbon black	total	100	0	0	0
CO-Source	other	50	50	0	0
Ethylene	other	5	95	85	100
Lubricants	total	67	33	9	50
Methanol	other	50	50	30	70
Petroleum coke	total	0	100	100	100
Pitch	total	0	100	100	100
Creosote oil	total	100	0	0	0
Naphthalene	total	50	50	20	70
Other tar products	total	100	0	0	0
Propylene	other	37	63	50	75
Toluene	other	17	83	70	97
Waxes, paraffins	total	0	100	40	100
Xylenes (o-,m-,p-,mixed xylene)	total	0	100	30	100
ortho-Xylene	other	0	100	30	100
meta-Xylene	total	0	100	30	100
para-Xylene	other	0	100	30	100
Intermediates					
Acetic acid	other	35	65	35	75
Acetone	other	60	40	40	65
Acrylic acid	other	100	0	0	5
Acrylonitrile	other	100	0	0	10
Adipic acid	other	100	0	0	5
Aniline	other	80	20	5	25
Bisphenol A	other	100	0	0	0
Butanol	total	19	81	70	90
Caprolactam	other	100	0	0	0
Cumene	total	100	0	0	5
Cyclohexane	total	20	80	60	100
Cyclohexanone	other	5	95	90	100
Dimethylterephthalate	other	100	0	0	0
Ethanol	total	0	100	70	100

Table 2.1 (continued)

Chemicals	Total consumption or 'other use' ^a	Mean (%)		MIN release ODU ^b (%)	MAX release ODU ^b (%)
		NODU (%) ^b	ODU (%) ^b		
Ethylbenzene	other	100	0	0	70
Ethylenedichloride	other	0	100	100	100
Ethylene glycol	other	0	100	70	100
Ethylene oxide	other	29	71	65	95
Formaldehyde	other	0	100	70	100
Methyl-Tert-Butyl-Ether (MTBE) ^{c)}	total	0	0	0	0
Higher alcohols	other	50	50	10	90
Orthophthalates	other	100	0	0	50
Phenol	other	0	100	70	100
Phthalic anhydride	other	0	100	30	100
Polyether-Polyols	other	100	0	0	50
i-Propanol	other	7	93	80	100
Propylene oxide	other	0	100	100	100
Styrene	other	100	0	0	0
Terephthalic acid	other	100	0	0	0
Isocyanates	other	100	0	0	0
Urea	other	0	100	0	100
Vinylchloride monomer	other	20	80	30	100
Products					
Acrylonitrile-Butadiene-Styrene	total	100	0	0	0
Butadiene Rubber	total	100	0	0	0
Ethylene-Propylene-Diene-Monomer	total	100	0	0	0
Epoxy resin	total	100	0	0	0
Melamineformaldehyde resin	total	100	0	0	0
Phenolic resin	total	100	0	0	0
Polyacetals	total	100	0	0	0
Polyacrylates	total	100	0	0	0
Polyacrylonitrile	total	100	0	0	0
Polyamide	total	100	0	0	0
Polycarbonate	total	100	0	0	0
Polyethylene	total	100	0	0	0
Polyethyleneterephthalate	total	100	0	0	0
Polypropylene	total	100	0	0	0
Polystyrene	total	100	0	0	0
Polyurethane	total	100	0	0	0
Polyvinylacetate	total	100	0	0	0

Table 2.1 (continued)

Chemicals	Total consumption or 'other use' ^a	Mean (%)		MIN release ODU ^b (%)	MAX release ODU ^b (%)
		NODU (%) ^b	ODU (%) ^b		
Polyvinylchloride	total	100	0	0	0
Styrene-Acrylonitrile	total	100	0	0	0
Saturated polyester	total	100	0	0	0
Styrene-Butadiene Rubber	total	100	0	0	0
Unsaturated polyester/alkyd resin	total	100	0	0	0
Urea formaldehyde resin	total	100	0	0	0

^a Chemicals labelled 'other' are used for the production of other chemicals included in NEAT. Chemicals labelled 'total' are not used for the production of other chemicals included in NEAT. See text for further explanation.

^b ODU = Oxidised During Use, NODU = Not-Oxidised During Use.

^c MTBE ends up as a antiknocking agent in the fuel pool and the emissions are thus taken into account in the CO₂ emissions from fossil fuel combustion.

NODU and ODU products. This could only be avoided if relevant survey data or other estimates were available for carbon losses from incomplete conversions, which is currently not the case. There are however indications that the magnitude of these emissions might be substantial (Tonkovich and Gerber, 1995 and Freed et al., 2005) and further research is therefore warranted (see discussion in Section 2.7).

- We assume that the structure of the chemical industry is very similar worldwide and bulk chemicals are made via the same production routes and similar production processes everywhere. However, some intermediates and final products can be made in more than one way. An example is phenol, which can be made from benzene, cumene and toluene. Other examples are the mixed product groups like polyamides where the various representatives (e.g. Polyamide 6 and Polyamide 6,6) are manufactured from different raw materials. In the NEAT model, default assumptions are made about the production routes in these cases. Model users can identify the actual production routes applied in the country based on an in-depth study for the respective country and can introduce these routes in the NEAT model.

The NEAT model has extensive data requirements. For a correct application of the model, production and trade data are needed for all 77 core products in the NEAT model. These data may not be available for all NEAT core products or the available data may be too aggregated due to inclusion of different types of products in one single product category in production statistics. In such cases, the data has to be estimated on the basis of capacity data, on the basis

of mass balance calculations, or by contacting producers. Apart from data availability problems, data reported in statistics can also be erroneous. One typical reason is that intermediates that are converted further on the same site (e.g. ethyl benzene to styrene) may not always be reported as production in production statistics.

The carbon balance in the NEAT model can be used to estimate, in CO₂ equivalents, the fraction of carbon associated with non-energy use in a country that is embodied in chemical products. It is important to realise that for this estimate, we express this fraction as a proportion of an “upstream carbon flow”; – i.e., we study carbon flows at a different level than so far. To make this clear, we refer to Figure 2.1 and 2.2. For the calculation of emissions from solvent and other product use, the aim was to estimate the emissions related to the final consumption downstream (E4 in Figures 2.1 and 2.2). We are now interested in the non-energy use as it is reported in the energy statistics; this is a feedstock value, thus representing an upstream flow. In the example of Figure 2.2, an estimate for non-energy use can be obtained by using the feedstock required for ethylene production. It is hence not necessary to study all the downstream material flows indicated in Figure 2.2. It is, in this case, sufficient to know the amount of ethylene produced in the country of study. In more general terms, the estimate for feedstock use can be obtained by adding the CO₂ equivalents of all (not only ethylene) basic chemicals produced from the hydrocarbon feedstocks⁹. The consumption of non-energy use refinery and coke oven products (the second element of non-energy use mentioned in the introduction) in CO₂ equivalents can directly be estimated by taking the consumption values of these products¹⁰. Summation of the two (production of basic chemicals from feedstocks and consumption of non-energy refinery and coke oven products) yields the carbon associated with non-energy use in a country that is embodied in chemical products.

⁹ The definition of basic chemicals is less straightforward as it may seem. In the Netherlands, for example, aromatics like benzene and even styrene are reported as energy commodities in energy statistics and only the conversion of these basic aromatics to more downstream chemicals (e.g. polystyrene) is reported as non-energy use. As a consequence, the production values of these more downstream products should be added to obtain an estimate for non-energy use that is comparable to the definition applied in the Dutch energy statistics (see Neelis et al., 2004 for more details).

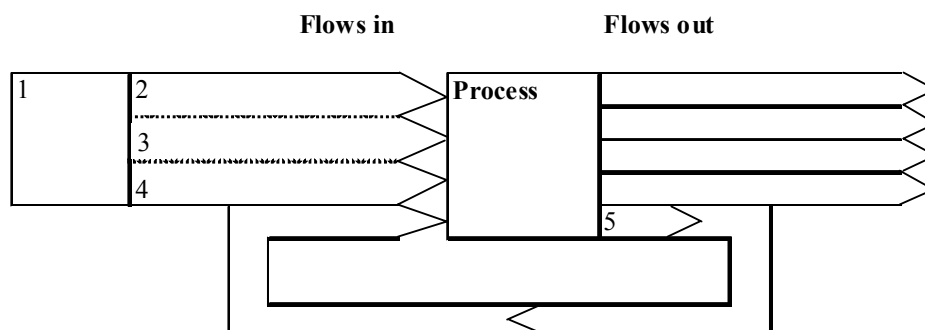
¹⁰ Of the NEAT basic chemicals, bitumen, lubricants, petroleum coke, pitch, creosote oil, naphthalene and waxes and paraffins are non-energy use refinery and coke oven products. The trade in these products is already accounted for in the energy statistics and these products therefore enter the calculation with their production values.

2.4 Industrial process emissions

Part of the carbon embodied in the fossil fuels that are used for non-energy purposes is directly oxidised to CO₂ during the production of chemical products, leading to industrial process emissions (E3 in Figure 2.1). In certain processes (e.g. production processes for ammonia, methanol, carbon black and the steam cracking process), part of the fossil fuel input is used as fuel (either directly or via the intermediate production of residual gases and other fuels). In energy statistics, there may be two ways to report non-energy use for these industrial processes. Using a gross definition of non-energy use, the total fossil fuel input is allocated to non-energy use. Using a net definition of non-energy use, the part that is used as fuel is subtracted from the non-energy use and is reported as final energy use. It is evident that the storage fractions used in Equation 2.1 in the IPCC-RA calculation should reflect the allocation method used between energy and non-energy use in order to yield the correct carbon storage and CO₂ emissions. In the IPCC-SA, there is also a risk of double counting or omission of emissions. If Equation 2.1 is used in the IPCC-SA to calculate emissions from fuel combustion, the emissions from non-energy use are already accounted for via Equation 2.1 (the part of non-energy not stored). In that case, these emissions should not again be counted as emissions in one of the other source categories. On the other hand, if the non-energy use is excluded from the emissions from fuel combustion (by setting storage fractions to 100% or by simply excluding non-energy use from the calculation), the emissions resulting from the non-energy use should be accounted for in one of the other source categories. In that case, the allocation method between energy and non-energy use used in the energy statistics determines the correct amount of emissions, since it can be assumed that emission from the part allocated to energy use are already accounted for under fuel combustion. In calculating emissions for these processes for national inventories, one should therefore always keep in mind the applied non-energy use definition in the energy statistics. In the current IPCC guidelines, the risk of double counting is acknowledged for ammonia production (IPCC, 1997, Vol 1, pp. 2.1 and 2.13), but some of the important processes for which double counting or omission of emissions is likely to happen (methanol, carbon black and steam cracking) are not separately discussed. The NEAT model contains a module to calculate the total CO₂ emissions from the relevant industrial processes. The processes are discussed in detail below. In Figure 2.3 we give a schematic general energy balance of a process in which a hydrocarbon feedstock is converted to chemicals.

We will use this figure to explain possible definitions of non-energy use for the relevant processes. The results of the NEAT model can be compared with the non-energy use figures in energy statistics and with the GHG inventory. This comparison is discussed in Section 2.6. It should be noted that the production and use of cokes in pig iron production is excluded

from the NEAT model, because these processes are normally covered in the energy conversion section of energy statistics and are therefore not part of the non-energy use.



- 1 Total hydrocarbon input into the process
- 2 Part of the input allocated to final energy use in energy statistics
- 3 Part of the input allocated to final non-energy use in energy statistics
- 4 Part of the input allocated to energy conversions in energy statistics
- 5 Energy by-products used within the process
- 6 Energy by-products used within the same sector
- 7 Energy by-products exported to other sectors
- 8 Main products
- 9 Energy losses

Figure 2.3 General energy balance of industrial processes producing chemicals from feedstocks (size of flows arbitrarily chosen)

2.4.1 Ammonia

Ammonia is most frequently produced from natural gas, but lower grade fuel oils or coal are also used. The hydrocarbon feedstock serves to produce hydrogen, which is then converted with nitrogen to produce ammonia. Depending on the fuel, steam reforming or partial oxidation is applied to produce hydrogen. In 1994, 77% of global ammonia capacity was based on steam reforming of natural gas, 13.5% on the partial oxidation of coal, 6% on steam reforming of naphtha, LPG and refinery gas, 3% on partial oxidation of heavy hydrocarbons, and 0.5% on the electrolysis of water. Excluding Asia, 90% of global ammonia capacity is operated on natural gas (IPTS, 2004). The default total CO₂ emissions factors from ammonia production chosen for the NEAT model are given in Table 2.2 and represent low (i.e. based on efficient plants) estimates based on a literature survey (Neelis et al., 2003). The model user has the opportunity to insert specific (higher) emission factors based on the situation in the country of study. In all processes applied, part of the hydrocarbon input is directly burned to provide heat for the endothermic formation of synthesis gas. Countries might allocate the total input into the process to non-energy use (Flow 1 equals Flow 3, and Flow 2 and 4 are zero in Figure 2.3) or might allocate part of the hydrocarbon input to final energy use of the input (Flow 2). In cases where the process exports energy (e.g. steam) to other processes (Flow 6)

or to other industries (Flow 7), part of the input might also be allocated to energy conversions (Flow 4)¹¹. For conventional steam reforming of natural gas, the part of the input used as fuel can easily be distinguished, because combustion and reforming take place in separate reactors. In these processes, approximately 30% of the input is burned and 70% is reformed to produce synthesis gas (e.g. Hinderink et al., 1996). In newer process configurations (e.g. auto thermal reforming) and for partial oxidation processes, the part used as fuel is less straightforward to determine. In the NEAT model, the use of CO₂ for the production of urea is accounted by subtraction from the overall CO₂ emissions. The subsequent use of urea is taken into account in the calculation of emissions from ‘solvent and other product use’.¹²

Table 2.2 Overview of default NEAT CO₂ emission factors for ammonia production

Process	kg CO ₂ /kg NH ₃	Comment
Steam reforming of natural gas	1.6	Based on a natural gas consumption of 28.5 GJ/t NH ₃ and an emission factor of 56 kg CO ₂ /GJ natural gas.
Partial oxidation of coal	3.9	Based on a total coal consumption of 42 GJ/t NH ₃ and an emission factor of 93 kg CO ₂ /GJ coal.
Partial oxidation of oil	2.5	Based on a total oil consumption of 34.5 GJ/t NH ₃ and an emission factor of 74 kg CO ₂ /GJ oil.

2.4.2 Methanol

Similar to ammonia, methanol is mainly produced from natural gas but depending on the raw material availability and prices in the country studied oil products and coal may also be used. Depending on the feedstock, steam reforming or partial oxidation is applied. The feedstock serves to produce synthesis gas (a mixture of hydrogen and carbon monoxide), which is then converted to methanol. Per tonne of methanol, an amount of carbon equivalent to 1.38 tonnes of CO₂ is embodied in the product. Some carbon is also emitted during methanol production; the CO₂ emission factors chosen for the NEAT model are given in Table 2.3. They again represent low estimates with the model user having the opportunity to insert country specific (higher) emission factors. Worldwide, almost 80% of the methanol is produced by steam reforming of natural gas (Appl, 1997). Contrary to ammonia production, the final objective in the production of synthesis gas is not to obtain a maximal hydrogen yield, but to obtain a hydrogen to carbon ratio between 2 and 3, based on the stoichiometry of methanol synthesis¹³. In partial oxidation, the ideal H₂/CO ratio can be obtained by adjusting the oxygen content. In the steam reforming of natural gas, the hydrogen to carbon ratio in the synthesis gas mixture

¹¹ This would require a statistical system that monitors the heat recovery within the chemical sector as energy conversions.

¹² We do not correct for other use of CO₂ in for example beverages. This carbon is finally released as CO₂ during use of these beverages. Since it is hard to track the trade in these beverages (and the carbon content), we decided to account for those emissions as emissions from ammonia production.

¹³ In methanol synthesis, two reactions take place: $\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH}$ and $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$.

is adjusted by purging part of the excess hydrogen or by the addition of CO₂ to the synthesis gas mixture (Chauvel and Lefebvre, 1989). For methanol production it is therefore not straightforward to determine, which part of the process input should be allocated to feedstock use and which part to fuel use. Similar to ammonia, countries will allocate the total input to non-energy use (Flow 1 equals Flow 3 in Figure 2.3) or might allocate part of the input to energy use (Flow 2) or to energy conversions (Flow 4).

Table 2.3 Overview of default NEAT CO₂ emission factors for methanol production

Process	kg CO ₂ /kg methanol ^a	Comment
Steam reforming of natural gas	0.4	Based on a natural gas consumption of 31.6 GJ/t methanol and an emission factor of 56 kg CO ₂ /GJ natural gas.
Partial oxidation of coal	2.2	Based on a total coal consumption of 38.6 GJ/t methanol and an emission factor of 93 kg CO ₂ /GJ coal
Partial oxidation of oil	1.4	Based on a total oil consumption of 38.4 GJ oil/t methanol and an emission factor of 74 kg CO ₂ /GJ oil.

^a In all cases, the carbon content of methanol (1.4 tonne CO₂ / tonne methanol) is deducted from the total hydrocarbon input.

2.4.3 Carbon black

Carbon black is primarily produced from oils, which originate from coal or crude oil. Another type of raw material used in much smaller quantities for special grades of carbon black is acetylene. More than 95% of the world production of carbon black is produced in the furnace black process. The advantage of the furnace black process is its great flexibility in manufacturing various grades of carbon black. For small amounts of special grade carbon black other processes are used (Voll and Kleinschmit, 1997). The heart of the furnace black process is the furnace in which the carbon black is formed. The oil feedstock is injected in a high-temperature zone. The temperature is maintained by burning a fuel with air. The oxygen is not sufficient for complete combustion of the feedstock, which is therefore pyrolysed to form carbon black. Natural gas is normally the fuel of choice, but other gasses, e.g. coke oven gas are also occasionally used (Voll and Kleinschmit, 1997). The tail gas from the carbon black process is available at high temperature and contains a certain amount of combustible gasses, the amount of which depends on the feedstock and the processing conditions. The gas must be burned off for environmental reasons and the energy is generally used to produce steam or electricity (Voll and Kleinschmit, 1997). The CO₂ emission factors for carbon black production chosen for the NEAT model are given in Table 2.4 and are based on one literature source (Voll and Kleinschmit, 1997). The model user has the opportunity to insert specific emission factors for the country of study. As a result of the process configuration (oil and natural gas are fed into one single reactor and the tail gas contains energy that is recovered),

there are again various ways of allocating the hydrocarbon input (Flow 1 in Figure 2.3) to non-energy use (Flow 3), energy use (Flow 2) and energy conversions (Flow 4).

Table 2.4 Overview of default NEAT CO₂ emission factors for carbon black production

Process	kg CO ₂ /kg carbon black	Comment
Furnace black process	1.9	Based on a total oil input of 69.6 GJ/t carbon black and a total natural gas input of 7.7 GJ/t carbon black and emission factors of 56 kg CO ₂ /GJ for natural gas and 74 kg CO ₂ /GJ for oil. The carbon content of carbon black (assumed to be 3.7 tonne CO ₂ / tonne carbon black) is deducted from the total hydrocarbon input.

2.4.4 Steam cracking

Steam cracking is by far the most important petrochemical process with respect to energy use. It leads to the key building blocks of the petrochemical industry, namely ethylene, propylene, butadiene and aromatics. A variety of feedstocks are used for steam cracking. In Western Europe, naphtha accounts for three quarters of the total steam cracker input (IPTS, 2003), while plants operating on Natural Gas Liquids dominate in the USA (Weissermel and Arpe, 2003). In NEAT, the ultimate yields are modelled, which have been estimated based on a best available technique reference document (IPTS, 2003), enquiries among industry experts and information from literature (Table 2.5). In addition to the high value basis chemical petrochemicals (Flow 8 in Figure 2.3), low value by-products are generated. These products are partly used to fuel the endothermic cracker reactions (Flow 5) and are partly recycled back to refineries (Flow 7) or used elsewhere within the petrochemical sector (Flow 6). The NEAT model calculates absolute values for the process energy and the backflows to refineries in CO₂ equivalents with the ethylene production and the feedstock mix as model inputs. The emission factors are given in Table 2.6. The remainder of the carbon is stored in chemicals. For steam cracking, the allocation to final energy and non-energy use is particularly problematic and can easily lead to substantial errors in national CO₂ emissions accounting (see Park, 2005 and Neelis et al., 2005 for examples). In some countries, the hydrocarbon input as a whole is regarded as non-energy use (Flow 1 equals Flow 3) and the backflows to the refineries might be double-counted in energy statistics, both as non-energy use and once more as energy use in refineries. For such countries, the fuel use in steam crackers (Flow 5 in Figure 2.3) might not be covered under emissions from fuel combustion and the emissions should be regarded as industrial process emissions from non-energy use to avoid omission of these emissions in the national totals. In the Netherlands, the conversion of the hydrocarbon input to the fuel by-products (Flow 5,6 and 7) is separately monitored, but this also results in difficulties for emission accounting since the emission factors of the fuels produced differ from the feedstock used (see Neelis et al., 2005).

Table 2.5 Ultimate yields of steam crackers with various feedstocks (in kg for 1000 kg of feedstock)

	Naphtha	Gas oil	Ethane	Propane	Butane
High Value Chemicals	645	569	842	638	635
Ethylene (E)	324	250	803	465	441
Propylene (P)	168	144	16	125	151
Butadiene	50	50	23	48	44
Aromatics	104	124	0	0	0
Fuel grade products and backflows	355	431	157	362	365
Hydrogen	11	8	60	15	14
Methane	139	114	61	267	204
Ethane and propane after recycle cracking	0	0	0	0	0
Other C4	62	40	6	12	33
C5/C6	40	21	26	63	108
C7+ non-aromatics	12	21	0	0	0
<430C	52	26	0	0	0
>430C	34	196	0	0	0
Losses	5	5	5	5	5
Total	1000	1000	1000	1000	1000

Table 2.6 Overview of default CO₂ emissions from fuel use in steam crackers and carbon equivalents of backflows to refineries

	Naphtha	Gas oil	Ethane	Propane	Butane
Specific CO ₂ emissions from fuel use steam crackers (Mt CO ₂ / Mt ethylene)	1.7	2.2	0.8	1.0	1.1
Specific CO ₂ equivalents of backflows steam crackers (Mt CO ₂ / Mt ethylene)	0.9	2.1	0.0	0.8	0.9

2.4.5 Carbon use in metals and inorganics production

The NEAT model also contains a module on the use of solid carbon for the production of various metals (except for pig iron production in blast furnaces) and inorganic products. The solid carbon is either used as reducing agent (e.g. silicon carbide) or in the form of electrodes used for electrolysis (e.g. aluminium) or in electric arc furnaces (e.g. electric steel). Sometimes a combination of electrodes and other solid carbon input is used (e.g. white phosphorus). Whether or not these emissions are regarded as industrial process emissions or as emissions from fossil fuel combustion depends on how the non-energy use of fossil carbon for metallurgical purposes is treated in the energy statistics of the country studied. The emission factors for all processes currently implemented in NEAT are given in Table 2.7 based on a report by Sjardin (2003). The primary data sources for this report are IPTS (2001) and Ullmann's (1997).

Table 2.7 Overview of default CO₂ emission factors from the production of metals and inorganics (Sjardin, 2003)

	Input raw materials wt. %			Specific CO ₂ emissions t CO ₂ /t product
	Pet coke	Pitch	Coke/coal	
Use of carbon electrodes				
Primary aluminium	84	16		1.55
Electric steel	70	30		0.01
White phosphorus	72	28		0.18
Ferrosilicon	72	28		0.17
Silicon metal	85	15		0.36
Calcium silicon	85	15		0.32
Ferromanganese	72	28		0.04
Silicomanganese	72	28		0.09
Ferrochromium	72	28		0.06
Ferrochromiumsilicon	72	28		0.11
Magnesium	85	15		0.05
Ferronickel	72	28		0.01
Tin	85	15		0.04
Use of other solid carbon				
White phosphorus	6		94	4.18
Titanium dioxide	100			0.49
Ferrosilicon			100	2.75
Silicon metal	100			4.49
Calcium silicon			100	2.39
Ferromanganese			100	1.75
Silicomanganese			100	1.57
Ferrochromium			100	1.57
Ferrochromiumsilicon			100	2.71
Lead			100	0.64
Ferronickel			100	1.35
Tin			100	1.08
Zinc			100	0.43
Calcium carbide	15	5	80	1.10
Silicon carbide	100			2.30

2.5 Total non-energy use, carbon storage, storage fractions and total fossil CO₂ emissions

We have now systematically dealt with all carbon flows related to the non-energy use of fossil fuels. We can use the results to obtain estimates for total non-energy use and carbon storage, which are independent from the energy statistics. Using the total primary energy supply as additional input, we can also estimate the total fossil CO₂ emissions.

2.5.1 Total non-energy use in CO₂ equivalents

As said in the introduction, the non-energy use of fossil fuel consists of two parts: the consumption of fossil fuels as feedstock and the consumption of non-energy use refinery and coke oven products. The first part can be estimated by taking:

- 1a. The CO₂ equivalents of *all* basic chemicals produced from non-energy use feedstocks. The calculation method has been explained in Section 2.3.
- 1b. The industrial process emissions resulting from the feedstock use. The calculation is discussed in Section 2.4.

The second part of non-energy use can be estimated by taking:

- 2a. The consumption of non-energy use refinery and coke oven products in CO₂ equivalents.
- 2b. The industrial process emissions resulting from the use of solid carbon in the production of metals and inorganic chemicals discussed in Section 2.4.

It should be emphasised that the total non-energy use in CO₂ equivalents very much depends on the definition of non-energy use applied for the industrial processes discussed in Section 2.4.

2.5.2 Carbon storage, storage fractions and total fossil CO₂ emissions

An overview of the calculation procedure for carbon storage, storage fraction and total fossil CO₂ emissions is given in Figure 2.4. The total primary energy supply multiplied with CO₂ emission factors for the various fuels yields a value for the total fossil CO₂ emission *potential* of the country (1 in Figure 2.4). Part of this total CO₂ emission potential is used for ‘non-energy use purposes’ (2, calculation explained above). The CO₂ equivalents of non-energy use are partly emitted as industrial process emissions (5, Section 2.3) and partly as emissions from solvent and other product use (6, Section 2.4). The remainder of the non-energy use is stored (i.e. not emitted, 3+4). In Figure 2.4, we show that the carbon storage consists of two elements:

- The consumption of NODU products in the country of study and
- The net export of all basic chemicals¹⁴, intermediates and final products included in the NEAT model.

¹⁴ Excluding the non-energy use refinery and coke oven products (footnote 9) for which the trade is already accounted for in the energy statistics.

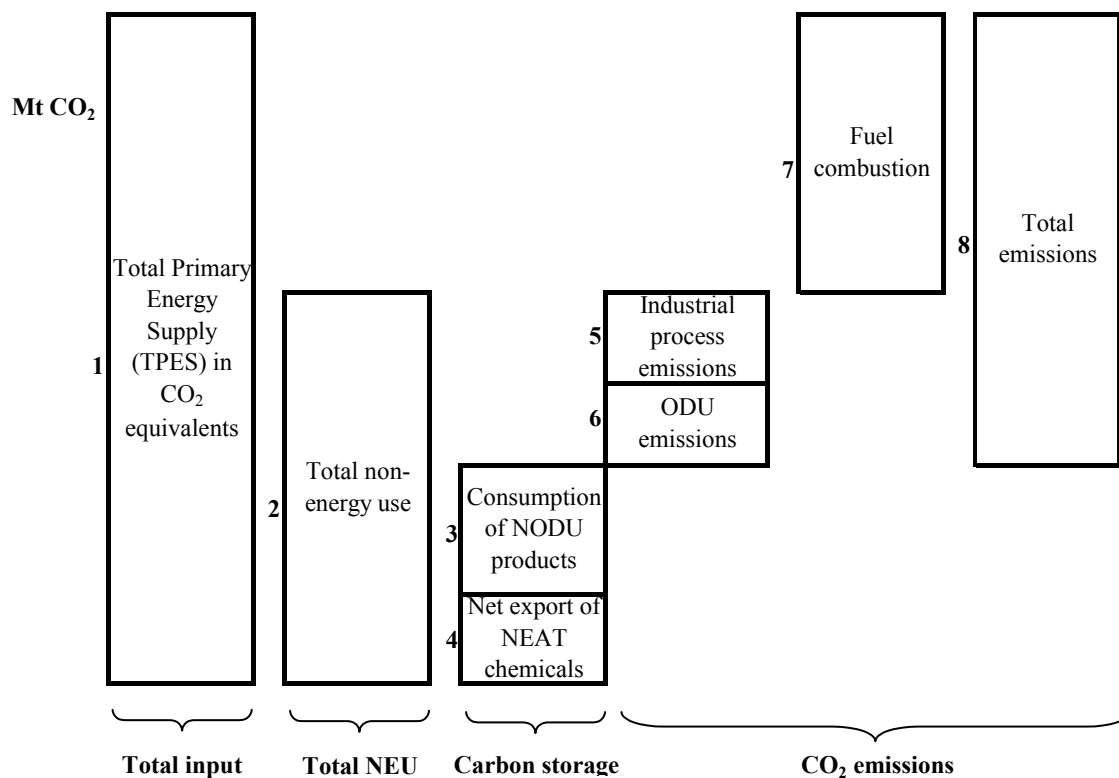


Figure 2.4 NEAT methodology for calculating CO₂ emissions and carbon storage

The first element has been estimated in the calculation of emissions from the use of ODU products (Section 2.3), where we divided the consumption of end-products and the consumption for other derivatives into a part used for ODU and a part used for NODU applications. The second element can be estimated by deducting the total consumption of carbon (ODU emissions and NODU products) and the industrial process emissions from the non-energy use or directly from the trade data used. This net export is positive for countries that are net exporters of carbon-containing chemicals and negative for net importers of these chemicals.

Deducting the carbon storage from the total CO₂ potential of the country yields and estimate for total fossil CO₂ emissions (8). Based on the carbon storage (3+4 in Figure 2.4) and the total non-energy use (2), the NEAT model also calculates carbon storage fractions for use in the IPCC-RA (3+4 divided by 2). These storage fractions will of course depend on the non-energy use definition chosen for the industrial processes discussed in Section 2.4.

2.5.3 Allocation to individual fuels

In the NEAT model, both the CO₂ emissions from non-energy use and the carbon storage are allocated to the various feedstocks used for non-energy use purposes. For the industrial process emissions, this allocation is straightforward. Emissions from ammonia are, for

example, allocated to the respective feedstock ammonia is made from. For ODU emissions and for carbon storage, the allocation is more complex, because downstream emissions have to be allocated back to upstream fuels with the help of the carbon balance used to calculate the emissions from solvent and other product use. For example, all the carbon storage and emissions from derivatives of steam cracking products are allocated to the steam cracker inputs. The allocation to individual fuels enables the model user to conduct analyses and comparisons on the level of individual fuels.

2.6 Comparisons with the official GHG inventory

The calculation procedure for total fossil CO₂ emissions obtained with the NEAT model is mathematical equivalent to the estimate for total fossil CO₂ emissions according to the IPCC-RA (Equation 2.1). The two can therefore directly be compared. Since the starting point of both calculations is the same (the total primary energy supply of the country), differences between the two estimates are by definition caused by differences in either:

1. The total non-energy use in CO₂ equivalents determined by NEAT and the total non-energy use in CO₂ equivalents used in the IPCC-RA calculation. The latter is obtained by multiplying the non-energy use according to the energy statistics with appropriate emission factors.
2. The proportion of ‘Carbon storage’ (3+4 in Figure 2.4) versus ‘CO₂ emissions’ (5+6 in Figure 2.4). In NEAT the division is calculated on basis on a material flow analysis, while in the IPCC-RA the division is usually based on the IPCC default storage fractions.

The comparison of the total non-energy use in CO₂ equivalents between NEAT and the IPCC-RA (difference 1) can be used to clarify which definitions for non-energy use are used in the energy statistics for the various industrial processes discussed in Section 2.4. This is an iterative process in which the model user should use both the NEAT model results and the non-energy use in CO₂ equivalents, which is used in the IPCC-RA calculation. If for example, a country produces methanol from natural gas, but does not report non-energy use of natural gas in the energy statistics, this is an indication that this process is not properly accounted for in the energy statistics and that emissions are overestimated in the national GHG inventory. Another example is the steam cracking process. Based on the NEAT model, one can judge whether a country is likely to use a gross (including backflows and fuel use) or net definition of non-energy use (excluding these flows) in the energy statistics. For the other industrial processes in the NEAT model, comparable comparisons can be made. The use of the NEAT model for clarification of non-energy use accounting practices can be found in the country

studies for Korea (Park, 2005), Italy (La Motta et al., 2005) and the Netherlands (Neelis et al., 2005). A summary is given in Patel et al., 2005.

Regarding the second difference (storage versus CO₂ emissions), it should in the first place be emphasised that the NEAT estimate for total fossil CO₂ includes all fossil CO₂ emissions, including fuel combustion, solvent and other product use and industrial processes. Only emissions from incineration without energy recovery are excluded. The IPCC-RA, however, is nowadays generally regarded as a method to calculate CO₂ emissions from fuel combustion only. This is also emphasised in recent versions of the Common Reporting Format used to report GHG emissions (SBSTA, 1999). Certain sections of the IPCC guidelines also stress the role of the IPCC-RA as a tool for estimating CO₂ emissions from fuel combustion only (e.g. IPCC, 1997, Volume 3, pp. 1.1.). On the other hand, in other sections of the guidelines, industrial process emissions and emissions from solvent and other product use are also stated to be included in the IPCC-RA emissions estimate (e.g. IPCC, 1997, Volume 3, pp. 1.25-27). The default carbon storage fractions provided in the IPCC guidelines were determined by Marland and Rotty (1984). They also aimed to calculate total CO₂ emissions rather than only emissions from fuel combustion. Recently, Marland and Marland (2003) follow the same approach. The use of the Marland and Rotty fractions is therefore inconsistent with the use of the IPCC-RA as a tool to estimate emissions from fuel combustion only. In the second place, it is by definition impossible that the use of default IPCC fractions will yield the correct emissions for all countries as long as there are no uniform definitions of non-energy use in the energy statistics, even if there would be consensus on the scope of the IPCC-RA.

As explained in Section 2.4, emissions from non-energy use can be omitted or double counted in the IPCC-SA. Whether or not this is likely to happen depends on the allocation between energy and non-energy use in the energy statistics and the use of these statistics in the IPCC-SA. Based on the comparison of the NEAT results with the IPCC-RA, one can therefore explore whether non-energy use emissions are consistently dealt with in the IPCC-SA calculation. This involves comparison of the NEAT model results with the emissions according to the IPCC-SA in the various source categories. This comparison is however by no means straightforward and requires detailed insight into the reporting practices of the country of study. However, it can be a very worthwhile exercise as the country analyses performed with the model show (Park, 2005; La Motta et al., 2005; Neelis et al., 2005).

2.7 Discussion

To our knowledge, the NEAT model is the only tool that systematically deals with all carbon flows related to the non-energy use of fossil fuels. The model calculates both CO₂ emissions

and carbon storage resulting from the non-energy use of fossil fuels independent from the energy statistics¹⁵ and the national GHG inventory. The lack of proper and consistent definitions for non-energy use is the most important problem of the current methods to calculate carbon storage and emissions from non-energy use. The NEAT model can help to identify which definitions are used in the energy statistics. Its application can guide people preparing national GHG inventories in treating GHG emissions from non-energy use in a consistent way.

To run the full NEAT model, production and international trade data for 77 organic chemicals is required, supplemented with production data for 18 inorganic chemicals and metals and with data on feedstock types and specific energy consumption (SEC) figures for some industrial processes¹⁶. The extensive data requirement is one of the main drawbacks of the model. However, the country studies for Korea (Park, 2005), Italy (La Motta et al., 2005) and the Netherlands (Neelis et al., 2005) show that it is in principle possible to collect the required data, either via close cooperation with national statistical offices (the Netherlands) or via consultancy companies collecting these data for business purposes (Italy, Korea).

By far the most time-consuming and data-intensive part of the NEAT model is the bottom-up carbon balance, resulting in an estimate for emissions from solvent and other product use (ODU products). As a result of the limited reliability of production data for chemical intermediates and as a result of the uncertain split between ODU and NODU products for some products, the largest uncertainty is present in this part (see e.g. Neelis et al., 2005). To reduce this uncertainty, it is planned to further study the final fate (ODU vs. NODU) of some complex products like lubricants.

An alternative would be to make detailed comparisons between the NEAT model estimates for solvent and other product use and other available emissions inventories based on comprehensive surveys of these emissions (e.g. Freed et al., 2005). These surveys have the advantage of directly surveying emissions rather than estimating them based on the consumption patterns of the intermediate precursor chemicals as it is done in the NEAT model. However, the surveys are not always complete and are not available for all countries. Based on the comparisons between NEAT and available studies, it might be possible to derive generic values (e.g. solvent emissions per capita) for implementation in NEAT, thereby reducing the need for the data-intensive carbon balance in the current NEAT model. This would make the model easier to apply also for countries with limited data availability. Such a

¹⁵ There may be exceptions based on the general data availability in the country of study. Sometimes, production and trade data for refinery products are not collected separately from the energy statistics and the energy statistics therefore become the only available source (e.g. in the Netherlands, Neelis et al., 2005)

¹⁶ When SEC values are not available, the model user can use the default values included in the model.

simplified model could focus on the upstream carbon flows related to the reported non-energy use in energy statistics (industrial process emissions and initial carbon storage in petrochemicals) and could rely on more detailed downstream emission estimates for the estimation of emissions from solvent and other product use.

An area requiring further research is the position of CO₂ emissions from incineration of “non-specs”, which result from incomplete conversions in the chemical industry and are used for energy purposes. In the NEAT methodology, these emissions are so far not explicitly modelled and are partly included in the emissions from solvent and other product use (ODU products). There are indications that the magnitude of these emissions might be substantial. For the US, they were estimated to be 9.5 Mt CO₂ in 1992 (Tonkovich and Gerber, 1995), which is more than 2% of the total non-energy use (379 Mt CO₂ in 2002 according to US-EPA, 2004).

The NEAT model can be extended in order to include the emissions from waste incineration. This requires substantial additional data analyses, which is strongly recommended for future research. By doing so, all CO₂ emissions from fossil fuel origin would be covered by the model. With such an extended model it would be possible to estimate the fraction of non-energy use that is finally incinerated, and to investigate the relative amount of waste emissions versus the non-energy use as a function of time

2.8 Conclusions

The NEAT (Non-energy use Emission Accounting Tables) model is a tool that systematically deals with the carbon flows related to the non-energy use of fossil fuels, based on a carbon flow analysis of the relevant sectors. Earlier model versions (Gielen and Patel, 1999) focussed on the correct calculation of carbon storage in petrochemical products and on the calculation of emissions from solvent and other product use. The current model version also calculates direct industrial process emissions (from e.g. ammonia) related to the non-energy use of fossil fuels and calculates total non-energy use, carbon storage and non-energy use emissions independent from energy statistics. We have shown that the results obtained with the extended model can be used as a valuable crosscheck for the non-energy use emission accounting in official GHG emission inventories. The model can help to identify which definitions for non-energy use are used in the energy statistics that are employed in the emission inventory. Based on this information, the NEAT model results can be used to improve national emission inventory methodologies in order to avoid double counting or omission of emissions.

Acknowledgements

This research was supported by the European Commission (Research Directorate General), 5th framework European Network for Research in Global Change (ENRICH) programme, through research contracts ENV-CT98-0776 and EVK2-CT-2000-80003 (International network Non-Energy Use and CO₂ emissions, NEU-CO₂).

References

- Appl, M, 1997. Ammonia, methanol, hydrogen, carbon monoxide – modern production technologies, CRU Publishing, London.
- Chauvel, A and Lefebvre, G, 1989. Petrochemical processes – technical and economic characteristics, 2 Volumes, Editions Technip, Paris.
- DOE/OIT, 2000. Energy and environmental profile of the US chemical industry, US Department of Energy, Office of Industrial Technologies, Prepared by Energetics, Columbia, Maryland.
- Freed, R, Mintz, C, Lanza, R, and Hockstad, L, 2005. Analytic framework for analyzing non-energy uses of fossil fuels as petrochemical feedstocks in the USA. Resources, Conservation and Recycling, Vol. 45, pp. 275-294.
- Gielen, DJ, and Patel, MK, 1999. The NEAT model, non-energy use emission accounting tables, in Proceedings of the first NEU-CO₂ workshop, 23-24 September, Paris, (accessible online via <http://www-n.chem.uu.nl/nws/www/nenergy/>).
- Gielen, D and Yagita, H, 2002. Carbon accounting for Japanese petrochemicals. Journal of Material Cycles and Waste Management, Vol. 4, pp. 51-61.
- Hinderink, AP, Kerkhof, FPJM, Lie, ABK, de Swaan Arons, J and van der Kooi, HJ, 1996. Exergy analysis with a flowsheeting simulator – II Application; Synthesis gas production from natural gas, Chemical Engineering Science, Vol. 51, pp. 4701-4715.
- IEA, 2002. Extended energy balances of OECD and Non-OECD countries, 2002 edition, two publications, International Energy Agency, Paris.
- IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Volumes 1, 2 and 3, Houghton, JT, Meira Filho, LG, Lim, B, Treanton, K, Mamaty, I, Bonduki, Y, Griggs, DJ and Callander, BA (Eds). Intergovernmental Panel on Climate Change (IPCC), Organization for Economic Cooperation and Development (OECD), International Energy Agency (IEA), Paris.
- IPCC, 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Prepared by the Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Published: IGES, Japan.
- IPTS, 2001. Reference Document on Best Available Technologies in the Non Ferrous Metals industries, European Commission, Institute for Prospective Technological Studies, Seville.
- IPTS, 2003. Reference Document on Best Available Technologies in the Large Volume Organic Chemical Industry, European Commission, Institute for Prospective Technological Studies, Seville.
- IPTS, 2004. Draft Reference Document on Best Available Techniques in the Large Volume Inorganic Chemicals, Ammonia, Acids and Fertiliser Industries, Draft March 2004, European Commission, Institute for Prospective Technological Studies, Seville.

- Marland, G and Rotty, RM, 1984. Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950 – 1982. *Tellus*, Vol. 36B, pp. 232-261.
- Marland, E and Marland G, 2003. The treatment of long-lived, carbon-containing products in inventories of carbon dioxide emissions to the atmosphere, *Environmental Science and Policy*, Vol. 6, pp. 139-152.
- La Motta, S, Ancona, P, Santino, D and Weiss, M, 2005. CO₂ Emission Accounting for the Non-Energy Use of Fossil Fuels in Italy: A Comparison between NEAT Model and the IPCC Approaches. *Resources, Conservation and Recycling*, Vol. 45, pp. 310-330.
- Neelis, M, Patel, M and de Feber, M, 2003. Improvement of CO₂ emission estimates from the non-energy use of fossil fuels in the Netherlands, Utrecht University, Copernicus Institute, Department of Science Technology and Society, Utrecht.
- Neelis, ML, Patel, M and Blok, K, 2005. CO₂ emissions and carbon storage resulting from the non-energy use of fossil fuels in the Netherlands, NEAT results for 1993-1999. *Resources, Conservation and Recycling*, Vol. 45, pp. 251-274. Chapter 3 of this thesis.
- Olivier, JGJ, and Peters, JAHW, 2005. CO₂ from non-energy use of fuels: A global, regional and national perspective based on the IPCC Tier 1 approach. *Resources, Conservation and Recycling*, Vol. 45, pp. 210-225.
- Park, HC, 2005. Non-energy fossil fuel use and CO₂ emissions in Korea, NEAT results. *Resources, Conservation and Recycling*, Vol. 45, pp. 295-309.
- Patel, M, Neelis, M, Gielen, D, Olivier, J, Simmons, T, and Theunis, J, 2005. Carbon dioxide emissions from non-energy use of fossil fuels: Summary of key issues and conclusions from the country analyses. *Resources, Conservation and Recycling*, Vol. 45, pp. 195-209.
- SBSTA, 1999. Report of the Subsidiary Body for Scientific and Technological Advice on its Tenth Session, Addendum: Draft Decision on Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention. Part I: UNFCCC Reporting Guidelines on Annual Inventories. Bonn, 31 May – 11 June 1999.
- Sjardin, M, 2003. CO₂ emission factors for non-ferrous metal, ferroalloys and inorganics industry, Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Tonkovich, ALY and Gerber, MA, 1995. *The Top 50 Commodity Chemicals: Impact of Catalytic Process Limitations on Energy, Environment and Economics*. Pacific Northwest Laboratory, Richland.
- Ullmann's, 1997. *Ullmann's encyclopedia of industrial chemistry*, Fifth edition on CD-ROM, Volume A5, John Wiley and sons.
- US-EPA, 2004. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, United States – Environmental Protection Agency, Washington DC.

Voll, M and Kleinschmit P, 1997. 'Carbon Black' in Ullmann's encyclopedia of industrial chemistry, fifth edition on CD-ROM, Volume A5, John Wiley and sons.

Weissermel, K and Arpe, HJ, 2003. Industrial Organic Chemistry, Fourth, Completely Revised Edition, Wiley-VCH, Weinheim.

CHAPTER 3

CO₂ emissions and carbon storage resulting from the non-energy use of fossil fuels in the Netherlands, NEAT results for 1993-1999*

Abstract

Estimating CO₂ emissions resulting from the non-energy use of fossil fuels is not straightforward, because part of the carbon is released quickly as CO₂ whereas another part is first embodied in organic chemicals. To contribute to a more accurate non-energy use CO₂ emission accounting, the NEAT (Non-energy use Emission Accounting Tables) model has been developed, which is in this paper applied to the Netherlands for the time period 1993-1999. For this period, we estimate the total non-energy use in CO₂ equivalents in the Netherlands to vary between 26.1 and 30.2 Mt CO₂ per year. Of this total, 4.6 – 6.6 Mt CO₂ is emitted in industrial processes and during product use. The remainder is stored, resulting in an overall storage fraction of approximately 80%. Given the uncertainties involved, we cannot distinguish clear trends for the years of study. We show that the definition of non-energy use has a significant effect on the calculated storage fractions. The carbon storage according to the Dutch national greenhouse gas (GHG) emission inventory is 5 – 9 Mt CO₂ lower compared to the NEAT result. As a result, total fossil CO₂ emissions (including those from fossil fuel combustion) according to the national inventory are higher by the same amount, which is 3 – 5% of the total Dutch emissions. The difference is among other things caused by difficulties associated with the direct use of non-energy use figures from the Dutch energy statistics for CO₂ emission accounting. We recommend improving the Dutch GHG emission inventory making use of the results of this study.

* This chapter is a slightly adapted version of a paper published in Resources, Conservation and Recycling, Vol. 45 (2005), pp. 251-274. The only alteration is the addition of footnote 9. Co-authors are M. Patel and K. Blok.

3.1 Introduction

A considerable fraction of fossil fuels is used for non-energy use purposes, either as feedstock in the petrochemical industry or for direct use such as bitumen used for road construction. Estimating CO₂ emissions resulting from the carbon embodied in the non-energy use of fossil fuels is by no means straightforward. Part of the carbon is oxidised to CO₂ during the production of certain chemicals (e.g. ammonia), whereas another part is first stored in chemical products with lifetimes ranging from days to decades or longer. These chemicals lead to emissions either during the use phase (e.g. solvents) or only in the waste treatment phase (e.g. incinerated plastics). In other cases, these chemicals do not lead to emissions at all within a time span relevant for emission accounting (e.g. asphalt or land filled plastics).

In their emission inventory guidelines (IPCC, 1997), the IPCC recommends two principle methods for calculating national greenhouse gas (GHG) emissions, the Reference Approach (IPCC-RA) and the Sectoral Approach (IPCC-SA). The IPCC-RA only calculates CO₂ emissions resulting from the use of fossil fuels and is supposed to be applied as a crosscheck for the IPCC-SA and as the exclusive emission inventory method for countries with limited data availability. The principal idea of the IPCC-RA is to subtract the amount of fossil carbon stored in products from the national total apparent carbon consumption to obtain a value for national CO₂ emissions. The carbon storage is calculated by multiplying the non-energy use of a certain fuel with a storage fraction for this fuel:

$$\begin{array}{ccccccc} \textit{carbon storage} & = & \textit{non-energy use} & * & \textit{emission factor} & * & \textit{storage fraction} \\ \textit{(t carbon)} & & \textit{(J)} & & \textit{(t carbon / J)} & & \textit{(\%)} \end{array}$$

Equation 3.1

In the more detailed IPCC-SA, CO₂ emissions from the use of fossil fuels are reported in various source categories. These include ‘Fuel combustion’, ‘Industrial Process Emissions’, ‘Solvent and other product use’¹ and ‘Waste’. The calculation of CO₂ emissions according to these source categories should be based on a combination of energy statistics and detailed bottom-up analyses, but – depending on the “Tier” applied - may include again the use of formula 1 to calculate the amount of carbon stored. The IPCC-RA and IPCC-SA and the difficulties associated with these methods with respect to non-energy use CO₂ emission accounting are discussed in more detail elsewhere (Neelis et al., 2005; Patel et al., 2005).

¹ Emissions from solvent and other product use are sometimes also reported as non-methane volatile organic compounds (NMVOC) emissions. In the context of this paper, we convert all flows to CO₂ equivalents and therefore refer to CO₂ emissions from solvent and other product use.

To contribute to a more accurate accounting of CO₂ emissions and carbon storage resulting from the non-energy use of fossil fuels, the Non-Energy use Emission Accounting Tables (NEAT) model has been developed. The model is based on a carbon flow analysis and is largely independent from energy statistics. The model is described in a separate paper (Neelis et al., 2005).

In the Netherlands, non-energy use accounted for 13.5% of the total primary energy supply in the year 2000. This is high compared to other countries (the European average is 6.5%) and is a consequence of a large chemical industry (values for 2000; IEA, 2002). The advantages that methods working independently from the energy statistics could have in determining emissions resulting from the non-energy use of fossil fuels have already been recognised at an early stage in the Netherlands. In fact, the NEAT model in its current form (as described by Neelis et al., 2005) has been developed out of a bottom-up carbon flow analysis for the Netherlands for 1992 described by Gielen (1997). The study by Gielen for 1992 has been used to determine country specific storage fractions for the Netherlands. These time-independent storage fractions are used in the Dutch IPCC-RA and IPCC-SA methodology for calculating greenhouse gas emissions in the Netherlands described in a methodology report by Spakman et al. (2003)². It is, however, unclear whether it is justified to use storage fractions determined for a single year for the calculation of CO₂ emissions and carbon storage in subsequent years, because it is not clear how large the yearly variations in non-energy use emissions, carbon storage and resulting storage fractions are. With the NEAT model, we can in detail explore these yearly variations. The aim of this paper is therefore:

- To investigate yearly variations in non-energy use emissions, carbon storage and resulting storage fractions in the Netherlands by conducting a time-series analysis for the period 1993-1999 with the NEAT model.
- To investigate the quantitative effects of methodological differences between the NEAT approach and the non-energy use emission accounting methodology applied in the Dutch GHG emission inventory.

In Section 3.2, the data sources used in this study are discussed. In Sections 3.3 and 3.4, we present the NEAT model results. The comparison with the official GHG inventory for the Netherlands is made in Section 3.5. The methodology applied in the NEAT model will only briefly be repeated here, for more detailed information the reader is referred to Neelis et al. (2005) elsewhere in this volume. The application of the NEAT model to the Netherlands is discussed in more extensively in Neelis et al. (2003).

² In this report, also the calculation of storage fractions using the study by Gielen for 1992 is described.

3.2 Data sources for the NEAT Netherlands model

Three data sources were used for this study:

1. International trade statistics according to the Combined Nomenclature 8-digit product classification used throughout the European Union (Eurostat, various years).
2. Production statistics according to the PRODCOM 8-digit product classification used throughout the European Union (Eurostat, various years). In the PRODCOM classification, the corresponding classification in the Combined Nomenclature classification is given for each product.
3. Energy balances of individual firms used for the preparation of the Dutch energy statistics.

Most chemicals in the Netherlands are produced by only a few (less than 5) producers. For this reason, the production statistics for about 90% and the trade statistics for about 10% of the products included in the NEAT model are confidential. These confidential data can be accessed at Statistics Netherlands, but the results can only be presented in aggregated form. An important reason for applying the NEAT model is to generate estimates that are independent from the energy statistics. For six NEAT core products (bitumen, lubricants, waxes and paraffins, MTBE (methyl tertiary butyl ether), petroleum coke and other tar products), this was not possible since no production and trade statistics independent from the energy statistics are collected for those products. Moreover, some of these products can be used both for energy and non-energy purposes (most notably petroleum coke) and only the detailed energy balances for the individual firms (data source 3) could be used to distinguish between the two.

3.3 CO₂ emissions from non-energy use

In this section, CO₂ emissions resulting from the non-energy use of fossil fuels are presented. Part of the carbon embodied in fuels used for non-energy use is embodied in chemicals. Some of these chemicals (e.g. solvents) lead to GHG emissions already during the use phase (fully or at least partially). In NEAT, these products are referred to as products that are ‘oxidised during use (ODU)’. Other chemicals only lead to emissions during incineration of post-consumer waste; these chemicals are referred to as products that are ‘not oxidised during use (NODU)’. The emissions from ODU products are assigned to the IPCC source category ‘solvents and other product use’ and are discussed in Section 3.3.1. Based on the total carbon embodied in chemicals and the domestic consumption of ODU and NODU products, the NEAT model also estimates the net trade flows of carbon containing chemicals. This estimate

is presented in Section 3.3.2. Another part of the carbon embodied in the fuels used for non-energy use is already oxidised during the production phase of certain chemicals such as ammonia, resulting in CO₂ emissions from ‘industrial processes’, discussed in Section 3.3.3.

3.3.1 Emissions from solvent and other product use

The NEAT model estimates, in CO₂ equivalents, the consumption of ODU and NODU products based on a carbon balance modelling the conversion from 22 basic chemicals to 55 intermediates and final products. The products included and the method to split the consumption into ODU and NODU fractions is described in Neelis et al. (2005). The downstream consumption of ODU and NODU products together in the Netherlands is given in Table 3.1 and varies between 7.8 and 12.4 Mt CO₂. Although 1995 was a good year for the chemical industry³ this cannot fully explain the very high number for 1995. The wide variation from year to year results from the poor quality of the technical production and international trade data used in the model. This is especially the case for the intermediate products in the model. Companies tend not to report (fully) the production volumes of chemicals that are converted on-site to other chemicals. In case of apparent mistakes, we made corrections to the raw data. Such apparent mistakes included missing production data in some of the years for some of the products and cases where the net export (export – import) of a product exceeded the production of that product. Corrections were made by contacting the companies producing the products under investigation and by using mass balance principles. Manually corrected data instead of statistical data were used for production values of about one quarter of the 77 products and for trade values of a few of the 77 products. No corrections were made in cases of less apparent mistakes such as unexplainable but not impossible variations for some products from year to year.

As explained by Neelis et al. (2005), a sensitivity analysis for the division between ODU and NODU derivatives of each chemical is implemented in the model. We assume the resulting ranges for the percentage of ODU and NODU products to reflect the 95% confidence interval for these percentages. We further assume the 95% confidence interval in the consumption values for each of the chemicals to be 50% of the difference between minimal and maximal consumption between 1993 and 1999 of that chemical, thereby attributing the full variation in consumption values in the years of study to the weak data situation. Using standard error propagation rules we then come to the 95% confidence intervals for the consumption of ODU and NODU products given in Table 3.1. Given these substantial error ranges, we cannot distinguish a clear trend in the emissions from solvent and other product use as calculated with the NEAT model.

³ Production index of 0.94 in 1994 and 0.96 in 1996 compared to 1.00 in 1995 according to VNCI (2004).

3.3.2 Net trade of organic chemicals

The carbon balance in the NEAT model can also be used to estimate, in CO₂ equivalents, the amount of the total carbon associated with non-energy use that is embodied in chemical products. This is done by summation of two elements:

- The CO₂ equivalents of the non-energy use refinery and coke oven products consumed for non-energy use applications and
- The amount of the carbon in hydrocarbon feedstocks, which is embodied in chemical products, estimated by taking the CO₂ equivalents of all basic chemicals produced from these feedstocks⁴.

The difference between the total non-energy use carbon embodied in chemical products upstream (at the level of feedstocks) and the consumption of ODU and NODU products downstream (Table 3.1) equals the net export of the chemical products included in the NEAT model. We present an overview in Table 3.2. The Table clearly shows the export-oriented nature of the Dutch petrochemical industry in which large amounts of basic chemicals and intermediates (6 – 9 Mt CO₂) and polymers (6 – 10 Mt CO₂) are exported. The increase in ethylene production capacity by 600 kt / year at the Dow chemical complex in Terneuzen in 2002 (Chemical and Engineering News, 2002) further enhanced the position of the Netherlands as major exporter of hydrocarbons in the years following the years of this study.

3.3.3 Industrial process emissions

For the calculation of CO₂ emissions from the production of ammonia, methanol and carbon black, we used the default CO₂ emission factors given by Neelis et al., 2005 multiplied with the production volumes for those chemicals in the years of study. In the Dutch energy statistics, energy conversions within industrial sectors (e.g. the conversion of feedstocks to hydrogen, methane and other fuels in steam crackers) are in detail monitored and parts of process inputs (in e.g. ammonia, methanol and carbon black), which are used as fuel are excluded from the non-energy use statistics and reported under final energy use (see also box 1 and Section 3.5). In our calculations, we corrected for this accounting practice: For

⁴ In the Dutch oil statistics survey (Statistics Netherlands, 2001) and consequently in the Dutch energy statistics, the pure aromatics benzene, toluene, the xylenes, ethylbenzene, styrene, naphthalene and cumene are included as energy commodities. As a result, the trade in these chemicals is already accounted for in the Dutch energy statistics and only the domestic consumption of these chemicals is reported as non-energy use. We adapted the NEAT calculations to reflect this accounting practice in the Netherlands and refer to Neelis et al. (2003) for a detailed description of the calculations. The Netherlands is a significant net exporter of these basic aromatics (approximately 5 Mt CO₂ equivalents). If these aromatics were not regarded energy commodities in the Dutch energy statistics, the production of these aromatics would be reported as non-energy use. The total primary energy supply and the total non-energy use in the Netherlands would in that case be about 5 Mt CO₂ equivalents higher.

Table 3.1 NEAT model results for final consumption of carbon in ODU and NODU products, the Netherlands, 1993-1999

	1993	1994	1995	1996	1997	1998	1999
Total consumption of carbon in chemicals (Mt CO ₂ / year)	7.8	8.0	12.4	8.4	8.8	11.2	10.0
<i>Estimated error (for each year) (Mt CO₂ / year)</i>				+/- 1.8			
Of which oxidised during use (ODU) (Mt CO ₂ / year)	1.3	1.7	3.0	1.8	2.1	2.3	2.6
<i>Estimated error (for each year) (Mt CO₂ / year)</i>				+/- 0.8			
Of which not-oxidised during use (NODU) (Mt CO ₂ / year)	6.5	6.3	9.4	6.6	6.7	8.9	7.4
<i>Estimated error (for each year) (Mt CO₂ / year)</i>				+/-1.5			
Percentage NODU in total consumption (%)	83	78	76	79	76	79	74

Table 3.2 NEAT model results for non-energy use carbon embodied in chemicals, net export and final consumption chemicals, the Netherlands, 1993-1999

	1993	1994	1995	1996	1997	1998	1999
Fraction of non-energy use carbon embodied in chemicals (Mt CO ₂ / year)	23.6	22.5	26.7	23.3	23.5	25.2	25.8
Total net export of chemicals included in NEAT (Mt CO ₂ / year)	15.8	14.5	14.3	14.8	14.7	14.0	15.8
Of which:							
Basic chemicals / intermediates (Mt CO ₂ / year)	9.4	7.7	7.7	7.6	6.3	5.2	6.1
Polymers (Mt CO ₂ / year)	6.4	6.8	6.6	7.2	8.4	8.8	9.7
Total domestic consumption of chemicals (Mt CO ₂ / year) (Table 3.1)	7.8	8.0	12.4	8.4	8.8	11.2	10.0

methanol and carbon black, we allocated a part of the process input (in CO₂ equivalents) equal to the carbon embodied in the methanol and carbon black product to non-energy use and the remainder to final energy use⁵. As a result, the industrial process emissions from these processes are zero by definition and all emissions are allocated to fuel combustion. For ammonia production, we assumed that a 70% vs. 30% split is made between final energy use and final non-energy use of the process input. In Section 3.6, we discuss whether the assumptions made with respect to non-energy use allocation are justified given the actual Dutch situation. For ammonia, we corrected the *gross* industrial process emissions (resulting from the non-energy use) for CO₂ embodied in urea to yield *net* industrial process emissions. The results are given in Table 3.3. The ammonia production is fairly constant over the years and as a consequence both the emissions from fuel combustion and the *gross* industrial process emissions from ammonia are quite stable. The *net* industrial process emissions from ammonia production increase from 2.4 to 2.9 Mt CO₂ between 1993 and 1999, because of a decreasing production of urea, leading to less CO₂ storage in urea. The emissions from ammonia production are about a factor 10 higher than the emissions from methanol and carbon black production, which are relatively stable over the years.

In the NEAT model, emissions from steam cracking are calculated based on ethylene production figures and the feedstock composition applied in the crackers. We based this feedstock composition for steam cracking in the Netherlands on the energy balances of the companies operating steam crackers in the Netherlands. The share of naphtha in the input was estimated at 81-86% with gas oil and LPG making up the rest. The resulting emissions and backflows from the steam cracker process as estimated with the NEAT model are given in Table 3.3. Analogous to the production of ammonia, methanol and carbon black, we assume that the fuel use and backflows from steam crackers are not included in the non-energy use according to the Dutch energy statistics, but are reported as final energy use. As a result, the industrial process emissions are zero by definition and the emissions are allocated to emissions from fuel combustion (in box 1, the difficulties associated with CO₂ emission accounting based on the Dutch energy statistics for the steam cracking process are further discussed). The industrial process emissions from the production of metals and inorganics are also given in Table 3.3. They were calculated combining production volumes for the various chemicals with the standard emission factors given in Neelis et al. (2005). The emissions range from 0.8 – 1.0 Mt CO₂ in the years of study and mainly result from the production of aluminium, phosphorus and silicon carbide.

⁵ For methanol, we further assume that the part used for the production of MTBE (approximately 0.4 Mt CO₂ equivalents in the years of study) is included as an energy conversion process and is therefore excluded from the non-energy use in the energy statistics.

Table 3.3 NEAT model results for CO₂ emissions in steam cracking and ammonia, methanol, carbon black, metals and inorganics production in the Netherlands, 1993-1999 (all values in Mt CO₂ equivalents per year)

	1993	1994	1995	1996	1997	1998	1999
Total natural gas input to ammonia production	4.9	4.9	4.9	4.6	4.9	5.0	5.0
Of which emissions from fuel combustion	1.5	1.5	1.5	1.4	1.5	1.5	1.5
Of which gross industrial process emissions	3.4	3.4	3.4	3.2	3.4	3.5	3.5
CO ₂ embodied in urea	1.0	0.7	0.7	0.7	0.6	0.7	0.6
Net industrial process emissions ammonia production ^a	2.4	2.7	2.7	2.5	2.8	2.8	2.9
Total natural gas input to methanol production	1.5	1.4	1.9	1.5	1.6	1.3	1.4
Of which emissions from fuel combustion	0.3	0.3	0.4	0.3	0.3	0.3	0.3
Of which CO ₂ embodied in methanol	1.2	1.1	1.5	1.2	1.2	1.0	1.1
Of which industrial process emissions methanol production	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total hydrocarbon input to carbon black production	0.7	0.6	0.7	0.7	0.8	0.6	0.6
Of which emissions from fuel combustion	0.2	0.2	0.3	0.2	0.3	0.2	0.2
Of which CO ₂ embodied in carbon black	0.4	0.4	0.5	0.4	0.5	0.4	0.4
Of which industrial process emissions	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total hydrocarbon input into steam cracking	24.1	24.0	27.2	24.9	24.2	24.3	26.8
Of which emissions from fuel combustion	4.2	4.1	4.7	4.3	4.2	4.2	4.6
Of which backflows from steam cracking	2.3	2.3	2.6	2.4	2.4	2.4	2.6
Of which industrial process emissions	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Industrial process emissions from metals and inorganics production	0.8	0.9	0.8	0.9	0.9	1.0	0.9

^a Determined by deducting 'CO₂ embodied in urea' from the gross industrial process emissions

3.4 Total non-energy use in CO₂ equivalents, carbon storage and storage fractions

In Table 3.4, we present an overview of the total non-energy use in CO₂ equivalents, the carbon storage and the resulting storage fractions. In Section 3.4.1, we will discuss the NEAT results. In Section 3.4.2 and 4.3, we will show the influence of non-energy use definition and system boundary choices on these results. The differences with the Dutch national inventory report on greenhouse gas emissions (NIR, Klein Goldewijk et al., 2004) will be discussed in Section 3.5.

3.4.1 NEAT model results

The non-energy use in CO₂ equivalents is calculated by adding the industrial process CO₂ emissions calculated in Section 3.3 of this paper (totals from Table 3.3) to the fraction of non-energy use carbon embodied in chemical products (Table 3.1). The total non-energy use in CO₂ equivalents is broken down into the various fuel types used for non-energy use purposes by allocating the industrial process CO₂ emissions to the respective fuels used and by allocating the basic chemicals to the feedstock they are produced from (natural gas or the total of ‘other oil products’). The total non-energy use in the Netherlands according to the NEAT model varies between 26 and 30 Mt CO₂ in the years of study. The total of ‘other oil products’ (the sum of all feedstocks in the petrochemical industry) and natural gas contribute approximately 90% to the total non-energy use, whereas the other fuels used for non-energy use purposes contribute approximately 10% to the total. The non-energy use of natural gas is stable in the years of study (varying between 4.2 to 4.5 Mt CO₂) as a result of the stable production volume of ammonia and methanol (together contributing more than 90% to the non-energy use of natural gas). For the total of ‘other oil products’, the total non-energy use varies between 19 and 23 Mt CO₂ in the years of study. We expect this value to have an uncertainty of +/- 2 Mt CO₂ as a result of the limited reliability of the production and trade statistics (comparable to the uncertainty in the consumption figures of chemicals given in Table 1). We are therefore reluctant to draw any conclusion based on the observed variation from year to year.

The carbon storage⁶ given in Table 3.4 consists of two parts:

- The consumption of NODU products in the country of study (Table 3.1) and

⁶ The use of the term ‘carbon storage’ might be confusing, because it includes carbon embodied in NODU products that are incinerated within the inventory year (assumed to be accounted for properly under emissions from fuel combustion or waste) and also includes carbon embodied in ODU products that lead to emissions abroad. We still decided to use the term to be consistent with the terminology used in the IPCC guidelines.

Table 3.4 Total non-energy use in CO₂ equivalents in the Netherlands, 1993-1999: comparison between NEAT and the NIR (Mt CO₂ / year)

	1992		1993		1994		1995		1996		1997		1998		1999	
	NIR	NEAT	NIR	NEAT	NIR	NEAT	NIR	NEAT	NIR	NEAT	NIR	NEAT	NIR	NEAT	NIR	NEAT
Coal/ignite/Coke																
Non-energy use	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3
Storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Storage Fraction (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal oil and tars																
Non-energy use	0.5	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Storage	0.5	0.6	0.7	0.5	0.6	0.5	0.6	0.5	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5
Storage Fraction (%)	100	92	100	90	100	91	100	91	100	91	100	90	100	88	100	88
Lubricants																
Non-energy use	0.4	0.2	0.2	0.3	0.3	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6
Storage	0.0	0.2	0.0	0.2	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4
Storage Fraction (%)	0	67	0	67	0	67	0	67	0	67	0	67	0	67	0	67
Bitumen																
Non-energy use	1.3	1.3	1.3	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.2	1.2
Storage	1.3	1.3	1.3	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.2	1.2
Storage Fraction (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Other oil products																
Non-energy use	18.8	19.9	15.8	19.3	16.1	22.7	15.4	19.7	13.9	13.9	20.1	16.0	22.2	15.7	22.4	17.9
Storage	15.5	18.4	12.9	17.2	13.2	19.7	12.6	17.9	11.4	11.4	18.0	13.1	19.9	12.9	19.7	14.6
Storage Fraction (%)	82	93	82	89	82	87	82	91	82	82	90	82	90	82	88	82
Natural gas																
Non-energy use	5.7	4.4	5.4	4.3	4.3	4.7	6.1	4.2	5.9	5.9	4.5	6.3	4.4	6.0	4.5	5.9
Storage	0.6	1.7	0.5	1.5	1.5	1.8	0.6	1.4	0.6	0.6	1.4	0.6	1.2	0.6	1.4	0.6
Storage Fraction (%)	10	39	10	36	10	37	10	34	10	10	31	10	27	10	30	10
Total																
Non-energy use	27.3	26.8	23.8	26.1	24.4	30.2	24.4	26.7	22.6	22.6	27.1	25.0	29.0	24.2	29.6	26.1
Storage	17.9	22.3	15.5	20.8	15.7	23.7	15.1	21.5	13.8	13.8	21.4	15.4	22.9	15.0	23.1	16.6
Emissions ^a	9.4	4.6	8.3	5.3	8.7	6.5	9.2	5.2	8.8	8.8	5.7	9.5	6.1	9.2	6.5	9.6
Storage Fraction (%)	66	83	65	80	64	78	62	81	61	61	79	62	79	62	78	63

^a The sum of emissions from solvent and other product use (Table 3.1) and industrial process emissions (Table 3.3)

- The net export of all basic chemicals, intermediates and final products included in the NEAT model (Table 3.2)⁷.

The carbon storage is stable in the years of study and varies between 21 and 23 Mt CO₂ in the years of study. The storage resulting from natural gas derived chemicals shows a clear trend, resulting from the decreasing production of urea (Table 3.3).

We also calculate storage fraction by dividing the carbon stored by the total non-energy use in CO₂ equivalents. The storage fraction for coal/lignite/coke is 0% since these products only lead to industrial process emissions. For bitumen and lubricants, the storage fraction equals the fraction that is not oxidised during use, 100% (bitumen) and 67% (lubricants) respectively (Neelis et. al., 2005). For coal oils and tars (residues from coke production), the fraction emitted in the Netherlands is approximately 10% (as part of the industrial emissions in Table 3.2) with the remaining 90% being stored in NODU products. The storage fraction for natural gas is between 27 and 39% and is the only one showing a clear trend as a result of the declining production of urea in the years studied. For oil products, a storage fraction of between 87 and 93% is calculated. The variation can be fully explained by the uncertainties in the fraction of ODU vs. NODU products (Table 3.1) and we can therefore not distinguish a trend. It is important to note that the carbon storage fractions presented in Table 3.4 must not be directly used for CO₂ emission calculations according to the IPCC-RA as long as there are differences in total non-energy use in CO₂ equivalents between the NEAT model and the NIR as is indeed the case in the Netherlands (see Section 3.5).

3.4.2 Influence of non-energy use definitions

In the results shown in Section 3.4.1, we used a net definition of non-energy use for the production processes for ammonia, methanol and carbon black and in the steam cracking process, excluding from the non-energy use the part of the hydrocarbon input which is directly or indirectly (via the production of waste gas) used as fuel. This was done to reflect the practice in Dutch energy statistics (see Section 3.3.2). In other countries, gross definitions of non-energy use are applied, allocating the total input into the processes mentioned above to non-energy use, thereby including the parts used directly or indirectly as fuel. In Table 3.5, we show the effect of this different definition of non-energy use on the non-energy use in CO₂ equivalents and on the storage fractions for both natural gas and the ‘other oil products’. The difference between the total non-energy use according to the gross and the net definition (for the total of natural gas and ‘other oil products’) equals the sum of the fuel combustion emissions and backflows given in Table 3.3. The results show that it is very important to

⁷ Except for the non-energy use refinery and coke oven products and the basic aromatics for which the trade is already accounted for in the energy statistics.

understand which definition is used in the non-energy use statistics applied in the inventory and to adapt the storage fractions accordingly in order to come up with correct estimates for carbon storage. Furthermore, it is important to realise that the CO₂ emissions from non-energy use calculated assuming either a gross or a net definition for non-energy use are incomparable to each other. In the case of a gross definition, some CO₂ emissions from fuel combustion are included in the emissions from non-energy use, whereas these are excluded in case of a net definition. For a further discussion on the influence of these differences on the correct methodology to be applied in national GHG inventories, we refer to Section 4 and 6 of the paper by Neelis et al. (2005).

3.4.3 Including all products in the calculated storage

In the results presented in Table 3.4, we excluded the consumption of ODU products, but included the consumption of NODU products in the calculated storage. This was done, because our hypothesis is that the emissions from the waste treatment of these NODU products are correctly accounted for in the GHG inventory, either as emissions from fuel combustion or from waste. One can also calculate a carbon storage in which the consumption of ODU products is also included. This choice could be made when reliable emission inventories for solvent and other product use are available (e.g. bottom up surveys). In that case, the calculation using the storage fractions only results in an estimate for CO₂ emissions, excluding ODU products. Depending on the definition of non-energy use applied, the calculation with the storage fractions in that case yields either an estimate for industrial process emissions (net definitions) or for industrial and some fuel combustion emissions (gross definition). In Table 3.6, we show the results using these system boundaries. The storage fraction for ‘other oil products’ is in this case close to 100%, because only a very small part results in direct CO₂ emissions (petroleum coke used in the metal industry).

3.5 Comparison with the National Inventory Report

Deducting the carbon storage according to NEAT (values according to Table 3.4) from the total primary energy supply of the Netherlands in CO₂ equivalents yields an estimate for total fossil CO₂ emissions, which can be compared with estimates according to the IPCC-RA and IPCC- SA. We show this comparison in Figure 3.1. We will compare the NEAT results with the IPCC-RA in Section 3.5.1 and with the IPCC-SA in Section 3.5.2.

Table 3.5 Effect of non-energy use definition on total non-energy use and storage fractions in the Netherlands, 1993-1999

	1993	1994	1995	1996	1997	1998	1999
Non-energy use natural gas, net definition (Mt CO ₂ / year)	4.4	4.3	4.7	4.2	4.5	4.4	4.5
Non-energy use natural gas, gross definition (Mt CO ₂ / year)	6.2	6.1	6.6	6.0	6.3	6.2	6.3
Carbon storage, natural gas, both definitions (Mt CO ₂ / year)	1.7	1.5	1.8	1.4	1.4	1.2	1.4
Storage fraction, natural gas, net definition (%)	39	36	37	34	31	27	30
Storage fraction, natural gas, gross definition (%)	28	25	27	24	22	19	21
Non-energy use other oil products, net definition (Mt CO ₂ / year)	19.9	19.3	22.7	19.7	20.1	22.2	22.4
Non-energy use other oil products, gross definition (Mt CO ₂ / year)	26.7	26.1	30.4	26.7	27.0	29.0	29.9
Carbon storage, other oil products, both definitions (Mt CO ₂ / year)	18.4	17.2	19.7	17.9	18.0	19.9	19.7
Storage fraction, other oil products, net definition (%)	93	89	87	91	90	90	88
Storage fraction, other oil products, gross definition (%)	69	67	65	67	67	69	66

Table 3.6 Effect of system boundary choices on total non-energy use and storage fractions in the Netherlands, 1993-1999

	1993	1994	1995	1996	1997	1998	1999
Non-energy use natural gas, both system boundaries (Mt CO ₂ / year)	4.4	4.3	4.7	4.2	4.5	4.4	4.5
Carbon storage, natural gas, excluding ODU products (Mt CO ₂ / year)	1.7	1.5	1.8	1.4	1.4	1.2	1.4
Carbon storage, natural gas, including ODU products (Mt CO ₂ / year)	2.0	1.6	2.0	1.7	1.7	1.6	1.6
Storage fraction, natural gas, excluding ODU products (%)	39	36	37	34	31	27	30
Storage fraction, natural gas, including ODU products (%)	45	37	42	40	38	36	36
Non-energy use other oil products, both system boundaries (Mt CO ₂ / year)	19.9	19.3	22.7	19.7	20.1	22.2	22.4
Carbon storage, other oil products, excluding ODU products (Mt CO ₂ / year)	18.4	17.2	19.7	17.9	18.0	19.9	19.7
Carbon storage, other oil products, including ODU products (Mt CO ₂ / year)	19.4	18.8	22.3	19.2	19.7	21.6	21.9
Storage fraction, other oil products, excluding ODU products (%)	93	89	87	91	90	90	88
Storage fraction, other oil products, including ODU products (%)	98	98	98	98	98	97	98

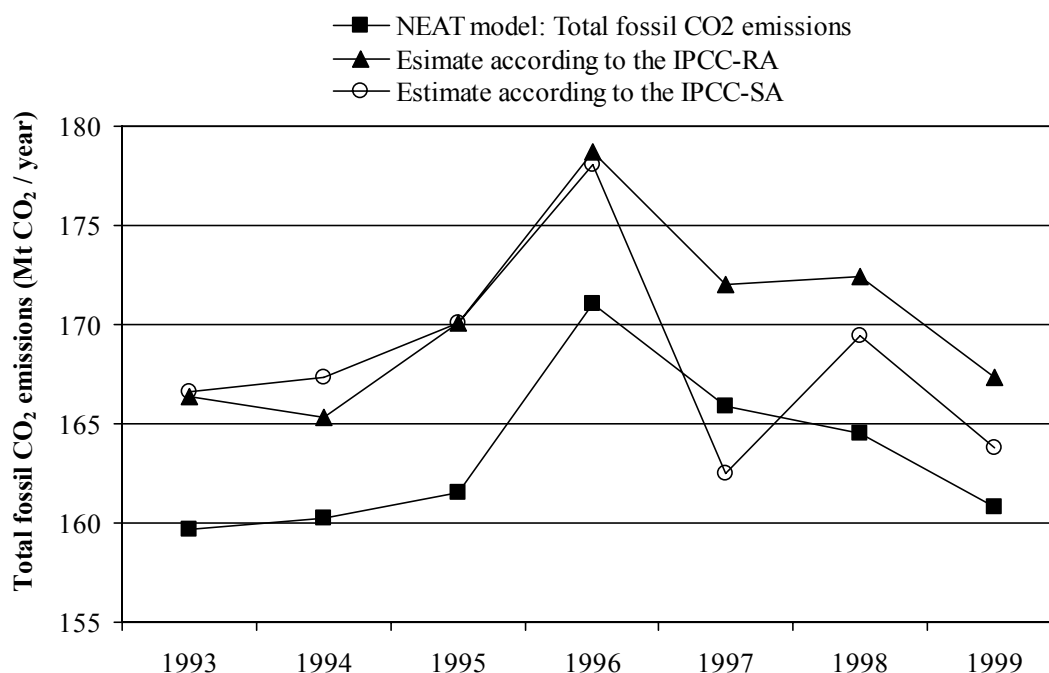


Figure 3.1 Total fossil CO₂ emissions in the Netherlands, 1993-1999: NEAT results compared to the NIR

3.5.1 Comparison with the IPCC-RA

The NEAT model estimate is 5.1 (1994) – 8.6 (1996) Mt CO₂ lower compared to the value according to the IPCC-RA. The difference is by definition equal to the difference in total carbon storage between NEAT and the NIR presented in Table 3.4, since both estimates are obtained by deducting the carbon storage from the total primary energy supply in the Netherlands (further discussed in footnote 9). The difference in carbon storage can either be caused by differences in (compare Equation 3.1):

- The storage fractions used in the NIR (based on the study by Gielen for 1992, see below) and calculated in the NEAT model and/or
- The total non-energy use in CO₂ equivalents used in the NIR and the total non-energy use in CO₂ equivalents according to the NEAT model.

Table 3.4 reveals major differences both in carbon storage and total non-energy use between the NEAT model and the NIR for especially the ‘other oil products’ and to a lesser extent also for natural gas. We will explore these differences on a fuel-by-fuel basis.

Coal/Lignite/Coke

For coal/lignite and coke, the storage fractions according to the NIR and NEAT are both 0%, because the use of these products for non-energy use purposes only lead to CO₂ emissions

from industrial processes and not to carbon storage. The small differences in non-energy use between NIR and NEAT is caused by small differences in specific emission factors between the actual Dutch situation and the default values used in the NEAT model.

Coal oils and tars

The use of coal tars and oils (residues of coke ovens) is in our NEAT calculations directly taken from the energy statistics. As a result, the total non-energy use according to the NIR and NEAT is equal, with the exception of 1999. In 1999, a fraction of the use of coal tars and oils is reported as final energy use in the energy statistics, whereas in all other years, the same use was reported as non-energy use. In NEAT, we corrected for this inconsistency. In the NIR, the total non-energy use of coal tars and oils is assumed to be stored, whereas in the NEAT model, small CO₂ emissions are calculated from coal tar. These are partly used for the production of anodes that are converted to CO₂ in the production of aluminium.

Lubricants and bitumen

For lubricants and bitumen, the consumption figures in the NEAT model were also taken directly from the energy statistics (see Section 3.2) and as a consequence, the non-energy use according to NEAT and NIR are identical. For bitumen, storage fractions of 100% are used both in the NEAT model and in the NIR. For lubricants, the NIR assumes no storage of lubricants, whereas a fraction of 67% is used in NEAT to correct for lubricants, which are incinerated with energy recovery (emissions are already accounted for as emissions from fuel combustion). There is, however, a strong need to further study the final fate of lubricants and their position in both energy statistics and GHG emission inventories (see also, Neelis et al., 2005).

Total 'other oil products'

The carbon storage of the 'other oil products' according to the NEAT model is much higher than the values according to the NIR (Figure 3.2). The difference can be explained as follows:

The storage fraction of 82% used in the NIR was derived based on an estimate of carbon storage of 15.4 Mt CO₂ for 1992 (Table 3.4). This value was derived from the study by Gielen (1997) for 1992 and differs in two ways from the NEAT carbon storage estimates presented in Table 3.4 and Figure 3.2. In the first place, Gielen gave two methodologically different storage estimates in his study for 1992. The first estimate (16.0 Mt CO₂ excluding bitumen) allocated emissions from exported ODU products to the Netherlands (producer approach), whereas the second estimate (18.1 Mt CO₂ excluding bitumen) allocated these emissions to

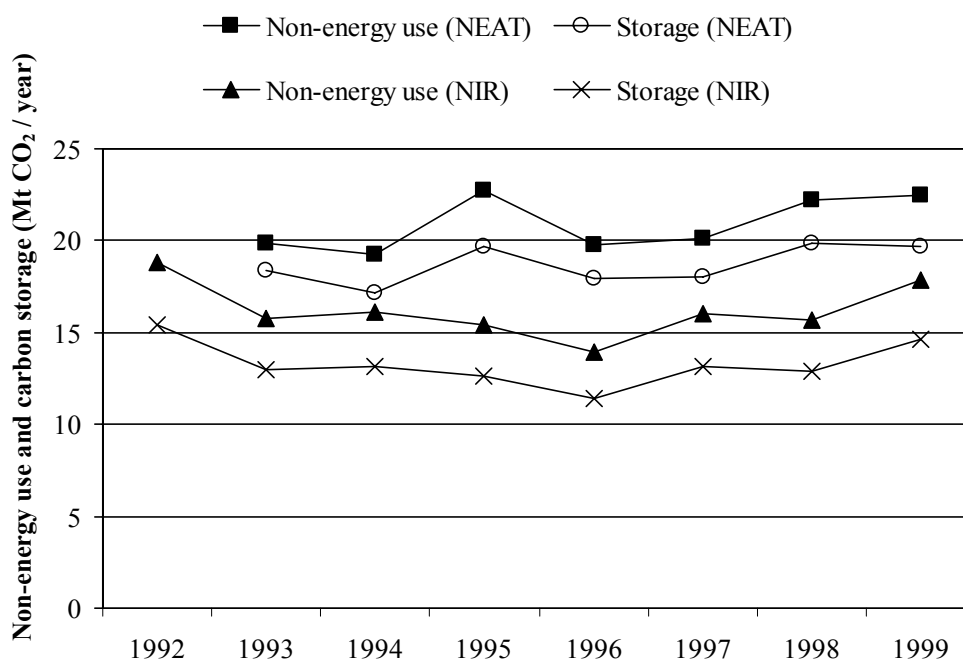


Figure 3.2 Non-energy use and carbon storage for 'other oil products' in the Netherlands, 1993-1999: NEAT results compared to the NIR

the importing country (consumer approach). The consumer approach is in line with the approach of the NEAT model and with the generally accepted principle of allocating emissions to the country where they take place. However, in the storage fraction calculation, the first storage estimate of 16.0 Mt CO₂ was used. For unclear reasons, 15.4 Mt CO₂ of this total has been allocated to the total of 'other oil products' and 0.6 to natural gas. This resulted in the storage fraction for oil products of 82% for 1992 (Spakman et al., 2003), which has been used ever since then (Table 3.4). In the second place, the considerable export of anodes for aluminium production produced from petroleum coke (part of the 'other oil products') has not been included in the carbon storage estimate for 1992. This export was 0.8 Mt CO₂ in 1993. Using the carbon storage estimates for the consumer rather than those for the producer approach and adding the storage in exported anodes to the carbon storage results in an estimated carbon storage for oil products for 1992 equal to 17.1 Mt CO₂ rather than the 15.4 Mt CO₂ used in the calculation of the storage fraction. This estimate (17.1 Mt CO₂) is quite in line with estimates for carbon storage obtained with the NEAT model (Table 3.4) and would have resulted in a storage fraction of 91% for 1992, which is also in line with the NEAT model estimates (Table 3.4).

The total non-energy use in CO₂ equivalents in 1992 in the NIR (18.9 Mt CO₂) is 1 Mt CO₂ lower compared to the NEAT estimate for 1993 (19.9 Mt CO₂). However, from 1992 to 1993, the non-energy use in the NIR dropped to 15.8 Mt CO₂, which is 4.1 Mt CO₂ lower compared

to the NEAT estimate for 1993. It is unclear why the non-energy use in the energy statistics (used directly in the NIR) dropped so significantly from 1992 to 1993, since the drop cannot be explained by developments in the relevant sectors. As a result of this drop, a carbon storage of 12.9 Mt CO₂ was calculated for 1993 in the NIR, which is 2.5 Mt CO₂ lower than the storage of 15.4 on which the calculation of the storage fraction was based and 4.2 Mt CO₂ lower compared to the storage of 17.1 Mt CO₂ according to the consumer approach and taking into account the export of anodes.

Text box 1 Difficulties associated with using Dutch energy statistics for CO₂ emission accounting

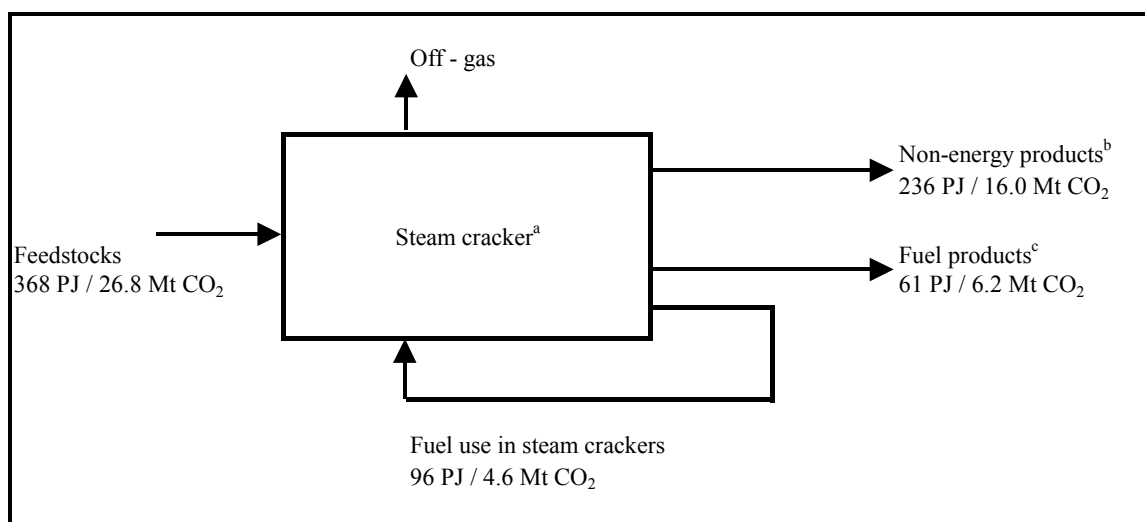
In the Dutch energy statistics, the conversion of one fuel (column: 'used for energy conversions') to another fuel (column: 'produced from energy conversions') is monitored as well as the final energy and non-energy use of fuels. This can cause problems when the energy statistics are applied to estimate CO₂ emissions. This can best be explained with the energy and CO₂ balance of the Dutch steam crackers in 1999 presented in Figure 3.3 (based on the NEAT steam cracker model). In steam crackers, the hydrocarbon feedstock is converted to non-energy use products, fuel gas used internally to fuel the endothermic process and remaining fuels, which are used elsewhere within or outside the chemical industry. It is very likely that the companies operating steam crackers report the production of the fuel gas used in the steam crackers (96 PJ) and of the remaining fuels (61 PJ) in the column: 'produced from energy conversions'. The use of these fuels will be put in the column: 'final energy use'. To close the energy balance, 157 PJ of the hydrocarbon input will be put in the column 'use for energy conversions'. The remainder of the input (211 PJ) will be allocated to the column 'non-energy use'. However, as a result of the endothermicity of the process, part of the energy of the fuel gas is in the cracker converted to chemical energy. As a result, the energy loss in the cracker is not 96 PJ, but only 71 PJ, with the remaining 25 PJ being embodied in the chemicals produced in the cracker (energy content of these chemicals 236 rather than 211 PJ). We checked these assumptions with the energy balances of firms operating steam crackers. This comparison showed that our basic reasoning is valid, but also that there are differences from year to year in the reporting practice of individual firms. The details of the comparison cannot be published for reasons of confidentiality. The resulting energy balance, already complex from an energy point of view, can easily create more problems when applied to CO₂ emission accounting. First, there is a gap between the two columns 'used for' and 'produced from' energy conversions, since the carbon content of the fuels produced (10.6 Mt CO₂) is not equal to the carbon content of the feedstock used ($157/368 * 26.8 \text{ Mt CO}_2 / \text{PJ} = 11.4 \text{ Mt CO}_2$). Secondly, the feedstock part, which is put in the column 'non-energy use', is equivalent to 15.4 Mt CO₂ ($211/368 * 26.8 \text{ Mt CO}_2$), whereas the non-energy products have a carbon content of 16.0 Mt CO₂. In general, it can for these reasons be doubted whether the non-energy use in the energy statistics can be used directly for CO₂ emission calculations, especially since the reporting practice varies from year to year and between firms. It would require detailed carbon, mass and energy balances for all firms operating steam crackers to assess these problems in more detail, since small inaccuracies in the assumptions can lead to substantial errors in the calculations due to the very large throughputs in the process. Because of the confidential nature of the information involved, such a comparison can only be done by Statistics Netherlands.

So far, the following reasons for the observed gap have been found:

- The non-energy use of fuels reported by the three firms operating steam crackers in the Netherlands to the energy statistics varies significantly from year to year. The total

is between 0.4 and 1.4 Mt (normal metric tonnes) lower than the production of ethylene, propylene, butadiene and other C₄ products from steam crackers. Multiplied with the carbon emission factor for naphtha (3.21 Mt CO₂ / Mt), this explains 1.3 - 4.5 Mt CO₂ of the difference in total non-energy use in CO₂ equivalents. This underreporting is most probably a direct result of the difficulties associated with the position of the complex energy conversions in the steam cracker process in the Dutch energy statistics and the direct use of these statistics for CO₂ emission accounting. We further elaborate on these difficulties in box 1.

- A considerable part of the non-energy use of ‘other oil products’ in the energy statistics results from the use of aromatics (50 PJ) and petroleum cokes (20 PJ). In the NIR, an emission factor of 73 kt CO₂ / PJ is used for these products, whereas both aromatics and petroleum cokes have emission factors quite different than 73 kt CO₂ / PJ. The correct emission factor for aromatics is about 80 kt CO₂ / PJ and for petroleum cokes the correct emission factor is even higher (approximately 100 kt CO₂ / PJ). Multiplication of the non-energy use from the energy statistics (in energy units) with their correct emission factors would yield a non-energy use in CO₂ equivalents of the ‘other oil products’ in the NIR that is approximately 0.9 Mt CO₂ higher. This systematic error is also made in 1992 and is therefore no explanation for the drop in non-energy use between 1992 and 1993.



^a The picture simplified. Recycle flows of unconverted ethane and propane and steam production and export are not shown.

^b In line with the Dutch energy statistics, we regard aromatics as energy commodities and only regard ethylene, propylene, butadiene and other C₄ products as non-energy products.

^c All remaining products (e.g. fuel oils, aromatics) minus the internal fuel use.

Figure 3.3 Simplified Dutch steam cracker balance for 1999 (based on the NEAT steam cracker model for 1999)

Natural gas

The methodological difference between consumer and producer approach also applies to natural gas derived chemicals such as urea. Applying the consumer approach to the data by Gielen for 1992 yields a storage estimate for natural gas equal to 1.8 Mt CO₂ rather than the 0.5 Mt CO₂ applied in the calculation of the storage fraction of 10% for 1992. This would for 1992 have resulted in a storage fraction of 32%. Figure 3.4 also shows significant differences in total non-energy in CO₂ equivalents between the NEAT model and the NIR. The following reasons for the gap have been identified:

- Within NEAT, the methanol used for the production of MTBE is subtracted from the non-energy use of natural gas because the MTBE is ultimately used as a component of transportation fuel. It has been found out that this correction has not been applied in the energy statistics. This correction is approximately 0.4 Mt CO₂ per year.
- In the Netherlands the raw material requirements for ammonia, methanol and carbon black production are higher than the estimates used in the NEAT model, which are based on very efficient plants. The reported non-energy use for ammonia production at the company level is about 0.8 Mt CO₂ higher compared to NEAT (or 0.3 t CO₂ per t ammonia). For methanol and carbon black, the inputs are 0.1 and 0.05 Mt CO₂ higher respectively.

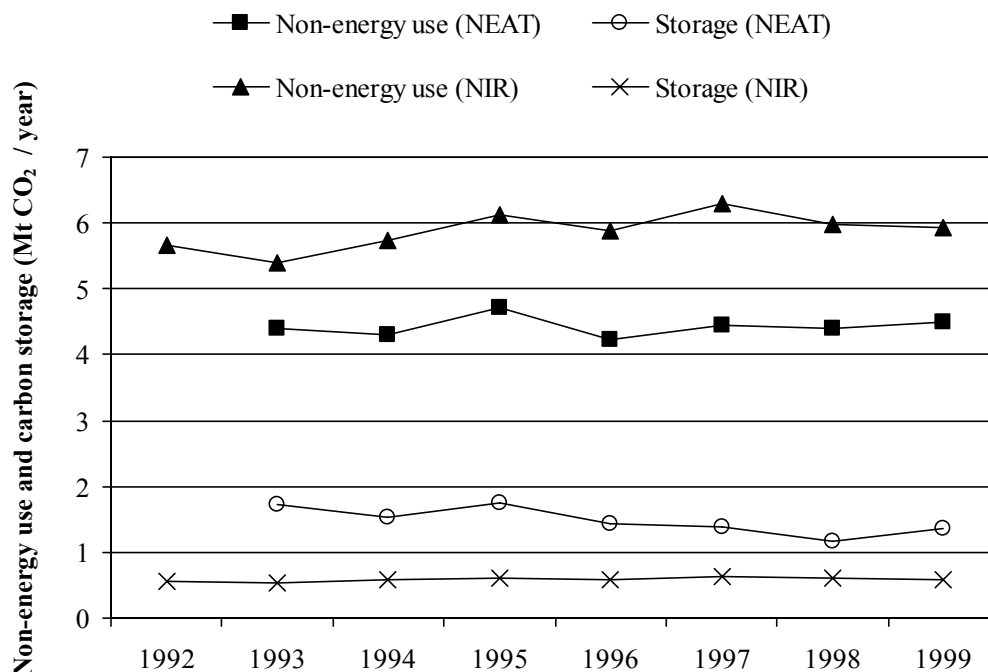


Figure 3.4 Non-energy use and carbon storage for natural gas in the Netherlands, 1993-1999: NEAT results compared to the NIR

The two reasons given above explain about 1.35 Mt CO₂ of the observed gap between the NIR and this study. The remainder of the gap (at most 0.4 Mt CO₂ in 1997) is less than 10% of the total non-energy use of natural gas for all years.

Summary

To summarise, we found two clear reasons for the difference between the NEAT estimate for carbon storage and the IPCC-RA estimate in the NIR:

- The producer approach methodology applied in the NIR that partly allocates emissions that occur abroad to the Netherlands (~ 2 Mt CO₂).
- Overlooking in the NIR methodology the carbon storage resulting from the export of anodes for aluminium production (~ 1 Mt CO₂).

The remainder of the difference is caused by non-energy use estimates in the energy statistics (and consequently in the NIR) that are much lower compared to the estimates according to the NEAT model.

3.5.2 Comparison with the IPCC-SA

The difference between the NEAT results and the IPCC-SA is comparable to the difference between NEAT and the IPCC-RA (Figure 3.1) with the exception for 1997 for which an unexplainable difference between the IPCC-RA and IPCC-SA is observed. In principle, the emissions according to NEAT, the IPCC-RA and the IPCC-SA should be more or less comparable, because all three estimates given in Figure 3.1 include the fossil CO₂ emissions from ‘industrial processes’ and the emissions from ‘solvent and other product use’ as well as fuel combustion emissions making the system boundaries between the three estimates comparable⁸. For the chemical industry, the IPCC-SA CO₂ emissions are as much as possible based on the CO₂ emission registration (ER) for individual firms and on the corresponding fuel use reported there. If, however, a company reports CO₂ emissions without reporting fuel use, the emissions are regarded CO₂ emissions resulting from non-energy use. The resulting CO₂ emissions from non-energy use are compared per sector with the non-energy use emission estimate using Equation 3.1 (the total emissions according to the NIR given in Table 3.4). The highest estimate of the two is used in the official CO₂ emission inventory. This method has several drawbacks:

⁸ The IPCC-RA is nowadays generally regarded as a tool to estimate CO₂ from fuel combustion only (see Neelis et al., 2005 for further details regarding the interpretation of the IPCC-RA). In the Netherlands, however, the approach intends to include also all fossil industrial process CO₂ emissions and emissions from ‘solvent and other product use’. Since the IPCC-SA in the Netherlands also uses the storage calculation from the IPCC-RA, these emissions are in the IPCC-SA also included under emissions from fuel combustion.

- As explained above, the storage fractions currently used in the NIR were determined based on work by Gielen for 1992, based on the producer approach and ignoring the storage in exported anodes for aluminium production. Furthermore, the storage was calculated for the country as a whole and cannot without adaptation be used at the level of individual sector.
- For the oil products, the emissions that are in the emission registration (ER) allocated to non-energy use (in cases where no fuel use reported in the emission registration) are high compared to expected values based on NEAT. It is very likely that at least part of these emissions actually correspond with emissions from fuel combustion. The residual CO₂ emissions for firms not individually reporting in the emission registration (ER) are estimated by deducting the reported fuel use in the emission registration from the total fuel use in the energy balance and multiplying the resulting ‘residual fuel use’ with default emission factors. The emissions falsely allocated to non-energy use can therefore easily be double-counted. This risk is acknowledged in the NIR (Klein Goldewijk et al., 2004, page A-30) and can be in the order of several Mt CO₂.

Without going into detail of the complex calculation methods for the IPCC-SA in the Netherlands (for details we refer to Spakman et al., 2003), one can say that the methodology applied contains enough elements that can explain the apparent overestimation of CO₂ emissions compared to NEAT results presented in this paper.

3.6 Conclusions

The yearly variations in carbon storage and non-energy use CO₂ emissions in the years of this study are shown to be limited. Using a net definition of non-energy use, excluding the fuel use in steam crackers and in ammonia, methanol and carbon black production from the non-energy use, we estimate the total non-energy use in CO₂ equivalent to vary between 26 and 30 Mt CO₂. Given the uncertainties involved (estimated to be +/- 2 Mt CO₂, mainly resulting from limited reliability of production and trade statistics), we cannot distinguish a clear trend in this total. Industrial process CO₂ emissions resulting from non-energy use vary between 3.2 and 3.8 Mt CO₂, emissions from the use of ODU products between 1.3 and 3.0 Mt CO₂. The latter have an estimated error of approximately 0.8 Mt CO₂ (again resulting from the limited reliability of production and trade statistics), which makes it difficult to distinguish a clear trend or to draw solid conclusions about the magnitude of these emissions. The remainder of the carbon embodied in the non-energy use (21 – 24 Mt CO₂) is stored in chemicals that are exported from the country or in products that remain un-oxidised during their use. Approximately 90% of the non-energy use in the Netherlands results from natural gas and the total of ‘other oil products’ (excluding bitumen and lubricants). The storage fraction for the

total of ‘other oil products’ varies between 87 and 93%, with the variation being the result of the variation in emissions from the use of ODU products. For natural gas, a storage fraction between 27 – 39% is calculated. The storage fraction for natural gas shows a declining trend as a result of the decreasing production of urea in the years of study.

We also calculated carbon storage fractions including all products produced from non-energy use in the carbon storage and using different definitions of non-energy use (including the total input into steam crackers and ammonia, methanol and carbon black production in the non-energy use). The effect on the resulting storage fractions is substantial, showing the importance of choosing storage fractions consistent with the desired system boundaries and consistent with the applied definitions of non-energy use.

The carbon storage according to the NEAT model is 5.1 – 8.6 Mt CO₂ higher compared to the carbon storage estimate in the NIR. As a result, total fossil CO₂ emissions according to the IPCC-RA are higher by the same amount, which is 3 - 5 % of the total fossil CO₂ emissions in the Netherlands. We have shown that this difference can partly be explained by a methodology that allocates emissions from product use abroad to the Netherlands (~2 Mt CO₂), partly by the omission of storage in exported anodes (~1 Mt CO₂) and partly by low estimates for total non-energy use in CO₂ equivalents in the Netherlands compared to the estimates according to the NEAT model (remainder of the difference)⁹. The latter is mainly caused by difficulties associated with the direct use of non-energy use figures from the Dutch energy statistics for CO₂ emission accounting. It is strongly recommended to critically assess the current emission inventory methodology in the Netherlands using the results of this study. Detailed analyses of the energy and carbon balances of the main companies for which non-energy use is relevant could help to identify possible improvements¹⁰.

The NEAT model is a valuable tool to generate estimates for total non-energy use in CO₂ equivalents, non-energy use CO₂ emissions, carbon storage and storage fractions, which are largely independent from the energy statistics. At the same time, the main drawback of conducting a material flow analysis like the NEAT model is the considerable data

⁹ As already discussed by Neelis et al. (2003), the consequence of a higher non-energy use (as calculated with the NEAT model) on the consistency of the energy statistics and the emission inventory as a whole was not further studied in detail. In-depth analysis of the energy statistics could result not only in a higher non-energy use, but also in a higher value for the Total Primary Energy Supply, which would then result in higher estimates for the total fossil CO₂ emissions. The in-depth analysis of the statistics presented in Chapter 4 (Table 4.7) indicates that this was indeed the case in the years of study.

¹⁰ Currently, the methodology for calculating emissions and carbon storage from non-energy use in the Dutch inventory is indeed being changed using the outcome of this study. The changes involve a different interpretation of the energy statistics (along the lines of text box 1) and a less prominent role of the Emission Registration data in the IPCC-SA.

requirement. The most data intensive part of the analysis is the preparation of a carbon balance that is used to model the downstream structure of the chemical industry. Aim of that balance is to estimate the emissions from ‘solvent and other product use’ (ODU products). As a result of the limited quality of the production and trade data, the largest uncertainty is also in this carbon balance. It is therefore recommended to conduct surveys for the emissions from solvent and other product use to further improve inventories of CO₂ emissions from non-energy use.

Acknowledgements

This research was partly supported by the European Commission (Research Directorate General), 5th framework European Network for Research in Global Change (ENRICH) programme, through research contracts ENV-CT98-0776 and EVK2-CT-2000-80003 (International network Non-Energy Use and CO₂ emissions, NEU-CO₂). Partly, the research was sponsored by the Dutch Ministry of Housing, Spatial Planning and the Environment. The empirical part of this research was executed at the Centre for Economic Micro Data (CEREM) at Statistics Netherlands. The views expressed in this article, however, are those of the authors. Dolf Gielen (International Energy Agency) is acknowledged for commenting on earlier drafts of this paper.

References

- Chemical and Engineering News, 2002. Cover Story: Petrochemicals, Chemical & Engineering News, Vol. 80, No. 11, pp. 21-26.
- Eurostat, various years. The PRODCOM (List of PROducts of the European COMmunity) and Combined Nomenclature classification are accessible online via the Eurostat website: <http://europa.eu.int/comm/eurostat/ramon/>.
- Gielen, DJ, 1997. Potential CO₂ emissions in the Netherlands due to carbon storage in materials and products, *Ambio*, Vol. 26, pp. 101-106.
- IEA, 2002. Energy Balances of OECD Countries, International Energy Agency, Paris.
- IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Volumes 1, 2 and 3, Houghton, JT, Meira Filho, LG, Lim, B, Treanton, K, Mamaty, I, Bonduki, Y, Griggs, DJ and Callander, BA (Eds). Intergovernmental Panel on Climate Change (IPCC), Organization for Economic Cooperation and Development (OECD), International Energy Agency (IEA), Paris.
- Klein Goldewijk, K, Olivier, JGJ, Peters, JAHW, Coenen, PWHG and Vreuls, HHJ, 2002. Greenhouse Gas Emissions in the Netherlands, 1990-2002, National Inventory Report 2004, Netherlands Environmental Assessment Agency, Bilthoven. The corresponding Common Reporting Format (CRF) tables used in this report are the submissions 2004, version 1.0.
- Neelis, M, Patel, M and de Feber, M, 2003. Improvement of CO₂ emission estimates from the non-energy use of fossil fuels in the Netherlands, Utrecht University, Copernicus Institute, Department of Science Technology and Society, Utrecht.
- Neelis, ML, Patel, M, Gielen, DJ and Blok, K, 2005. Modelling non-energy use CO₂ and carbon storage with the Non-energy use Emission Accounting Tables (NEAT) model. *Resources, Conservation and Recycling*, Vol. 45, pp.226-250. Chapter 2 of this thesis.
- Patel, M, Neelis, M, Gielen, D, Olivier, J, Simmons, T, and Theunis, J, 2005. Carbon dioxide emissions from non-energy use of fossil fuels: Summary of key issues and conclusions from the country analyses. *Resources, Conservation and Recycling*, Vol. 45, pp. 195-209.
- Spakman, J, van Loon, MMJ, van der Auweraert, RJK, Gielen, DJ, Olivier, JGJ and Zonneveld, EA, 2003. Method for calculating greenhouse gas emissions, Emission Registration Series/Environmental Monitor, Nr. 37b, March 2003; electronic update of No. 37, July 1997, Dutch Ministry of Housing, Spatial Planning and the Environment, the Hague.
- Statistics Netherlands, 2001. Z029 - Aardoliegrondstoffen en aardolieproducten, Statistics Netherlands, Voorburg.
- VNCI, 2004. Jaarverslag 2003, Vereniging van de Nederlandse Chemische Industrie, Leidschendam.

CHAPTER 4

Towards consistent and reliable Dutch and international energy statistics for the chemical industry*

Abstract

Consistent and reliable energy statistics are of vital importance for proper monitoring of energy efficiency policies. In recent studies, irregularities have been reported in the Dutch energy statistics for the chemical industry. We studied in-depth the company data that form the basis of the energy statistics in the Netherlands between 1995 and 2004 to find causes for these irregularities. We discovered that chemical products have occasionally been included resulting in statistics with an inconsistent system boundary. Lack of guidance in the survey for the complex energy conversions in the chemical industry also resulted in large fluctuations for certain energy commodities. The findings of our analysis have been the basis for a new survey that is used since 2007. We demonstrate that the annual questionnaire used for the international energy statistics can result in comparable problems as observed in the Netherlands. We suggest to include chemical residual gas as energy commodity in the questionnaire and to include the energy conversions in the chemical industry in the international energy statistics. In addition, we think the questionnaire should be explicit about the treatment of basic chemical products produced at refineries and in the petrochemical industry to avoid system boundary problems.

* Accepted for publication in Energy Policy. Co-author is J.W. Pouwelse.

4.1 Introduction

Consistent and reliable energy statistics are of vital importance for proper monitoring of policies aiming to improve energy efficiency and / or to reduce CO₂ emissions. Energy statistics are, for example, one of the key inputs into the yearly National Inventory Reports submitted by countries under the Kyoto protocol (UNFCCC, 2007) and are also essential for monitoring energy intensity developments of countries and sectors over time (e.g. OECD/IEA, 2004). The compilation of consistent and reliable energy statistics requires a good statistical system with good reporting mechanisms, clear definitions and sound procedures for data checking.

This paper zooms in on the compilation of reliable energy statistics for the chemical industry. In 2003, the final energy use of the chemical industry worldwide amounted to 32 EJ (excluding energy conversion losses, but including the use of fossil fuels as feedstock). This is approximately 1/3rd of the final energy use of the total industrial sector and more than any other single sector of industry. Total worldwide CO₂ emissions in the chemical industry amounted to approximately 1 Gt CO₂ (excluding upstream emissions from the production of electricity), 18% of the total industrial CO₂ emissions (OECD/IEA, 2006).

A number of studies report a lack of clarity and inconsistencies related to energy statistics for the chemical industry in both international and national energy statistics, especially in relation to the reporting of the use of fossil fuels as feedstock. Worrell et al. (1994) concluded already in 1994 that the quality of international statistics for the petrochemical industry was insufficient to draw robust conclusions about energy efficiency developments. Patel et al. (1999) found considerable differences in the statistical definition of fossil fuel consumption for feedstock purposes between Italian, German and Dutch energy statistics. More in-depth country studies on feedstock energy use and related CO₂ emissions for Italy, Japan, Korea, the Netherlands and the USA summarized by Patel et al. (2005) confirmed that feedstock energy use data in the energy statistics are incomparable across countries, resulting in significant uncertainties in CO₂ emission accounting. For the Dutch energy statistics, irregularities are also reported in publications on the monitoring of energy efficiency developments in the Netherlands. In a study analysing energy efficiency trends in the Dutch manufacturing industry between 1980 and 1995, Farla and Blok (2000) reported that feedstock use was not ‘properly (or uniformly) defined’ in the statistics. Neelis et al. (2004, 2005a) draw a similar conclusion when trying to reproduce the feedstock energy use data in the Dutch energy statistics using independent physical production trends for the chemical industry.

The studies mentioned challenged us to study in-depth the causes for the observed irregularities in the Dutch energy statistics for the chemical industry. We did this by analysing

the energy statistics surveys as returned to Statistics Netherlands by the most important chemical companies in the Netherlands between 1995 and 2004. These surveys form the basis for the energy statistics for the Dutch chemical industry. Based on the findings of this analysis, we aimed to improve the survey used in the compilation of the statistics to avoid irregularities in the future. We visited the chemical companies returning the survey to better understand the procedures followed at the companies and to ensure commitment from the side of the companies in responding correctly to the improved questionnaire. With our study, we also aimed to derive lessons based on the analysis for the Netherlands for international improvement and harmonization of energy statistics for this important sector of industry.

In this paper, we present an overview of our findings. We first make clear in general terms why the compilation of energy statistics for the chemical industry is such a difficult task (Section 4.2). To introduce the reader into the way the energy statistics for the chemical industry are made in the Netherlands, we then summarize in Section 4.3 the survey used for the compilation of the Dutch energy statistics in the chemical industry. In Section 4.4, we summarize the most important findings of our in depth-analysis of the surveys returned by the most important chemical firms in the Netherlands between 1995 and 2004. Based on our findings, we prepared a new improved energy statistics survey that has been in use since January 2007. The changes made in this improved survey are discussed in Section 4.5, as well as some remaining challenges in relation to the changes made. In Section 4.6, we draw lessons towards consistent and reliable energy statistics for the chemical industry also in the international energy statistics. We end with conclusions in Section 4.7.

4.2 Energy statistics for the chemical industry – why is it so difficult

We can clarify the difficulties related to the compilation of good energy statistics in the chemical industry using the example of three representative process types in the chemical industry.

Process type 1 – Feedstock to chemical products and fuels

In the steam cracking process, hydrocarbon feedstock (e.g. ethane, naphtha or gas oil) is cracked to lower olefins (ethylene, propylene and butadiene), pyrolysis gasoline and a number of by-products. The light by-products of the process (hydrogen and methane) are normally used as fuel in the cracker furnaces to sustain the endothermic cracking reactions. Worldwide, the energy use by steam crackers is estimated by Ren et al. (2006) and Neelis et al. (2007) to

Table 4.1 Simplified mass, energy and carbon balance of a steam cracker using naphtha or gas oil as feedstock

	Calorific value GJ / t ^a	Carbon content t CO ₂ / t ^b	Mass t ^c	Energy GJ	Carbon t CO ₂
Input:					
Naphtha as feedstock	44.5	3.08	1000	44500	3084
Output:					
Ethylene	47.2	3.14	324	15283	1018
Propylene	45.8	3.14	168	7688	528
Butadiene	44.5	3.25	50	2227	163
<i>Sub-total basic chemical products</i>			<i>542</i>	<i>25197</i>	<i>1709</i>
Pyrolysis gasoline	43.0	3.30	156	6708	514
Hydrogen	120.0	0.00	11	1319	0
Methane	50.0	2.75	139	6954	382
Other products returned to refinery	43.0	3.15	152	6536	479
<i>Sum of all products</i>			<i>1000</i>	<i>46715</i>	<i>3084</i>
Total residual gas (hydrogen / methane)	55.2	2.55	150	8274	382
Total residual gas (standard tonnes) ^d	45.2	2.09	183	8274	382
Input:					
Gas oil as feedstock	43.0	3.11	1000	43000	3106
Output:					
Ethylene	47.2	3.14	250	11793	786
Propylene	45.8	3.14	144	6589	453
Butadiene	44.5	3.25	50	2227	163
<i>Sub-total basic chemical products</i>			<i>444</i>	<i>20608</i>	<i>1401</i>
Pyrolysis gasoline	43.0	3.30	166	7138	547
Hydrogen	120.0	0.00	8	960	0
Methane	50.0	2.75	114	5703	314
Other products returned to refinery	43.0	3.15	268	11524	845
<i>Sum of all products</i>			<i>1000</i>	<i>45933</i>	<i>3106</i>
Total residual gas (hydrogen / methane)	54.6	2.57	122	6663	314
Total residual gas (standard tonnes) ^d	45.2	2.13	147	6663	314

^a Values for ethylene, propylene, butadiene, hydrogen and methane based on the pure chemical compounds. Values for naphtha, gas oil, pyrolysis gasoline and other products based on 2006 IPCC guidelines (IPCC, 2006).

^b Values for ethylene, propylene, butadiene, hydrogen and methane based on the pure chemical compounds. Values for pyrolysis gasoline and other products based on 2006 IPCC guidelines (IPCC, 2006). Naphtha and gas oil calculated to close the overall carbon balance.

^c Yields based on Neelis et al. (2005b). Other C₄, <430 oC and >430 oC included in other products. Aromatics, C₅/C₆ and C₇+non-aromatics included in pyrolysis gasoline.

^d In the Dutch statistics, residual gas should be reported as standard tonnes with a calorific value of 45.2 GJ / t (Section 4.3). In this row, we calculate these standard tonnes and the resulting 'standardized' emission factors.

be close to 3 EJ per year, approximately 10% of total energy consumption of the total chemical industry (including feedstock use). To a very large extent (over 80%), the fuels used to supply heat for the steam cracking process are feedstock-derived. The liquid heavy by-products that are produced in the steam cracker are in many cases used as fuel elsewhere, e.g. in steam boilers or furnaces at the same site or elsewhere, for example in the refinery. The mass, energy and carbon balance of a steam cracker using gas oil and naphtha as feedstock is provided in Table 4.1. In the table, we assume the pyrolysis gasoline being delivered to a nearby basic aromatic plant (see below) and the other fuel by-products being returned to a nearby refinery to be blended into the fuel oil pool. The pyrolysis gasoline produced in steam crackers is, together with reformat from catalytic reforming in refineries the main source for chemical-grade aromatics, which are separated in aromatic plants. The non-aromatic parts of the input flows to aromatic plants are normally either returned to refineries or are used as feedstock in the steam cracking process. In Figure 4.1, we present typical simplified mass flows of aromatic plants processing either pyrolysis gasoline or reformat, assuming that the non-aromatic products are returned to refineries.

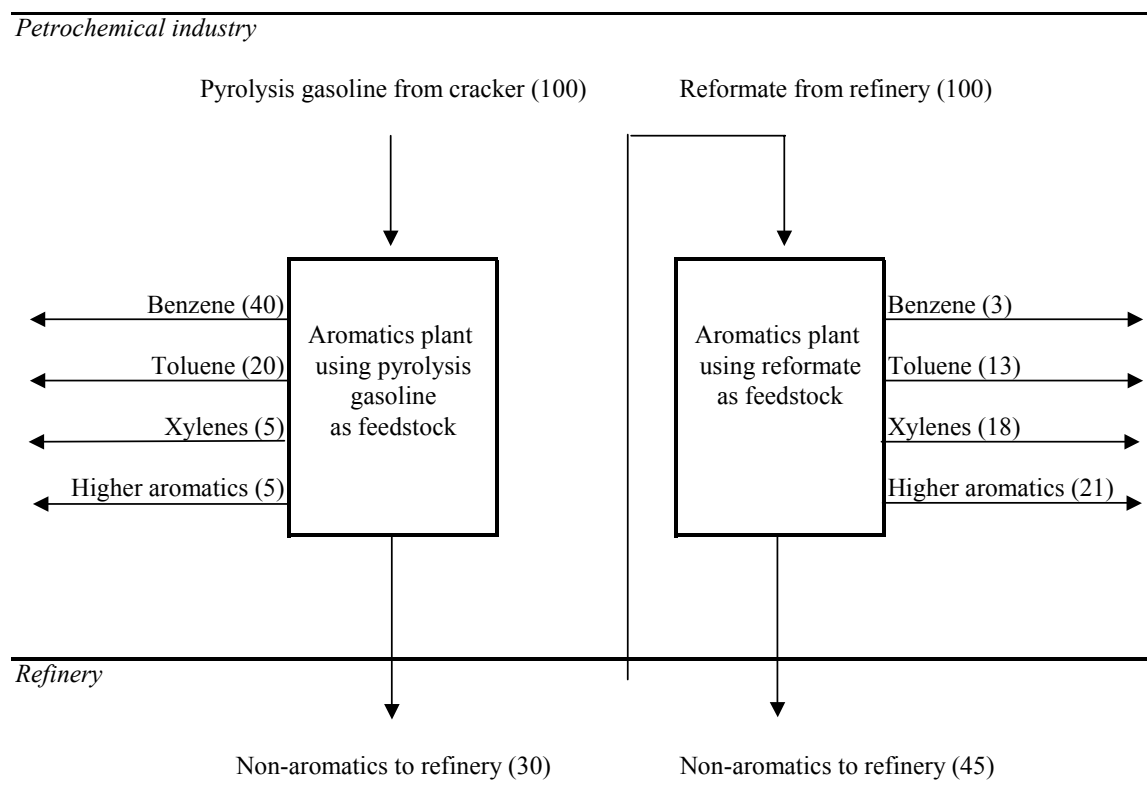


Figure 4.1 Typical feedstock composition (%) for aromatics recovery (based on Emmrich et al., 1999)

Process type 2 – Chemical products to by-product fuels

The basic chemical products (lower olefins and aromatics) produced in steam crackers and aromatics plants are further processed and converted. Functional groups are added to the double bonds in the olefins and aromatics and via a variety of unit processes, plastics and other consumer end products are produced. None of these chemical conversions are 100% selective towards the desired product and by-products are formed. The by-products are often used as fuel in e.g. steam boilers or as fuel in furnaces to directly heat processes. One example of a non-selective process with by-product fuel production is the production of acrylonitrile from propylene and ammonia. In other processes fuel by-products are produced as a result of the desired chemical reaction. An example is the production of hydrogen in dehydrogenation reactions.

Process type 3 – Chemical products to additives

In a few specific processes, chemical products are blended into fuel products and are therefore finally used as energy commodity. An important representative of this process type are additives for gasoline, such as ethyl – tertiary – butyl – ether (ETBE), an anti-knock agent that is produced from ethanol and butylene.

Conclusions from the three process types

In relation to the compilation of energy statistics for the chemical industry, we draw the following conclusions:

- A. The energy commodities that are used as feedstock in the petrochemical industry are converted to basic chemical products and to by-products that are used as fuel either in the same process, in other processes in the chemical industry or in other sectors, e.g. refineries. The energy commodities that are used as feedstock are thus indirectly also used as fuel. The figures given in the steam cracker example show that this feedstock-derived fuel use represents a significant share of the total fuel consumption in the chemical industry.
- B. Next to the fuels derived from feedstock, the conversion of basic chemical products and their derivatives to other chemical products results in low-value by-products, which are also used as fuels in the chemical industry.
- C. In a few specific processes, chemical products are converted into products (e.g. additives for gasoline) that are finally used as energy commodities.

To summarize, we conclude that in the chemical industry, various types of conversions take place between energy commodities, but also between energy commodities and chemical products. In the course of these conversions, the boundary between energy commodities and chemical products is crossed in both directions. The complexity of these conversions makes

the compilation of good and consistent energy statistics for the chemical industry a difficult task.

4.3 Dutch energy statistics for the chemical industry – structure of the survey

In the Netherlands, monthly balances for oil products are prepared by Statistics Netherlands based on a general energy survey with a detailed focus on oil products. The survey is sent to the refineries and oil traders in the Netherlands and to the main chemical companies producing basic chemical products from hydrocarbon feedstock (Statistics Netherlands, 2006). A simplified outline of the survey that has been in use until January 2007 is presented in Table 4.2¹.

The oil products survey is, together with various other energy use surveys, also used in the compilation of the annual Dutch energy statistics (Statistics Netherlands, 2007)². The energy balance for each company and for each of the products included in the oil statistics survey consists of the following items (column number in brackets):

Total plant boundary consumption of energy commodity by the company (F)

=

Product receipts (B) – Product Deliveries (L) – Stock changes (A – N)

=

Production (C,D and E) – Input conversions (G,H and I) – Final use (J and K) – Losses (M)

¹ Over the years, the survey has been changed in a number of ways (e.g. a switch from a paper survey with separate files for each individual product to an electronic survey with all products on one sheet). The basic layout and structure of the survey has however remained unchanged since 1980.

² To limit the scope and size of this paper, we do not discuss the other surveys that are used in the compilation of the Dutch energy balances and the methodology to prepare the energy statistics based on the response to the surveys. This will, however, receive some attention when we summarize the remaining challenges in relation to the changes made in the oil statistics survey (Section 4.5).

Table 4.2 Survey used in Dutch energy statistics (Statistics Netherlands, 2006, translation by authors)

Code	Product	Initial stock	Re-ceipts	Production via		Total	Input into		Final use		Deliveries	Losses ^c	Final Stock		
				CHP ^a	Blending ^b		CHP ^a	Blending ^b	Feed-stock	Heat, light, power					
		A	B	C	D	E	F	G	H	I	J	K	L	M	N
...	...														
5	Chemical residual gas ^d														
8	Naphthas														
9	Aromatics														
...	...														
36	Other products not Chapter 27														
...	...														
40	Steam														
41	Electricity (1000 kWh)														

^a Combined Heat and Power (CHP) production.

^b Other conversions, including steam and hot water not produced via CHP production.

^c Including flares and measurement differences.

^d Report as 1000 kg calculated with a lower calorific value of 45.1962 GJ / t.

The product list used in the survey consists of 41 numbered product groups and contains for each product group references to the 8-digit product codes³ of the Combined Nomenclature (CN) classification used within the European Union for international trade (EC, 2005). We give a part of the product list from the survey in Table 4.3.

Table 4.3 Fragment of product list used in Dutch oil statistics survey until 2007 (Statistics Netherlands, 2006, translation by authors)

Code	Product	Statistical code from Combined Nomenclature (EC, 2005) ^a
...
5	Chemical residual gas	-
...
7	Liquefied gases	...
7a	Propane	2711 1211 – 2711 1219 – 2711 1291 EX – 2711 1293 EX – 2711 1294
...
7e	Other liquefied gases	2711 1400
...
9	Aromatics	2707 1010 – 2707 1090 – 2707 2010 – 2707 2090 - 2707 3010 – 2707 3090 – 2707 5010 – 2707 5090 - 2707 9911 – 2707 9919 – 2707 9930 – 2902 2000 - 2902 3000 – 2902 4100 – 2902 4200 – 2902 4300 - 2902 4400 – 2902 5000 – 2902 6000 – 2902 7000 2902 9010 – 2902 9030 – 2902 9090
...
29	Other products from Chapter 27 of CN	2707 4000 – 2707 6000 – 2707 9100 – 2707 9950 - 2707 9970 – 2707 9999 – 2708 1000 – 2708 2000
...
36	Other products not from Chapter 27 of CN	To be specified
...

^a EX means “part of”.

The product list includes references to product codes from five different Chapters of this CN:

- Chapter 25: Salt; sulphur; earths and stone; plastering materials, lime and cement (product group 37: sulphur)
- Chapter 27: Mineral fuels, mineral oils and products of their distillation; bituminous substances; mineral waxes (majority of product groups).

³ To avoid confusion between references to products from the oil statistics (numbered from 1 – 41, Table 4.3) and chapters and codes from the CN, we refer to the products from the oil statistics as product groups and to the CN chapters and codes as chapter and product codes.

- Chapter 29: Organic chemical products (product group 9: aromatics and 31-33: GTBA, MTBE and methanol).
- Chapter 34: Soap, organic surface-active agents, washing preparations, lubricating preparations, artificial waxes, prepared waxes, polishing or scouring preparations, candles and similar articles, modelling pastes, 'dental waxes' and dental preparations with a basis of plaster (product group 22: lubricants).
- Chapter 38: Miscellaneous chemical products (product group 22: lubricants, product 30 and 34: anti-knock agents with or without lead).

The default unit of reporting for all products is 1000 kg with the exception of electricity (MWh) and natural gas (1000 m³). Refinery gas (product 4) and chemical residual gas (product 5) should be reported in standardized tonnes with a calorific value of 45.2 GJ / t. In Text box 1, we give the definition of the most important items in the survey.

Text box 1 Definition of items in the Dutch energy statistics survey (Statistics Netherlands, 2006, translation by authors)

Column D/H: Blending

If a product is blended or administratively transferred from one or several other products, the quantities should be reported here. Totalised over all products, there should therefore be always equal amounts in columns D and H.

Column E: Production via other conversions, inclusive steam and hot water not produced via CHP:

Report the total quantity of product that is produced crude oil and / or other oil products by processing. Quantities of intermediate products that have been produced in the reporting period and are further converted into other products in the same reporting period, do not have to be reported. If, however, stock of these products is build up or if these products are sold, this has to be reported.

Column I: Input into other conversions, inclusive steam and hot water not produced via CHP

Report the quantity of product that is used in the process to produce other products included in the survey.

Column J: final use as feedstock:

Report in this column the quantity of product that is used a feedstock in the production of (basic) chemical products that do not occur in this survey, because they are not regarded energy carriers.

Column K, final use as source for heat, light or power

The use as source for heat, light or power after which no energy carriers are left. For example, report here the amount of products used as fuel in furnaces. Also report here the quantities of product that, via conversion into live steam, is used as source of heat or power (e.g. turbine-driven pumps) for own use. The produced steam in that case does not have to reported under production of other energy carriers (column E).

4.4 Dutch energy statistics for the chemical industry – main findings of the in-depth analysis of company surveys

For reasons of confidentiality, we cannot disclose in detail quantitative findings for each of the individual companies, described in an internal confidential report published by Statistics Netherlands (Neelis, 2006a). In qualitative terms, we discovered the following three problems in the energy statistics for the chemical industry.

1. Unclear guidance for energy conversion processes in the chemical industry
2. Occasional inclusion of chemical products in the energy statistics
3. Insufficient acknowledgement of the complexity of the industry, in processing the data and in the statistical process in general.

4.4.1 Problem 1 – Unclear guidance for complex energy conversion processes

Lack of guidance for processes with energy conversions in the chemical industry

In the oil statistics survey, it is possible to report conversions between energy commodities. Inputs into energy conversion processes should be reported in Column I and production from energy conversions should be reported in Column E (Table 4.2). However, clear guidance is lacking for the conversion process discussed in Section 4.2 where either the input or (part of) the output is a chemical product rather than an energy commodity. In certain processes such as steam cracking, an energy commodity is converted into both energy commodities and chemical products. The input into these processes is therefore partly used as an input into energy conversions and is partly used as feedstock for the production of (basic) chemical products. The input into energy conversions should be reported in Column I and the use as feedstock should be reported in Column J. In the explanatory notes to the survey, there is no clear guidance on how to make the division over the two columns. The only guidance given is that companies responding to the survey are asked by Statistics Netherlands to check whether the conversion loss, i.e. the difference in mass units between inputs into conversions (column I) and production from conversions (column E) is within the norm. The norm as such is not specified, but in practice, a norm of close to 0% has been in use internally at Statistics Netherlands⁴. This minimal guidance ignores the complexity of the energy conversions in the steam cracker. For example, in many cases multiple feedstocks are used in the cracker. The same product (e.g. chemical residual gas) is thus produced from multiple inputs (e.g. naphtha and gas oil) in the same monthly reporting period. In these cases, the survey can be completed

⁴ Companies were requested to correct their survey in case the conversion efficiency was far from 100% or Statistics Netherlands manually corrected the survey by shifting entries from column I to column J (feedstock use).

in various ways, which all comply with the guidance that the conversion losses are within the norm. Take as an example a company operating a steam cracker that uses in a month, equal amounts of gas oil and naphtha as feedstock for the cracker (Table 4.1). If we assume that the cracker uses its own residual gas (hydrogen and methane) as fuel in the process and that the process does not require additional fuel, there are various ways of reporting to the survey. The two extreme cases of returning the survey for such a cracker are shown in Table 4.4: the conversion balance is closed first using naphtha and then using gas oil for the remaining part (situation a) or first using gas oil and using naphtha for the remaining part (situation b). Both method a) and b) shown in Table 4.4 comply with the guidance given in the questionnaire, but result in different entries for gas oil and naphtha in the various columns and therefore, via multiplication with the calorific value, also in different energy balances. Other, more realistic options are that companies divide the inputs into conversion over gas oil and naphtha in accordance with the ratio in the input or in accordance with the respective amounts of residual gas produced from gas oil and naphtha respectively. Analysis of the surveys returned by the firms confirmed that the companies did not use a consistent division over the conversion and feedstock columns over the years. Another problem in dividing the input into a single process over two columns is that 0% conversion losses (in mass units) does not necessarily result in 0% conversion losses in energy units and that the use of standard tons for refinery gas and chemical residual gas results in an energy balance that lacks a physical basis to the process involved.

Consequences for the resulting energy statistics

The lack of guidance with respect to energy conversion processes in the chemical industry and the practice of using mass units in the oil statistics survey with some products included in standard tons have had the following consequences for the resulting energy statistics in the years of study:

1. Large fluctuations in the columns ‘input into energy conversions’ and ‘final use as feedstock’ for various energy commodities over the years (due to the lack of guidance in case of multiple inputs).
2. Mass, energy and CO₂ balances that lack a clear physical relation to the actual process (due to the use of standard tons for gaseous fuels).
3. Difficulties in using the energy statistics for CO₂ emission accounting (due to use of mass units in the survey).

The second and third consequences are best explained using the example of the naphtha cracker specified in Table 4.1. The energy balance is constructed from the entries in mass units provided by the individual companies by multiplication with the net calorific values of

Table 4.4 Two methods of responding to the oil statistics survey in case of multiple feedstock (arbitrary mass units)

	Receipts		Production via other conversions		Input into other conversions		Final use as feedstock		Final use as source for heat, light, power		Deliveries		Total consumption	
	B	E	I	J	K	L	F							
Method A:														
Naphtha	1000	0	1000	0	0	0	1000							
Gas oil	1000	0	72	928	0	0	1000							
Aromatics	0	322	0	0	0	322	-322							
Residual gas	0	330	0	0	330	0	0							
Other products	0	420	0	0	0	420	-420							
Total	2000	1072	1072	928	330	742	1258							
Method B:														
Naphtha	1000	0	72	928	0	0	1000							
Gas oil	1000	0	1000	0	0	0	1000							
Aromatics	0	322	0	0	0	322	-322							
Residual gas	0	330	0	0	330	0	0							
Other products	0	420	0	0	0	420	-420							
Total	2000	1072	1072	928	330	742	1258							

the fuels involved. The resulting carbon dioxide (CO₂) balance can be constructed by multiplication with the emission factors. We show the results in Table 4.5, assuming that the correct calorific values and emission factors are used (Table 4.1).

Table 4.1 and the balances shown in Table 4.5 make clear that:

- The steam cracking process is an endothermic process. The energy content (calorific value) of the products leaving the cracker exceeds the energy content of the cracker feedstock (Table 4.1). To sustain the endothermic cracker reaction, the residual gas (and other fuels) is burned in the cracker furnaces. Part of this final energy use is therefore converted to chemical energy embodied in the chemical products of the process. The final use as feedstock for conversion into chemical products (22.6 TJ, Table 4.5) is for this reason smaller than the energy content of the chemical products ethylene, propylene and butadiene (25.2 TJ, Table 4.1).
- The CO₂ emissions from the cracker (382 ton CO₂, Table 4.5) can be calculated by multiplying the amount of residual gas used in the furnace with the correct emission factor. The remainder of the carbon present in the feedstock is in our simplified example embodied in the energy commodities sold and in the chemical products (1709 ton CO₂, Table 4.1). In the carbon balance, this is the sum of the difference between input into and production from conversions ($1515 - 1376 = 139$ ton CO₂) and the reported use as feedstock of naphtha (1570 CO₂).
- The use of actual tons (150 tons) rather than standard tons (183 tons) would result in different mass, energy and carbon balances, making the feedstock use dependent on the definition of the standard ton.
- The energy and carbon balances that can be calculated from the mass balance are sensitive to the correct calorific values and emission factors applied. Especially for product groups with strongly varying composition (e.g. chemical residual gas), this could easily result in errors.

4.4.2 Problem 2 – Inclusion of chemical products in the energy statistics

Feedstock use is defined as the use of energy commodities for the production of (basic) chemical products that are not included in the survey, because they are not regarded energy commodities (Box 1, Column J). This definition implies that only those products should be included in the response to the survey that are regarded energy commodities in line with the product list (Table 4.3). Products that can be regarded (basic) chemical products should not be included. In the analysis of the surveys from the period 1995-2004, we discovered that in several cases, (basic) chemical products have been included by the chemical companies in response to the survey. Partly, this has been due to methodological weaknesses in the product definition in the survey and partly this has been due to erroneous reporting by the companies:

Table 4.5 Mass, energy and CO₂ balance for the naphtha cracker of Table 4.1

	Receipts		Production via other conversions		Input into other conversions		Final use as feedstock		Final use as source for heat, light, power		Deliveries		Total consumption
	B	E	I	J	K	L	F						
Mass (t)													
Naphtha	1000	0	491	509	0	0	0	1000					
Aromatics	0	156	0	0	0	156	0	-156					
Residual gas	0	183	0	0	0	183	0	0					
Other products	0	152	0	0	0	152	0	-152					
Total	1000	491	491	509	183	308	692						
Energy (GJ)													
Naphtha	44500	0	21851	22649	0	0	0	44500					
Aromatics	0	6708	0	0	0	6708	0	-6708					
Residual gas	0	8274	0	0	0	8274	0	0					
Other products	0	6536	0	0	0	6536	0	-6536					
Total	44500	21518	21851	22649	8274	13244	31256						
CO₂ (t)													
Naphtha	3084	0	1515	1570	0	0	0	3084					
Aromatics	0	514	0	0	0	514	0	-514					
Residual gas	0	382	0	0	0	382	0	0					
Other products	0	479	0	0	0	479	0	-479					
Total	3084	1376	1515	1570	382	993	2091						

Methodological weakness – Basic aromatics included in the survey

In the product group aromatics (product 9), reference is made to product codes from both Chapter 27 and 29 of the CN. Chapter 27 includes mixtures of hydrocarbon compounds, whereas the product codes in Chapter 29 refer to chemical-grade well defined organic compounds. The 12 product codes from Chapter 29 that are included in the definition of product group 9 (Table 4.3) thus refer to separate chemically defined organic compounds. The products include the basic aromatics such as benzene (code 2902 2000) and toluene (code 2902 3000) that are separated from aromatic mixtures, but also more downstream products such as ethylbenzene (code 2902 6000) and cumene (2902 7000) that are produced out of basic aromatics and other basic chemical products such as ethylene (for ethylbenzene) and propylene (for cumene). It is hard to regard those separate chemically defined organic aromatic compounds as energy commodities, because their use is in principle limited to the use as chemical product. The inclusion of these (basic) chemical products in a survey used for oil and energy statistics is illogical⁵ and also contradicts the wording of the feedstock definition according to which the (basic) chemical products are not part of the survey. It should be noted that formally there is no contradiction, because (basic) chemical products are in the feedstock definition defined as those products that do not occur in the survey, classifying all products that are included (including the separate chemically defined aromatics from Chapter 29) automatically as energy commodities. It was not possible to check whether in the years of study the five companies indeed included the (basic) aromatics that are mentioned in the survey consistently in their response to the survey, since it was not possible to decisively judge whether the reported aromatics refer to mixtures or to chemically defined aromatic compounds.

There is one explanation for the illogical inclusion of at least some of the (basic) aromatics in the oil statistics survey product list. The most important companies processing oil are the oil refineries. Product lists used in energy statistics therefore normally include all the products that are produced by petroleum refineries, including those which are not used as energy commodity, but for non-energy purposes. Examples of such products are bitumen (product group 25) and lubricants (product group 22). To ensure that an overall conversion balance of a refinery can be made, it is necessary to monitor the total output of the refinery, including also these non-energy products. The fact that basic aromatics are also produced within refineries from reformat produced in catalytic reforming therefore offers an explanation for the inclusion of these aromatics in product list used in energy statistics (Table 4.3). Benzene,

⁵ In European legislation on the taxation of energy products (EU, 2003), the definition of the term ‘energy products’ includes the products with CN codes 2901 and 2902 (basic chemical products, including the aromatics, but also e.g. ethylene and propylene). In many cases, financial and tax departments within companies return the survey and in view of this legislation, it is for them not directly counter-intuitive or illogical to consider basic chemical products as energy product. We further discuss as part of problem 3 (Section 4.3).

toluene and xylene are for this reason also mentioned as ‘other products’ in the international oil statistics survey (Section 4.6). Although this is most probably historically the reason to include some of the aromatic products in the survey, it offers no direct explanation for the inclusion of also more downstream aromatic products such as ethylbenzene, styrene and cumene in the survey. In addition, it also results in a potentially selective coverage of these products in the energy statistics, because some of these products (e.g. styrene) are also processed by companies receiving the more general ‘industrial energy use’ survey in which these aromatics are not included.

Methodological weakness – ‘Other products not from Chapter 27 of the CN’

To deal with products that cannot easily be classified into the defined product groups in the survey, two product groups are included for ‘other products’. Product group 29 is included for other products that can be classified within one of the product codes of Chapter 27 of the CN, but which product codes are not mentioned at one of the other product groups in the survey. Product group 36 is included for other products that cannot be classified into one of the product codes from Chapter 27 of the CN. The latter product group 36 was never intended to be used for the various (basic) chemical products produced by the chemical firms responding to the survey such as ethylene and propylene. However, ethylene (product code 2901 2100 in the CN) and propylene (code 2901 2200) do fall under the definition of product group 36 (Other products not belonging to Chapter 27 of the CN). In fact, all product and materials processed by the chemical companies do fall under this definition⁶. In the analysis of the surveys returned by the companies, it was found out that some (basic) chemical products from Chapter 29 of the CN such as ethylene, propylene, cyclohexane and phthalic anhydride have been included in the response to the survey as product group 36. During the company visits it became clear that one of the reasons to do so was that some other (basic) chemical products classified in Chapter 29 of the CN (the basic aromatics, see above) were also included in the product list.

Erroneous reporting – (Basic) chemical products also in other product groups

In the detailed analysis of the survey returned, it was discovered that occasionally the chemical companies reported some (basic) chemical products also erroneously in other product groups. Quantitatively, the most important example in the years of study 1995-2004 has been the inclusion of ethylene, propylene and butadiene in product group 7e (other liquefied gases). This mistake was caused by the reference to product code 2711 1400 in the CN for product group 7e (Table 4.3). This product is in the CN defined as *Ethylene*,

⁶ The addition ‘to be specified’ in the definition of product group 36 (Table 4.3) could be used as a control check by Statistics Netherlands to ensure that only energy commodities are included in this product group. In the analysis it became clear, however, that the specification was not always given and that (basic) chemical products, if reported, have not been removed in the resulting statistics (see also problem 3).

Propylene, Butylene and Butadiene, liquefied (EC, 2005). From the notes in the introduction to Chapter 27 of the CN, it becomes clear that this product group does not include quantities of separate chemically defined ethylene, propylene, butylene or butadiene, which are included in Chapter 29 of the CN⁷, but this has not been understood properly by the company responding. As a result of a lack of detailed knowledge about the company at the side of Statistics Netherlands (see Problem 3), this erroneous reporting have remained undiscovered for many years.

Quantitative consequences for the resulting energy statistics

The occasional inclusion of chemical products within the energy statistics results in energy statistics with an inconsistent system boundary. This results in an inconsistent and erroneous total energy use and feedstock use. We clarify this using again the example of a naphtha cracker (Table 4.1). We assume the company operating this cracker to erroneously regard the propylene produced in the steam cracker as an energy commodity rather than as a chemical product and reporting this propylene as ‘other liquefied gases’. The resulting mass, energy and CO₂ of this company is presented in Table 4.6.

Including propylene as energy commodity results in the following changes compared to the balance in which propylene is regarded a chemical product (Table 4.5):

- The total energy consumption of the company drops with 7.7 TJ, the energy content of the propylene, which is erroneously regarded as an energy carrier.
- The output from energy conversion (Column E) increases with exactly the same amount.
- Input into energy conversions increases and final use as feedstock decreases with 7.5 TJ. The small difference with the 7.7 TJ mentioned above results from the different calorific value of propylene compared to naphtha. In mass units, the changes in all three columns are identical.

The occasional inclusion of chemical products thus results in differences for the total energy consumption, the energy conversion columns and the feedstock column of the energy statistics. The final use for energy purposes (column K) is not influenced. In the example we assume the propylene erroneously included to be exported by the company in question. This raises the question what would happen if the propylene had been delivered domestically to another company. At Statistics Netherlands, the domestic consumption of the relevant

⁷ This is also clear from Eurostat publications on the linkage between the CN and the PRODCOM classification, where the following remark is included for CN product group 2711 1400: excl. ethylene with a purity $\geq 95\%$ and propylene, butylene and butadiene with a purity $\geq 90\%$ (Eurostat, 2006).

Table 4.6 Mass, energy and CO₂ balance for the naphtha cracker of Table 4.1 in case propylene is regarded an energy commodity

	Imports	Production via other conversions	Input into other conversions	Final use as feedstock	Final use as source for heat, light, power	Exports	Total consumption
Mass (t)	B	E	I	J	K	L	F
Naphtha	1000	0	659	341	0	0	1000
Liquefied gases	0	168	0	0	0	168	-168
Aromatics	0	156	0	0	0	156	-156
Residual gas	0	183	0	0	183	0	0
Other products	0	152	0	0	0	152	-152
Total	1000	659	659	341	183	476	524
Energy (GJ)							
Naphtha	44500	0	29327	15173	0	0	44500
Liquefied gases	0	7688	0	0	0	7688	-7688
Aromatics	0	6708	0	0	0	6708	-6708
Residual gas	0	8274	0	0	8274	0	0
Other products	0	6536	0	0	0	6536	-6536
Total	44500	29205	29327	15173	8274	20932	23568
CO₂ (t)							
Naphtha	3084	0	2033	1052	0	0	3084
Liquefied gases	0	528	0	0	0	528	-528
Aromatics	0	514	0	0	0	514	-514
Residual gas	0	382	0	0	382	0	0
Other products	0	479	0	0	0	479	-479
Total	3084	1904	2033	1052	382	1521	1563

products (e.g. liquefied gases, aromatics etc.) are shifted to the column for feedstock use and therefore do not result in errors in the total energy consumption and the total feedstock use. Only in case of exports of erroneously incorporated chemical products, the national energy use is influenced. The overall quantitative effect for the Netherlands can therefore be estimated looking at the net export of the occasionally included chemical products by the companies involved. For the chemical products included under product groups 36 (other products, not from Chapter 27 of the CN) and for the company erroneously reporting ethylene, propylene and butadiene under product group 7 (liquefied gases), we have been able to determine the net export in the period 1995-2004 and the resulting error in feedstock and total energy consumption use in the petrochemical industry (Table 4.7). For details, we refer to Neelis (2006 a,b).

Table 4.7 Quantitative effects of occasional inclusion of chemical products in the energy statistics on the final use as feedstock (excl. electricity) and total energy consumption in the chemical industry (excl. fertilizers). All values in PJ per year.

Year	Total energy consumption reported ^a	Feedstock use reported ^a	Underestimation due to inclusion of chemical products	Corrected total energy consumption	Corrected Feedstock use
1995	523	233	66	589	299
1996	496	211	47	543	258
1997	515	237	36	543	273
1998	499	227	44	543	271
1999	545	255	53	598	308
2000	572	291	33	605	324
2001	595	307	59	654	365
2002	614	306	75	689	381
2003	659	347	63	722	411
2004	683	364	51	734	414

^a Statistics Netherlands (2007)

The large underestimation of feedstock use in the Dutch energy statistics by 14 – 28 % between 1995 and 2004 as a result of the inclusion of chemical products in the energy statistics confirms the findings by Neelis et al. (2004, 2005 a,b). In these studies, it was concluded that the observed feedstock use in the Netherlands was unexpectedly low when compared to estimates for feedstock use based on the production of relevant chemical products in the Netherlands. The total energy consumption of the chemical industry has been underestimated by 5 – 13 % between 1995 and 2004. Expressed as percentage of the total energy consumption in the Netherlands, the underestimation has been approximately 1 – 2%, given the fact that the total energy consumption in the Netherlands was approximately 3000 PJ in the years of study.

Based on our detailed analysis, we also estimated the total export of the pure chemical-grade aromatics included in Chapter 29 of the CN and the resulting change in the energy statistics in case the system boundary of the energy statistics would exclude these chemical-grade aromatics from the energy statistics. If chemical-grade aromatics would be outside the system boundary, we estimate the total energy use and the feedstock use of the chemical industry to further increase by approximately 50 PJ, since the Netherlands is a net exporter of these chemical-grade aromatics. This estimate is based on an own interpretation of the type aromatic flows (mixtures or chemical-grade pure aromatics) at the companies included in the survey and should be regarded only as a rough estimate for the order of magnitude.

4.4.3 Problem 3 – Complexity of the petrochemical industry not acknowledged in the statistical process

In our analysis, we also discovered as an underlying problem that the complexity of the petrochemical industry has not been acknowledged by Statistics Netherlands in the statistical process. There was no involvement from chemical industry experts in the compilation of the statistics and insufficient contact between Statistics Netherlands and the companies responding to the survey on the purpose of the oil statistics survey and on the response to the survey. As a result, errors, once made, could remain for a long time within the system, before being discovered. This has for example been the case for the reporting of ethylene, propylene and butadiene in the product group ‘liquefied gases’ as discussed above. It was also found out that complete and accessible methodological descriptions of the statistical system that is used to process the returned company surveys into published oil and energy statistics were not available at the side of Statistics Netherlands. As a result, personnel changes at the side of the companies filling the survey and at the side of the Statistics resulted in small differences in the methodologies used, which were not in detail documented. As a result, a full quantitative analysis of the various identified problems was not always possible.

Also at the side of the petrochemical industries, the complexity of the conversions in the chemical industry in relation to good and reliable energy statistics has been insufficiently acknowledged. Without any doubt, the companies have a clear view on the various hydrocarbon flows within their companies. The oil statistics survey is, however, normally filled in and returned by financial / tax departments using business accounting software. These departments often lack specific technical knowledge about the complex hydrocarbon flows within the companies, the nature of energy conversions and the use of energy commodities as feedstock. The information exchange within units of the company that do have this knowledge, e.g. the energy coordinator, is not always optimal, partly because the survey is in general not given much priority compared to reports to the government with a

more formal legislative background such as environmental reports, emission reports for the emission trading system etc.

4.5 Changes implemented in the oil statistics survey

4.5.1 Implemented changes

To cope with the three problems discussed above, the survey used in the Dutch oil statistics survey has been changed in the following ways:

Clearer guidance for energy conversions

To better cope with conversion processes where hydrocarbon feedstock is converted into chemical products and energy commodities, the following changes were implemented:

- A. The columns for ‘final use as feedstock’ (column J, Table 4.2) and the column for ‘input into energy conversions’ (column I) are combined into a single column. As a result, companies no longer artificially have to split inputs into a single process (e.g. naphtha and gas oil into the steam cracker process) into different columns in the oil statistics survey. Still it would be possible to allocate a fraction of the input to feedstock use internally by Statistics Netherlands. They are in the position to ensure that the allocation is made in a consistent way. So far no decision has been made about separate reporting of feedstock use in the published statistics.
- B. The mass balance principle is no longer used as a check for the conversion losses. Instead, using standard or company-specific (see next point) calorific values, the mass balance is converted into an energy balance and the conversion loss in energy units is used as check for the conversion losses. In the guidance it is explained that for refineries, the loss should be close to 0%. For chemical companies, the ‘conversion loss’ can be substantially higher, because in the conversion in the chemical industry, a large fraction of the input is converted to chemical products that are no longer regarded energy carriers and are therefore not included. The term ‘loss’ should therefore strictly be interpreted as the difference between input and output of energy commodities.
- C. Companies are explicitly asked to provide calorific values of the energy carriers in case the calorific values differ from the standard calorific values provided.

The resulting survey that should be returned by the steam cracker of our example is given in Table 4.8.

Table 4.8 Mass, energy and carbon balance for steam cracker company responding to the new survey

	Receipts		Production via other conversions		Input into other conversions		-		Final use as source for heat, light, power		Deliveries		Total consumption
	B	E	I	K	L	F							
Mass (t)													
Naphtha	1000	0	1000	0	0	0	0	0	0	0	0	0	1000
Aromatics	0	156	0	0	0	0	156	0	0	0	156	0	-156
Residual gas	0	183	0	0	0	183	0	0	0	0	0	0	0
Other products	0	152	0	0	0	0	152	0	0	0	152	0	-152
Total	1000	491	1000	1000	183	183	308	0	0	0	308	0	692
Energy (GJ)													
Naphtha	44500	0	44500	0	0	0	0	0	0	0	0	0	44500
Aromatics	0	6708	0	0	0	0	6708	0	0	0	6708	0	-6708
Residual gas	0	8274	0	0	0	8274	0	0	0	0	0	0	0
Other products	0	6536	0	0	0	0	6536	0	0	0	6536	0	-6536
Total	44500	21518	44500	44500	8274	8274	13244	0	0	0	13244	0	31256
CO₂ (t)													
Naphtha	3084	0	3084	0	0	0	0	0	0	0	0	0	3084
Aromatics	0	514	0	0	0	0	514	0	0	0	514	0	-514
Residual gas	0	382	0	0	0	382	0	0	0	0	0	0	0
Other products	0	479	0	0	0	0	479	0	0	0	479	0	-479
Total	3084	1376	3084	3084	382	382	993	0	0	0	993	0	2091

The difference between inputs into and outputs from energy conversions equals 23.0 TJ. This equals the calorific value of the chemical products produced (25.2 TJ) minus the endothermicity of the process (2.2 TJ, see Table 4.1, difference between naphtha input and the sum of all outputs). The difference in carbon content between input into and output from conversions is 1709 t CO₂, equal to the carbon content of the chemical products produced. Another solution to better cope with those processes where hydrocarbon feedstock is converted to energy commodities and chemical products would be to ask in the survey for the total mass, energy and carbon balance of inputs and outputs for these processes, including also the chemical products. The statisticians at Statistics Netherlands could use this information as a crosscheck for the reported data by matching the three balances (mass, energy and carbon) and could then include only the energy commodities in the reported energy statistics. Although theoretically better, this solution would further increase the administrative burden on the companies and would bring chemical products back into the survey, which caused significant problems in the past (Problem 2). The decision was therefore made to solely focus on the energy commodities and to use the energy balance as a check.

Exclusion of chemical products from the energy statistics

To avoid reporting of chemical-grade products in the energy statistics (Problem 2), the following changes have been made in the product classification:

- D. The pure chemical grade aromatic products from Chapter 29 of the Combined Nomenclature are no longer included in the product list, because they cannot reasonably be regarded as energy commodities.
- E. Entries in the product group ‘other products not from Chapter 27 of the CN’ are since January 2007 only possible for refineries and no longer for the companies in the chemical industry responding to the survey. The inclusion of this product group for refineries allows refineries to report the total refinery output and hence the correct calculation of refinery losses. However, since these products (e.g. propylene, aromatics, bitumen and lubricants) cannot reasonably be regarded energy commodities anymore, the production of chemical products at refineries (i.e. other products, not from Chapter 27 of the CN) in the final energy balances could be included as a separate item: production of chemical products at refineries.

More frequent involvement of expertise in statistical process

The study as such has helped Statistics Netherlands to develop a better view on the complexity of compiling reliable energy statistics for the chemical industry. The outcome of the study and the set up of the new survey has been discussed with the chemical companies that receive the survey. This helped Statistics Netherlands to better understand the production processes taking place in the chemical industry and helped the companies to better understand

the aim of the survey. It is planned to organize yearly meetings between Statistics Netherlands and the respondents to the questionnaire. At these meetings, not only the contact person responsible for responding to the questionnaire, but also the energy coordinator of the companies will be invited to these meeting in order to stimulate a more optimal exchange of relevant information within the firms.

4.5.2 Remaining challenges / recommendations for further improvement of energy statistics for the chemical industry

The new oil statistics survey is in use since January 2007. In relation to the implementation of the changes into the total energy statistics system in the Netherlands and the resulting CO₂ emission accounting, which is based to a large extent on these energy statistics, we identify the following important remaining challenges:

1. Energy commodities derived from chemical products (Section 4.2, process type 2 and 3).
2. Total coverage of fuels combusted.
3. Implementation into the resulting energy statistics - treatment of other sectors with feedstock use.

Energy commodities derived from chemical products (process type 2 and 3)

In some cases, the inputs into processes where energy commodities are produced are not energy commodities as in the steam cracker example, but chemical products that are not included in the survey. In Section 4.2, we distinguished by-product fuels derived from chemical conversions and chemical products that are blended into fuel products. For the Netherlands, carbon losses in the first category were estimated by Neelis et al. (2007) at 1.6 Mt CO₂ for the Netherlands in 2000 (i.e. approximately 10% of the reported CO₂ emissions of the chemical industry in 2005 (Brandes et al., 2007))⁸. Partly these losses result in direct CO₂ emissions, e.g. in ethylene oxide production where over-oxidation of the ethylene used as raw material results in CO₂. In the Dutch CO₂ emission inventory methodology, these emissions are estimated independently using relevant activity data. When the carbon losses are in the form of fuel-grade by-product that are used as fuel, the production of these fuels could be regarded as a form of 'primary energy production' from raw materials that are not regarded energy commodities. This is comparable to common reporting methodologies for waste incineration where either the waste itself or the steam produced from waste is regarded primary energy consumption. The company visits made clear that it is difficult for the companies responding to the survey to distinguish in the internal accounting systems between

⁸ This estimate excludes conversions where the fuel by-products is a result of the desired chemical reaction (e.g. dehydrogenations).

fuels produced from energy commodities and from chemical products. In practice, fuels derived from conversion between chemical products will therefore be reported as production from conversions in the response to the survey. The production of these fuels thus lowers the observed 'conversion loss', which is in line with the interpretation of 'conversion loss' given above (the difference in a company between the input and output of energy commodities in conversion processes). Disadvantage is that these fuels produced from conversions between chemicals are not separately visible in the statistics.

In line with international practice (see Section 4.6), the production of chemical products such as additives, that are blended into e.g. gasoline and which are therefore finally used as energy commodities will be reported as 'primary production' in the energy statistics by Statistics Netherlands.

Total coverage of fuels combusted

The total coverage of fuels combusted is especially important, because the national CO₂ emission inventory is to a large extent based on the energy statistics. Guiding principle in the emission accounting in the Netherlands is that, for the chemical industry, the difference in carbon content between inputs to conversions and output from conversions is assumed to be stored in chemical products, thereby not resulting in CO₂ emissions. For the steam cracker of our example, this is a valid assumption as becomes clear from Table 4.8. The difference in carbon content between input to conversions and production from conversions equals exactly the carbon embodied in the chemical products (compare Table 4.1). This assumes, however, that all fuels are indeed reported in response to the survey in the column 'production from energy conversions', subsequently put under final consumption and accounted for as CO₂ emissions. It should be checked on a regular basis whether companies indeed report all fuels produced on-site in response to the survey).

Implementation in the energy statistics – other sectors with feedstock use

In the preparation of the annual Dutch energy balances, also a decision should be made about the treatment of flows in other sectors of industry that are currently included as feedstock and non-energy flows. An important example is the use of coal and coke in the blast furnaces. In analogy with the chemical industry, this input is currently partly reported as 'input into conversions' and partly as 'feedstock use' in the energy balances. The part included in the 'input into conversions' is taken equal to the amount of blast furnace gas produced (in energy units). Other examples are the use of petroleum coke for the production of anodes used for aluminium production and the use of natural gas for ammonia production. The type of use and the size order of the relevant flows are well known at Statistics Netherlands and it is planned to use as much as possible a uniform approach to the various conversion processes.

Next step – detailed carbon and energy balances based on all available sources

As a next step for further improvement of the energy statistics and as check for the resulting CO₂ balances, we strongly recommend conducting regular checks on the mass, energy and CO₂ balances of the most important chemical firms in the Netherlands. These checks should involve all source data from these firms to the government such as production data, direct emission reports provided as part of the Emission Trading System (ETS) and environmental reports. These checks could help to identify whether the various flows are properly accounted for the energy statistics and can help to guarantee that CO₂ emissions for the chemical industry are calculated based on the best available information.

4.6 Similar problems in international energy statistics

What lessons can be drawn from our analysis of the Dutch situation for a more consistent treatment of the chemical industry also in the international energy statistics? For the compilation of the yearly international energy statistics, five annual questionnaires are used for respectively oil, natural gas, coal, renewables and electricity/heat (Eurostat/IEA/UN, 2006a-e). The questionnaires are often referred to as the joint annual questionnaires since they are used jointly by Eurostat, the International Energy Agency (IEA) and the United Nations (UN). The three institutions, however, separately process and publish statistics. The questionnaires are structured from the perspective of the main energy supplying and energy conversion sectors. The chemical industry is, together with other industrial sectors, regarded a final energy consuming sector. In the natural gas and coal questionnaire, the consumption of fuels in these final energy consuming sectors should either be classified as final energy or final non-energy use. Non-energy use in these two surveys is defined as in Text box 2 with special reference to the use of natural gas and coals as feedstock for the production of chemical products.

Text box 2 Definition of non-energy use in the Eurostat/IEA/UN natural gas and coal questionnaire (Eurostat/IEA/UN, 2006b,c)

Report by sector and sub-sector non-energy use of natural gas. This category includes feedstocks in processes such as cracking and reforming for the purpose of producing ethylene, propylene, butylene, aromatics, butadiene and other non-energy hydrocarbon-based raw materials. Do not include amounts of energy consumed as fuel for petrochemical processes such as steam cracking, ammonia production and methanol production.

Non-energy use of coal includes uses as feedstocks to produce fertilizer and as feedstocks for other petrochemical products.

Text box 3 Definition of items for the petrochemical industry in the Eurostat/IEA/UN oil questionnaire (Eurostat/IEA/UN, 2006a)

Table 2B: Gross inland deliveries

Report only those quantities of fuels delivered to the petrochemical sector.

Table 2B: Energy use in the petrochemical sector

Report quantities of oil used as fuel for petrochemical processes such as steam cracking.

Table 2B: Non-energy use in the petrochemical sector

Report quantities of oil used in the petrochemical sector for the purpose of producing ethylene, propylene, butylene, synthesis gas, aromatics, butadiene and other hydrocarbon-based raw materials in processes such as steam cracking, aromatics plants and steam reforming. Exclude amounts of fuel used for fuel purposes.

Table 2B: Backflows from petrochemical sector to refineries

These are finished or semi-finished products, which are returned from final consumers to refineries for processing, blending or sale. They are usually by-products of petrochemical manufacturing.

Table 3: Petrochemical industry in the transformation sector

Report quantities of backflows returned from the petrochemical sector, whether returned to refineries for further/processing blending or used directly. The product allocation is calculated using the same proportion of product split for Gross deliveries to the petrochemical sector. Example: 500 units (430 of naphtha and 70 of LPG) are input to the Petrochemical industry. Of the 500, 300 are used as feedstock for the production of petrochemical, 200 units are returned. The total amount of input into the Transformation sector is 200, which is split over Naphtha and LPG (e.g. for LPG backflows: $(70/500) \times 200 = 28$, for Naphtha backflows: $(430/500) \times 200 = 172$).

Table 3: Final consumption in the chemical industry

This heading includes petroleum products used for energy purposes and as feedstocks. However, consumption should be net, after deduction of backflows. The breakdown of net consumption by product should be calculated applying the same proportion of product split for gross deliveries. Example: 500 units (430 of naphtha and 70 of LPG) are input to the Petrochemical industry. Of the 500, 300 are used as feedstock for the production of petrochemicals, 200 are returned. The total amount reported for the Petrochemical industry consumption is 300 (500-200), which is split over naphtha and LPG (e.g. for LPG consumption: $(70/500) \times 300 = 42$, for Naphtha consumption: $(430/500) \times 300 = 258$).

In the oil statistics survey, a separate table (Table 2B) is included dealing with the petrochemical industry. This table is shown in Table 4.9. The definitions of the four items in this table are provided in Box 3. It is recognized that backflows exist from the petrochemical industry to refineries. To get a closed balance for the refinery, these backflows should be accounted for by correcting the total gross deliveries to the petrochemical sector with the quantities that are delivered back to the refinery. These backflows are subsequently included as refinery input under the product group 'refinery feedstock'. The correction from gross deliveries to net deliveries in the petrochemical sector is done by introducing the petrochemical industry as one of the transformation sectors in Table 3 of the survey. In this

Table 4.9 Survey used in international energy statistics (Eurostat/IEA/UN, 2006a)

	Crude oil	Natural gas	Liquids	...	Naphtha	...	Other products	Total
	A	B	F	...	Y	...	Z	Z
Total gross inland deliveries (observed)	1							
Of which: petrochemical flows:								
Gross deliveries to petrochemical sector	2							
Energy use in petrochemical sector	3							
Non-energy use in petrochemical sector	4							
Backflows from petrochemical sector to refineries	5							
Total net deliveries	6							
Of which: net deliveries to petrochemical sector	7							

transformation sector, the backflows should be reported. The product allocation is calculated using the same proportion of product split for gross deliveries to the petrochemical sector (see Box 3 for an example). The net deliveries (i.e. the gross deliveries corrected for the backflows) is to be included in Table 3 under final consumption in the chemical industry, split into non-energy use and energy use, in accordance with the entries in Table 2B.

The product list included in the oil statistics survey included provided in Table 4.10. Regarding the oil products survey used for the compilation of the international energy statistics, we draw the following conclusions:

1. The fuels derived from feedstock that are used in the petrochemical industry (e.g. from steam cracking and aromatics production) are not included in the product list used in the questionnaire.
2. A number of products are included in the questionnaire that is not only produced within the refinery sector, but also within the chemical industry (additives/oxygenates, lubricants and the chemical products listed under ‘other products’). Except for the additives/oxygenates⁹, clear guidance on the inclusion of the products when produced outside the refinery is missing¹⁰.
3. It is confusing that in the description of ‘energy use in the petrochemical industry’ (Box 3) reference is made to the steam cracking process. The main fuel actually being used in this process is not included in the questionnaire (first bullet point) and the production of this fuel cannot be reported in the questionnaire, because no reference is made whatsoever to the conversion from feedstock to energy carriers that are used as fuel within the industry.
4. In none of the questionnaires, explicit reference is made to fuels where the input is not another energy carrier, but a chemical product¹¹.

⁹ According to the oil survey, receipts of additives/oxygenates by refineries and blending plants from outside the refinery sector (note authors: the chemical sector) should be included as indigenous production (domestic receipts) or imports (receipts from foreign origin).

¹⁰ The survey is ambiguous on this point. The addition ‘produced within the refineries’ in the definition of ‘other products’ seems to imply that the production of these products within the chemical sector should not be included. Also the format of the survey points in this direction since production of finished products can only be included as refinery output in the survey. However, in the guidance on reporting imports and exports, it is stated that also ‘petroleum products imported or exported directly by the petrochemical industry should be included’. Whether this refers only to direct imports and exports of hydrocarbon feedstock such as naphtha or also to the other products such as propylene and aromatics is not fully clear. This ambiguity could therefore easily result in an inconsistent system boundary comparable to what has been observed in the Netherlands, especially because refineries are often integrated with the production of basic chemicals.

¹¹ One way of including these fuels is via the renewables questionnaire as ‘production’ of waste of non-renewable origin (solids or liquids) combusted directly for the production of electricity and/or heat.

Table 4.10 Product list used in international energy statistics (Eurostat/IEA/UN, 2006a)

Number	Product
1	Crude oil
2	Natural Gas Liquids (NGL)
3	Refinery Feedstocks
4	Additives / Oxygenates
5	Other Hydrocarbons
6	Refinery Gas (not liquefied)
7	Ethane
8	Liquefied Petroleum Gases (LPG)
9	Naphtha
10	Motor Gasoline
11	Aviation Gasoline
12	Gasoline Type Jet Fuel
13	Kerosene Type Jet Fuel
14	Other Kerosene
15	Gas/Diesel Oil
16	Fuel Oil
17	White Spirit and industrial spirit
18	Lubricants
19	Bitumen
20	Paraffin Waxes
21	Petroleum Coke
22	Other products ^a

^a All products not specifically mentioned above, for example: tar and sulphur. This category also includes aromatics (e.g. BTX or benzene, toluene and xylene) and olefins (e.g. propylene) produced within refineries.

Because an important fuel that is used in the petrochemical industry (i.e. feedstock derived chemical residual gas) is not included in the energy statistics, it is not possible to directly calculate CO₂ emissions based on the international energy statistics. To our knowledge, this is one of the largest sources of fossil CO₂ emissions that cannot be calculated based on the energy statistics. Calculations of CO₂ emissions in the chemical industry for national inventories should therefore be based on the reported feedstock use, e.g. via the use of storage fractions or should be based on methodologies independent from the energy statistics. Regardless the exact methodology used, for a consistent and full accounting methodology for CO₂ emissions in the chemical industry, it is vital to have a clear view how feedstock use, energy use and energy conversions in the chemical industry are included in the energy statistics used for the national inventory. This is also stressed in the new 2006 IPCC Guidelines for greenhouse gas inventories (IPCC, 2006). As a result of the current ambiguity in the questionnaire as summarized in the four points above, this clear view is currently lacking. As a result it is also difficult to make reliable cross-country comparisons of the energy use of the chemical industry and to compare energy efficiency levels for this industry among countries.

To improve this situation, it could be considered to change the oil statistics survey and the resulting international energy statistics in the following way:

- Inclusion of a product category ‘chemical residual gas’.
- Inclusion of a row where conversions in the chemical industry can be reported to acknowledge the fact that the petrochemical industry is a sector where important energy conversions take place.
- More explicit guidance on the reporting of production of chemical products at refineries in relation to production of the same products within the petrochemical industry (e.g. comparable to the suggested approach for the Netherlands discussed in Section 4.5.1).

Incorporating the first two changes would make it possible to report how an important fraction of the energy in the chemical industry is actually being consumed (i.e. via the conversion of feedstock material to fuels) and which fuels are actually being used (chemical residual gas). The treatment of the petrochemical industry becomes in such a way comparable to the treatment of the coal transformation sectors (blast furnaces, coke ovens), where the coal input is transformed into derived gases (blast furnace gas, coke oven gas). Our analysis for the Netherlands as well as the analysis by Farla and Blok (2001) on the quality of the energy statistics for the iron and steel industry shows that inclusion of energy conversion and derived gases in the statistics as such does not automatically result in good quality statistics. Some countries might for example not be capable of delivering data on conversions within the chemical industry, because their data structure is based on surveying only refineries and not on surveying also important industrial end users. They will only report the total feedstock delivery to the chemical industry (i.e. a gross definition of feedstock use that includes the final use of part of the feedstock as fuel). The international organizations publishing international energy statistics based on the joint questionnaire could for the time being, estimate for such countries the production of chemical residual gas from the gross delivery of feedstock, comparable to what is done for blast furnaces and coke ovens. Alternatively, they could adjust the data for countries that do deliver the data on energy conversions to a gross definition of feedstock use to make the reported feedstock data comparable among countries¹². We would like to stress, however, that the Dutch experience with energy statistics for the petrochemical shows that monitoring of the key energy conversions in the petrochemical industry (i.e. at least steam cracking and aromatics processing) is well possible.

¹² In the new 2006 IPCC Guidelines (IPCC, 2006) emissions from key processes that use feedstock-derived fuels are separately included with emission factors based on the output. If the statistics used to compile the inventory use a net definition of feedstock use (i.e. excluding parts which are used as fuel), the inventory maker should make sure that he does not double-count emissions (i.e. via the emission factors for the industrial processes and via the energy use of the fuels). In the case of a gross definition, there is no risk of such double counting.

Also in other countries (e.g. the USA), the residual fuel production in the petrochemical industry is already being monitored. Inclusion of these conversions also in the published international energy statistics would contribute to a better understanding of energy use in the chemical industry and can be an impetus for countries to start collecting these data as well.

4.7 Conclusions

The chemical industry is a very complex industry for the compilation of energy statistics, because of the multiple conversions between energy commodities and chemical products. Based on our analysis for the Netherlands, we conclude that for a consistent treatment of the energy conversions between energy commodities and chemical products in national or international energy statistics for the chemical industry, it is essential to:

1. Define clearly in which way the various conversion processes in the chemical industry are included in the energy statistics.
2. Define clearly which products are seen as energy commodities and which products are seen as chemical products, i.e. to define clearly the system boundaries of the energy statistics.
3. Acknowledge the complexity of the petrochemical industry by involving expert knowledge in the statistical process.

Our analysis has made clear that none of these prerequisites has been fully met in the years of our study in the Netherlands, resulting in inconsistencies and large quantitative errors in the statistics. We conclude that the joint questionnaire used to compile international energy statistics is also ambiguous both with respect to the system boundaries and to the treatment of energy conversions. The changes in the Dutch questionnaire used to compile the Dutch energy statistics and the suggested changes in the international questionnaire provide important improvements towards better and more consistent energy statistics for the chemical industry.

Acknowledgements

We thank the Dutch ministry of Economic Affairs for their financial support of this work. Joost Huurman, Otto Schwertz and Sander Brummelkamp (Statistics Netherlands) are acknowledged for their contribution to this work.

References

- Brandes, LJ, Ruysenaars, PG, Vreuls, HHJ, Coenen, PWHG, Baas, K, van den Berghe, G, van den Born, GJ, Guis, B, Hoen, A, te Molder, R, Nijdam, DS, Olivier JGJ, Peek, CJ, van Schijndel, MW, 2007. Greenhouse Gas Emissions in the Netherlands 1990-2005. National Inventory Report 2007, Netherlands Environmental Assessment Agency, Bilthoven.
- EC, 2005. Commission Regulation (EC) No 1719/2005 of 27 October 2005 amending Annex 1 to Council Regulation 9EEC) No 2658/87 on the tariff and statistical nomenclature and on the Common Customs Tariff. Official journal of the European Union, 28.10.2005.
- Emmrich, G, Ennenbach, F, Ranke, U, Lusch, A, 1999. Krupp Uhde Processes for Aromatics Recovery, in proceedings of 1st European Petrochemicals Technology Conference, 21-22 June 1999, Britannia International Hotel, London.
- EU, 2003. Council Directive No. 2003/96/EC of 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity. Official journal of the European Union, 31.10.2003.
- Eurostat, 2006. 2007 Combined Nomenclature codes not present in PRODCOM list 2007, Luxemburg,
- Eurostat/IEA/UN, 2006a. Oil - Annual Questionnaire 2005 and Historical Revisions, Joint questionnaire for compilation of energy statistics used by Eurostat, International Energy Agency and United Nations.
- Eurostat/IEA/UN, 2006b. Natural Gas - Annual Questionnaire 2005 and Historical Revisions, Joint questionnaire for compilation of energy statistics used by Eurostat, International Energy Agency and United Nations.
- Eurostat/IEA/UN, 2006c. Coal - Annual Questionnaire 2005 and Historical Revisions, Joint questionnaire for compilation of energy statistics used by Eurostat, International Energy Agency and United Nations.
- Eurostat/IEA/UN, 2006d. Renewables - Annual Questionnaire 2005 and Historical Revisions, Joint questionnaire for compilation of energy statistics used by Eurostat, International Energy Agency and United Nations.
- Eurostat/IEA/UN, 2006e. Electricity and Heat - Annual Questionnaire 2005 and Historical Revisions, Joint questionnaire for compilation of energy statistics used by Eurostat, International Energy Agency and United Nations.
- Farla, J and Blok, K, 2000. The use of physical indicators for the monitoring of energy intensity developments in the Netherlands, 1980-1995. *Energy*, Vol. 25, pp. 609-638.
- Farla, JCM and Blok, K, 2001. The quality of energy intensity indicators for international comparison in the iron and steel industry. *Energy Policy*, Vol. 29, pp. 523-543.

- IPCC 2006. 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K(eds). Published: IGES, Japan.
- Neelis M, 2006a. De bruikbaarheid van de Nederlandse Prodcom- en energiestatistieken voor de berekening van CO₂ emissies en energiebesparing in de chemische industrie - openbare samenvatting, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Neelis M, 2006b. De bruikbaarheid van de Nederlandse Prodcom- en energiestatistieken voor de berekening van CO₂ emissies en energiebesparing in de chemische industrie – volledige vertrouwelijke rapportage, Statistics Netherlands, Voorburg.
- Neelis, M, Patel, M and Blok, K, 2005. CO₂ emissions and carbon storage resulting from the non-energy use of fossil fuels in the Netherlands, NEAT results for 1993-1999. Resources, Conservation and Recycling, Vol. 45, pp. 251-274. Chapter 3 of this thesis.
- Neelis, M, Patel M, Blok K, Haije W. and Bach P, 2007. Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes, Energy, Vol. 32, pp. 1104-1123. Chapter 6 of this thesis.
- Neelis, M, Ramirez, A, Patel, M, 2004. Physical indicators as a basis for estimating energy efficiency developments in the Dutch industry, Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Neelis, M, Ramirez, A, Patel, M, 2005. Physical indicators as a basis for estimating energy efficiency developments in the Dutch industry – Update 2005. Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Statistics Netherlands, 2006. Z029 - Aardoliegrondstoffen en aardolieproducten, Statistics Netherlands, Voorburg.
- Statistics Netherlands, 2007. Energiebalans Nederland, accessible online via <http://www.statline.cbs.nl>
- OECD/IEA, 2004a. Oil Crises & Climate Challenges - 30 years of energy use in IEA countries, Organisation for Economic Cooperation and Development, International Energy Agency, Paris.
- OECD/IEA, 2006. Energy Technology Perspectives, Organization for Economic Cooperation and Development, International Energy Agency, Paris.
- Patel, M, Jochem, E and Marscheider-Weideman, F, 1999. CO₂ emissions from non-energy use – Methodological aspects and case study for Germany, Ambio, Vol. 28, pp. 175-181.
- Patel, M, Neelis, M, Gielen, D, Olivier, J, Simmons, T and Theunis J., 2005. Carbon dioxide emissions from non-energy use of fossil fuels: Summary of key issues and conclusions from the country analyses, Resources, Conservation and Recycling, Vol. 45, pp. 195-209.

- Ren, T, Patel, M and Blok, K, 2006. Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. *Energy*, Vol. 31, pp. 425-451.
- UNFCCC, 2007. National Inventory Submissions 2005. United Nations Framework Convention on Climate Change (UNFCCC), accessible via www.unfccc.int/national_reports/items/1408.php.
- Worrell E, Cuelenaere RFA, Blok, K and Turkenburg WC, 1994. Energy consumption by industrial processes in the European Union. *Energy*, Vol. 19, pp. 1113-1129.

CHAPTER 5

Energy efficiency developments in the Dutch energy intensive manufacturing industry, 1980 – 2003*

Abstract

We studied energy efficiency trends in the Dutch manufacturing industry between 1995 and 2003 using indicators based on publicly available physical production and specific energy consumption data. We estimated annual primary energy efficiency improvements in this period at 1.3% on average, with the individual subsectors ranging between –0.1 and 1.5%. Energy efficiency developments with respect to electricity, fuels/heat and non-energy use have been monitored separately and are shown to differ significantly (for the sum of the sectors studied: 1.9% for electricity, 2.6% for fuels/heat and –0.1 % for non-energy use respectively). We combined our results with those from a previous, similar study for 1980 – 1995 and show that over the full time period, efficiency improvements of 1% per year have been achieved on average. Based on comparison with other sources and a detailed uncertainty analysis, we conclude that we developed a reliable top-down monitoring framework for studying energy efficiency trends of the manufacturing industry that can also be applied in other countries where similar data is available. We also showed that substantial differences exist between energy consumption data available from energy statistics and according to the Long Term Agreement monitoring reports, stressing the need for ongoing independent checks of available energy consumption data to avoid problems in future evaluations of energy efficiency policies.

* Published in Energy Policy, Vol. 35 (2007), pp. 6112-6131. Co-authors are A. Ramírez-Ramírez, M. Patel, J. Farla, P. Boonekamp and K. Blok.

5.1 Introduction

Improving energy efficiency is regarded one of the most important options to reduce the emissions of greenhouse gases and the dependency of countries on energy imports (e.g. Metz et al., 2001; EZ, 2005). The large number of national and international policy measures directed towards energy efficiency improvements confirms that policy makers share this view. In order to assess the effectiveness of these policy measures, quantitative methods for measuring energy efficiency improvements are required as was recently also emphasised in the directive on energy end use efficiency and energy services by the European Council and Parliament (EU, 2006). We can monitor energy efficiency developments by quantifying the ratio of energy input and the useful output of a certain activity over time. A distinction can be made between bottom-up and top-down approaches for monitoring energy efficiency improvements (Bowie and Malvik, 2005). In bottom-up approaches, energy efficiency improvements are monitored by adding up the effect of individual specific energy efficiency improvement measures. In top-down approaches, efficiency improvements are based on more aggregate sectoral energy consumption data in relation to the output of the sector. The useful output of an activity can be defined in either physical (e.g. litres of beer produced or person kilometres driven) or monetary units (e.g. GDP of a country or value added of a sector). The choice for either physical or monetary indicators of activity in top-down monitoring of energy efficiency trends depends, among other things, on the desired aggregation level in combination with data availability and data quality (Freeman et al., 1997; Farla and Blok, 2000; Worrell et al., 1997; Boonekamp, 2006).

It is widely accepted that for the evaluation of energy efficiency developments in the manufacturing industry the use of physical indicators of activity, either stand-alone or in combination with monetary indicators, contributes to a better understanding of energy efficiency developments. Examples of studies using physical indicators to analyse energy efficiency developments in the manufacturing industry (especially the energy intensive manufacturing industry) are Phylipsen et al. (1998), Worrell et al. (1997) and Persson et al. (2006). Farla and Blok (2000) mention the close relationship with the concept of specific energy consumption (energy use at the process level) and the international comparability of the resulting energy efficiency indicators as arguments advocating the use of physical indicators in the manufacturing industry. Also, the use of physical production allows filtering out changes in energy use resulting from structural changes within industrial sectors (e.g. a different product mix or the switch from primary to secondary resources), although the ability to do so depends on the types and number of products included in the analysis.

In the Netherlands, physical indicators of activity have also been used intensively for energy efficiency monitoring within the framework of the two generations of Long Term Agreements

(LTA-1 and LTA-2) and the Covenant Benchmarking energy efficiency. These agreements have been the main governmental policies to promote energy efficiency in the industrial sector in the Netherlands since the 1990s, supported by various other policy instruments summarised in Table 5.1.

Table 5.1 Policy instruments for industrial energy efficiency in the period 1995 – 2003. Based on Boonekamp et al. (2002, 2005).

Instrument	Period
<i>Covenants</i>	
LTA-1	1989-2000
LTA-2	2001-2012
Benchmarking covenant	1999-2012
Environmental Action Plan (MAP)	1991-2000
<i>Regulations</i>	
Energy in the environmental permit	1993- present
<i>Fiscal instruments</i>	
Energy Investment Tax Cut (EIA)	1997- present
Variable tax deduction (VAMIL)	1991- present
Regulating energy tax (REB)	1996 -present
<i>Subsidies</i>	
Tenders Industrial Energy Savings (TIEB)	1989-1999
Subsidy scheme for energy conservation techniques (BSET)	1993-1996
CO ₂ reduction plan	1997-2002

The first generation of LTA's on energy efficiency (LTA-1) were voluntary agreements contracted in the period 1992 – 1996 between the Dutch government and particular sectors of industry. The LTA-1 aimed to increase the energy efficiency of a sector by a specific percentage between a base year and an end year (for most sectors 20% between 1989 and 2000, corresponding to 2.0% per year). In 1999, the energy intensive plants consuming more than 0.5 PJ per year signed the Covenant Benchmarking energy efficiency. In this covenant, running until 2012, they committed themselves to be among the world leaders in energy efficiency as soon as possible, but not later than 2012, resulting in required energy efficiency improvements that vary per sector and depend on e.g. the current distance to the world top and the expected development of the world top over time (SenterNovem, 2006).

Part of the less energy intensive industries (companies with a yearly primary energy consumption below 0.5 PJ) signed the second generation of LTA's (LTA-2), also running until 2012. The LTA-2 does not focus on energy efficiency only, but also on other energy topics such as sustainable product development and renewable energy. Companies participating in the LTA-2 are obliged to set-up an energy efficiency plan, which for a period of 4 years describes the goals with respect to energy efficiency improvements. For the first

period (2001 – 2004), the goals for the 16 participating industrial sectors varied between 2.4% and 46% total efficiency improvement (0.8% – 14.3% per year) (SenterNovem, 2005), including improvements due to the use of renewable energy and sustainable product development.

The monitoring methodologies of the LTA-1, LTA-2 and the Covenant Benchmarking are based on confidential production and energy use data of the participating companies. For the industrial sector, mainly physical production data is used. In the LTA-1 monitoring reports, improvement in the energy efficiency indicator determined by top-down indicators is explained by bottom-up overviews of implemented energy efficiency improvement measures. The LTA-1 have been reviewed by Das et al. (1997), Rietbergen et al. (2002) and Farla and Blok (2002). In the latter study, the authors assessed the monitoring methodologies and also the quantitative results of the LTA-1 until 1996. They concluded that the monitoring methodologies of the LTA-1 were insufficiently transparent and recommended independent supervision and verification of the LTA monitoring results. For 1980 – 1995, independent estimates for energy efficiency trends in the energy intensive manufacturing industry based on publicly available physical production data are available from a study by Farla and Blok (2000). This analysis was also used in the LTA assessment study mentioned above (Farla and Blok, 2002). No independent estimates are, however, available beyond 1995, the period in which the LTA-1 for the industrial sector has been replaced with the Covenant Benchmarking and the LTA-2.

This challenged us to analyse in detail energy efficiency trends in the manufacturing industry in the Netherlands since the middle of the 1990s, using a methodology based on publicly accessible physical production and energy use data. This is the main aim of this paper. In addition, we also aim to compare our results with those according to the LTA-1 in order to explore whether the LTA-1 monitoring results could be reproduced using an independent top-down monitoring methodology. Further aims of this paper are to quantitatively assess the effect of data uncertainties on the resulting energy efficiency indicators and to explore the feasibility of using our methodology also in other countries. We would like to stress that the focus of this paper is not on finding bottom-up explanations for the observed changes in energy efficiency of the manufacturing industry or to explain in detail differences in energy efficiency developments between sectors and over time.

In many ways, the methodology developed in this study resembles the methodology used in the study by Farla and Blok (2000). An important addition compared to their method is the focus on both final energy use data and primary energy use data. Other additions are the inclusion of more products per subsector of industry, the separate analysis of the ferrous and non-ferrous basic metal industry and the inclusion of an energy efficiency indicator based on

physical production also for the food industry, one of the non energy intensive subsectors of industry. These latter results are discussed in a separate paper (Ramirez et al., 2006). Despite the differences between the two methods, it is possible to combine our results for 1995 – 2003 with the results for 1980 – 1995 obtained by Farla and Blok (2000), allowing to also present and analyse energy efficiency trends in the Dutch manufacturing industry for the total period 1980 – 2003. In Section 5.2, the methodology and data sources used in this study are discussed. In Section 5.3, we discuss per industrial subsector the realised energy savings and the data-related and methodological uncertainty related to our results. Where possible, we compare our results with the results according to the LTA-1. In a final paragraph, we show the results for the total of the sectors studied. In Section 5.4, we draw conclusions from our study that are relevant for policy makers and explore the feasibility of using the methodology for future monitoring of energy efficiency in the Netherlands and other countries.

5.2 Methodology and data collection

5.2.1 General methodology

We monitor the development of energy efficiency in industrial sectors via an energy efficiency indicator EEI:

$$EEI_{j,k} = \frac{E_{actual,j,k}}{E_{reference,j,k}}$$

Equation 5.1

In which:

- k = Year of analysis with 0 denoting the base year 1995;
- j = Type of energy demand (electricity, fuels/heat, non-energy use);
- $EEI_{j,k}$ = Energy Efficiency Indicator for type of energy demand j in year k ;
- $E_{actual,j,k}$ = Actual energy use from energy statistics for type of energy demand j in year k ;
- $E_{reference,j,k}$ = Reference energy use for type of energy demand j in year k ;

The reference energy use represents the amount of energy an industrial sector would have used if no improvements in energy efficiency had taken place with respect to a certain base year (in our case 1995). The reference energy use is therefore also referred to as ‘frozen-efficiency’ energy use. The reference energy is based on the physical production of products of an industrial sector and the specific energy consumption for these products in the base year 1995:

$$E_{reference,j,k} = \frac{\sum_i SEC_{i,j,0} * P_{i,k}}{\sum_i SEC_{i,j,0} * P_{i,0}} * E_{actual,j,0}$$

Equation 5.2

In which:

$SEC_{i,j,0}$ = Specific energy demand for energy demand type j to produce product i in the base year (e.g. in GJ per tonne of product);
 $P_{i,k}$ = Physical production of product i in year k .

If for the base year all products are accounted for and the SEC's reflect the real energy demand in the base year, the reference energy use could simply be calculated by multiplication of the production of all products of an industrial sector with the specific energy demand. In practice, the incompleteness of available data makes it impossible to include all products of sector (Section 5.2.3). We therefore scale the frozen efficiency energy use for the products included in the analysis to the energy use of the total sector. We distinguish three types of final energy demand: electricity use, fuels/heat use and fuel use for non-energy purposes. Steam and fuel demand is first combined using a conversion factor of 1.11 for steam (corresponding with a boiler efficiency of 90%). The reference energy in primary energy demand is calculated by multiplying the reference energy use per final demand type with a conversion factor f per type of final energy demand for the base year 1995. For the fuels/heat and non-energy use, a conversion factor of 1 is used and for electricity a specific factor is used that already accounts for the penetration of combined heat and power in the sector in the base year. Division of the actual primary energy use with this reference primary energy demand yields a primary energy efficiency indicator.

5.2.2 Energy use data, sector classification and energy use in the base year

We used energy use data from the annual energy balances for the Dutch manufacturing industry (Statistics Netherlands, 2005). In these annual balances, the net available energy is given per industrial subsector and per energy carrier. The net available energy is calculated from a number of balance items:

$$\begin{aligned} \text{Net available energy} &= \text{Purchased energy} - \text{Sold energy} + \text{Own winning} + \text{Stock changes} \\ &= \text{Final energy use} + \text{Final non-energy use} + \text{Input to CHP} - \text{Output of CHP} + \\ &\quad \text{Input to other conversions} - \text{Output of other conversions} \end{aligned}$$

Equation 5.3

For the food, chemical and paper industry, we corrected the basic data to include also combined heat and power (CHP) plants operated by joint ventures of energy and industrial companies. Non-energy use data for the chemical industry was corrected based on a study by Neelis (2006a). Energy use for the paper industry was first corrected to exclude energy use of the publishing industry. More details on these corrections are given in the footnotes below Table 5.2. Total primary energy use is calculated from the net available energy use of a sector using constant conversion factors of 2.50 for electricity bought from or delivered to the grid (reflecting an efficiency of 40%) and 1.11 for heat bought from or sold to third parties (reflecting an efficiency of 90%). From the total primary energy and the final energy use data for the base year 1995, we calculate conversion factors for electricity for use in the calculation of the reference primary energy use. An overview of the final energy use, net available energy use, total primary energy use is given in Table 5.2. We calculated energy efficiency indicators (EEI) based on physical production data for 10 of the 14 industrial sectors distinguished in the annual energy balance of the Netherlands. These sectors cover 87% of the total primary energy of the Dutch manufacturing industry.

5.2.3 Selection of products, physical production data and specific energy consumption data

We included as many products as possible in the analysis with data availability (i.e. production or specific energy consumption data) being the only limitation. Compared to the previous study by Farla and Blok (2000), we have been able to include considerably more products for a number of sectors (e.g. the fertilizer and chemical industry), thereby increasing the energy coverage and reliability of the resulting energy efficiency indicator (see Table 5.4 below for an overview of the energy coverage). The main source for production statistics is the Prodcom statistics (Eurostat, various years). Some of the Prodcom data is confidential (e.g. when a commodity is produced by a limited amount of producers), but for the purpose of this project, we had access to all data via the Centre for Research of Economic Microdata (CEREM) framework of Statistics Netherlands that allows researchers to use confidential data provided that results are only published in aggregated form. For some products, the Prodcom data contained obvious errors, e.g. in the chemical industry, where some companies tend to report only production for sale rather than total physical production including the part of production that is further processed on-site. This limited the number of products that could be included in the analysis. For some other sectors, other data was used, because they proved better suitable for the purpose of our study than the Prodcom statistics. Glass production is for example included in the Prodcom statistics in too much detail (more than 50 different products) and with various physical units (e.g. m³ for packaging glass and m² for flat glass). In these cases, we use data from industry associations or data obtained via personal

Table 5.2 Final energy, net available energy use, total primary energy use in the Netherlands in the base year 1995 (all values in PJ) (Statistics Netherlands 2005)

Sectors in bold covered with physical indicators	Fuels		Steam		Electricity		Total primary energy use ^d	
	Final energy use ^a	Final non-energy use	Net available energy	Final energy use ^a	Net available energy ^b	Final energy use ^{a,c}		Net available energy
Food, beverages and tobacco industry^{e,f}	47.39	0.20	81.11	20.45	-1.17	20.57	14.03	114.90
Textile, clothes and leather industry	6.18	0.00	6.79	0.56	0.14	2.06	1.97	11.87
Paper industry, printing and publishing	9.41	0.00	36.95	15.06	-0.36	11.62	4.09	46.79
Paper industry^{f,g}	7.39	0.00	33.79	15.06	-0.36	8.91	1.38	36.84
Fertilizer industry	27.70	75.75	110.65	3.24	4.01	3.65	1.20	118.11
Chemical industry, excl. fertilizers^{f,h}	154.87	298.80	583.61	84.43	9.29	40.32	11.71	623.22
Building materials industryⁱ	30.05	0.00	31.04	0.55	0.00	4.94	4.73	42.87
Iron and steel basic metals industry	33.01	55.97	93.91	3.37	0.00	8.39	7.57	112.84
Non-ferrous basic metals industry	4.10	2.95	7.53	1.49	1.16	16.56	16.51	50.09
Metal products industry	22.76	12.80	36.48	0.72	0.06	14.16	14.05	71.67
Plastics, rubber and other manufacturing industry	5.78	0.00	5.81	2.25	2.24	6.61	6.61	24.82
Manufacturing industry, not specified by branch	0.00	5.10	5.10	0.00	0.00	0.00	0.00	5.10
Total	348.64	451.57	1032.77	147.18	15.03	137.79	83.86	1259.11
Covered with physical indicators^e	304.51	433.67	941.63	128.59	12.94	103.34	57.14	1098.85
Covered with physical indicators	87%	96%	91%	87%	86%	75%	68%	87%

^a Including the conversion losses (input - output) of the other energy conversions. ^b For a definition of net available energy use, see Equation 3. ^c In the energy balance, non-energy use of electricity (use for electrolysis) is distinguished from other electricity use. In this study, we do not make this distinction and include all electricity use as final energy use. ^d Net available fuel use + net available steam use / 0.9 + net available electricity use / 0.4. ^e Results for the food, beverages and tobacco industry are discussed in Ramirez et al. (2006). ^f For the food, chemical and paper industry, we corrected the net available energy to include combined heat and power plants operated by joint ventures between energy and industrial companies this info is available from separate publications (1994-1997: (Statistics Netherlands, 1994-1998), 1998-2003: (Statistics Netherlands, 2006b)). ^g Excluding printing and publishing industry using data from Statistics Netherlands (2006a). ^h Non-energy use and total primary energy use are corrected upwards with 66 PJ for 1995 based on Neelis (2006a). For the other years of this study, non-energy use is corrected upwards by 47 (1996), 36 (1997), 44 (1998), 53 (1999), 33 (2000), 59 (2001), 75 (2002) and 63 (2003) PJ. ⁱ In the Dutch energy balance, some of the fuels used in cement kilns (1.97 PJ in 1995) are included as non-energy use. For the purpose of this study, we include this part as final energy use.

communications. Specific energy consumption data have been taken from a variety of open literature sources and were chosen to reflect as good as possible the situation in the Netherlands in the base year of our analysis 1995. In some cases, it was possible to use the energy balances directly to determine the specific energy consumption. An example is the production of ammonia. The non-energy use of natural gas in the fertilizer industry can be fully allocated to ammonia production. Combination of ammonia production data and the reported non-energy use yields an estimate for the specific feedstock (non-energy) use for ammonia production. An overview of the products included and the specific energy use figures is given in Table 5.3. The resulting energy coverage per type of final energy use is given in Table 5.4 and will be further discussed in Section 5.3.

5.2.4 Methodology for uncertainty analysis

We quantitatively assessed the uncertainty in the various input variables used in the analysis with the following method. First, we assessed the uncertainty of all input variables and translated these uncertainties into probability density functions (PDFs) for the input variables (i.e. production data, specific energy consumption data and the data from the energy statistics). In a second phase, these PDFs were used to generate a PDF for the output variable using the Crystal Ball 2000 software package (Decisioneering, 2000). For the PDFs of the input variables, we use triangular distributions¹. For the data from the energy statistics, we assume the extremes of the triangular distribution to be +/- 5% of the reported value. The systematic errors resulting from the way energy statistics are compiled (e.g. sampling methodology) are estimated by Boonekamp et al. (2001) at 1% based on communications with Statistics Netherlands. We did, however, identify additional uncertainties related to e.g. wrong reporting by companies and therefore use a higher uncertainty range. For the specific energy consumption data we use triangular distributions with the extremes based on an analysis of the range of specific energy consumption data as they were found in literature thereby taking into account the years and countries to which the literature data referred (resulting ranges are given in Table 5.3). For the production statistics, we used as default a triangular distribution with the extremes being +/- 5% of the reported value, equal to the estimated error in the energy statistics. It should be stressed that we only quantitatively assessed data related uncertainties and not the methodological uncertainties associated with our approach such as the incomplete and changing energy coverage of the products included in the reference energy use over time. These aspects will be separately discussed when discussing our results.

¹ In a triangular distribution, we assume that the value is more likely to be near the mean than far away. We selected a triangular distribution because its 'apparently arbitrary shape and sharp corners are a convenient way to telegraph the message that the details of the shape of the distribution are not precisely known. This may help to prevent over-interpretation of results or a false sense of confidence.' (Morgan and Henrion, 1990).

Table 5.3 Overview of data sources and assumptions uncertainty analysis

Product and physical unit of measurement (tonne if nothing is mentioned)	Prodcom code (PC) or source for production statistics	SEC, electricity		SEC, fuels/heat		SEC, non-energy use		Sources for SEC values ^a
		GJ / physical unit ^a	%	GJ / physical unit ^a	%	GJ / physical unit ^a	%	
<i>Chemical industry, excl. fertilizers</i>								
Ethylene	24141130; Neelis (2006b)	0.30	20%	30.00	20%	72.00	20%	Neelis et al. (2003a); Chauvel et Lefebvre (1989); Patel, 2003)
Methanol	24142210	0.20	10%	8.10	10%	25.40	10%	Neelis (2006c)
Carbon black	24131130	1.70	10%	17.20	10%	37.00	10%	Neelis (2006c)
Basis aromatics ^b	2414223/25/43/45	1.00	20%	5.00	20%	-	-	Neelis, et al. (2003b)
Phosphorus	24131160	46.50	20%	12.50	20%	34.30	10%	Strucker (1994); Neelis (2006c)
Silicon carbide	24135450	25.70	10%	3.30	10%	22.90	10%	Strucker (1994); Neelis (2006c)
Chlorine ^c	24131111	11.00	10%	2.40	10%	-	-	IPTS (2001a)
Polyethylene	24161035/39/50/90	2.50	40%	0.80	40%	-	-	Hydrocarbon Processing (2003)
Polypropylene	24165130/50	0.40	40%	0.80	40%	-	-	Hydrocarbon Processing (2003)
Polyethyleneterephthalate	24164060/6/64	0.70	10%	4.80	10%	-	-	Boustead (2002)
Ethylene glycol ^d	24142310	1.10	20%	9.90	20%	-	-	Neelis et al. (2003b)
Salt	14401000	0.10	20%	1.90	20%	-	-	Strucker (1994)
Caustic soda	24131525	0.00	20%	6.70	20%	-	-	Strucker (1994)
Disodiumcarbonate	24133310	0.80	20%	12.20	20%	-	-	Strucker (1994)
Polystyrene	24162035/39/90	0.50	30%	1.40	30%	40.50	20%	Hydrocarbon Processing (2003); Calorific value

Table 5.3 (Continued)

Product and physical unit of measurement (tonne if nothing is mentioned)	Prodcom code (PC) or source for production statistics	SEC, electricity		SEC, fuels/heat		SEC, non-energy use		Sources for SEC values ^a
		GJ / physical unit ^a	%	GJ / physical unit ^a	%	GJ / physical unit ^a	%	
<i>Chemical industry, excl. fertilizers</i>								
Terephthalic acid	24143435	1.70	10%	3.80	20%	27.00	20%	Boustead (2002); Calorific value
Styrene ^e	24141250; Neelis (2006b)	0.20	10%	6.30	10%	-	-	Neelis, et al. (2003b)
Styrene ^f	24141250; Neelis (2006b)	1.40	40%	10.40	40%	-	-	Neelis, et al. (2003b)
Cyclohexane	24141213	0.10	10%	-1.70	10%	37.50	20%	Neelis et al. (2003b); Calorific value
Sodiumtripolyphosphate	24133270	-	-	5.00	20%	-	-	Struker (1994)
Plasticisers ^g	24664640	0.30	20%	6.90	20%	-	-	Neelis et al. (2003b)
<i>Fertilizer industry</i>								
Nitric acid (tonne N)	24151050	0.50	30%	-12.00	30%	-	-	Worrell (1994)
Ammonia (tonne N)	24151075/77	0.08	40%	10.12	5%	28.95	5%	Chauvel and Lefebvre (1989)
Urea (tonne N)	24153013/19	0.16	30%	5.78	30%	-	-	Nieuwlaar (2001a) Neelis (2006c)
Ammonium nitrate (tonne N)	24153030	0.05	30%	-1.90	30%	-	-	EFMA (2000)
Other nitrogen fertilisers	24153043/45/ 80 / 90	0.69	40%	2.54	40%	-	-	EFMA (2000)

Table 5.3 (Continued)

Product and physical unit of measurement (tonne if nothing is mentioned)	Prodcom code (PC) or source for production statistics	SEC, electricity		SEC, fuels/heat		SEC, non-energy use		Sources for SEC values ^a
		GJ / physical unit ^a	%	GJ / physical unit ^a	%	GJ / physical unit ^a	%	
<i>Iron and steel industry</i>								
Total pig iron production	Eurostat (2001, 2003)	0.46	30%	3.58	30%	10.20	10%	Neelis (2006c); Eurostat (2001); Annema et al., (1992); IPTS (2001b)
Crude Steel (Basic Oxygen Furnace)	IISI (2004) Eurostat (2001, 2003)	0.08	30%	0.05	30%	-	-	Annema et al. (1992)
Crude Steel (Electric Arc Furnace)	IISI (2004) Eurostat (2001, 2003)	1.72	30%	0.47	30%	-	-	Gielen and van Dril (1997)
Hot rolled products	IISI (2004) Eurostat (2001, 2003)	0.40	30%	1.80	30%	-	-	Gielen and van Dril (1997)
Cold rolled products	IISI (2004) Eurostat (2001, 2003)	0.50	30%	1.10	30%	-	-	Gielen and van Dril (1997)
<i>Paper industry</i>								
Newsprint paper ^b	VNP (1993-2002)	4.80	10%	7.70	10%	-	-	Mulder and Sinon (1994)
Coated paper and writing paper	VNP (1993-2002)	2.30	10%	7.80	10%	-	-	Mulder and Sinon (1994)
Uncoated paper and writing paper	VNP (1993-2002)	4.80	10%	7.70	10%	-	-	Mulder and Sinon (1994)
Household and sanitary paper	VNP (1993-2002)	3.60	10%	7.50	10%	-	-	Mulder and Sinon (1994)

Table 5.3 (Continued)

Product and physical unit of measurement (tonne if nothing is mentioned)	Prodcom code (PC) or source for production statistics	SEC, electricity		SEC, fuels/heat		SEC, non-energy use		Sources for SEC values ^a
		GJ / physical unit ^a	%	GJ / physical unit ^a	%	GJ / physical unit ^a	%	
<i>Paper industry</i>								
Corrugated case materials	VNP (1993-2002)	1.40	10%	5.90	10%	-	-	Mulder and Sinon (1994)
Wrapping papers ¹	VNP (1993-2002)	1.40	10%	5.90	10%	-	-	Mulder and Sinon (1994)
Grey board (including specialties) ¹	VNP (1993-2002)	1.40	10%	5.90	10%	-	-	Mulder and Sinon (1994)
Folding box board	VNP (1993-2002)	2.60	10%	8.80	10%	-	-	Mulder and Sinon (1994)
<i>Building materials industry</i>								
Clinker	Mergelsberg (2004, 2005)	0.25	20%	3.42	20%	-	-	Nieuwlaar (2001b)
Cement	PC 26511230/ 50 / 90	0.19	20%	0.63	20%	-	-	Nieuwlaar (2001b)
Tiles (1000 pieces)	PC 26401250	0.29	30%	7.02	30%	-	-	de Castro (1992) ¹
Bricks (1000 WF ^b)	KNB (2003, 2004)	0.19	30%	4.67	30%	-	-	de Castro (1992) ¹
Paving bricks (1000 WF ^b)	KNB (2003, 2004)	0.21	30%	5.13	30%	-	-	de Castro (1992) ¹
Glass	Beerkens (2004, 2005)	1.30	10%	6.81	10%	-	-	Nieuwlaar (2001b)
<i>Non-ferrous basic metal industry</i>								
Primary aluminium	PC 27421153	54.90	5%	3.70	20%	-	-	Alsema (2000)
Secondary aluminium	PC 27421155	0.60	40%	5.70	40%	-	-	Alsema (2000)

Table 5.3 (Continued)

Product and physical unit of measurement (tonne if nothing is mentioned)	Prodcom code (PC) or source for production statistics	SEC, electricity		SEC, fuels/heat		SEC, non-energy use		Sources for SEC values ^a
		GJ / physical unit ^a	%	GJ / physical unit ^a	%	GJ / physical unit ^a	%	
<i>Non-ferrous basic metal industry</i>								
Primary zinc production	PC 27431230 Keijssers (2004)	14.80	5%	2.40	20%	-	-	Alsema (2000)
Anode production	Frijlink (2004) ; Alcan (2004)	0.40	20%	3.90	20%	27.57	10%	Alsema (2000); Neelis (2006c)

^a The percentages refer to the boundaries used in the triangular distributions (Section 5.2.4). For more information about the sources used for the specific energy consumption values, we refer to Neelis et al. (2004, 2005).

^b The production processes for benzene, toluene, p-xylene, o-xylene and m-xylene are highly integrated. Separate SECs are therefore difficult to distinguish.

^c Assuming 50% of chlorine to be produced with membrane cells, 32% with mercury cells and 18% with diaphragm cells (Nieuwlaar, 2001a).

^d Including the production of ethylene oxide.

^e Including ethylbenzene manufacture.

^f Including ethylbenzene manufacture, via the combined propylene oxide / styrene route.

^g Including alcohol production.

^h In the study by Mulder and Sinon (1994), the company producing newsprint paper was categorised in the uncoated paper and writing paper. Therefore, the SEC values for this category are used for newsprint paper.

ⁱ Values for corrugated case materials used.

^j According to Mulder and Sinon (1994), the division between specialties and grey board was 16% vs. 84%. The SEC values of specialties and grey board are added using these percentages.

^k WF stands for Waal Formaat, a brick with dimensions 20*10*5 cm (Novem, 2000).

^l In de Castro (1992), SEC values of 2.70 GJ fuels / tonne and 0.11 GJ electricity / tonne are given. We use a specific weight of 1.73 kg / WF bricks, 1.90 kg / WF paving bricks and 2.60 kg per tile (Huizinga et al., 1992) to come to the SEC values given here.

Table 5.4 Energy coverage of products included in the reference energy use in this study (%)

	Fuels/heat	Non-energy use	Electricity	Total primary energy use
Paper industry	89%	-	86%	87%
Fertilizer industry	82%	100%	58%	91%
Chemical industry, excl. fertilizers	52%	84%	46%	66%
Building materials industry	70%	-	57%	66%
Iron and steel basic metals industry	87%	101%	82%	93%
Non-ferrous basic metals industry	41%	100%	91%	86%
Total covered in this study	61%	89%	64%	78%

5.2.5 Combining the results with results from 1980 – 1995

As explained in the introduction, we combine our results for the period 1995 – 2003 with the results obtained by Farla and Blok (2000) for 1980 – 1995. To do so, we had to deal with some differences between the current study and the study for 1980 – 1995. One difference is the use of updated energy use for 1995 in the current study, based on Statistics Netherlands (2005). To ensure consistency, we replaced the 1995 energy use data from the former study with the newly available data. Another difference is the use of other specific energy consumption (SEC) data in the old study. We recalculated the energy efficiency indicators for 1980 – 1995 using the specific energy consumption data applied in this study and the production data available from the old study. In this way, we got a consistent time series. An exception was the chemical industry for which this approach was not possible (see Section 5.3.2). A third difference is a different way of calculating primary energy use. Farla and Blok converted the net available energy use of a sector using actual grid electricity conversion efficiencies (increasing from 36 – 38% between 1980 and 1995) and by valuing steam with 75% of its heat content. Also, climate correction was applied. We ensured consistency by recalculating primary energy use for 1980 – 1995 based on the assumptions used in this study (i.e. no climate correction and fixed conversion efficiencies of 40% for electricity and 90% for steam respectively). We would like to stress that our recalculations for the period 1980 – 1995 to correct for the three differences mentioned did not result in any significant changes in the estimate annual efficiency improvements between 1980 and 1995 compared to the estimates by Farla and Blok (2000). The fourth difference regards the product coverage. In this study, we have been able to include more products per sector, thereby increasing the quality of the reference energy use as indicator for the frozen energy efficiency developments. In the discussion of the results per subsector we will further discuss this.

5.3 Results and discussion

5.3.1 Summary of results

In Figure 5.1, we summarise the average annual reduction in the EEI between 1995 (the base year of the analysis) and 2003. Detailed yearly results are given in Appendix A. We include the uncertainty bars (95% confidence interval) determined with the method described in Section 5.2.4. In Table 5.5, we include the average reduction in EEI between 1980 and 1995, the period between 1989 and 2000 (the full period of the LTA-1) and 1995 and 2000, the period of the LTA-1 studied in detail in this paper. Below, we discuss the results per individual subsector and for the total of the sectors analysed.

Table 5.5 Average annual decrease in primary energy efficiency indicator (% / year)

	80-95 ^a	95-03	80-03 ^b	89-00	89-00 LTA	95-00	95-00 LTA
Chemical industry, excl fertilizers		1.5%				1.5%	
Chemical industry, excl fertilizers, excl. non-energy use		3.2%				4.0%	
Fertilizers	2.3%	0.9%	1.8%	0.7%		1.9%	
Fertilizers, excl. non-energy use ^c	<i>6.8%</i>	1.6%	<i>4.9%</i>	<i>3.6%</i>		3.6%	
Total chemical sector		1.4%				1.6%	
Total chemical sector, excl. non-energy use		3.1%			2.6%	4.0%	3.6%
Iron and steel basic metals industry		1.0%				0.2%	
Iron and steel basic metals industry, excl. non-energy use		2.0%			1.6%	0.4%	1.3%
Non-ferrous basic metals industry		1.4%				0.3%	
Non-ferrous basic metals industry, excl. non-energy use ^d		1.4%			1.6%	<i>0.4%</i>	2.0%
Total basic metals industry	0.4%	1.1%	0.6%	-0.1%		0.3%	
Total basic metals industry, excl. non- energy use ^d	0.4%	1.7%	0.9%	<i>-0.1%</i>	1.6%	<i>0.4%</i>	1.4%
Building materials industry	1.5%	1.1%	1.3%	1.2%	1.2%	0.4%	0.7%
Paper industry	2.5%	-0.1%	1.6%	0.9%	2.2%	-0.2%	2.1%
Total industry		1.3%				1.3%	
Total industry, excl. non-energy use ^d		2.5%			2.3%	2.7%	3.0%
Total industry, excl. total chemical industry	0.9%	0.9%	0.9%	0.3%		0.2%	
Total industry, excl. total chemical industry, excl. non-energy use ^d	0.9%	1.2%	1.0%	<i>0.4%</i>	1.7%	<i>0.3%</i>	1.4%

^a Data exclusive non-energy use are for the period 1982-1995. For 1980 and 1981, no non-energy use estimates available. ^b Data exclusive non-energy use are for the period 1982-2003. For 1980 and 1981, no non-energy use estimates available. ^c Data in italics are uncertain estimates, because of the unclear definition of non-energy use in the fertilizer industry (see text). ^d Data in italics cannot directly be compared with the LTA-1 data (see text).

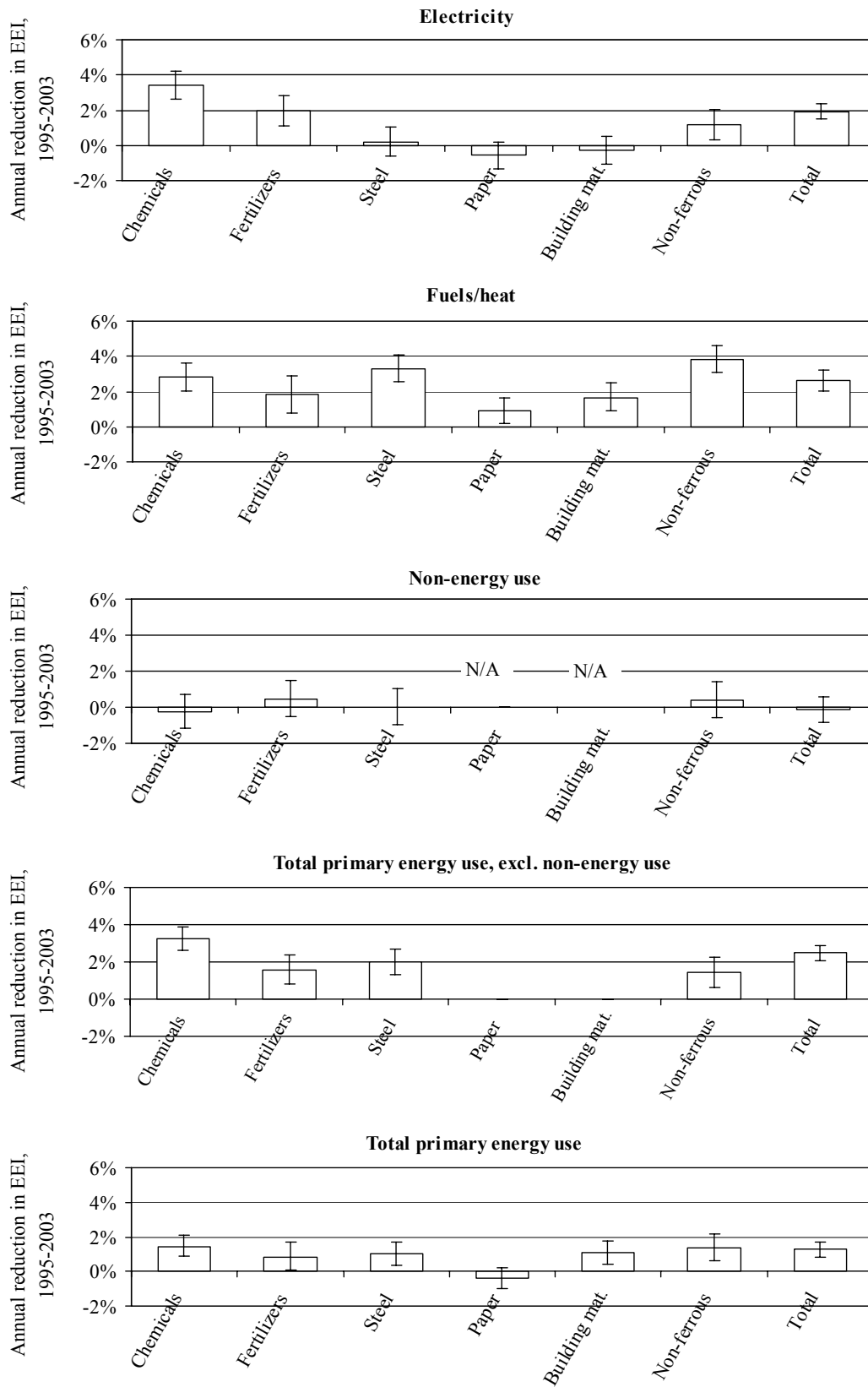


Figure 5.1 Annual reduction in EEI between 1995 and 2003 (% / year)

5.3.2 Chemical sector

Chemical industry, excl. fertilizers

The development of the reference energy use in the Farla and Blok study was based on specific energy use data including non-energy use. Since the underlying production data in the analysis for 1980 – 1995 were confidential (Farla and Blok, 2000), we could not calculate EEI developments excluding non-energy use before 1995. The upward correction of non-energy use in the energy statistics for the chemical industry, excl. fertilizers in the period 1995 – 2003 based on Neelis (2006a) could not be made before 1995. As a result, also no consistent time-series for total primary energy use including non-energy use are available for the period 1980 – 1995. These two factors explain the omission for 1980 – 1995 in Table 5.5 .

For the period 1995 – 2003, we estimate the reduction in EEI at 2.8% per year for fuels/heat (95% confidence range between 2.0% and 3.6%) and 3.4% per year for electricity use (95% confidence range between 2.6% and 4.2%). The EEI for non-energy use fluctuates between 0.90 and 1.11. A change in the EEI for non-energy use can be expected if the yield of the different products from steam cracking changes over time (e.g. as a result of changing feedstock distributions), but is most probably caused by remaining inconsistencies in the energy statistics. This is further discussed below. In primary energy terms, we estimate efficiency improvements at 3.2% per year on average between 1995 and 2003, excluding non-energy use (95% confidence range between 2.6% and 3.8%). This is equivalent to 103 PJ savings on primary energy use per year. Increased use of combined heat and power contributes 9 PJ to this total. The uncertainty ranges given above relate to estimated data uncertainties. In addition, also methodological uncertainties are important:

- The products included in the reference energy use cover only 66% of the total primary energy use of the sector (Table 5.4) and are biased towards the energy intensive products. Products of a number of subsectors are not covered in the analysis (e.g. industrial gases, fine chemicals, specialty polymers). Different growth rates of the products included and not included in the reference energy use could therefore lead to wrong results. We visualize this in Figure 5.2. Between 1995 and 2003, the reference energy use increased by 35% and the actual energy use by only 20% resulting in an observed EEI of 0.89 in 2003, i.e. an energy efficiency improvement of 11% in this time period. If the non-covered products have grown in this period by only 20% rather than 35%, the actual energy efficiency improvement for the industry is only 7.5% instead of the 11.0% observed. If, on the other hand, the growth rate of the non-covered products has been 50%, actual savings would be 14.2% rather than the observed 11.0%. These ranges are in the same order as the data related uncertainties estimated via the method explained in Section 5.2.4. We show for comparison also the

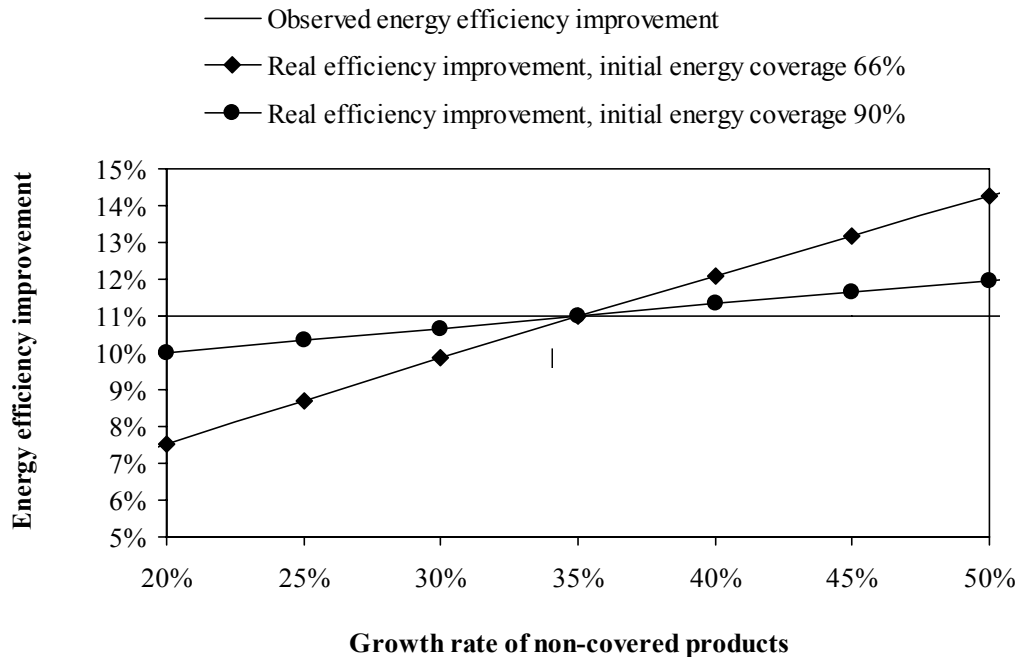


Figure 5.2 Actual energy efficiency improvements in case of different growth rates of covered and non-covered products for initial coverage of 66% and 90%. Growth rate of covered products 35%.

effect of different growth rate of covered and non-covered products in case the covered products cover 90% of the energy use in the base year. In that situation, the difference between observed and actual energy efficiency improvements is far less. Based on the comparison with the LTA-1 data (see below), we are confident that for the period until 2000, our indicator is a reliable indicator for the frozen efficiency energy use of the chemical industry. The effect of low and changing coverage could however be studied in more detail, e.g. by comparing the value added growth of subsector of the chemical industry that are not covered with those covered and by analysing detailed energy use data at the level of individual firms or subsectors. We leave this for a further analysis.

- We included the steam cracking process using production of ethylene only, because the production statistics of the other steam cracker products (e.g. propylene and butadiene) proved to be unreliable. We also did not correct for yearly differences in feedstock distribution for steam cracking, because data was unavailable. Varying product yields and feedstock distributions can have an effect on the specific energy consumption, but our indicator cannot capture these effects. Variations in the type of feedstock applied in the steam cracking process can change the specific non-energy

use (expressed per tonne of ethylene) by up to 15%² and can have an even larger effect on the fuels/heat and electricity use of the steam cracking process. This methodological uncertainty could therefore explain part of the fluctuation in EEI for non-energy use between 0.90 and 1.11 in the years of study and can also add to the uncertainty in the EEI for fuels/heat and electricity use. However, given the good match between our reference energy use and the reference energy use according to the LTA-1 (see below) and the relatively stable feedstock distribution², we consider it more likely that the fluctuation in the EEI for non-energy use is caused by remaining inconsistencies in the non-energy use data from the energy statistics. The default uncertainty range for data from the energy statistics (+/- 5%) might therefore not be valid for non-energy use data in the chemical industry.

Fertilizer industry

For the fertilizer industry, the annual reduction in primary EEI is estimated at 0.9 % per year between 1995 and 2003 (95% confidence level between 0.1% and 1.7%). This corresponds to primary energy savings of 4 PJ primary energy use per year in 2003 compared to 1995. Average annual EEI reductions for electricity are estimated at 2.0% (confidence range between 1.1% and 2.8%) and for fuels/heat at 1.8% (range between 0.8% and 2.9%). Changes in the efficiency and use of CHP in the fertilizer industry had a negative effect on the EEI for primary energy of about 1 PJ, resulting in lower primary savings compared to the savings on final fuels/heat and electricity use. Annual reductions in the EEI for non-energy use of fuels are estimated at 0.5% per year. Reduction in EEI with respect to non-energy use are possible, because the feedstock into ammonia plants is not defined as the calorific value of the ammonia product, but probably as the natural gas input into the reforming process. Different plant set-ups or differences in operation might result in different amounts of natural gas used in the reformer and can therefore also change the EEI for non-energy use. It should be noted, however, that in the surveys used to prepare the Dutch energy statistics, feedstock use is not precisely defined. Therefore, practices might differ from plant to plant and it can be questioned whether the allocation between final energy and final non-energy use is made in a consistent way throughout the years, especially before 1995. We therefore put the results without non-energy use before 1995 in italics in Table 5.5.

The detailed results per year (Appendix A) reveal a sudden increase in EEI in 2002 and 2003. This increase can possibly be attributed to low capacity utilization factors as a result of a declining production. The drop in EEI in 2000 and 2001 can most probably be attributed to

² We base this range on the specific energy use in butane, propane, naphtha and gas oil cracking as given by Neelis et al. (2003a). The actual fluctuation will be less, because the feedstock mix normally does not change much from year to year. For 1993-1999, the feedstock mix has for example been more or less stable (Neelis et al., 2003a).

the closure of the oldest (and least efficient) ammonia production facility in the Netherlands. The reference energy use is based on products that cover the majority of the fuels/heat and non-energy use of the sector (82% and 100% respectively) and slightly more than 50% of the electricity use. Based on this energy coverage, we conclude that the reference energy use is a reliable indicator for the frozen efficiency developments in the fuels/heat and non-energy use, but might be less accurate for the electricity use of the sector. Over the full period 1980 – 2003, the average annual drop in EEI was 1.8%. It should be noted, however, that in the reference energy use by Farla and Blok for 1980 – 1995, only ammonia was included and structural changes between different types of nitrogen fertilizers are therefore not monitored in that period.

Total chemical sector, comparison with the LTA-1

We further assessed the methodological uncertainties, the quality of the energy statistics and the reliability of our results by comparing our results with the results obtained within the LTA-1 framework (Figure 5.3), including the total chemical sector. To ensure consistency with the LTA, we excluded from the primary energy use figures (left graph), the non-energy use of fuels, but also the non-energy use of electricity as it is reported in the energy statistics. For the reference energy use, this was not possible, because it is unknown which part of the electricity use in e.g. chlorine production is regarded non-energy in the energy statistics and which accounting practices the various firms use. The trend of the reference energy use according to the LTA is comparable in the years of the current study (1995 – 2000). Since in the LTA index, all products of the companies that took part in the agreement are included, it is likely that the reference energy use according to the LTA reflects quite accurately the actual frozen efficiency development in the chemical industry. The fact that the LTA index corresponds so well with the reference energy use developed in this study for the years 1995 – 2000, is an indication that the reference energy use is a reliable indicator for the frozen efficiency development, despite the relatively low energy coverage of approximately 50% in the base year³.

The development of the total primary energy use in the LTA differs significantly from the development of the total primary energy use in our study (Figure 5.3, left side). In absolute values, the difference fluctuates between 0 PJ (1992) and 20 PJ (1995), corresponding to 0% – 6% of the value reported in the statistics. Studying the background of the observed differences in more detail is difficult, because underlying company data from both the LTA and the energy statistics is confidential and some methodological differences exist between the energy statistics and the LTA-1. We conclude that, despite the efforts at Statistics

³ The coverage including non-energy use is 66%, but for fuels/heat and electricity use, the coverage is about 50%.

Netherlands to make the LTA-1 and the data from energy statistics consistent (Pouwelse, 1997), there are still differences between the two datasets, a conclusion also drawn already by Farla and Blok (2002). The differences between the LTA-1 and our calculations in the average annual reductions of the EEI for 1995 and 2000 (4.0% vs. 3.6%, Table 5.5) can be attributed to these differences.

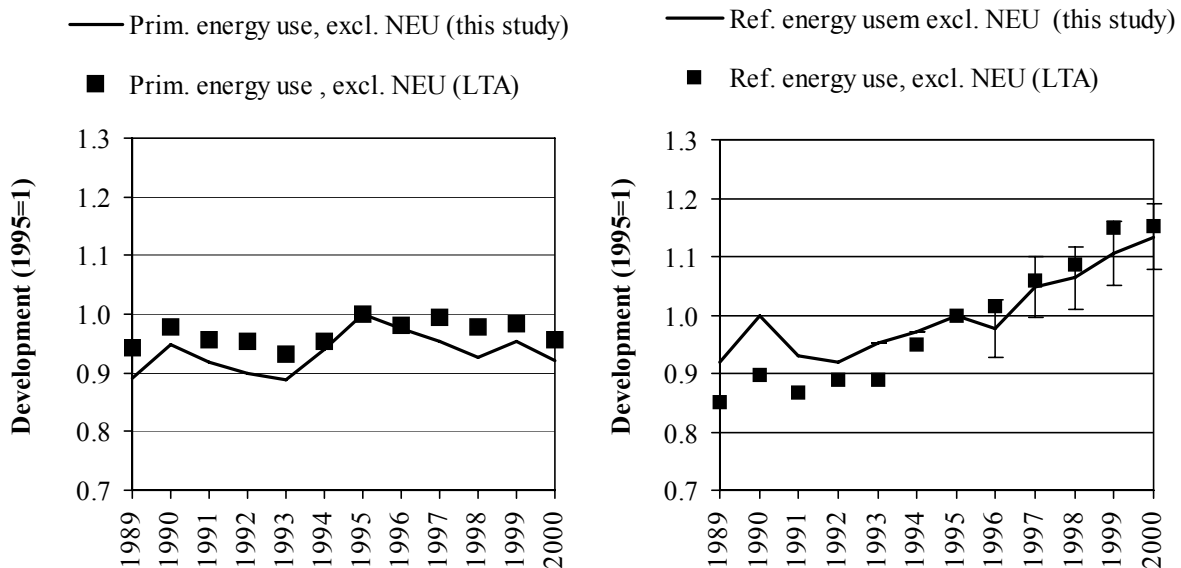


Figure 5.3 Primary energy use and reference use according to our study for the total chemical industry and according to the LTA (Novem, 2001a)

5.3.3 Basic metals industry

Iron and steel basic metal industry

The average annual reduction in the EEI for the iron and steel industry between 1995 and 2003 is estimated at 1.0% per year (confidence interval between 0.3% and 1.7%) when we include non-energy use and 2.0% (confidence interval between 1.3% and 2.7%) when we exclude non-energy use. This corresponds to yearly primary energy savings of 10 PJ in 2003 compared to the base year level. Changes in the efficiency and use of CHP are not important for this industry (<1 PJ). Efficiency improvements have mainly been achieved with respect to fuels/heat use (3.3% per year) and less with respect to electricity use (0.2% per year). Non-energy use (coal and coke use as reductant in the blast furnace) has been stable in the period 1995 – 2003. The products included in the reference energy use cover 93% of the total primary energy use of the iron and steel basic metals industry.

We compare our results with the LTA for the iron and steel industry in Figure 5.4. The system boundaries are not 100% comparable, because the LTA includes the energy use resulting from

the production of coke, whereas this is excluded in this study (difference is approximately 6 PJ in 1995). We therefore show an indexed line (1995=1). The development of the reference energy use according to our study coincides well with the development according to the LTA-1 in the period 1993 – 2000 when indexed to 1995. The match for 1989 – 1991 is less convincing. This might be caused by different growth rates of coke versus iron and steel production or by different growth rates in the various types of steel products. These changes are taken into account in LTA-1 where 26 different products are distinguished, whereas they are not included in the reference energy use in this study. Without further detailed analysis on the company level, it is very difficult to assess the difference in more detail. The realised energy use from the energy statistics for 1993 – 2000⁴ fits well with the energy use according to the LTA with the exception of 2000, where the energy statistics indicate an increase of 3.5 PJ, whereas the energy use according to the LTA-1 remains stable. This difference also explains fully the different estimate of annual EEI reduction (0.4% vs. 1.3%) between 1995 and 2000 between LTA-1 and our study (Table 5.5). In 2000, a new thin slab caster was taken into use in the iron and steel industry. According to the text of the LTA-1 monitoring report (Novem, 2001c), this resulted in additional primary energy use of 1 PJ due to testing of the new machine, which is however not visible as increased energy consumption in the energy use figures in the monitoring report of the LTA-1.

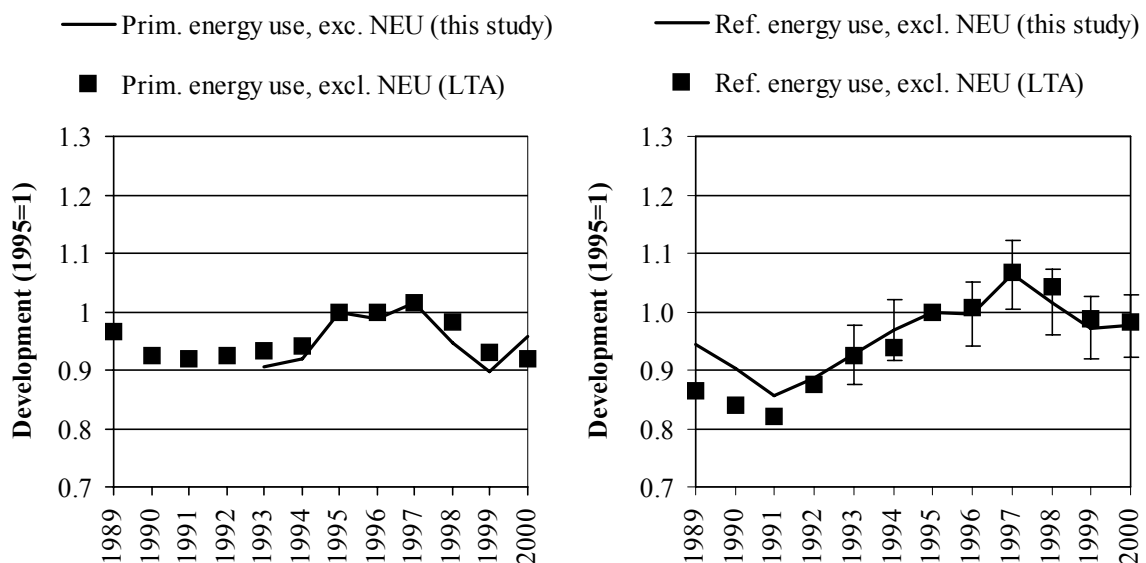


Figure 5.4 Primary energy use and reference energy use for the iron and steel industry according to our study and the LTA (Novem, 2001 b)

⁴ No separate data for the iron and steel industry are available before 1993.

Non-ferrous industry

Annual EEI reductions in the non-ferrous basic metals industry between 1995 and 2003 have been 1.4% per year (confidence interval between 0.6% and 2.2%), corresponding to annual primary savings of 7 PJ per year in 2003 compared to 1995. Efficiency improvements have mainly been accomplished with respect to fuels/heat use (3.8% per year), but also with respect to final electricity use (1.2%). The EEI for non-energy use fluctuates between 0.88 and 1.19 in the years of study. Non-energy use in the non-ferrous industry relates to the use of petroleum cokes for the production of anodes by one of the primary aluminium producers. The variation in the EEI is most probably caused by the different shares of petroleum coke (monitored in the energy statistics) and other raw materials used such as coal tar and the remaining parts of old anodes, which are not monitored in the energy statistics.

The products include all non-energy use of the sector in the base year and almost all (91%) of the electricity use. The energy coverage for fuels/heat use is, however, much lower with 41%. This might be due to the fact that the energy use for downstream processing of the metals is not taken into account in the specific energy consumption figures used. In the LTA-1 for the non-ferrous industry, the electricity used for electrolysis in aluminium and zinc production was not taken into account, because it was considered there as non-energy use. Since we took all electricity use into account, it is not possible to make a sound comparison between the LTA-1 results and our study for the non-ferrous industry.

Total basic metals industry – developments 1980 – 1995 and comparison with LTA

For the period before 1993, no separate data for the ferrous and non-ferrous basic metals industry was available and the analysis for 1980 – 1995 has therefore been done for the total basic metals industry by Farla and Blok (2000). The average annual EEI reduction between 1980 and 2003 is estimated at 0.6% per year. If, for reasons of comparison with the LTA-1, we would exclude the use of coal and coke in the blast furnace and the use of petroleum coke in the production of anodes (both allocated to non-energy use), average annual reductions are 0.9%. The comparison with the LTA-1 results for the total basic metals industry for 1989 and 2000 reveals much higher savings in the LTA-1 compared to our results, but the two are not fully comparable as a result of the inclusion of the total electricity use in the reference energy use for the non-ferrous industry in our study and the inclusion of coke production in the LTA-1. The main reasons for the differences between the LTA-1 and our study are 1) the difference in realised energy use in the iron and steel industry in 2000 between our study and the LTA-1 and 2) the different development of the reference energy use in the iron and steel industry between 1989 and 1991, maybe as a consequence of the number of products covered.

5.3.4 Paper industry

According to our study, there has been a small increase of annually 0.1% in the EEI (confidence interval between -0.6 and +0.6%) in the paper and board industry between 1995 and 2003, corresponding to additional energy use of 0.5 PJ in 2003 compared to 1995. The sector has become more fuel efficient (0.9% per year), but this offset by additional electricity use (-0.6%). In addition, there was a small decrease in the use of CHP in the paper industry, which is equivalent to an additional fuel use of 1.5 PJ. The energy coverage of the products included in the reference energy use in the base year is 87%. This is about the same as the energy coverage of 85% found for 1986 by Farla and Blok (2000). The industry converting paper and board to final products is included in the primary energy use in the energy statistics, but is not included in the reference energy use. The inclusion of the paper and board converting industry in the observed energy use of the sector can offer an explanation for the absence of efficiency improvements according to our indicator as becomes clear from the comparison of our results with the results obtained within the framework of the LTA-1 (Figure 5.5).

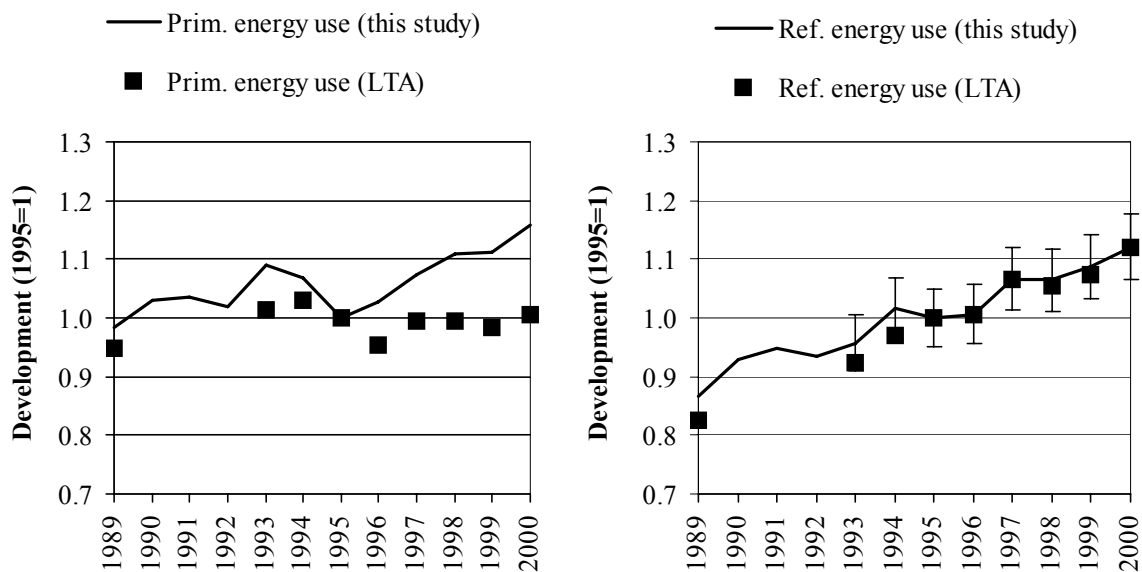


Figure 5.5 Primary energy use and reference energy use for the paper industry according to our study and according to the LTA (Novem, 2001c)

The comparison shows an almost identical development of the reference energy use according to our study and the LTA. The realised energy use in the LTA however, grows much slower compared to the energy statistics. In 1995, the realised energy use in the LTA is 86% of the realised energy use according to the energy statistics (well in line with the energy coverage of 87% as given above), whereas this share drops to 75% in 2000. Farla and Blok (2002) have already drawn a similar conclusion in their evaluation of the LTA-1 when comparing data for

1989 and 1996. If we assume both the LTA and the energy statistics to be right, this indicates that in 2000 the paper and board converting industry consumes a much larger share of the energy use of the sector and has doubled its energy use between 1995 and 2000. This is not confirmed by energy use data at the level of industrial subsectors (Statistics Netherlands, 2006a). According to these statistics, the paper and board converting industry consumes a rather constant fraction of the energy use of the total paper and board industry. The comparison therefore raises questions about the validity of LTA-1 and / or Statistics Netherlands energy consumption data. A more detailed assessment would only be possible based on confidential data at the level of individual firms. As a result of significant reductions in EEI in the period 1980 – 1995 (2.5% per year), the annual reduction in primary EEI between 1980 and 2003 is still estimated at 1.6% per year despite the absence of savings in the last decade.

5.3.5 Building materials industry

Between 1995 and 2003, annual reductions of the EEI in the building materials industry are estimated at 1.1% (confidence interval between 0.4 and 1.8%), corresponding to savings of 3.5 PJ per year in 2003 compared to 1995 levels. The industry has become slightly less efficient with respect to electricity use (annual EEI reduction of -0.3%) and more efficient with respect of fuels/heat use (EEI reduction of 1.7% per year). Over the total period 1980-2003, the average annual reduction in primary EEI is estimated at 1.3%.

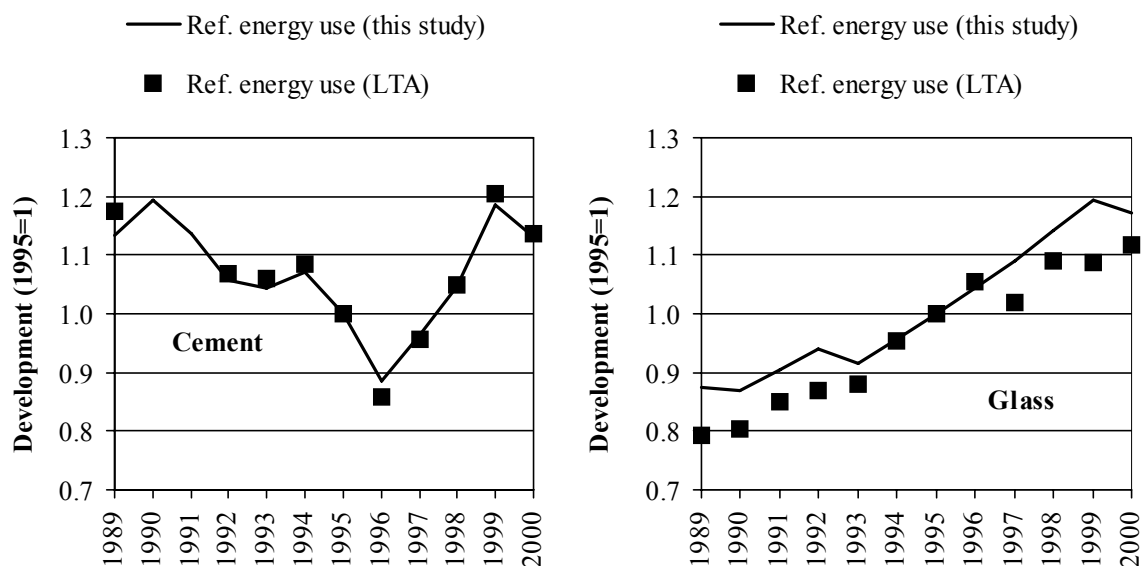


Figure 5.6 Reference energy use for cement and glass according to our study and the LTA (Novem, 2001d,e)

The energy coverage of the products included in the reference energy use is relatively low (66%). This corresponds with the 67% found by Farla and Blok for 1986 using a comparable set of products, indicating that the relative share of the products included in the reference energy use has not changed over time. Overall comparison with an LTA is not possible, because there is no single LTA for the building industry. We show the comparison of the reference energy use according to our study and the LTA for the cement and glass industry in Figure 5.6. For the cement industry, the reference energy use according to our study and the LTA are consistent, showing the reliability of the clinker and cement production statistics used in our study. For glass, the overall trend is comparable with the LTA, but deviations are substantial (up to 10%). A possible explanation is the lack of detail that can be obtained with our study. Physical production figures are only available for the total glass production, whereas a further specification to various types of glass has been used in the LTA.

5.3.6 Total of sectors studied

For the sum of the sectors studied in this paper, the annual primary EEI reduction is estimated at 1.3% between 1995 and 2003 (confidence interval between 0.9 and 1.7%), corresponding to annual savings of 120 PJ in 2003 compared to 1995. Annual reduction in the EEI for electricity were 1.9% and for fuels/heat even 2.6% per year. Efficiency improvements on non-energy use have been -0.1%. If we exclude non-energy use, annual EEI reductions have on average been 2.5% per year between 1995 and 2003. The savings are dominated by the chemical industry. If we exclude the chemical industry, annual reductions are 0.9% (including non-energy use) and 1.2% (excluding non-energy use) for 1995 – 2003.

Unfortunately, we cannot show energy efficiency developments for the sum of all sectors studied for the total period 1980 – 2003, because of the lack of consistent data on energy use in the chemical industry before 1995. If we exclude the chemical industry, we obtain the results given in Figure 5.7. On average, annual EEI reductions have been 1.0% per year between 1982 and 2003 excluding non-energy use (i.e. coal and coke use in the iron and steel industry and the use of petroleum coke for anode production in aluminium production). If we include non-energy use, annual reductions have been 0.9% per year between 1980 and 2003.

5.4 Overall conclusions, policy relevance and recommendations

We studied in detail energy efficiency developments in the Dutch manufacturing industry for the period 1995 – 2003 based on publicly available physical production and energy use data. We conclude that since the middle of the 90s, significant energy efficiency improvements have been made in the industrial sectors studied. The efficiency improvements vary widely from sector to sector, from year to year, and also between the various types of energy use

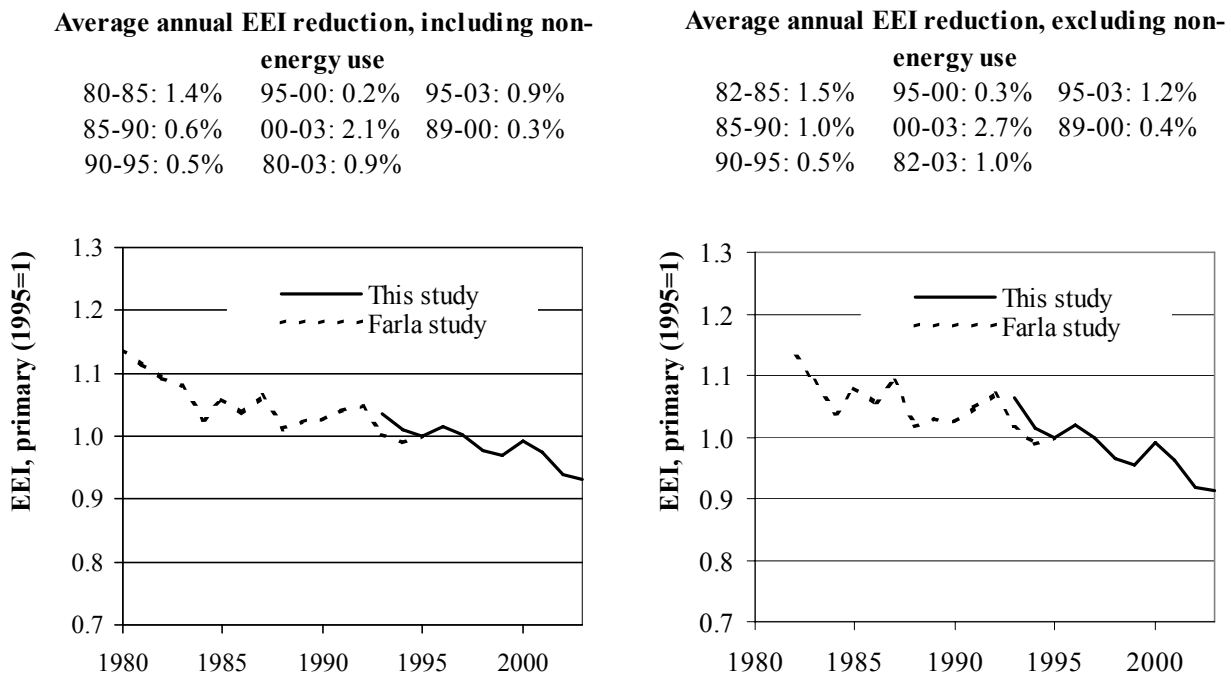


Figure 5.7 EEI for sum of sectors studied, 1980 – 2003, excluding the total chemical industry

distinguished (electricity, fuels/heat and non-energy use). Further bottom-up studies are required in addition to this top-down analysis to find the explanatory factors behind the observed differences. In the study by Ramirez et al. (2006) for the industry, a good match could be found between the top-down analysis and bottom-up data based on implemented energy efficiency projects. Based on the comparison of our results with those from a previous study for 1980 – 1995, we conclude that the rate of energy efficiency improvement is not slowing down in the last decade compared to the period before. Over the full time period 1980 – 2003, energy efficiency improvements are estimated at about 1% per year, excluding the chemical industry for which no reliable data are available. This is rather low compared to the goal of 2.7 % efficiency improvement per year recently advocated in for the EU (EC, 2006). We can conclude that additional energy efficiency policies are required to reach these more ambitious goals. For the Netherlands, additional policies required to increase the rate of energy efficiency improvements from 1% to 2% per year are explored in a recent study by Daniels et al. (2006).

For some of the LTA-1 sectors (e.g. the paper, iron/steel and chemical industry), we showed that still substantial differences exist between the development of the energy use according to the LTA-1 monitoring reports and the publicly available energy statistics, resulting in different and often higher efficiency improvements estimated in the LTA-1 compared to our

study. It is not possible to further assess these differences, because underlying data used in the LTA-1 monitoring is confidential. Although no longer relevant for the LTA-1, we strongly recommend introducing yearly checks in the various data flows from the individual companies to the government (monitoring Benchmarking Covenant, energy statistics survey, environmental reports, production statistics, emission reports etc.) to detect inconsistencies at the lowest level of aggregation and avoid similar problems in future policy evaluations. A detailed analysis on the company level comparing production and energy statistics data for the most important chemical companies in the Netherlands has proven that with relatively little effort, major improvements can be made in improving the quality of official statistics (Neelis, 2006a).

The quantitative uncertainty analysis performed as part of this study makes clear that the uncertainty ranges of the input data result in uncertainty ranges of 3.5 – 8 % in the resulting energy efficiency indicator (95% confidence interval). This makes it difficult to draw robust conclusions on energy efficiency developments from year to year. We analysed also the contribution of the various input parameters on the final uncertainty in the energy efficiency indicators. These analyses showed that the contribution of the production data and energy consumption data exceed by far the contribution of the specific energy consumption data. On top of the data related uncertainty, we also assessed methodological uncertainties caused by the fact that our reference energy use does not include all products of the individual subsectors. We did this by comparing the development of our reference energy use with the development of the reference energy use according to the LTA-1. In the LTA-1, all products of a sector were included in the reference energy use and the LTA-1 reference energy use is therefore in principle a very reliable indicator for the frozen efficiency energy use of the sectors. For the sectors studied, a good match was found between the LTA-1 and the reference energy use in this study based on publicly available production data. Therefore, we are confident that the reference energy use used in this study is a reliable indicator for most sectors of industry at least for the period of the LTA-1 (1989 – 2000). Ramirez et al. (2006) have also drawn this conclusion for the food industry, based on similar and additional evidence. We would like to stress, however, that the incomplete energy coverage of the products included in the reference energy, remains a source of methodological uncertainty and might result in erroneous results, especially in analyses over long time-series or for heterogeneous sectors such as the chemical and building materials industry. We recommend further studying the effect of these methodological uncertainties e.g. via a specific case study as outlined for the chemical industry in Section 5.3.2, using also economic and more detailed energy use data at the level of subsectors or individual firms.

We demonstrated in this paper that for the Netherlands, a framework for energy efficiency monitoring could be developed using physical production and energy use data that are in

principle publicly available for research purposes. The framework allows a good insight into the energy efficiency trends in the manufacturing industry. The main source of physical production data used (the Prodcom statistics) is also available for the other EU countries as are national energy statistics. The methodology could therefore also be used to conduct similar analyses in other EU countries, allowing cross-country comparisons of energy efficiency levels. The method could therefore contribute to reliable and independent cross-country monitoring of energy efficiency developments and cross-country comparisons of energy efficiency levels, which is an important conclusion in view of the increasing importance of European-wide energy efficiency policies.

Acknowledgements

This work was funded by the Platform Monitoring Energy Savings via the Policy Studies unit of the Energy Research Centre of the Netherlands (ECN). The empirical part of this research was executed at the Centre for Research of Economic Microdata (CEREM) at Statistics Netherlands. The views expressed in this report, however, are those of the authors. The authors would like to thank Dr. Jeroen van der Sluijs (Utrecht University) for his help on the development of the uncertainty analysis.

Appendix A Detailed results (continued on next pages)

	1995	1996	1997	1998	1999	2000	2001	2002	2003
<i>Chemical industry, excl. fertilizers</i>									
Reference final electricity use	1.00	1.02	1.10	1.12	1.13	1.21	1.12	1.25	1.33
Final electricity use, energy statistics	1.00	0.98	1.00	1.00	0.96	0.98	1.00	1.02	1.01
Energy efficiency indicator (EEI)	1.00	0.96	0.91	0.89	0.85	0.81	0.89	0.82	0.76
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference final fuels/heat use	1.00	0.97	1.04	1.05	1.12	1.13	1.21	1.25	1.37
Final fuels/heat use, energy statistics	1.00	0.98	0.95	0.92	1.01	0.98	0.99	1.08	1.09
Energy efficiency indicator (EEI)	1.00	1.01	0.92	0.88	0.91	0.87	0.82	0.86	0.80
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference non-energy use	1.00	0.96	1.00	1.00	1.06	1.02	1.10	1.16	1.34
Final non-energy use, energy statistics	1.00	0.86	0.91	0.91	1.03	1.09	1.22	1.28	1.37
Energy efficiency indicator (EEI)	1.00	0.90	0.91	0.90	0.97	1.06	1.11	1.10	1.02
95% confidence interval EEI		7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
Reference primary energy use (excl. non-energy use)	1.00	0.98	1.05	1.07	1.12	1.14	1.19	1.25	1.36
Reference primary energy use, energy statistics, excl. non-energy use	1.00	0.98	0.96	0.93	0.97	0.93	0.96	1.04	1.05
Energy efficiency indicator (EEI)	1.00	1.00	0.92	0.87	0.87	0.81	0.81	0.83	0.77
95% confidence interval EEI		5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Reference primary energy use	1.00	0.97	1.03	1.04	1.09	1.09	1.15	1.21	1.35
Primary energy use, energy statistics	1.00	0.92	0.94	0.92	1.00	1.01	1.09	1.15	1.20
Energy efficiency indicator (EEI)	1.00	0.95	0.91	0.88	0.92	0.93	0.95	0.95	0.89
95% confidence interval EEI		5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
<i>Fertilizer industry</i>									
Reference final electricity use	1.00	0.95	1.02	1.02	0.97	1.04	0.99	0.85	0.90
Final electricity use, energy statistics	1.00	1.07	0.95	1.03	0.93	0.88	0.77	0.75	0.77
Energy efficiency indicator (EEI)	1.00	1.12	0.93	1.01	0.96	0.85	0.77	0.87	0.85
95% confidence interval EEI		7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Reference final fuels/heat use	1.00	0.95	1.01	1.03	1.02	1.06	0.93	0.88	0.82
Final fuels/heat use, energy statistics	1.00	0.94	0.93	0.97	0.92	0.86	0.69	0.72	0.71
Energy efficiency indicator (EEI)	1.00	0.99	0.91	0.94	0.90	0.82	0.74	0.82	0.86
95% confidence interval EEI		8.5%	8.5%	8.5%	8.5%	8.5%	8.5%	8.5%	8.5%

	1995	1996	1997	1998	1999	2000	2001	2002	2003
<i>Fertilizers</i>									
Reference non-energy use	1.00	0.99	1.04	1.04	1.03	1.06	0.94	0.89	0.84
Final non-energy use, energy statistics	1.00	0.95	1.00	1.01	1.00	1.01	0.85	0.81	0.81
Energy efficiency indicator (EEI)	1.00	0.96	0.96	0.97	0.97	0.95	0.90	0.91	0.96
95% confidence interval EEI		8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%
Reference primary energy use (excl. non-energy use)	1.00	0.95	1.02	1.02	1.01	1.05	0.94	0.87	0.84
Reference primary energy use, energy statistics, excl. non-energy use	1.00	0.97	0.95	0.99	0.92	0.87	0.73	0.74	0.74
Energy efficiency indicator (EEI)	1.00	1.02	0.94	0.97	0.92	0.83	0.77	0.85	0.88
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference primary energy use	1.00	0.98	1.03	1.03	1.02	1.06	0.94	0.88	0.84
Primary energy use, energy statistics	1.00	0.96	0.98	1.01	0.98	0.96	0.81	0.79	0.78
Energy efficiency indicator (EEI)	1.00	0.98	0.95	0.97	0.95	0.91	0.85	0.89	0.93
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
<i>Iron and steel/basic metals industry</i>									
Reference final electricity use	1.00	0.98	1.05	1.00	0.96	0.99	1.04	1.08	1.16
Final electricity use, energy statistics	1.00	0.96	1.00	0.98	0.97	1.13	1.13	1.10	1.14
Energy efficiency indicator (EEI)	1.00	0.98	0.95	0.98	1.01	1.14	1.08	1.02	0.99
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference final fuels/heat use	1.00	1.00	1.07	1.02	0.98	0.97	1.04	1.06	1.15
Final fuels/heat use, energy statistics	1.00	1.00	1.01	0.92	0.85	0.85	0.87	0.87	0.88
Energy efficiency indicator (EEI)	1.00	1.00	0.95	0.90	0.86	0.88	0.84	0.82	0.76
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference non-energy use	1.00	1.00	1.05	1.01	0.96	0.90	0.96	0.97	1.06
Final non-energy use, energy statistics	1.00	0.99	1.06	1.03	0.98	0.89	0.97	0.98	1.06
Energy efficiency indicator (EEI)	1.00	0.99	1.01	1.02	1.02	0.99	1.01	1.01	1.00
95% confidence interval EEI		8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%
Reference primary energy use (excl. non-energy use)	1.00	1.00	1.06	1.02	0.97	0.98	1.04	1.07	1.15
Reference primary energy use, energy statistics, excl. non-energy use	1.00	0.99	1.02	0.95	0.90	0.96	0.96	0.96	0.98
Energy efficiency indicator (EEI)	1.00	0.99	0.96	0.93	0.92	0.98	0.93	0.90	0.85
95% confidence interval EEI		5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%

	1995	1996	1997	1998	1999	2000	2001	2002	2003
<i>Iron and steel basic metals industry</i>									
Reference primary energy use	1.00	1.00	1.06	1.01	0.97	0.94	1.00	1.02	1.10
Primary energy use, energy statistics	1.00	0.99	1.04	0.99	0.94	0.93	0.96	0.97	1.02
Energy efficiency indicator (EEI)	1.00	0.99	0.98	0.98	0.97	0.99	0.97	0.95	0.92
95% confidence interval EEI	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%
<i>Paper industry</i>									
Reference final electricity use	1.00	1.00	1.07	1.05	1.08	1.12	1.07	1.10	1.13
Final electricity use, energy statistics	1.00	1.01	1.10	1.11	1.13	1.20	1.11	1.19	1.19
Energy efficiency indicator (EEI)	1.00	1.00	1.03	1.06	1.05	1.07	1.04	1.08	1.05
95% confidence interval EEI	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Reference final fuels/heat use	1.00	1.01	1.07	1.07	1.10	1.13	1.07	1.12	1.13
Final fuels/heat use, energy statistics	1.00	1.12	1.14	1.11	1.09	1.09	1.03	1.05	1.05
Energy efficiency indicator (EEI)	1.00	1.11	1.07	1.03	0.99	0.97	0.97	0.94	0.93
95% confidence interval EEI	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Reference non-energy use									
Final non-energy use, energy statistics									
Energy efficiency indicator (EEI)									
95% confidence interval EEI									
Reference primary energy use (excl. non-energy use)									
Reference primary energy use, energy statistics, excl. non-energy use									
Energy efficiency indicator (EEI)									
95% confidence interval EEI									
Reference primary energy use	1.00	1.01	1.07	1.06	1.09	1.12	1.07	1.11	1.13
Primary energy use, energy statistics	1.00	1.03	1.07	1.11	1.11	1.16	1.12	1.15	1.17
Energy efficiency indicator (EEI)	1.00	1.02	1.01	1.04	1.02	1.03	1.05	1.04	1.03
95% confidence interval EEI	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
<i>Building materials industry</i>									
Reference final electricity use	1.00	1.00	1.05	1.10	1.16	1.14	1.11	1.07	1.05
Final electricity use, energy statistics	1.00	1.07	1.14	1.10	1.13	1.23	1.18	1.13	1.07
Energy efficiency indicator (EEI)	1.00	1.07	1.09	1.00	0.98	1.08	1.06	1.05	1.02
95% confidence interval EEI	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%

	1995	1996	1997	1998	1999	2000	2001	2002	2003
<i>Building materials industry</i>									
Reference final fuels/heat use	1.00	0.96	1.01	1.06	1.09	1.08	1.07	1.02	0.99
Final fuels/heat use, energy statistics	1.00	1.05	1.04	0.99	1.00	1.01	0.99	0.86	0.87
Energy efficiency indicator (EEI)	1.00	1.09	1.03	0.93	0.91	0.94	0.93	0.85	0.87
95% confidence interval EEI	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference non-energy use									
Final non-energy use, energy statistics									
Energy efficiency indicator (EEI)									
95% confidence interval EEI									
Reference primary energy use (excl. non-energy use)									
Reference primary energy use, energy statistics, excl. non-energy use									
Energy efficiency indicator (EEI)									
95% confidence interval EEI									
Reference primary energy use	1.00	0.97	1.02	1.07	1.11	1.10	1.08	1.04	1.01
Primary energy use, energy statistics	1.00	1.05	1.07	1.02	1.04	1.07	1.05	0.94	0.93
Energy efficiency indicator (EEI)	1.00	1.08	1.05	0.95	0.93	0.98	0.96	0.91	0.92
95% confidence interval EEI		5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%
<i>Non-ferro basic metals industry</i>									
Reference final electricity use	1.00	1.04	1.07	1.23	1.28	1.30	1.30	1.41	1.39
Final electricity use, energy statistics	1.00	1.04	1.07	1.19	1.24	1.29	1.26	1.25	1.27
Energy efficiency indicator (EEI)	1.00	1.00	1.00	0.96	0.97	1.00	0.97	0.88	0.91
95% confidence interval EEI		7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Reference final fuels/heat use	1.00	0.93	0.98	1.09	1.14	1.19	1.17	1.18	1.20
Final fuels/heat use, energy statistics	1.00	0.93	1.00	0.99	0.91	1.00	0.86	0.87	0.88
Energy efficiency indicator (EEI)	1.00	1.00	1.02	0.90	0.80	0.84	0.73	0.74	0.73
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference non-energy use	1.00	0.84	0.86	0.99	1.08	1.09	1.09	1.12	1.04
Final non-energy use, energy statistics	1.00	0.85	0.78	0.88	1.16	1.18	1.20	1.34	1.01
Energy efficiency indicator (EEI)	1.00	1.01	0.91	0.88	1.08	1.08	1.11	1.19	0.97
95% confidence interval EEI		8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%

	1995	1996	1997	1998	1999	2000	2001	2002	2003
<i>Non-ferrous metals industry</i>									
Reference primary energy use (excl. non-energy use)	1.00	1.03	1.06	1.22	1.26	1.29	1.29	1.38	1.37
Reference primary energy use, energy statistics, excl. non-energy use	1.00	1.03	1.06	1.16	1.20	1.26	1.21	1.20	1.22
Energy efficiency indicator (EEI)	1.00	1.00	1.01	0.96	0.95	0.98	0.94	0.87	0.89
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Reference primary energy use	1.00	1.02	1.04	1.20	1.25	1.27	1.28	1.37	1.35
Primary energy use, energy statistics	1.00	1.02	1.04	1.15	1.19	1.25	1.21	1.21	1.21
Energy efficiency indicator (EEI)	1.00	1.00	1.00	0.95	0.96	0.98	0.95	0.89	0.90
95% confidence interval EEI		6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
<i>Total industry</i>									
Reference final electricity use	1.00	1.01	1.08	1.12	1.13	1.18	1.14	1.22	1.27
Final electricity use, energy statistics	1.00	1.00	1.03	1.06	1.05	1.09	1.08	1.09	1.09
Energy efficiency indicator (EEI)	1.00	0.99	0.96	0.94	0.92	0.92	0.95	0.89	0.86
95% confidence interval EEI		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Reference final fuels/heat use	1.00	0.97	1.04	1.05	1.09	1.10	1.15	1.17	1.26
Final fuels/heat use, energy statistics	1.00	0.99	0.97	0.94	0.99	0.97	0.95	1.00	1.02
Energy efficiency indicator (EEI)	1.00	1.02	0.94	0.90	0.91	0.88	0.83	0.86	0.81
95% confidence interval EEI		5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Reference non-energy use	1.00	0.97	1.01	1.01	1.04	1.02	1.05	1.09	1.22
Final non-energy use, energy statistics	1.00	0.89	0.95	0.94	1.02	1.05	1.13	1.16	1.23
Energy efficiency indicator (EEI)	1.00	0.92	0.93	0.93	0.98	1.03	1.07	1.06	1.01
95% confidence interval EEI		5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%	5.5%
Reference primary energy use (excl. non-energy use)	1.00	0.99	1.05	1.07	1.10	1.13	1.15	1.20	1.28
Reference primary energy use, energy statistics, excl. non-energy use	1.00	0.99	0.99	0.97	0.99	0.98	0.98	1.02	1.03
Energy efficiency indicator (EEI)	1.00	1.01	0.95	0.91	0.90	0.87	0.86	0.86	0.82
95% confidence interval EEI		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Reference primary energy use	1.00	0.98	1.03	1.04	1.08	1.08	1.11	1.15	1.24
Primary energy use, energy statistics	1.00	0.95	0.97	0.96	1.00	1.01	1.04	1.08	1.12
Energy efficiency indicator (EEI)	1.00	0.97	0.94	0.92	0.93	0.94	0.94	0.94	0.90
95% confidence interval EEI		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%

References

- Alcan, 2004. Milieujaarverslag 2003. Alcan, Vlissingen.
- Alsema EA, 2000. ICARUS 4: Sector study for the basic non-ferrous metals Industry, Utrecht University, Department of Science, Technology and Society, Utrecht.
- Annema JA, Albers RAW, Boulan RP, 1992. Procesbeschrijvingen Industrie - Productie van primair ijzer en staal (SPIN map), Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven.
- Beerkens R, 2004. Personal communication on glass production in physical units, personal communication with Ruud Beerkens, 9 February 2004.
- Beerkens R, 2005. Personal communication on glass production in physical units, personal communication with Ruud Beerkens, 17 February 2005.
- Boonekamp, PGM, Mannaerts, H, Vreuls, HHJ and Wesselink, B, 2001. Protocol Monitoring Energy Savings, Energie onderzoek Centrum Nederland, Novem, Centraal Plan Bureau, Rijksinstituut voor Volksgezondheid en Milieu, Petten.
- Boonekamp PGM, Harmsen R, Kets A and Menkeveld M, 2002. Besparingstrends 1990-2000, Besparing, instrumenten en effectiviteit. Energieonderzoek Centrum Nederland, Petten.
- Boonekamp PGM, Kroon P, Bakker SJA and de Vries HJ, 2005. Indicators of domestic efforts to reduce CO₂ emissions in the Netherlands, Energieonderzoek Centrum, Nederland, Petten.
- Boonekamp PGM, 2006. Evaluation of methods used to determine realised energy savings, Energy Policy, Vol. 34, pp. 3977-3992.
- Boustead I, 2002. Eco-profiles of the European plastics industry, Polyethylene terephthalate, a report for the European Centre for Plastics in the Environment, Brussels.
- Bowie, R and Malvik, HV, 2005. Developing a framework for energy efficiency improvements in the EU, Energy - Zeitschrift der Osterreichischen energieagentur, Vol. 2, No. 5, pp. 10-14.
- de Castro JFM, 1992. Energiekentallen, Deelrapport Baksteen, in: de Castro JFM, van Heijningen RJJ, Worrell, E and Hazewinkel JHO (editors), Energiekentallen in relatie tot preventie en Hergebruik van afvalstromen, Novem, Utrecht.
- Chauvel, A and Lefebvre, G, 1989. Petrochemical processes – technical and economic characteristics, Part 1: Synthesis-gas derivatives and major hydrocarbons, Editions Technip, Paris, France.
- Daniels, BW, van Dril, AWN, Boerakker, YHA, Godfroj, P, van der Hilst, F, Kroon, P, Menkveld, M, Seebregts, AJ, Tigchelaar, C and de Wilde, HPJ, 2006. Instrumenten voor energiebesparing. Instrumenteerbaarheid van 2% besparing per jaar. Energieonderzoek Centrum Nederland, Petten.

- Das MC, Driessen PPJ, Glasbergen P, Habermehl N, Vermeulen WJV, Blok K, Farla JCM and Korevaar EM, 1997. *Evaluatie Meerjarenaafspraken over Energie-Efficiency*. Universiteit Utrecht, Vakgroep Milieukunde, Vakgroep Natuurwetenschap en Samenleving, Utrecht.
- Decisioneering, 2000. *Crystal Ball 2000*. Decisioneering Software, Denver, Colorado.
- EC, 2006. COM(2006) 545 final of 19.10.2006. Communication from the Commission: Action Plan for Energy Efficiency: Realising the Potential.
- EFMA, 2000. *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*, Booklet 1-8. European Fertilizer Manufacturers' Association, Brussels.
- EU, 2006. Directive 2006/32/EC of the European Parliament and of the Council of 05.04.2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. *Official Journal of the European Union*, 27.04.2006.
- Eurostat, various years. The PRODCOM list (List of PROducts of the European COMMunity). Classification is accessible online via the Eurostat website: <http://europa.eu.int/comm/eurostat/ramon/>.
- Eurostat, 2001. *Iron and steel, yearly statistics*. Eurostat, Luxembourg.
- Eurostat, 2003. *Iron and steel, yearly statistics*. Eurostat, Luxembourg.
- EZ, 2005. *Energierapport 2005. Nu voor later*. Ministerie van Economische Zaken, Den Haag.
- Farla JCM and Blok K, 2000. The use of physical indicators for the monitoring of energy intensity developments in the Netherlands, 1980-1995. *Energy*, Vol. 25, pp. 609-638.
- Farla JCM and Blok K, 2002. Industrial long-term agreements on energy efficiency in The Netherlands. A critical assessment of the monitoring methodologies and quantitative results. *Journal of Cleaner Production*, Vol. 10, pp. 165-182.
- Freeman, SL, Niefer, MJ and Roop, JM, 1997. Measuring industrial energy efficiency: practical issues and problems, *Energy Policy*, Vol. 25, pp. 703-714.
- Frijlink H, 2004. Personal communication on the production of anodes at Pechiney, Vlissingen, 30 March 2004.
- Gielen DJ and van Dril AWN, 1997. The basic metal industry and its energy use, prospects for the Dutch energy intensive industry, Energy Research Centre of the Netherlands, Petten.
- Huizinga K, Verburgh JJ, Matthijsen AJCM and Coenen PHWG, 1992. *Procesbeschrijvingen Industrie: Grofkeramische Industrie (SPIN map)*, Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven.
- Hydrocarbon Processing, 2003. *Petrochemical processes 2003*. Hydrocarbon processing, Vol. 82, No. 3, pp. 72-124.
- IISI, 2004. *Steel statistical yearbook 2004*. International Iron and Steel Institute (IISI), Brussels.

- IPTS, 2001a. Reference Document on Best Available Techniques in the Chlor-Alkali manufacturing industry. European Commission, Institute for Prospective Technological Studies, Seville.
- IPTS, 2001b. Reference Document on Best Available Techniques in the Ferrous Metals processing industry. European Commission, Institute for Prospective Technological Studies (IPTS), Seville.
- Keijssers, L, 2004. Personal communication on zinc production at Pasmenco Budel Zinc, March 2004.
- KNB, 2003-2004. Jaarverslag 2002 en 2003, Koninklijk Verbond van Nederlandse Baksteenfabrikanten, de Steeg.
- Mergelsberg P, 2004. Personal communication on clinker production at ENCI Maastricht, 9 March 2004.
- Mergelsberg P, 2005. Personal communication on clinker production at ENCI Maastricht, 17 January 2005.
- Metz, B, Davidson, O, Swart, R and Pan, J (editors), 2001. Climate Change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.
- Morgan MG and Henrion, M. 1990. Uncertainty. A guide to dealing with uncertainty in quantitative risk and policy analysis, Cambridge University Press, New York.
- Mulder BMP and Sinon AMJ, 1994. Energy Use and Conservation in the Dutch Paper and Board Industry, CADDET Energy Efficiency Newsletter, Vol. 3, pp. 10-12.
- Neelis M, 2006a. De bruikbaarheid van de Nederlandse Prodcom- en energiestatistieken voor de berekening van CO₂ emissies en energiebesparing in de chemische industrie - openbare samenvatting, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Neelis M, 2006b. De bruikbaarheid van de Nederlandse Prodcom- en energiestatistieken voor de berekening van CO₂ emissies en energiebesparing in de chemische industrie – volledige vertrouwelijke rapportage, Statistics Netherlands, Voorburg.
- Neelis M, 2006c. Calculation based on detailed energy statistics.
- Neelis, M, Patel, M and de Feber, M, 2003a. Improvement of CO₂ emission estimates from the non-energy use of fossil fuels in the Netherlands, Utrecht University, Copernicus Institute, Department of Science Technology and Society, Utrecht.
- Neelis, M, Patel MK and Bach, P, 2003b. Inventory of processes in the chemical and refinery industries. Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Neelis, M, Ramirez, A, Patel, M, 2004. Physical indicators as a basis for estimating energy efficiency developments in the Dutch industry, Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.

- Neelis, M, Ramirez, A, Patel, M, 2005. Physical indicators as a basis for estimating energy efficiency developments in the Dutch industry – Update 2005. Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Nieuwlaar E, 2001a. ICARUS-4: Sector Study for the Chemical Industry. Utrecht University, Department of Science, Technology and Society, Utrecht.
- Nieuwlaar E, 2001b. ICARUS 4: Sector study for the Building Materials Industry. Utrecht University, Department of Science, Technology and Society, Utrecht.
- Novem, 2000. Voortgangsrapportage ontwikkeling energie-efficiency in de grofkeramische industrie over 1999, Novem, Utrecht.
- Novem, 2001a. Eindrapportage ontwikkeling energie-efficiency in de chemische industrie over de periode 1989-2000, Novem, Utrecht.
- Novem, 2001b. Eindrapportage ontwikkeling energie-efficiency in de Nederlandse IJzer- en staalproducerende industrie (NIJSI) en behandelende industrie over de periode 1989-2000, Novem, Utrecht.
- Novem, 2001c. Eindrapportage meerjarenafspraak energie-efficiency papier- en kartonindustrie (VNP), 1989-2000, Novem, Utrecht.
- Novem, 2001d. Eindrapportage ontwikkeling energie-efficiency in de Nederlandse cementindustrie over de periode 1989-2000, Novem, Utrecht.
- Novem, 2001e. Eindrapportage ontwikkeling energie-efficiency in de glasindustrie over 2000, Novem, Utrecht.
- Patel M, 2003. Cumulative energy demand (CED) and cumulative CO₂ emissions for products of the organic chemical industry. *Energy*, Vol. 28, pp. 721-740.
- Persson, TA, Claeson Colpier, U and Azar, C, 2006. Adoption of carbon dioxide efficient technologies and practices: an analysis of sector-specific convergence trends among twelve nations. *Energy Policy*, Vol. 35 (5), pp. 2869-2878.
- Phylipsen, GJM, Blok, K and Worrell, E, 1998. Handbook on international comparisons of energy efficiency in the manufacturing industry, Utrecht University, Department of Science, Technology and Society, Utrecht.
- Pouwelse H, 1997. Correcties CBS-cijfers organische chemie. Personal Communication Hans Pouwelse (Statistics Netherlands) and Jacco Farla (Utrecht University), August 1997.
- Ramirez CA, Blok, K, Neelis, M and Patel M, 2006. Adding apples and oranges: The monitoring of energy efficiency in the Dutch food industry, *Energy Policy*, Vol. 34, pp. 1720-1735.
- Rietbergen MG, Farla JCM and Blok K, 2002. Do agreements enhance energy efficiency improvement? Analysing the actual outcome of long-term agreements on industrial energy efficiency improvement in the Netherlands. *Journal of Cleaner Production*, Vol. 10, pp. 155-163.
- SenterNovem, 2005. Meerjarenafspraken energie-efficiency, Resultaten 2004, SenterNovem, Utrecht.

- SenterNovem, 2006. Covenant Benchmarking Energie-Efficiency. Verificatiebureau Benchmarking Energy-efficiency, SenterNovem,Utrecht.
- Statistics Netherlands, 2005. Energiebalans Nederland, jaarcijfers 1995-2003, part 1 in digital format, personal communication with Leendert Pleijsier, Statistics Netherlands, 28 June 2005, Voorburg.
- Statistics Netherlands, 2006a. Energieverbruik en kosten industrie en turf-, zand-, klei-,etc. winning, Statistics Netherlands, Voorburg, Accessed online via <http://www.statline.cbs.nl>
- Statistics Netherlands, 2006b. Production means electricity 1998-2004, Statistics Netherlands, Voorburg, Accessed online via <http://www.statline.cbs.nl>
- Statistics Netherlands, 1994-1998. Energie Balans Nederland, deel 2, Statistics Netherlands, Voorburg.
- Struker A, 1994. Sectorstudie anorganische chemie. Energieonderzoek Centrum Nederland, Petten.
- VNP, 1993-2002. Jaarverslagen 1993-2002, Vereniging van Nederlandse Papier- en kartonfabrieken, Hoofddorp.
- Worrell E, 1994. Potentials for improved use of industrial energy and materials. PhD thesis, Utrecht University, Utrecht.
- Worrell E, Price L, Martin N, Farla J and Schaeffer R, 1997. Energy intensity in the iron and steel industry: a comparison of physical and economic indicators. Energy Policy, Vol. 25, pp. 727-744.

CHAPTER 6

Approximation of theoretical energy saving potentials for the petrochemical industry using energy balances for 68 key processes*

Abstract

We prepared energy and carbon balances for 68 petrochemical processes in the petrochemical industry for Western Europe, the Netherlands and the world. We analysed the process energy use in relation to the heat effects of the chemical reactions and quantified in this way the sum of all energy inputs into the processes that do not end up in the useful products of the process, but are lost as waste heat to the environment. We showed that both process energy use and heat effects of reaction contribute significantly to the overall energy loss of the processes studied and recommend addressing reaction effects explicitly in energy efficiency studies. We estimated the energy loss in Western Europe in the year 2000 at 1620 PJ of final energy and 1936 PJ of primary energy, resulting in a total of 127 Mt CO₂. The losses identified can be regarded as good approximations of the theoretical energy saving potentials of the processes analysed. The processes with large energy losses in relative (per tonne of product) and absolute (in PJ per year) terms are recommended for more detailed analysis taking into account further thermodynamic, economic, and practical considerations to identify technical and economic energy saving potentials.

* Published in Energy, Vol. 32 (2007), pp. 1104-1123. Co-authors are M.Patel, K.Blok, W.Haije and P.Bach.

6.1 Introduction¹

In the year 2000, the industrial sector accounted for a final worldwide energy use of 91 EJ, 32% of the total energy use. The share of the chemical industry within the industrial sector was 30% (27.9 EJ, 13.5 EJ of which was feedstock) (IEA, 2002). More energy-efficient technologies in the chemical industry could, therefore, contribute significantly to nationwide and worldwide energy savings and a reduction of CO₂ emissions. Several energy saving directions can be identified for the chemical industry, ranging from short-term implementation of incremental process improvements to innovative, radical new process designs or new process routes. In order to prioritise research and development (R&D) efforts directed towards energy savings, it is important to identify the theoretical energy saving potentials for the various processes applied in the chemical industry.

In this paper we aim to approximate theoretical energy saving potentials for the petrochemical industry by analysing the sum of all energy inputs into the process that do not end up in useful products of the process, but are lost to the environment. These total losses can be divided into three categories:

- In the chemical industry, raw materials are converted to products with a different chemical composition and energy content (see Section 6.2.2 for further explanation on how the energy content of commodities was calculated). In exothermic reactions, the products have a lower energy content compared to the raw materials and in endothermic reactions the products have a higher energy content compared to the raw materials. From an energy balance perspective, exothermic processes can export energy and have a negative theoretical energy requirement. Endothermic processes, on the other hand, always require energy. All chemical processes use more process energy than suggested by the theoretical minimum energy requirement calculated based on the energy balance. We define the *excess final energy use* as the difference between actual process energy use and the theoretical minimum energy requirements based on the energy balance.
- Some of the raw material in a number of processes is not converted to the desired product or products; it is lost. We refer to these losses as *losses due to non-selectivity*. They can be the result of either the formation of undesired low value fuel-grade by-products or the over-oxidation of the raw material, which results in process heat.

¹ This paper is an extended and improved version of a paper presented at the European Congress on Economics and Management of Energy in Industry (ECEMEI), held in Estoril, Portugal on 6-9 June 2004. The conference paper is published in a special issue of Applied Energy (Neelis et al., 2007).

- The third type of loss comprises losses resulting from the production of steam and electricity from primary energy carriers. We refer to these as *energy conversion losses*.

The overview given above indicates that process energy use as such is a poor indicator of the total energy loss of a process and cannot serve as a basis to assess theoretical energy saving potentials, because it does not account for the heat effect of the chemical reactions taking place in the process. In detailed studies on energy saving potentials of individual processes and in more theoretical studies on potentials for energy savings in chemical processes, the heat effect of reaction is always regarded a key element in understanding the structure of energy use in a process (e.g. Hinderink et al., 1996; Radgen, 1997; Leites et al., 2003; Korevaar, 2004, just to name a few). In contrast to these detailed studies, overview studies focussing on energy in the chemical industry as a whole do not usually address the heat effects of chemical reactions (e.g. APME, 1994-2003; Gielen et al., 1996; DOE/OIT, 2000; Worrell et al., 2000; Joosten, 2001 and Patel, 2003). They focus mainly on the process energy use of the various processes. One exception is a study by Lange (2001) in which the heat effect of the reaction is considered to be an important element in understanding the cost structure of processes in the chemical industry. That study, however, gives no totals for the sum of the processes studied and only discusses a few of the specific processes individually. Tonkovich and Gerber (1995) and Lange (2002) quantified carbon losses resulting from non-selectivity for a large number of processes, but they do not directly relate these losses to the energy content of raw materials and products.

The present paper extends the existing body of work by presenting a comprehensive overview study that quantifies bottom-up total energy losses in the petrochemical industry. The losses are identified in relative terms (per tonne of product) for the individual processes and in absolute terms (PJ per year) for the totals of the processes studied in the Netherlands, Western Europe (EU-15 + Norway and Switzerland), and the World for the year 2000. Total CO₂ emissions resulting from the energy loss are also quantified. Section 6.2 presents our research approach and input data and Section 6.3 discusses the results of the analysis.

Our analysis comprises an energy analysis that quantifies the difference in energy content between all process inputs and the products of the process at standard conditions (298.15 K and 1 bar). The individual processes are studied as black boxes, i.e., the flows between the various unit operations (reactors, separation equipment etc.) and the actual temperature and pressures of these flows are not considered. We convert the final process energy use back to primary fuels. At the level considered in this study, an exergy analysis based on the second law of thermodynamics would yield comparable overall results, since the difference between chemical exergy and energy content for fuels and for most of the commodities crossing the system boundaries used in our analysis differ by less than 10% (Szargut et al., 1988). As a

result, the total energy loss as identified in this study is close to the total exergy loss and can therefore be regarded as a good approximation of the theoretical energy saving potential of the process analysed. The division over the three loss categories identified would, however, be different in the case of an exergy analysis, which becomes clear from the following example. When steam is produced in a boiler, the energy efficiency is very high (we assume 90%), but the exergy efficiency is much lower, depending on the temperature and pressure of the steam produced. The exergy conversion losses in the production of steam are therefore much larger than the energy conversion losses. On the other hand, the process exergy use of a process using steam is much lower than the process energy use, because of the low exergy content of steam compared to the energy content.

As we talk about theoretical potentials, we exclude any considerations of (current) technical or economic feasibility, which are explicitly taken into account when determining technical and economic potentials. This means that our results are more important for the longer term. They provide an indication of processes where – in principle – large savings can be achieved. The lists of processes presented can in that sense be regarded as priority lists for research and development programmes. To identify technical and economic energy savings potentials based on our results, more detailed analyses are required taking into account further thermodynamic (including aspects related to the second law of thermodynamics such as the necessity for driving forces required for reactions and heat transfer) as well as economic and practical considerations related to energy saving options. In Section 6.4, we briefly discuss this further and give some general energy saving directions based on our results. The discussion (Section 6.5) identifies the main uncertainties associated with the approach we used and compares our results with other available sources. Finally, conclusions are given in Section 6.6.

6.2 Research approach, input data, and basic assumptions

6.2.1 Model overview

For our analysis, we used a spreadsheet model containing the production processes of 51 (listed in Appendix A) of the most important petrochemicals with respect to production volume. The selection of products was based on available data. Of the petrochemicals listed in the US production of top 50 chemicals (DOE/OIT, 2000), we did not include vinyl acetate (Nr. 37), methyl chloride (Nr. 48) and methyl methacrylate (Nr. 50). We also included ammonia (hydrocarbon feedstock) and chlorine (very important intermediate for the petrochemical industry). Since some of the products can be produced by more than one process route, the total number of processes included was 68. For a number of processes, there was more than one dataset available and approximately 300 datasets are therefore

included in the spreadsheet model. We used the dataset most likely to represent the average technology in use in Western Europe in 2000. When there was only one process dataset available, we used that dataset in the analysis without adjusting for process improvements that might have taken place over time.

The variables included for each of the datasets are shown in Figure 6.1. We calculated various energy and CO₂ emission indicators based on these variables. Table 6.1 presents the definition of the indicators for which results are discussed in Section 6.3. Throughout the paper, we refer to the variables and indicators shown in Figure 6.1 and Table 6.1 without explicit reference.

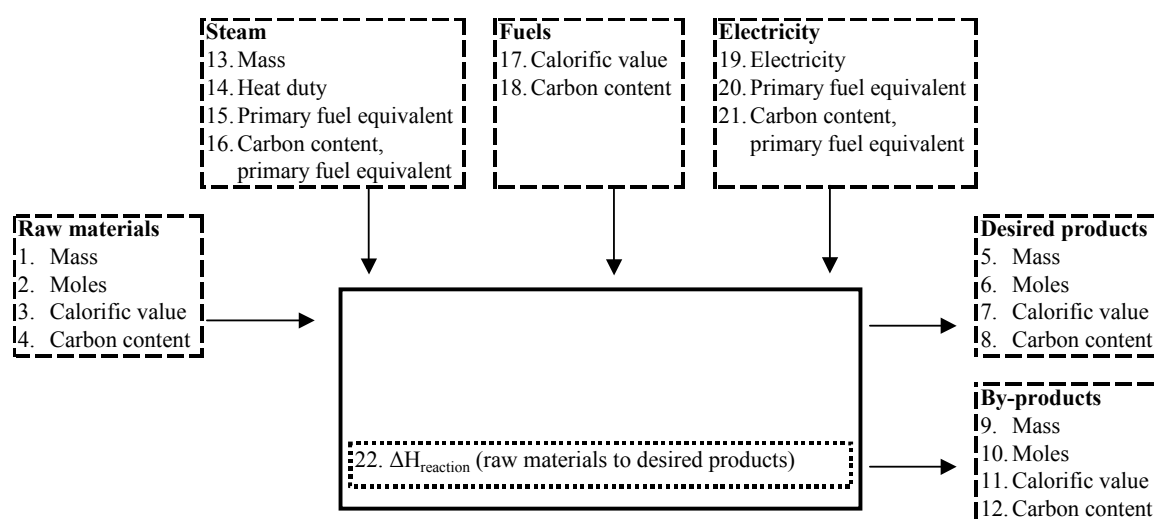


Figure 6.1 Overview of the variables included in the datasets

Table 6.1 Definition of indicators

No.	Indicator name (unit)	Formula (numbers refer to the variables in Figure 1)
1	Theoretical final energy use (J_f)	+22
2	Theoretical heat effect of reaction (J_f)	-22
3	Total final energy use (J_f)	14+17+19
4	Total primary energy use (J_p)	15+17+20
5	Heat effect of reaction (J_f)	3-7-11
6	Energy conversion losses (J_p)	15+20-14-19
7	Total final energy loss (J_f)	14+17+19+3-7-11
8	Total primary energy loss (J_f)	15+17+20+3-7-11
9	Excess final energy use (J_f)	14+17+19-22
10	Losses due to non-selectivity (J_f)	3-7-11+22
11	Carbon losses, energy use, primary (t CO ₂)	16+18+21
12	Carbon losses, reaction (t CO ₂)	4-8-12
13	Total carbon losses, primary (t CO ₂)	4-8-12+16+18+21

In most of the included processes, raw materials are converted into products having a different chemical composition. In the processes that stand at the beginning of the chain of chemical conversions, the raw material is often a commodity, which is included in energy statistics. Two examples are the use of naphtha in olefin production and natural gas in ammonia production². In the majority of processes included, however, the raw material is a basic or intermediate chemical commodity with a uniform and well-defined chemical composition, which is further converted to another chemical commodity (e.g., the conversion of ethylene to ethylene oxide). The heat of the stoichiometric reaction ($\Delta H_{\text{reaction}}$) from raw material to the desired product or products is included (variable 22) in the model. Some processes produce not only the desired products, but also small amounts of organic or inorganic by-products. In our model, we included only sellable chemical-grade commodities as by-products of a process and not the production of undesired fuel-grade by-products, which we considered part of the losses due to non-selectivity. An exception is made for the steam cracking process; for this process, we included all products, including the fuel by-products (see Section 6.3 and Appendix A for details). We also included the mass, molar quantity, and energy content for the raw materials, products, and by-products of the processes. Normally, only the flows in mass units are given in the datasets from literature that are the basis of our model. The assumptions made in estimating the remaining variables from these mass flows are explained in Section 6.2.2. Also studied was the process energy use, divided into direct fuel use, steam use, and electricity use. We did, however, not separately identify various types of end uses (e.g. compression, pumping, heating etc.) of the process energy use. For electricity and steam use, we included both final energy use and primary fuel equivalents. Final energy use is expressed throughout this paper with subscript *f* or *e* (for electricity), primary energy equivalents with subscript *p*. The assumptions made for energy conversion efficiencies and CO₂ emissions factors are explained in Section 6.2.3. We did not include additional non-energy inputs into the processes that were not part of the conversions taking place, such as cooling water, solvents and catalysts.

Our model also contains production figures for chemical commodities for three geographical regions in the year 2000: Netherlands (NL), Western Europe (WE), and the world. The share of each process route in the total production is also incorporated for those chemicals for which different process routes are included in the analysis, again for the three geographical regions included. The sources of the production volumes and process shares are discussed in Section 6.2.4.

² In international energy statistics (e.g. IEA, 2002), the use of energy commodities as raw material in the chemical industry is included as a memo item under the final consumption of the chemical industry and is referred to as feedstock use in the chemical industry. See Section 6.6.5 for a comparison between our data and the data from international energy statistics.

6.2.2 Properties of raw materials, products, and by-products

For chemical commodities with a well-defined chemical composition, we converted the quantities in mass units to moles and carbon content using the molecular composition of the commodity. The energy content of a commodity containing carbon, hydrogen, and/or sulphur (molecular composition $C_xH_yS_z$) was calculated based on the heat of formation ($\Delta H_{\text{formation}}$) using the following formula:

$$\begin{aligned} \text{Energy content} = & x * \Delta H_{\text{formation, CO}_2 \text{ (g)}} + (y/2) * \Delta H_{\text{formation, H}_2\text{O (g)}} \\ & + z * \Delta H_{\text{formation, SO}_2 \text{ (g)}} - \Delta H_{\text{formation, commodity}} \end{aligned}$$

Equation 6.1

This formula calculates the energy content, using CO_2 , H_2O and SO_2 as the reference substances for the elements carbon, hydrogen and sulphur. The pure elements are implicitly taken as the reference substance for the other elements (if present in the commodity)³. For fuel commodities containing just hydrogen, carbon, sulphur, and nitrogen (i.e., the majority of the commodities involved in our analysis), the energy content as calculated with Formula 1 is normally referred to as the calorific value (lower heating value, LHV) in literature. The heat of formation of the commodities was taken from Aspen Plus flowsheeting software (Aspen Technology, 2001). For the commodities not present in that dataset, the heat of formation was calculated based on Brandrup and Immergut (1989) or by using estimation methods given in Szargut et al. (1988). For the energy commodities used as raw material in the chemical industry (e.g., natural gas and naphtha), we employed the energy content (calorific value) and CO_2 emission factors reported by IPCC (1997).

6.2.3 Properties for electricity, fuels and steam

Using IEA publications (IEA, 2002), we derived an overall CO_2 emission factor of 62 kg CO_2 / GJ for the fuel mix used for final consumption in the chemical industry in Western Europe. This emission factor was then applied to calculate the associated CO_2 emissions of the fuel use reported in the datasets (variable 18). For the fuels used in the steam cracking and steam reforming processes, we use process-specific emission factors, which are explained in the notes to Appendix A. The datasets used in some cases distinguish between low-pressure (LP), middle-pressure (MP) and high-pressure (HP) steam. We assumed heat duties of 2.4, 2.6, and

³ This choice was made for practical reasons: all losses of hydrogen, carbon and sulphur were implicitly assumed to leave the process as CO_2 , H_2O , and SO_2 , respectively, with an energy content of 0. Another option would be to use the heat of formation of commodities directly as energy content (taking the pure elements as reference for all elements present in the commodity). With such a reference system, however, the losses of carbon, hydrogen and sulphur in the form of CO_2 , H_2O and SO_2 should be quantified to avoid mistakes, because the energy content of these substances is then not equal to 0.

2.8 GJ_f / tonne for LP, MP and HP steam, respectively⁴. In cases where the type of steam was not specified in the dataset, we used the properties of MP steam. We assume this heat duty (final energy) to be produced from fossil fuels with a boiler having an energy efficiency of 90% to calculate primary fuel equivalents. For the fuels used in steam generation, we used the same emission factors as we used for direct fuel use (62 kg CO₂ / GJ). For electricity, we used a 41% efficiency for the conversion from final to primary fuel equivalents and a 210 kg CO₂ / GJ_e emission factor, based on data in Graus and Voogt (Graus and Voogt, 2005) for fossil electricity generation in Germany, France, the UK + Ireland, and the Nordic European countries.

2.4 Sources for production data and for shares of production processes

The majority of production figures of the chemicals for the year 2000 (given in Appendix A) were obtained from the chemical profile pages published in *Chemical Market Reporter* (1994-2005), the product profile pages in *European Chemical News* (1994-2005) and the product focus pages in *Chemical Week* (1994-2005). These sources were complemented with data from grey literature and textbooks containing production figures (e.g., Weissermel and Arpe, 2003). Publicly available company data were also used in some cases. If there was just data for years close to 2000, we used linear inter- and extrapolations to obtain production data for 2000 or applied the growth rates mentioned in the literature. In cases where only capacity data were available, we used capacity utilisation rates mentioned in the literature source or a default capacity utilisation rate of 86%, a value for the Dutch chemical industry in the period 1999-2003 (VNCI, 2004). For chemicals produced via more than one process route, the shares of the various process routes were obtained in most cases from Weissermel and Arpe (2003) and complemented with other sources like the three journals given above.

6.3 Results

The results in absolute terms shown in this section refer to calculations for Western Europe in the year 2000. The corresponding results for the Netherlands and the world can be deducted from Appendix A and Figure 6.8 and Figure 6.9 in Section 6.3.4. Background data on the 68

⁴ We assumed pressure and temperature of 4 bar / 175 °C for LP steam, 10 bar / 280 °C for MP steam and 40 bar / 400 °C for HP steam respectively, based on Patel (2003). The heat duty was considered equal to the enthalpy difference between steam having these temperature and pressure levels and liquid water at 25°C, corrected for return condensate having an enthalpy of 0.4 GJ / tonne compared to liquid water at 25°C (Statistics Netherlands, 2004b).

individual processes included in the model are summarised in Appendix A and documented in more detail in Neelis et al. (2005a)⁵.

6.3.1 Excess final energy use

From an energy balance perspective, exothermic processes can export energy and have a negative theoretical energy requirement. Endothermic processes, on the other hand, always require energy. We define the theoretical final energy use (from an energy balance perspective) as the $\Delta H_{\text{reaction}}$ from raw materials to desired products (indicator 1, variable 22). Figure 6.2 shows the actual final energy use (indicator 3) as a function of this theoretical final energy use.

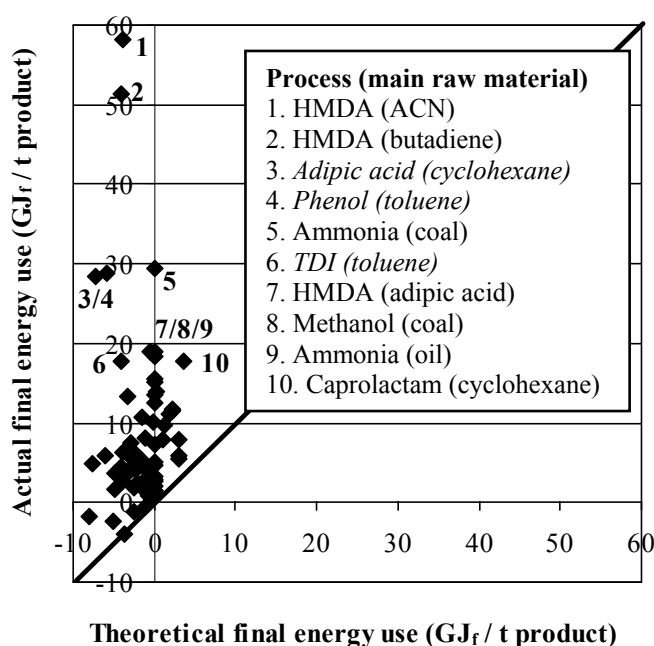


Figure 6.2 Theoretical final energy use ($\Delta H_{\text{reaction}}$, indicator 1) versus actual final energy use (indicator 3). Note: the processes printed in italics are uncertain estimates based on single sources published before 1990 (see Section 6.5).

As can be seen in Figure 6.2, most processes included in the model are exothermic: i.e., the products of the process have an energy content that is lower than the energy content of the raw material entering the process. Endothermic processes are the steam cracking process⁶, the

⁵ The results in this paper differ slightly from those in Neelis et al. (2005a). In this paper we use a different efficiency and emission factor for electricity production, made additional corrections for by-products of PO, MDI, and TDI production (see notes to Appendix A), and corrected the worldwide production volume for PET.

⁶ The steam cracking process to produce olefins and aromatics is included in such a way that the internal use of part of the fuel products is visible. No ideal desired stoichiometric reaction is defined, because of the multiple

production of chlorine, and the dehydrogenations of ethylbenzene to styrene and isopropanol to acetone. In these processes the products have a higher energy content than the raw material. Figure 6.2 shows that some of the processes involving exothermic reactions recover energy available from the exothermic reaction to the extent that they become net exporters of energy in the form of steam. The majority of the exothermic processes, however, are net consumers of process energy. We defined the excess final energy use of a process (indicator 9) as the difference between the actual and theoretical final energy use (i.e., the distance between the data points and the line $y=x$) and listed the ten processes with the largest excess final energy use. We converted the indicators shown in GJ per tonne of product to total PJ per year, taking into account production volumes and shares of the various process routes. A graph of the excess final energy use for the sum of all processes is shown in Figure 6.3 as are the 10 processes with the largest excess final energy use.

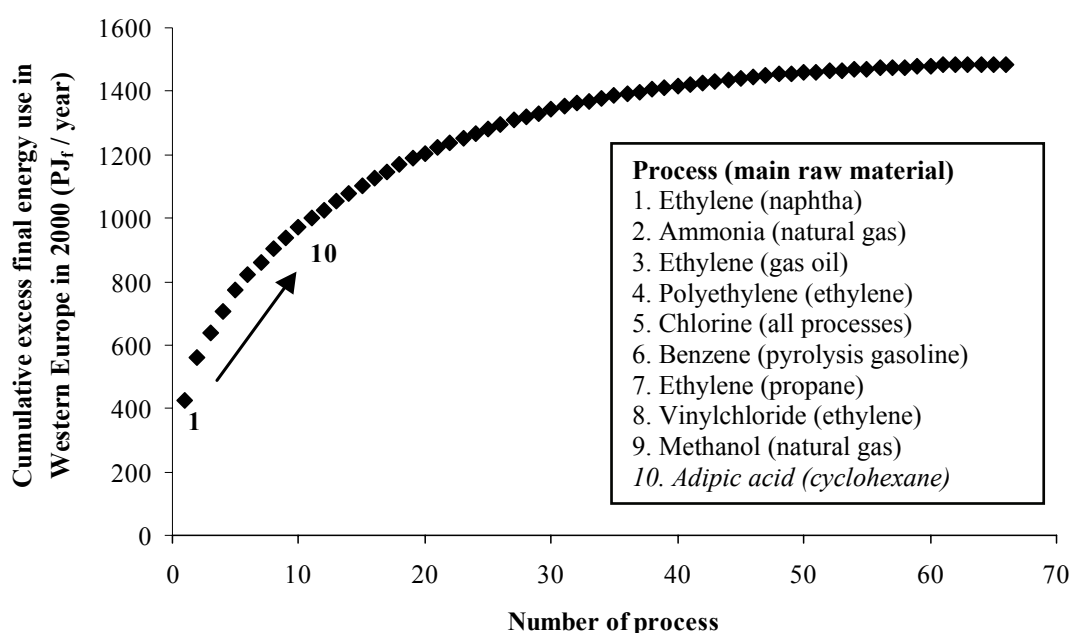


Figure 6.3 Cumulative excess final energy use (indicator 9) in Western Europe in 2000 for the processes included in the model. Individual processes (data points) are ranked in the order of decreasing total excess final energy use. Note: the process printed in italics is uncertain estimate based on single sources published before 1990 (see Section 6.5).

The total excess final energy use for the sum of the processes included in the analysis was estimated to be 1482 PJ_f in 2000. We could not calculate the heat of the stoichiometric

products produced. Instead, the stoichiometric heat of reaction is set equal to the heat effect of reaction, which is calculated as the difference between the total cracker output and the cracker input. Part of the cracker output (i.e., the fuel by-products) is used to fuel the process. This amount is included as final fuel use. The resultant figures are expressed per tonne of total products produced.

reaction and the heat effect of reaction with sufficient accuracy for a limited number of processes (see notes in Appendix A). For those processes, we set the excess final energy use in Figure 6.3 equal to the total final energy use.

6.3.2 Losses due to non-selectivity

In many processes, part of the raw material is not converted to the desired products - it is lost. We refer to this type of loss as *losses due to non-selectivity* and quantify them by comparing the actual difference in energy content between the raw materials and products of the process (indicator 5) with the theoretical difference in energy content between raw materials and desired products. The latter is equal to the negative value of the $\Delta H_{\text{reaction}}$ from raw materials to desired products (indicator 2)⁷. We show this comparison in Figure 6.4. Processes that have a 100% conversion from raw materials to desired products according to the stoichiometric reaction are located on the $y = x$ line shown in Figure 6.4. In practice, however, not all of the raw material is converted to the desired products: it is lost due to non-selectivity. This loss (indicator 10) is equal to the vertical distance between the data points and the $y = x$ line.

The losses due to non-selectivity can be the result of either the formation of undesired low-value fuel-grade by-products⁸ or the over-oxidation of the hydrocarbon raw materials, leading to process heat and direct CO₂ emissions. The energy in the second case becomes directly available as process heat within the reactor, whereas the energy in the first case is embodied in low-value by-products that might be burned with energy recovery. It is not always clear whether the second type of energy recovery is netted off in the process datasets as found in literature. Part of the losses due to non-selectivity, therefore, might have been double-counted in our analysis, first as losses due to non-selectivity and again as final energy use (for a discussion, see Section 6.5). It should be noted that the effect of raw material losses on the heat effects of reaction is substantial. If 0.01 tonne of a hydrocarbon raw material is lost per tonne of product, the heat effect of reaction increases by 0.1 – 0.5 GJ_f / tonne in the form of either heat or low-value by-products (considering that the energy content of the hydrocarbons used as raw materials ranges between 10 and 50 GJ/tonne). This constitutes a significant fraction of the heat of reaction of most processes, as shown in Figure 6.4. The 10 processes with the largest losses due to non-selectivity are also listed in Figure 6.4. The list shows that oxidation reactions, in particular, are often difficult to control in a selective way. In ethylene

⁷ In our approach, the heat effect of reaction is the difference in energy content between the raw materials and the products of a process. Thus, exothermic reactions in our model have a positive heat effect of reaction and endothermic reactions a negative heat effect of reaction (Table 6.1). This is exactly opposite to the convention used for the $\Delta H_{\text{reaction}}$ (variable 22).

⁸ Although some products might be valuable, their concentrations might be too low to justify a complicated and/or expensive product separation process. The losses due to non-selectivity also include losses via light and heavy purge (bleed) streams in recycle loops.

oxide production, for example, 18 mass % of the ethylene is burned rather than converted to ethylene oxide. This results in a heat effect of reaction of 9.1 GJ_f/tonne ethylene oxide rather than the 2.4 GJ_f/tonne in the case of a stoichiometric conversion from ethylene to ethylene oxide.

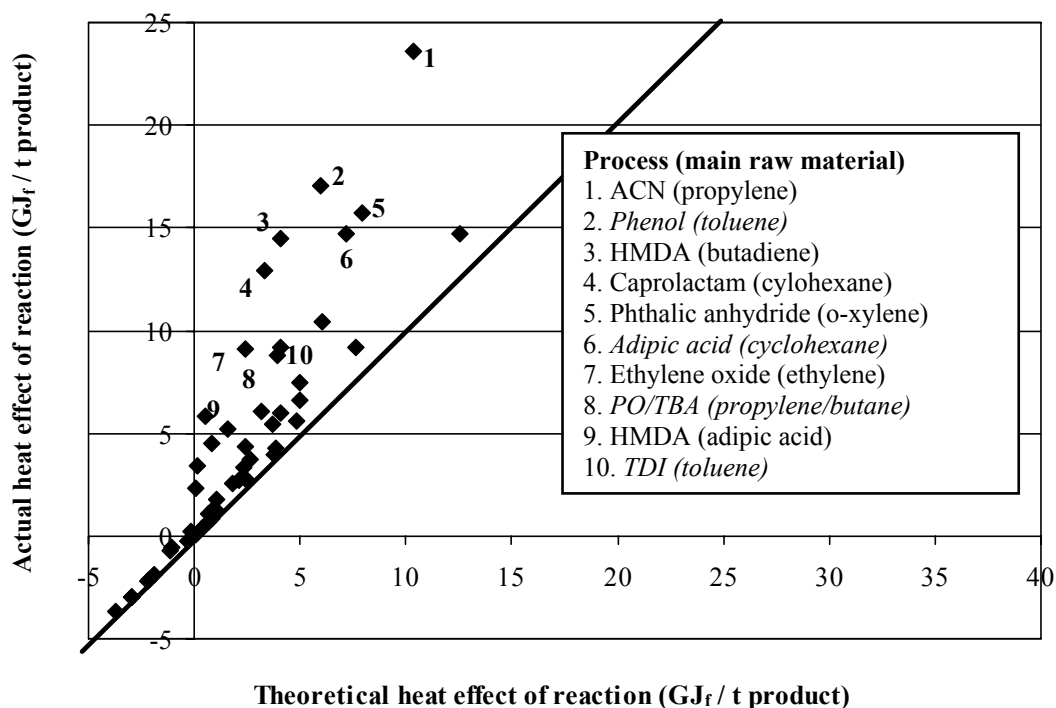


Figure 6.4 Theoretical heat effect of reaction ($-\Delta H_{\text{reaction}}$, indicator 2) versus actual heat effect of reaction (indicator 5). Note: the processes printed in italics are uncertain estimates based on single sources published before 1990 (see Section 6.5)

As with the excess final energy use, we converted the losses due to non-selectivity per tonne of product to total losses per year, taking into account the production volumes of the chemical commodities and the shares of the various process routes. A graph of the losses due to non-selectivity for the sum of the processes and a list of the 10 processes with largest losses in 2000 are presented in Figure 6.5. Total losses due to non-selectivity of the processes analysed amounted to 138 PJ_f in 2000. Losses due to non-selectivity are small compared to the excess final energy use of the processes (138 PJ_f and 1482 PJ_f, respectively; compare Figure 6.3 with Figure 6.5). The economic importance of these losses, however, is more significant because raw material costs are generally much higher than energy costs. Furthermore, it is important to realise that raw material losses also result in avoidable energy use in the more upstream processes to produce this raw material, an effect that we did not quantify in this study.

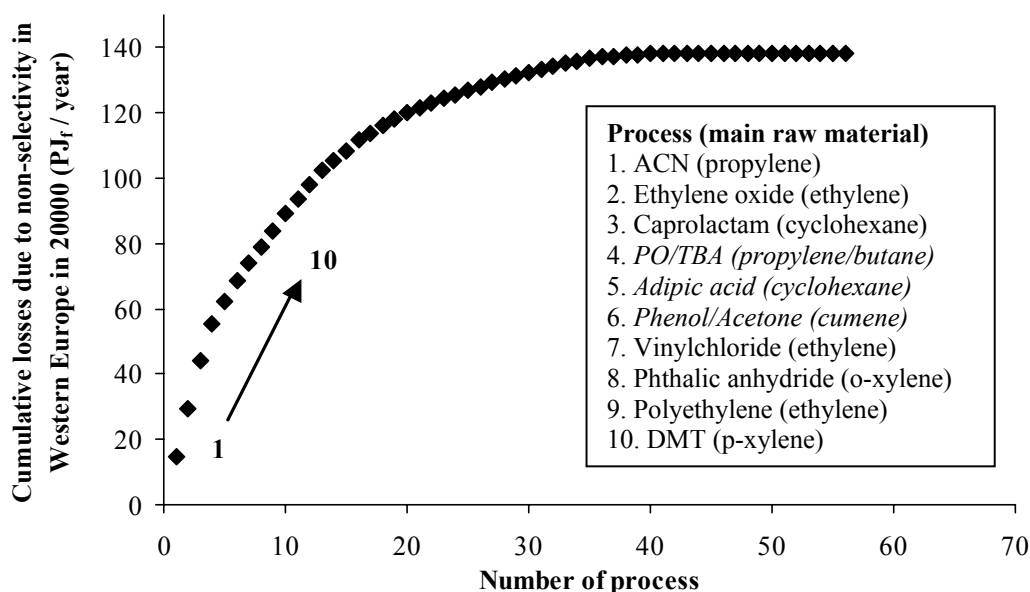


Figure 6.5 Cumulative losses due to non-selectivity (indicator 10) in Western Europe in 2000 for the processes included in the model. Individual processes (data points) are ranked in the order of decreasing losses due to non-selectivity. Note: we excluded the processes for which the heat of the stoichiometric reaction and the reaction effects are not included (Appendix A). The processes printed in italics are uncertain estimates based on single sources published before 1990 (see Section 6.5)

6.3.3 Total energy losses and CO₂ emissions

The total final energy loss of the processes (indicator 7) equals the sum of the heat effect of reaction (indicator 5) and the total final energy use (indicator 3). By definition, the total final energy loss is also equal to the sum of losses due to non-selectivity (indicator 10) and excess final energy use (indicator 9). The total primary energy loss (indicator 8) equals the sum of the final energy loss and the energy conversion losses (indicator 6). The energy conversion losses are equal to the difference between final and primary energy use (indicator 4 – indicator 3).

The contribution of the losses due to non-selectivity, excess final energy use and energy conversion losses to the total primary energy loss for all processes having a primary energy losses exceeding 15 GJ_f / tonne of product are given in Figure 6.6. The processes with large losses due to non-selectivity, a large excess final energy use, and large energy conversion losses can be readily identified by the three bar sections. We converted the indicators shown in GJ per tonne of product to total PJ per year, taking into account production volumes and shares of the various process routes. The processes with total primary energy losses exceeding 20 PJ_p in 2000 are presented in Figure 6.7.

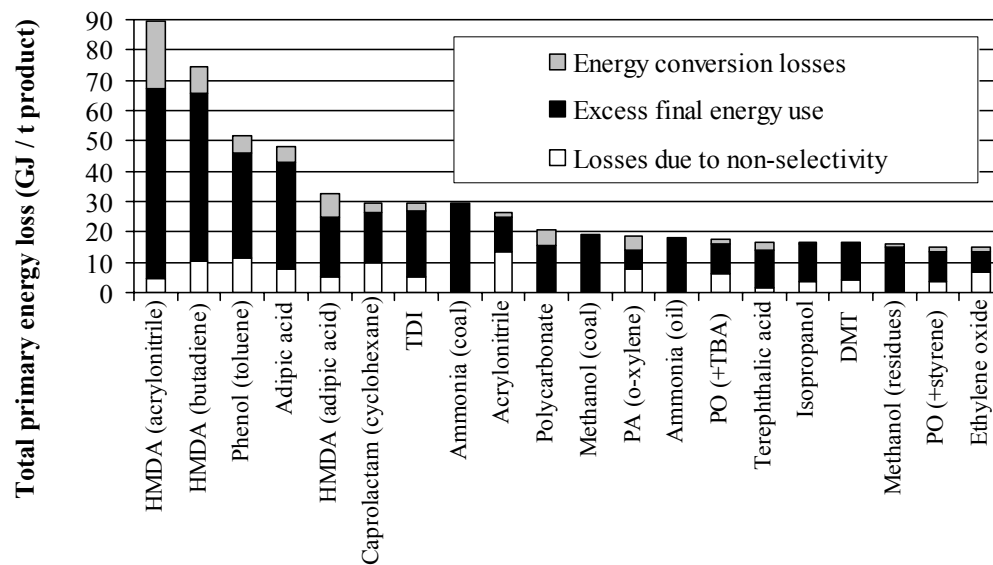


Figure 6.6 Processes with total primary energy losses (indicator 8) exceeding 15 GJ_p / tonne product. Note: we considered the final energy use to equal the total final energy use and the losses due to non-selectivity to equal 0 for those processes for which the heat of the stoichiometric reaction and the reaction effects were not included (Appendix A)

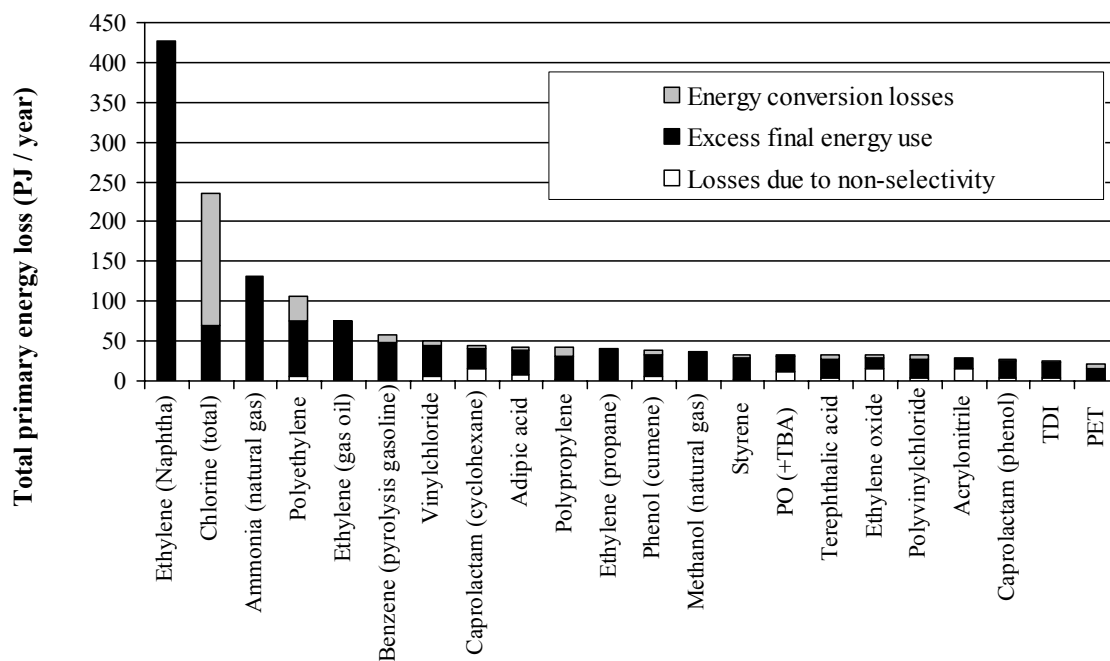


Figure 6.7 Processes with total primary energy losses (indicator 8) exceeding 20 PJ_p in Western Europe in 2000. Note: we considered the final energy use to equal the total final energy use and the losses due to non-selectivity to equal 0 for those processes for which the heat of the stoichiometric reaction and the reaction effects were not included (Appendix A)

Figure 6.8 and Figure 6.9 show, respectively, the total primary energy loss and the total CO₂ emissions in such a way that the energy and CO₂ emission profiles of the petrochemical industry become visible. Petrochemical feedstocks (naphtha, gas oil, LPG, ethane) are first converted into basic chemical (olefins and aromatics) in the endothermic steam cracking process⁹. The overall heat effect of reaction of the steam cracking process was estimated to be -129 PJ (endothermic) in 2000. The endothermic reaction was sustained by burning 689 PJ_f of fuels, leading to a total of 33 Mt CO₂ emissions. The total final energy loss in the steam cracking process was therefore 560 PJ_f (689 - 129). The conversion of sodium chloride to chlorine (another important basic chemical) is also endothermic with a heat effect of reaction of -62 PJ_f in 2000. This reaction was sustained by supplying 131 PJ_f of final energy per year, resulting, under the assumptions given in Section 6.2.3, in a total of 25 Mt CO₂ emissions. The total final energy loss therefore equalled 69 PJ_f (131 - 62). Since the energy input into chlorine production is electricity, the total primary energy loss was much higher (236 PJ_p, Figure 6.7). Final energy use in the production of a third important basic chemical (ammonia) was estimated to be 152 PJ_f in 2000 (excluding feedstock use, which we defined as the LHV of the ammonia product), resulting in a total of 17 Mt CO₂ emissions.

In subsequent chemical conversion steps, heteroatoms are added to the double bonds in the olefins and aromatics produced via steam cracking in conversions that are mainly exothermic. The heat effect of reaction for the sum of these more downstream processes was estimated at 342 PJ_f (exothermic) in 2000. The theoretical heat effect of reaction for the sum of those processes only equalled 204 PJ_f. Therefore, more than 40% of the heat effect of reaction resulted from losses due to non-selectivity (138 PJ_f per year; i.e., 342 - 204, Figure 6.5). Carbon losses resulting from these losses due to non-selectivity were estimated at 9 Mt CO₂ in 2000 (excluding emissions from ammonia and methanol production). The remaining processes had a final energy use of 497 PJ_f per year, resulting in 35 Mt CO₂ emissions. According to the defined stoichiometric reactions, the processes could produce 204 PJ_f of energy if they ran 100% according to the defined stoichiometric reactions and without energy losses; in practice they consumed 497 PJ_f. The excess final energy use in those processes, therefore, was 701 PJ_f (497 + 204) in 2000.

The total final energy loss for the sum of the processes included equalled 1620 PJ_f. Since the energy conversion losses (using the assumptions given in Section 6.2.3) were estimated to be 316 PJ_p, the total primary energy loss equalled 1936 PJ_p. The results clearly show that the heat effect and carbon losses of reaction contribute significantly to the overall energy loss and CO₂ emissions of the chemical industry. These effects, however, are not directly visible in energy

⁹ Some of the aromatics and a small amount of propylene are recovered in refineries and not via steam cracking.

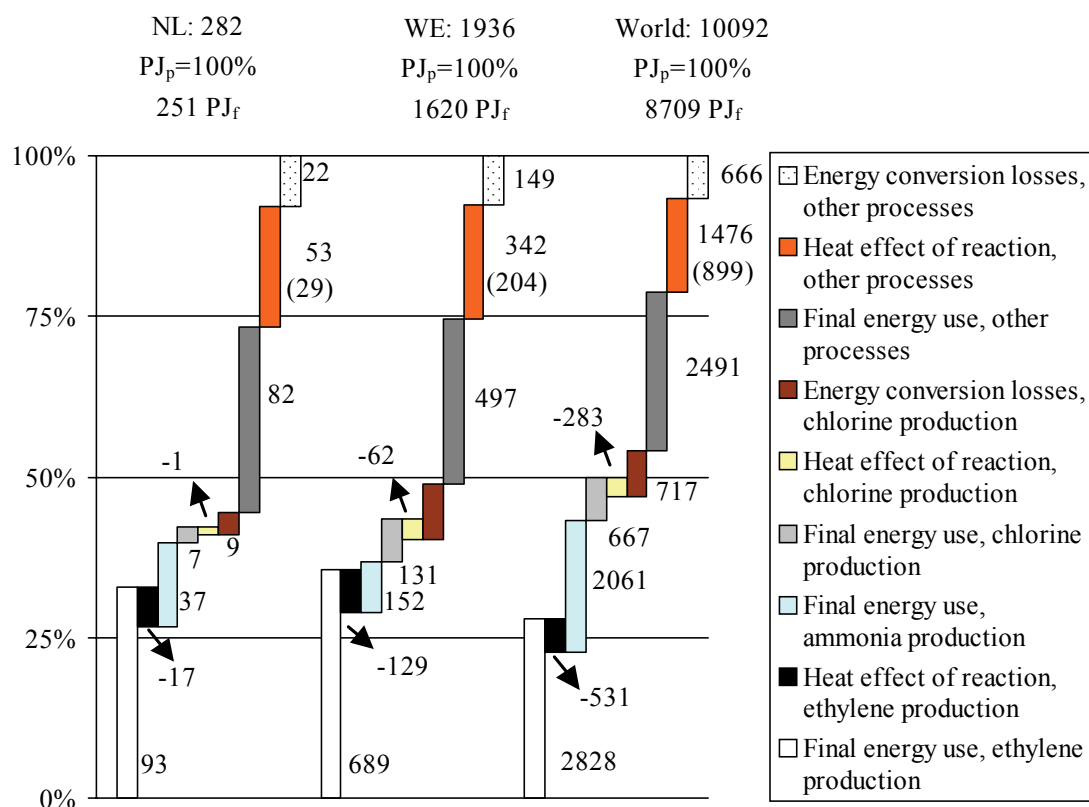


Figure 6.8 Overview of the total final and primary energy losses (indicator 7 and 8) in the year 2000. Note: ethylene, ammonia and chlorine production are given separately to show their major contribution to the totals. Figures in parentheses are the theoretical heat effects of reaction

statistics and are often not explicitly addressed or quantified in life-cycle analyses and energy efficiency studies for the chemical industry. They should, however, be considered in order to get a proper overview of the energy use and energy saving and CO₂ reduction possibilities in the chemical sector.

6.4 General directions for energy savings based on our findings

Our analysis was based on the first law of thermodynamics and quantified the sum of all energy inputs into the process that do not end up in the useful products of the process, but are lost as waste heat to the environment. As explained in the introduction, the total primary energy loss can be regarded as a good approximation of the theoretical energy saving potential of the processes involved. To identify technical and economic energy saving potentials based on our results, it is necessary to conduct more detailed analyses at the level of

individual unit operations (e.g. reactors, separation equipment, compressors etc.) using both first and second law aspects as well as practical and economic considerations related to energy saving options. The processes with large losses identified in this study (Figure 6.2 - Figure 6.7) are recommended for such detailed analyses. In this section we will briefly discuss some general directions for energy savings based on our black box analysis without having the intention of giving a complete overview.

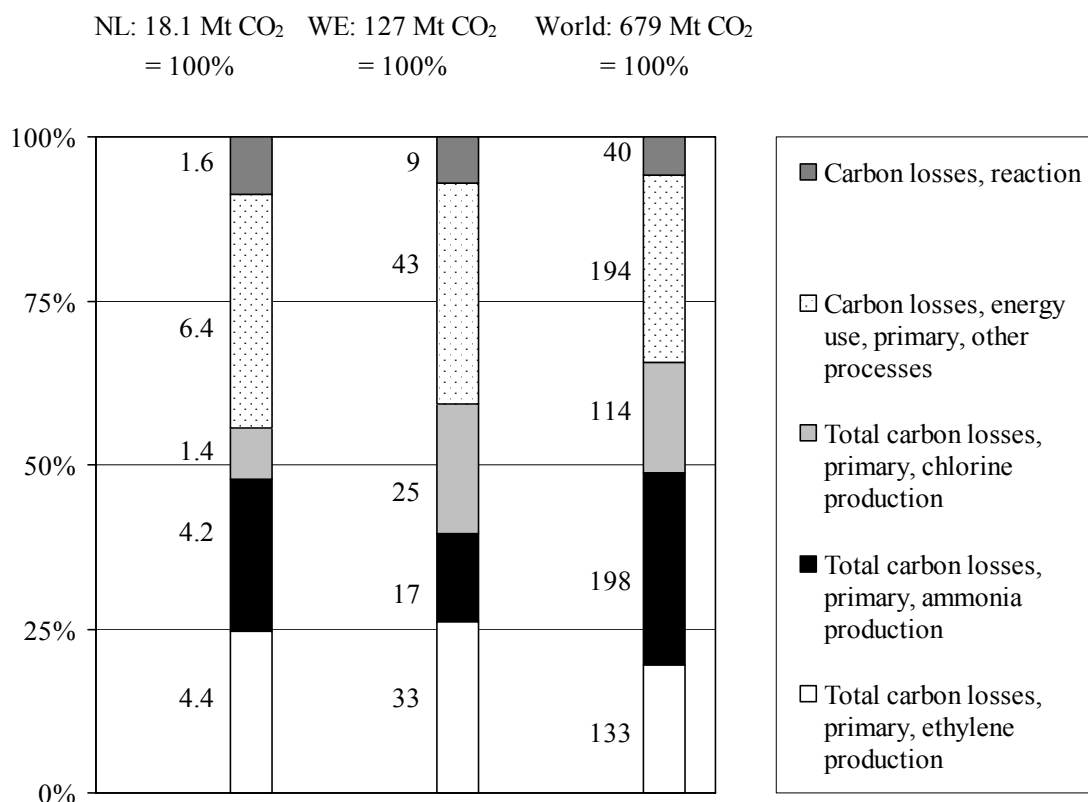


Figure 6.9 Overview of total primary carbon losses (indicator 13) in the year 2000. Note: ethylene, ammonia and chlorine production are given separately to show their major contribution to the totals.

Our analysis was based on average technology in place in Western Europe in 2000. These processes are less energy efficient than processes using *best available techniques* (BAT). Based on BAT data for ammonia, methanol and ethylene production (steam cracking), we estimate that for these processes, the energy saving potential related to the implementation of BAT processes ranges between 10 and 50% of the current final energy use (Neelis et al., 2005a). This (rather broad) range indicates that the potential related to the implementation of BAT processes is substantial. Because of the significant uncertainties in both the BAT data and our average process data (see Section 6.5) and the unavailability of further data on BAT processes, it is, however, difficult to draw more robust conclusions about the total potential related to the implementation of BAT processes.

Based on the distinction between the three types of losses, we distinguish between improvements with the aim to lower the *losses due to non-selectivity of processes*, those with the aim to lower the *excess final energy use* of processes and those with the aim to lower the *energy conversion losses* of the processes. Energy conversion losses can be lowered by more efficient steam and electricity production (e.g., combined heat and power production) or by switching from electricity to fuel use where possible (e.g., avoid the use of electricity for heating purposes). This is not further discussed in the present paper.

With the exception of polyethylene, all processes listed in the top 10 of processes with the largest losses due to non-selectivity (Figure 6.5) involve oxidation reactions. These reactions are often difficult to control in a selective way. Over-oxidation in these processes results in the formation of by-products such as hydrogen cyanide in the production of acrylonitrile and CO₂ in the production of ethylene oxide. One possibility for lowering the losses due to non-selectivity is the development of (*more selective*) *catalysts*. Past examples of selectivity improvements using better catalysts are numerous. For instance, the selectivity in ethylene oxide production increased from around 70% in the 1960s to more than 80% nowadays (Lange, 2001) and the selectivity of catalysts used in acrylonitrile production has also steadily improved over time (Chauvel and Lefebvre, 1989). These two processes, however, are still at the top of our list of processes with large losses due to non-selectivity, thus leaving room for further improvements.

A chemical process can, in a simplified way, be seen as the combination of a reaction section and a separation/purification section. Separation/purification normally requires energy, whereas the reaction section is either an energy consumer (endothermic conversions) or an energy producer (exothermic conversions). In this paper, we did not separately identify losses in the reaction and separation/purification sections. With respect to the chemical conversions, both Leites et al. (2002) and Korevaar (2004) argued that it is desirable from an exergy point of view to perform exothermic reaction at high temperatures and to supply heat to endothermic reactions at the lowest possible temperatures (if possible, via coupling with an exothermic reaction). This contradicts, however, the desire for a high degree of conversion, which is favoured by low temperatures for exothermic reactions and high temperatures for endothermic reactions¹⁰. Process concepts that can help partly overcome this contradiction are *heat exchange and membrane reactors*. If a heat exchange reactor is applied for exothermic conversions, a gradual decrease in temperature can be used so that part of the reaction is conducted at a high temperature (to allow withdrawal of heat at a high temperature level) and

¹⁰ The desire for a high temperature is also limited by the availability of material that can withstand high temperature with negligible corrosion. Material improvement is therefore also a direction to reduce energy losses.

part at a low temperature (to reach a reasonable degree of conversion). Given the importance of the heat effect of reaction in the total energy loss of the process (Figure 6.8), it is clear that the potential benefit of such reactors for the processes analysed in this study could be substantial. This is confirmed in a study by Hugill (2003). The application of membrane reactors can help to shift the equilibrium in reactors, allowing operation at more favourable reactor conditions. The application of membranes in the production of synthesis gas used for ammonia production can, for example, help to reach the same conversion rates in the endothermic reaction at a much lower temperature (Delft et al., 2005). Another, more drastic way to reduce energy losses is to shift to *other process routes*, using other raw materials. As shown by Lange (2001), past changes in choice of raw materials often resulted in a lower heat effect of reaction and lower energy losses. In another paper (Lange, 2002), Lange mentions caprolactam, adipic acid and vinyl chloride as products for which research activities on alternative routes are taking place. Not surprisingly, these processes also appear in the lists of processes with large losses presented in Section 6.3 of this paper. Another option is to make use of *biomass raw materials* or *bioconversion technologies* such as enzymatic conversions and / or fermentation. The potentials for such routes (e.g., for caprolactam and adipic acid present in our lists of processes with large losses) have been studied by a number of researchers (Crank et al., 2004 and van Tuil et al., 2004).

According to the first law of thermodynamics, energy cannot be lost. Therefore, the energy loss calculated in this study equals the flow of *waste heat* to the environment in the form of cooling water, hot off-gases from furnaces etc. Even without the process improvements considered above, one general focus for energy savings is to find a suitable use for this waste heat. Whether or not waste heat can be used for applications such as heat pumps, heating of buildings etc. depends, among other things, on the temperature level of the waste heat flow to the environment. Without looking into the processes, it is not possible to analyse the temperature of the waste heat disposal. Other studies (Carp and Bach, 2001 and Spoelstra et al., 2002) have shown that at least some of the waste heat becomes available at temperature levels suitable for such useful applications (exceeding 50 °C). Examples of waste heat applications in the Rotterdam area are its use for space heating (Anonymous, 2004) and it being used by other industries via co-siting (Anonymous, 2005).

6.5 Discussion

6.5.1 Uncertainties

The number of datasets taken into account in our calculations ranged from 1 to 12 per process. For those process routes for which several datasets were available, we used the dataset most likely to represent the average technology used in Western Europe in 2000. In

cases, where only one process dataset was available, we use this dataset without adjusting for process improvements that might have taken place over time. Unfortunately, information on highly energy-integrated chemical plants was not available for this study. For this reason, the results for the individual processes may have a significant range of uncertainty. Based on the number of process datasets available and on the types of sources used, we marked the processes for which we estimated the final energy use data shown in Figure 6.2 to have an uncertainty of less than 10% (21 of the 68 processes) with a “1” in Appendix A. For most of the remaining processes, we estimated the uncertainty to be between 10 and 30% and marked them with a “2” in Appendix A (34 of the 68 processes). Those processes with an even higher uncertainty range (over 30%), based on one single source published before 1990 (e.g. Chauvel and Lefebvre, 1989) are marked with a “3” in Appendix A (13 of the 68 processes).

We did not account for geographical differences in energy efficiency between and within the three regions studied. Instead, we based all analyses on process energy data that were considered representative for Western Europe. Some insight in the ranges observed in practice can be obtained by looking at the ranges for processes reported in literature. For example, ranges for fuel use in steam crackers of 15-25 GJ/tonne ethylene for ethane cracking, 25-40 GJ/tonne for naphtha cracking, and 40-50 GJ/tonne for gas oil cracking have been reported for European steam crackers (IPTS, 2003). Since there is no clear indication that European steam crackers are clearly more energy efficient than the worldwide average (Phylipsen et al., 2002), these ranges can also be regarded as indicative for the worldwide situation for this process. Because such comparative data were not available for most of the processes included, it was difficult to draw robust conclusions about the geographical differences in energy efficiency based on the current set of data. We estimated the uncertainty in the production volumes to be in the order of about 10-20% and the uncertainties in the shares of the various process routes to be about 5-10%. We base this range on the capacity data and production volumes from different sources, which are included in the model.

Some of the losses due to non-selectivity are in the form of low value fuel grade by-products. When these fuel by-products are burned, energy might be recovered. If this energy recovery is not deducted from the energy use of the process found in the datasets, the energy use may be double-counted as losses due to non-selectivity and again as final energy use. The same is true for carbon losses from reaction. We can conclude from Figure 6.5 that such double-counting for Western Europe is maximally 138 PJ_f or 9 Mt CO₂/year, approximately 8% of the total final energy use and CO₂ emissions. In reality, double-counting is less, because the losses due to non-selectivity in some of the processes (e.g., ethylene oxide production) are the result of over-oxidation of the feedstock, which leads to direct CO₂ emissions and to the formation of heat.

The main focus of this study was on the energy use within the processes rather than on the energy conversion sector. We therefore calculated the CO₂ emissions from steam and electricity generation using the rather simple method described in Section 6.2.3. In actual practice in the chemical industry, a fraction of the heat and power used is produced in combined heat and power (CHP) plants rather than in the separate systems we assumed. In the year 2000, for example, 215 PJ_e of electricity and 350 PJ_f of heat were produced from 781 PJ_p of fuels in CHP units in the European Union's chemical industry, i.e., with an overall efficiency of 72% (Loesoenen, 2003). This is 34% of the final electricity and 26% of the final fuel use reported in international energy statistics (IEA, 20002). A total of 37 PJ electricity and 78 PJ heat was produced in CHP plants in the Dutch chemical industry in 2000, with an overall efficiency of 80% (Statistics Netherlands, 2004a). This equals 86% of electricity use and 43% of fuel use in 2000 (IEA, 2002). Total primary energy savings in these CHP plants are 15% for the European Union and 19% for the Netherlands compared to our reference of separate production. For fuel and steam use, we used CO₂ emissions factors derived from the fuel mix applied in the chemical industry in Western Europe. For electricity, we used an average emission factor and the efficiency of fossil generation of electricity in a few European countries. These emission factors do not take into account process-specific and regional differences or the implementation of combined heat and power. Our simplified approach is justified given the scope of the study. It is, however, important to keep in mind the assumptions made when using data from Appendix A or from the figures shown.

6.5.2 Comparison with other sources

For the Netherlands, we compared the results of the total of processes covered in this study with the energy use of the petrochemical industry (and ammonia and chlorine production), as it can be found in national energy statistics (Table 6.2). We divided the final energy use into electricity, fuel, and heat use to allow a better comparison. The comparison was complicated, however, by the unclear definition of feedstock use in energy statistics¹¹. In the steam reforming and steam cracking processes, the raw material (e.g., natural gas or naphtha) is used partly as feedstock and partly as fuel. The use as fuel can take either directly (e.g., natural gas in ammonia production) or via the intermediate production of fuel gas (steam cracking). In the Netherlands, a net definition of feedstock use is applied in which parts of the raw material that are used as fuel are excluded from the feedstock use¹². The same system boundaries were applied in Table 6.2. The results from our model for the use of fuels and heat fit reasonably well with the published Dutch statistics, given the uncertainties in both our model results and the energy statistics. The coverage for electricity use is much lower (60%). This can be partly

¹¹ These issues are currently being studied in a research project financed by the European Commission (NEU-CO₂, 1999-2006).

¹² The non-energy use accounting is quite complex in the Netherlands. We refer to Neelis et al. (2005b) for details.

explained by some major electricity consuming processes (e.g., industrial gases) that were not included in our model, but were included in the energy use of the ‘other basic chemical industry’ in the Dutch energy statistics. Furthermore, our model did not account for the electricity use of on-site facilities such as lighting, and space heating.

Table 6.2 Comparison of final energy use and final energy loss in the Netherlands between our model and the Dutch energy statistics for the petrochemical industry for the year 2000

	Model ^a	Energy statistics ^b	Coverage	Final energy loss (Figure 6.8)
	PJ _f / year	PJ _f / year	%	PJ _f / year
Electricity	18	30	60	18
Fuels	155	117	95	155
Heat	45	94		45
Feedstock	328	352	93	-
Heat effect of reaction	-	-	-	32
Total	546	593	92	251

^a Feedstock use is raw material input into olefin, ammonia and methanol production minus the fuel use in these processes.

^b Based on data from Statistics Netherlands (2005). Electricity use of the organic and other basic chemical industry plus the final non-energy use of electricity in the inorganic basic chemical industry (chlorine production). Fuel use of the organic and other basic chemical industry plus the final energy use of natural gas in the fertiliser industry (ammonia production). Feedstock use (final non-energy use) of the organic and other basic chemical industry plus the final non-energy use of the fertiliser industry (ammonia production).

Our model could only be compared with energy use data for the chemical industry as a whole for Western Europe and the world, since energy statistics comparable to our system boundaries were unavailable (Table 6.3). For the Western European and worldwide figures, we assumed a gross definition of feedstock use for olefin production (allocating the total input into the crackers to non-energy use, corrected for reported backflows to refineries) and a net definition of feedstock use for methanol and ammonia production (allocating only the calorific value of the products to feedstock use). Based on a detailed comparison on the level of individual fuels, this choice of definition proved to yield the most reasonable results¹³. We can conclude that the processes included cover approximately 30% of the electricity use and 70% of the combined fuel and feedstock use in the chemical sector. This energy coverage is reasonably in line with other available sources:

¹³ If a net definition was applied for steam cracking and the fuel use in the crackers was excluded, one would expect a major final use of chemical rest gas in the chemical industry. This is indeed the case for the Netherlands (where a net definition is applied), but not for many other countries.

Table 6.3 Comparison of final energy use and final energy loss in Western Europe and the world between our model and international energy statistics for the chemical industry for the year 2000

	Model ^a	Energy statistics ^b	Coverage	Final energy loss (Figure 6.8)
	PJ _f /year	PJ _f /year	%	PJ _f /year
Western Europe				
Electricity	197	674	29	197
Fuels	306	1337	42	987
Heat	285	58		285
Feedstock	2246	2752	82	-
Heat effect of reaction	-	-	-	151
Total	3034	4821	63	1620
World				
Electricity	844	3131	26	844
Fuels	3040	9194	43	5700
Heat	1503	1155		1503
Feedstock	12379	14414	86	-
Heat effect of reaction	-	-	-	658
Total	17665	27894	63	8709

^a Except for 40% of the fuel use in ethane crackers (which require non-feedstock-derived fuels; 9 PJ in WE, 168 PJ worldwide), fuel use excludes the fuel use in olefin production. This fuel use is included in feedstock use, see the text for further explanation. The feedstock use is the raw material input into ammonia and methanol production minus the fuel use in these processes and the raw material input into olefin production minus backflows from olefin production to the refineries as reported in the energy statistics (631PJ in Western Europe; 1108 PJ worldwide).

^b Energy statistics from IEA (2002).

- According to the US Department of Energy (2000), more than 50% of electricity used in the US is consumed by subsectors of the chemical industry (industrial gases, industrial inorganic chemicals excluding chlorine phosphatic fertilisers) that were not covered in this analysis.
- According to the same source, 47% of total energy use in the US chemical industry is consumed in the drugs (6%), soaps/cleaners (3%), agricultural (9%), inorganics (25%) and other subsectors (4%) that were to a large extent not covered by our analysis.
- The heat reported in the international energy statistics only represents heat bought from third parties. The fuel reported as final consumption includes fuel used for direct fuel applications (e.g., in furnaces) as well as fuel used for steam generation, either in stand-alone steam boilers or in cogeneration plants, but excludes the amount of fuel used for the generation of electricity in cogeneration units, which should be reported

in the energy conversion sector¹⁴. As a result, the fuel consumption figures in the energy statistics include losses in steam generation, which are not included in final energy use figures according to our model (Figure 6.8).

6.6 Conclusions

We prepared energy and carbon balances for 68 processes in the petrochemical industry. We analysed the sum of all energy inputs (both process energy use and the energy content of the raw materials) that do not end up in the useful products of the process, but are lost to the environment. The total energy loss identified can be regarded as a good approximation of the theoretical energy saving potential of the processes analysed. For the total of the processes studied, we estimated the energy loss in Western Europe in the year 2000 to be 1936 PJ_p, resulting in a total of 127 Mt CO₂. We distinguished between excess final energy use, losses due to non-selectivity and energy conversion losses, which contributed 77, 7 and 16%, respectively, to the total energy loss. Similar divisions were found for the Netherlands and the world, where total losses were quantified at 282 and 10092 PJ_p respectively. We showed that both the heat effect of reaction and the process energy use contribute significantly to the overall energy loss of the individual processes and recommend that studies on energy efficiency improvement potentials in the chemical industry address the heat effect of reaction (which is not directly visible in energy statistics) more explicitly. We identified several processes with large energy losses and advocate that they be further analysed to identify technical and economic saving potentials, taking into account further thermodynamic, economic and practical limitations to energy saving options. Such analyses will require more in-depth studies at the level of unit operations, taking into account aspects related to the second law of thermodynamics. We showed that the potential energy savings from the implementation of BAT processes might in the order of 10-50% of the current final energy use. Based on the types of losses distinguished, we gave some general directions of energy savings, such the use of more selective catalysts to reduce losses due to non-selectivity, the

¹⁴ This practice raises the question of how the fuel input in auto-producer CHP plants is allocated to the electricity and heat produced. In the electricity and heat survey, the countries are asked to use national methodologies. In cases where an adequate national method is lacking, the IEA recommends allocation of the input between electricity and heat in proportion to the energy content of the heat and electricity produced (Eurostat/IEA/UN, 2003). This latter method leads to steam generation efficiencies equal to the overall efficiency of the cogeneration units, which in the chemical industry in the European Union averages 72% (Section 6.5.1). When this efficiency is applied to the steam generated in CHP plants (Section 6.5.1) we can conclude that the final fuel use according to the energy statistics includes 136 PJ of energy lost in steam generation. Deducting this amount from the reported final fuel use leads to a coverage of 47% in Western Europe.

use of novel process concepts such as membrane or heat exchange reactors, the use of totally new process routes based on biomass, and a better use of waste heat available from the various processes.

Acknowledgements

We would like to thank Evert Nieuwlaar (Utrecht University, Copernicus Institute, Unit Science, Technology and Society) and Jean-Paul Lange (Shell) for their review of previous drafts of this paper.

Abbreviations		MP	middle pressure
ACN	acrylonitrile	MTBE	methyl tert-butyl ether
BAT	best available technology	NL	Netherlands
CHP	combined heat and power	PET	polyethylene terephthalate
DMT	dimethylterephthalate	PO	propylene oxide
EU	European Union	TBA	tert-butyl alcohol
HDMA	hexamethylene diamine	TDI	toluene diisocyanate
HP	high pressure	WE	Western Europe
LCA	life-cycle-analysis		
LHV	lower heating value	<i>Subscripts</i>	
LP	low pressure		
LPG	liquefied petroleum gas	e	electricity
MDI	diphenyl-4,4-diisocyanate	f	final
ACN	acrylonitrile	p	primary

Appendix A (continued on next pages)

	Ethylene	Ammonia	Poly-ethylene
Production volume, the Netherlands	kt / year	2666	1331
Production volume, Western Europe	kt / year	19788	10658
Production volume, World	kt / year	91000	40856
Reaction route	Steam cracking of naphtha	Steam reforming of natural gas	Addition polymerisation of ethylene
Share, the Netherlands	83%	0%	100%
Share, Western Europe	75%	5%	100%
Share, World	51%	21%	100%
Source	Neelis (2003)	Neelis (2003)	DOE/OIT (2000)
Uncertainty indicator (Section 6.5)	1	1	2
Heat of stoichiometric reaction	GJ _r /t	4.61	-3.83
Electricity use	GJ _e /t	0.00	2.04
Fuel use	GJ _f /t	47.00	18.30
Steam use	GJ _f /t	0.00	0.00
Total primary energy use	GJ _p /t	47.00	18.30
Heat effect of reaction	GJ _r /t	-8.52	4.30
Total final energy loss	GJ _f /t	38.48	6.98
Total primary energy loss	GJ _p /t	38.48	9.98
Excess final energy use	GJ _f /t	38.48	6.51
Losses due to non-selectivity	GJ _r /t	0.00	0.47
Carbon losses, energy use, primary	t CO ₂ /t	2.29	0.47
Carbon losses, reaction	t CO ₂ /t	-	0.03
Total carbon losses, primary	t CO ₂ /t	2.29	0.50
Notes	a	a	b

	Chlorine	Benzene from py-gas aromatics	Benzene from toluene aromatics	p-xylene from reformate aromatics	Polypropylene	Vinyl-chloride
Production volume, the Netherlands	537	1402	1402	430	888	430
Production volume, Western Europe	9704	6966	6966	1591	6558	5500
Production volume, World	44084	30200	30200	16000	27833	26746
Reaction route	Electrolysis of sodium chloride (diaphragma)	Electrolysis of sodium chloride (mercury)	Electrolysis of sodium chloride (membrane)	p-Xylene from aromatics cut	Addition of polypropylene	Integrated chlorination /oxychlorination
Share, the Netherlands	22%	66%	11%	100%	100%	100%
Share, Western Europe	22%	58%	20%	100%	100%	100%
Share, World	60%	20%	20%	100%	100%	100%
Source	IPTS (2001)	IPTS (2001)	IPTS (2001)	IPTS (2003)	HP (2003)	IPTS (2003)
Uncertainty indicator (Section 6.5)	1	1	1	2	2	1
Heat of stoichiometric reaction	6.41	6.41	6.41	Separation	-2.47	-2.32
Electricity use	10.69	12.82	10.04	0.92	0.66	0.72
Fuel use	0.00	0.00	0.00	2.67	1.37	3.60
Steam use	6.27	0.00	1.85	7.01	6.74	0.51
Total primary energy use	33.05	31.26	26.55	12.69	10.47	5.93
Heat effect of reaction	-6.41	-6.41	-6.41	Separation	Separation	3.32
Total final energy loss	10.56	6.40	5.48	10.60	8.77	8.15
Total primary energy loss	26.64	24.85	20.14	12.69	10.47	9.24
Excess final energy use	10.56	6.40	5.48	10.60	8.77	7.15
Losses due to non-selectivity	0.00	0.00	0.00	Separation	Separation	1.00
Carbon losses, energy use, primary	2.68	2.69	2.24	0.84	0.69	0.41
Carbon losses, reaction	0.00	0.00	0.00	-	-	0.07
Total carbon losses, primary	2.68	2.69	2.24	0.84	0.69	0.48
Notes	c	c	c	d	d	d

		Polyvinyl- chloride	Ethyl- benzene	Urea	Styrene	MTBE	Methanol	
Production volume, the Netherlands	kt / year	447	1210	881	1243	934	731	
Production volume, Western Europe	kt / year	5269	5183	4988	4588	3360	3270	
Production volume, World	kt / year	25398	20351	118436	20067	20867	27900	
Reaction route		Addition polymerisation of vinylchloride	Alkylation of benzene	Reaction of ammonia with CO ₂	Dehydrogenation of ethylbenzene	Reaction of isobutene and methanol	Steam reforming of natural gas	Partial oxidation of coal
Share, the Netherlands		100%	100%	100%	29%	100%	100%	0%
Share, Western Europe		100%	100%	100%	85%	100%	88%	3%
Share, World		100%	100%	100%	85%	100%	88%	3%
Source		HP (2003)	HP (2003)	EFMA (2000)	Patel (1998)	IPTS (2003)	Appl (1997)	FhG-ISI (1999)
Uncertainty indicator (Section 6.5)		2	2	1	2	1	1	1
Heat of stoichiometric reaction	GJ _r /t	-2.11	-1.07	-0.04	1.11	-0.65	-	-
Electricity use	GJ _e /t	0.58	0.07	0.08	0.22	0.06	0.00	0.65
Fuel use	GJ _f /t	0.00	2.51	0.00	1.68	0.00	12.47	14.51
Steam use	GJ _f /t	1.80	-3.10	1.97	6.19	3.86	0.00	0.00
Total primary energy use	GJ _p /t	3.40	-0.76	2.38	9.10	4.43	12.47	16.09
Heat effect of reaction	GJ _r /t	2.68	1.20	0.09	-0.57	0.65	-	-
Total final energy loss	GJ _f /t	5.05	0.68	2.14	7.53	4.56	12.47	15.16
Total primary energy loss	GJ _p /t	6.08	0.44	2.47	8.53	5.08	12.47	16.09
Excess final energy use	GJ _f /t	4.49	0.56	2.09	6.98	4.57	-	-
Losses due to non-selectivity	GJ _f /t	0.57	0.13	0.05	0.54	0.00	-	-
Carbon losses, energy use, primary	t CO ₂ / t	0.24	-0.04	0.06	0.58	0.11	-	-
Carbon losses, reaction	t CO ₂ / t	0.04	0.01	0.02	0.05	0.00	-	-
Total carbon losses, primary	t CO ₂ / t	0.29	-0.03	0.08	0.63	0.10	0.44	1.41
Notes					e		a	a

	PET	Poly-styrene	Poly-urethane	Cumene	Ethylene oxide	Phenol
Production volume, the Netherlands	kt / year	396	187	344	353	103
Production volume, Western Europe	kt / year	3028	2797	2678	2176	2065
Production volume, World	kt / year	13244	7720	9631	13410	5586
Reaction route	Esterification of terephthalic acid with ethylene glycol	Addition polymerisation of styrene	Reaction of TDI with polyols	Alkylation of propylene with benzene	Oxidation of ethylene	Oxidation of cumene
Share, the Netherlands	100%	100%	50%	100%	100%	0%
Share, Western Europe	100%	100%	50%	100%	100%	5%
Share, World	100%	100%	50%	100%	100%	4%
Source	Boustead (2002)	HP (2003)	Boustead (1997)	HP (2003)	Patel (1998)	Chauvel Lefebvre (1989)
Uncertainty indicator (Section 6.5)	1	2	1	2	2	3
Heat of stoichiometric reaction	0.15	-0.67	-	-0.91	-2.39	-3.82
Electricity use	0.70	0.37	1.50	0.04	1.02	0.94
Fuel use	1.63	0.53	0.00	0.00	0.00	0.00
Steam use	2.42	0.01	0.00	1.80	3.09	23.14
Total primary energy use	6.02	1.46	3.66	2.11	5.91	34.48
Heat effect of reaction	0.22	1.08	-	1.31	9.14	7.03
Total final energy loss	4.97	2.00	-	3.16	13.25	16.97
Total primary energy loss	6.25	2.53	-	3.42	15.05	19.31
Excess final energy use	4.59	1.59	-	2.76	6.49	13.76
Losses due to non-selectivity	0.38	0.41	-	0.40	6.75	3.21
Carbon losses, energy use, primary	0.41	0.11	0.32	0.13	0.43	0.82
Carbon losses, reaction	0.04	0.03	-	0.03	0.45	0.26
Total carbon losses, primary	0.45	0.15	-	0.17	0.88	1.07
Notes	f		g			h

		Tere-phthalic acid	Formaldehyde	Butadiene	Propylene oxide	Polyether polyols	Acetone
Production volume, the Netherlands	kt / year	249	351	352	602	413	129
Production volume, Western Europe	kt / year	1959	1850	1839	1656	1337	1280
Production volume, World	kt / year	17000	6450	7868	4877	4816	3900
Reaction route		Oxidation of p-xylene	Oxydehydro- methanol	From steam cracking	Indirect oxidation via chlorohydrin	Indirect polyaddition of epoxies to an initiator	Dehydro- genation of isopropanol
Share, the Netherlands		100%	100%	100%	0%	100%	100%
Share, Western Europe		100%	100%	100%	46%	100%	17%
Share, World		100%	100%	100%	51%	100%	10%
Source		Boustead (2002)	IPTS (2003)	Chauvel Lefebvre (1989)	Chauvel Lefebvre (1989)	Chauvel Lefebvre (1989)	Chauvel Lefebvre (1989)
Uncertainty indicator (Section 6.5)		1	1	2	3	2	3
Heat of stoichiometric reaction	GJ _r /t	-7.62	-3.72	Separation	-3.78	-3.94	1.21
Electricity use	GJ _e /t	1.69	0.77	0.90	0.00	3.18	0.20
Fuel use	GJ _f /t	1.63	0.00	0.00	0.00	5.74	0.00
Steam use	GJ _f /t	1.65	-4.77	6.43	13.86	18.02	9.77
Total primary energy use	GJ _p /t	7.58	-3.43	9.34	15.40	33.52	11.34
Heat effect of reaction	GJ _r /t	9.21	5.43	Separation	-	16.53	-0.75
Total final energy loss	GJ _f /t	14.18	1.42	7.33	-	43.46	9.22
Total primary energy loss	GJ _p /t	16.79	1.99	9.34	-	50.04	10.59
Excess final energy use	GJ _f /t	12.58	-0.28	7.33	-	30.88	8.76
Losses due to non-selectivity	GJ _f /t	1.59	1.70	Separation	-	12.59	0.47
Carbon losses, energy use, primary	t CO ₂ / t	0.57	-0.17	0.63	0.95	2.26	0.71
Carbon losses, reaction	t CO ₂ / t	0.15	0.12	0.00	0.33	0.68	0.03
Total carbon losses, primary	t CO ₂ / t	0.72	-0.05	0.63	1.28	2.94	0.75
Notes					i	i	k

	Cyclo-hexane	Nitro-benzene	Acetic acid	Ethylene glycol	DMT	Acrylonitrile
Production volume, the Netherlands	232	0	0	237	103	172
Production volume, Western Europe	1255	1225	1214	1170	1128	1125
Production volume, World	5100	2468	7310	12200	3096	4704
Reaction route	Hydrogenation of benzene	Nitration of benzene	Carbonylation of methanol	Hydration of ethylene oxide	Oxidation of p-xylene, esterification with methanol	Ammoxidation of propylene
Share, the Netherlands	100%	-	-	100%	100%	100%
Share, Western Europe	100%	100%	80%	100%	100%	100%
Share, World	100%	100%	80%	100%	100%	100%
Source	Patel (1998)	Chauvel (1998) Lefebvre (1989)	Patel (1998)	Patel (1998)	Patel (1998)	Patel (1998)
Uncertainty indicator (Section 6.5)	2	3	2	2	2	2
Heat of stoichiometric reaction	GJ _r /t	-0.85	-1.78	-4.83	-6.05	-10.34
Electricity use	GJ _e /t	0.09	0.63	0.02	0.26	0.90
Fuel use	GJ _f /t	0.00	0.00	0.00	0.94	0.00
Steam use	GJ _s /t	-1.28	1.29	1.67	4.37	0.50
Total primary energy use	GJ _p /t	-1.19	1.56	1.91	6.44	2.75
Heat effect of reaction	GJ _r /t	2.77	0.85	5.59	3.70	23.58
Total final energy loss	GJ _f /t	1.59	2.19	7.28	9.27	24.98
Total primary energy loss	GJ _p /t	1.58	2.41	7.50	10.14	26.33
Excess final energy use	GJ _f /t	1.25	2.19	6.52	8.22	11.74
Losses due to non-selectivity	GJ _f /t	0.33	0.77	0.76	1.05	4.40
Carbon losses, energy use, primary	t CO ₂ /t	-0.07	0.46	0.12	0.41	0.37
Carbon losses, reaction	t CO ₂ /t	0.02	0.00	0.06	0.05	0.34
Total carbon losses, primary	t CO ₂ /t	-0.05	0.10	0.18	0.47	0.71
Notes						

	Capro-lactam	Adipic acid	Aniline	Urea Formaldehyde resin	MDI	2 Ethyl-hexanol
Production volume, the Netherlands	189	0	0	145	241	0
Production volume, Western Europe	1000	898	875	814	813	775
Production volume, World	4160	2100	3010	2129	2159	2408
Reaction route	From cyclohexane	Oxidation of cyclohexane	Hydrogenation of nitrobenzene	Condensation of urea with formaldehyde	Condensation of aniline with formaldehyde, phosgenation to MDI	Hydroformylation of propylene
Share, the Netherlands	0%	100%	-	100%	100%	-
Share, Western Europe	54%	46%	100%	100%	100%	100%
Share, World	54%	46%	100%	100%	100%	100%
Source	Patel (1998)	Chauvel Lefebvre (1989)	Chauvel Lefebvre (1989)	Patel (1998)	Patel (1998)	Patel (1998)
Uncertainty indicator (Section 6.5)	2	3	3	2	2	2
Heat of stoichiometric reaction	-9.27	-21.86	-4.99	-	-1.74	-3.80
Electricity use	3.96	1.08	0.29	0.18	3.88	0.29
Fuel use	0.80	0.10	0.00	0.00	0.00	0.00
Steam use	32.40	23.14	-2.57	2.51	1.07	6.02
Total primary energy use	46.45	28.45	-2.15	3.22	10.66	7.39
Heat effect of reaction	36.23	32.14	7.47	-	3.06	3.99
Total final energy loss	73.38	56.47	5.19	-	8.01	10.30
Total primary energy loss	82.68	60.59	5.32	-	13.72	11.39
Excess final energy use	46.43	46.19	2.71	-	6.69	10.10
Losses due to non-selectivity	26.95	10.28	2.48	-	1.32	0.20
Carbon losses, energy use, primary	3.11	0.79	-0.12	0.21	0.89	0.48
Carbon losses, reaction	0.88	0.25	0.06	-	0.14	0.00
Total carbon losses, primary	4.00	1.04	-0.06	-	1.03	0.48
Notes	1	1	1	m	n	n

	Phthalic anhydride	Bisphenol A	Iso-propanol	Polyamide 66	Polyamide 6	Poly-carbonate	Acetaldehyde
Production volume, the Netherlands	69 kt / year	280	215	133	133	103	0
Production volume, Western Europe	695 kt / year	641	520	496	496	488	470
Production volume, World	3200 kt / year	2300	1806	2237	2237	1500	2566
Reaction route	Oxidation of o-xylene	Condensation of phenol with acetone	Hydration of propene	Polycondensation of adipic acid with hexamethylenediamine	Polymerisation of caprolactam	Polycondensation of bisphenol-A with phosgene	Oxidation of ethylene
Share, the Netherlands	100%	0%	100%	100%	100%	100%	-
Share, Western Europe	94%	6%	100%	100%	100%	100%	100%
Share, World	85%	15%	100%	100%	100%	100%	100%
Source	Patel (1998)	Chauvel Lefebvre (1989)	Chauvel Lefebvre (1991)	Patel (1998)	Patel (1998)	Patel (1998)	Patel (1998)
Uncertainty indicator (Section 6.5)	2	3	3	2	2	2	2
Heat of stoichiometric reaction	-7.97 GJ _f /t	-12.53	-1.58	0.27	-0.14	-	-4.97
Electricity use	3.81 GJ _e /t	1.80	0.09	0.40	0.40	2.66	0.29
Fuel use	0.00 GJ _f /t	0.00	5.20	13.02	9.66	0.00	0.00
Steam use	-5.57 GJ _f /t	-11.14	5.40	0.60	0.00	12.86	3.34
Total primary energy use	3.10 GJ _p /t	-7.99	11.42	14.65	11.55	20.77	4.42
Heat effect of reaction	15.73 GJ _f /t	14.69	5.24	-0.27	3.43	-	6.63
Total final energy loss	13.97 GJ _f /t	5.35	15.93	13.74	13.48	-	10.26
Total primary energy loss	18.83 GJ _p /t	6.70	16.66	14.37	14.97	-	11.05
Excess final energy use	6.20 GJ _f /t	3.19	12.27	13.74	10.20	-	8.60
Losses due to non-selectivity	7.76 GJ _f /t	2.16	3.65	0.00	3.28	-	1.66
Carbon losses, energy use, primary	0.42 tCO ₂ /t	-0.39	0.71	0.93	0.68	1.44	0.29
Carbon losses, reaction	0.60 tCO ₂ /t	0.78	0.25	0.00	0.26	-	0.11
Total carbon losses, primary	1.01 tCO ₂ /t	0.39	0.96	0.93	0.94	-	0.40
Notes						0	

Footnotes to Appendix A

^a We did not specify a desired stoichiometric reaction for the production of ethylene, because of the multiple products produced. We used the actual observed heat effect of reaction as the heat of the stoichiometric reaction. In Section 6.3, we express the results per tonne of total products and regarded the total output of the cracker as product. To obtain the results per tonne of total product (including e.g., propylene), we multiplied the values per tonne of ethylene given here with the ethylene yield (0.324 for naphtha, 0.250 for gas oil, 0.803 for ethane, 0.465 for propane). Some of the products are used to fuel the process. These amounts are included under fuel use. We used an emission factor of 48.7 kg CO₂ / GJ for naphtha and gas oil cracking and emission factor of 43.3 kg CO₂ / GJ for ethane and propane cracking (Neelis et al., 2003) instead of the emission factor given in Section 6.2 to account for the fact that the fuels used contain mainly methane and hydrogen.

^b We did not specify a stoichiometric reaction for ammonia and methanol production, because it would have involved an arbitrary choice between the amount of hydrogen produced from the raw material and the amount of hydrogen produced from steam. We allocated an amount of raw material equivalent to the ammonia and methanol product (18.6 GJ / tonne and 19.9 GJ / tonne respectively) to feedstock use, the remainder to fuel use. To obtain a value for the total raw material input, the energy content of ammonia and methanol should be added to the reported fuel use. We used the emission factors of the raw materials used to calculate CO₂ emissions from ammonia and methanol production instead of the general fuel emission factor given in Section 6.2.

^c We assumed stoichiometric conversion of sodium chloride, because it was unclear how the excess sodium chloride is lost. In Section 6.3, we express the results per tonne of total products, including 0.028 tonne hydrogen and 1.128 tonne sodium hydroxide.

^d We covered the total aromatics production with this three generic process configurations (Phylipsen et al., 2002). The benzene not produced from py-gas or toluene is produced as by-product in the production of p-xylene from reformat. Toluene, o-xylene and m-xylene are produced as by-products of the three processes given. In Section 6.3, we express the result per tonne of total products in which we regard the total output of the processes as product. To obtain these values, we multiplied the values per tonne of benzene given here with the benzene yield (0.275 for benzene from py-gas and 0.83 for benzene from toluene). The values per tonne of p-xylene from reformat are multiplied with the p-xylene yield (0.380).

^e The remaining styrene is produced as co-product in the production of propylene oxide. In Section 6.3, we express the results per tonne of total products, including 0.02 tonne of hydrogen.

^f No detailed process description was available for the production of PET from dimethylterephthalate. We therefore used a share of 100% for PET production from terephthalic acid.

^g The energy content and heat of polymerization for polyurethane depend on the type of polyurethane produced. This could not be calculated with sufficient accuracy. The heat effects of reaction and related indicators were therefore not calculated.

^h In Section 6.3, we express the results per tonne of total products, including 0.61 tonne acetone for cumene oxidation.

ⁱ The only process description for the chlorohydrin route available included also the electrolysis of salt to produce chlorine. To avoid double-counting, we estimated the electricity and steam use for chlorine production by assuming that one mole of chlorine is required for every mole of propylene and deducted this amount from the reported electricity and steam use. The resultant electricity and steam use is given in the table. Since the consumption of some of the raw materials was not given in the literature source, the heat effects of reaction and related indicators could not be calculated. In Section 6.3, we express the results per tonne of total products, including 2.45 tonne tert-butyl alcohol (indirect oxidation via tert-butyl-hydroperoxide), 2.29 tonne styrene (indirect oxidation via ethylbenzene hydro peroxide), 1.01 tonne sodium chloride and 0.76 tonne hydrochloric acid (chlorohydrin route).

^j The energy content and heat of polymerization for polyetherpolyols depend on the type of polyetherpolyols produced. This could not be calculated with sufficient accuracy. The heat effects of reaction and related indicators were therefore not calculated.

^k The remaining acetone is produced as co-product in the production of phenol. In Section 6.3, we express the results per tonne of total products, including 0.03 tonne hydrogen.

^l The stoichiometric reactions include the production of ammonium sulphate by-product. In Section 6.3, we express the results per tonne of total products, including 1.8 tonne (from cyclohexane) or 4.4 tonne (from phenol) ammonium sulphate.

^m The energy content and heat of polymerization for urea formaldehyde could not be calculated with sufficient accuracy. The heat effects of reaction and related indicators were therefore not calculated.

ⁿ In Section 6.3, we express the results per tonne of total products, including 0.63 tonne hydrochloric acid.

^o Data were only available on electricity and steam use. The heat effects of reaction and related indicators, therefore, were not calculated.

^p In Section 6.3, we express the results per tonne of total products, including 0.95 tonne hydrochloric acid.

References

- Anonymous, 2004. Eerste stap in nieuw warmtedistributienet in Rotterdam, Accessed via <http://www.energiemanagement.net>, September 2004.
- Anonymous, 2005. Co-siting. Information provided on <http://www.portofrotterdam.com>, 2005.
- APME, 1994-2003. Eco-Profiles of the European Plastics industry. Various reports on different types of plastics, prepared by Dr. I. Boustead. Association of Plastics Manufacturing in Europe, Brussels.
- Appl, M, 1997. Ammonia, methanol, hydrogen, carbon monoxide – modern production technologies, CRU Publishing, London.
- Aspen Technology, 2001. Aspen Properties, part of Aspen Engineering Suite 11.1. Cambridge, Massachusetts.
- Boustead I, 1997. Eco-profiles of the European plastics industry, Report 9: Polyurethane precursors (TDI, MDI, Polyols, a report for ISOPA, Brussels.
- Boustead I, 2002. Eco-profiles of the European plastics industry, Polyethylene terephthalate, a report for the European Centre for Plastics in the Environment, Brussels.
- Brandrup, J and Immergut, E, 1989. Polymer Handbook - Third Edition. John Wiley and Sons, New York.
- Chauvel, A and Lefebvre, G, 1989. Petrochemical processes – technical and economic characteristics, 2 Volumes, Editions Technip, Paris.
- Chemical Market Reporter, 1994-2005, Various issues.
- Chemical Week , 1994-2005, Various issues.
- Carp, JA and Bach, PW, 2001. Market potential for thermohydraulic engines using waste heat sources, Energy Research Centre of the Netherlands, Petten, 2001.
- Crank, M, Patel, MK, Marscheider-Weidemann, F, Schleich, J, Hüsing, B and Angerer, G, 2004. Techno-economic feasibility of large-scale production of bio-based polymers in Europe (PRO-BIP), Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Utrecht.
- Delft, Y, Correia, L, Overbeek, J, Meyer, D, Pex, P, Dijkstra, J and Jansen, D, 2005. Hydrogen membrane reactor for industrial hydrogen production and power generation, in: 7th International Conference on Catalysis in Membrane Reactors, Cetraro.
- DOE/OIT, 2000. Energy and environmental profile of the US chemical industry, US Department of Energy, Office of Industrial Technologies, Prepared by Energetics, Columbia, Maryland.
- EFMA, 2000. Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry, Booklet 1-8. European Fertilizer Manufacturers' Association, Brussels.
- European Chemical News, 1994-2005, Various issues.

- Eurostat/IEA/UN, 2003. Electricity and Heat - Annual Questionnaire 2004 and Historical Revisions, Joint questionnaire for compilation of energy statistics used by Eurostat, International Energy Agency and United Nations.
- FhG-ISI, 1999. C-Ströme. Abschätzung der Material, Energie- und CO₂-ströme für modellsysteme in Zusammenhang mit dem nicht-energetischen verbrauch, orientiert am lebensweg- Stand und Szenarienbetrachtung. Band-I, Abschätzungen für dat Gesamtsystem. Fraunhofer Institut für Systemtechnik und Innovationsforschung, Karlsruhe.
- Gielen, DJ, Vos, D and van Dril, AWN, 1996. The petrochemical industry and its energy use, prospects for the Dutch energy intensive industry, Energy Research Centre of the Netherlands, Petten.
- HP, 2003. Petrochemical processes 2003. Hydrocarbon processing, Vol. 82 (3), pp. 72-124.
- IPTS, 1996. Reference Document on Best Available Techniques in Ammonia production, European Commission, Institute for Prospective Technological Studies, Seville.
- IPTS, 2001. Reference Document on Best Available Techniques in the Chlor-Alkali manufacturing industry, European Commission, Institute for Prospective Technological Studies, Seville.
- IPTS, 2003. Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry, European Commission, Institute for Prospective Technological Studies, Seville.
- Graus, W and Voogt, M, 2005. Updated comparison of power efficiency on grid level, Ecofys, Utrecht.
- Hinderink, AP, Kerkhof, FPJM, Lie, ABK, de Swaan Arons, J and van der Kooi, HJ, 1996. Exergy analysis with a flowsheeting simulation - II. Application; Synthesis Gas production from natural gas. Chemical Engineering Science, Vo. 51, pp. 4701-4715.
- Hugill, JA, 2003. HEX-reactor applications in the Netherlands - A non-confidential summary, Energy Research Centre of the Netherlands, Petten.
- IDEA, 1991. An international database for Ecoprofile analysis. International Institute for Applied Systems analysis, Laxenburg.
- IEA, 2002. Extended energy balances of OECD and Non-OECD countries, 2002 edition, two publications, International Energy Agency, Paris.
- IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Volumes 1, 2 and 3, Houghton, JT, Meira Filho, LG, Lim, B, Treanton, K, Mamaty, I, Bonduki, Y, Griggs, DJ and Callander, BA (Eds). Intergovernmental Panel on Climate Change (IPCC), Organization for Economic Cooperation and Development (OECD), International Energy Agency (IEA), Paris.
- Joosten, L, 2001. The Industrial Metabolism of Plastics - Analysis of Material Flows, Energy Consumption and CO₂ Emissions in the Lifecycle of Plastics. PhD thesis Utrecht University, Utrecht.

- Korevaar, G, 2004. Sustainable Chemical Processes and Products - new design methodology and design tools. PhD thesis Delft University of Technology, Delft.
- Lange, JP, 2001. Fuels and chemicals manufacturing - guidelines for understanding and minimizing the production costs. *CATTECH*, 2001, Vol. 5, No 2., pp. 82-95.
- Lange, JP, 2002. Sustainable development: efficiency and recycling in chemicals manufacturing. *Green Chemistry*, Vol. 4, pp. 546-550.
- Leites, IL, Sama, DA and Lior, N. The theory and practice of energy saving in the chemical industry: some methods for reducing thermodynamic irreversibility in chemical technology processes, *Energy*, Vol. 28, pp. 55-97.
- Loesoenen, P, 2003. Combined Heat and Power (CHP) Plant Statistics in the EU, 2000. *Statistics in Focus*, Theme 8, Eurostat, Luxemburg.
- Neelis, M, Patel, M, Blok, K and Bach, PW, 2007. Analysis of energy use and carbon losses in the chemical industry. *Applied Energy*, Vol. 84, pp. 853-862.
- Neelis, ML, Patel, MK, Bach, PW and Haije, WG, 2005a. Analysis of energy use and carbon losses in the chemical and refinery industries, Energy research Centre of the Netherlands, Petten, 2005.
- Neelis, M, Patel, M and Blok, K, 2005b. CO₂ emissions and carbon storage resulting from the non-energy use of fossil fuels in the Netherlands, NEAT results for 1993 – 1999. *Resources, Conservation and Recycling*, Vol. 45, pp. 251-274. Chapter 3 of this thesis.
- Neelis, M, Patel, M and de Feber, M, 2003. Improvement of CO₂ emission estimates from the non-energy use of fossil fuels in the Netherlands, Utrecht University, Copernicus Institute, Department of Science Technology and Society, Utrecht.
- Nieuwlaar, 2001. ICARUS-4: Sector Study for the Chemical Industry. Utrecht University, Department of Science, Technology and Society, Utrecht.
- Non-energy use and CO₂ emissions, 1999-2006. Project funded by the European Commission, 1999-2006.
- Patel, M, 1998. Personal Communication with industry.
- Patel, M, 2003. Cumulative Energy Demand (CED) and cumulative CO₂ emissions for products of the organic chemical industry. *Energy*, Vol. 28, pp. 721-740.
- Phylipsen, D, Blok, K, Worrell, E and de Beer, J., 2002. Benchmarking the energy efficiency of the Dutch industry: an assessment of the expected effect on energy consumption and CO₂ emissions, *Energy Policy*, Vol. 30, pp. 663-679.
- Plinke, E, Schüssler, R and Kämpf, K. *Konversion Chlorchemie*, Endbericht, Prognos AG, Basel.
- Radgen, P, 1997. Pinch and exergy analysis of a fertilizer complex, part 2. Nitrogen, Vol. 225, pp. 27-39.
- Radgen, P, 1996.. Pinch and exergy analysis of a fertilizer complex, part 1. Nitrogen, Vol. 224, pp. 30-38.

- Spoelstra, S, Haije, WG and Dijkstra, JW, 2002. Techno-economic feasibility of high-temperature high-lift chemical heat pumps for upgrading industrial waste heat. *Applied Thermal Engineering*, Vol. 22, pp. 1619-1630.
- Statistics Netherlands, 2004a. Z029 - Aardoliegrondstoffen en aardolieproducten, Statistics Netherlands, Voorburg.
- Statistics Netherlands, 2004b. Productie middelen electriciteit, Accessed online via <http://www.statline.cbs.nl>
- Statistics Netherlands, 2005. Energie balansen voor de chemische industrie, Accessed online via <http://www.statline.cbs.nl>.
- Szargut, J, Morris, DR and Steward, FR, 1988. Exergy analysis of thermal, chemical and metallurgical processes, Springer Verlag, Berlin.
- Tebodin, 1996. Milieu-effect rapport voor de oprichting van de Basell styreen monomeer / propeenoxidefabriek in Moerdijk, Den Haag.
- Tonkovich, ALY and Gerber, MA, 1995. The Top 50 Commodity Chemicals: Impact of Catalytic Process Limitations on Energy, Environment and Economics. Pacific Northwest Laboratory, Richland.
- van Tuil, R, de Jong, E, Scott, E, Weusthuis, R, Vellema, S, de Keizer, I and Croezen, H, 2004. Biomass for the chemical industry. CE, Delft.
- VNCI, 2004. Jaarverslag 2003, Vereniging van de Nederlandse Chemische Industrie, Leidschendam.
- Weissermel, K and Arpe, HJ, 2003. *Industrial Organic Chemistry*, Fourth, Completely Revised Edition, Wiley-VCH, Weinheim.
- Worrell, E, Phylipsen, D, Einstein, D and Martin, N, 2000. Energy Use and Energy Intensity of the U.S. Chemical Industry. Ernest Orlando Lawrence Berkeley National Laboratory, Energy Analysis Department, Environmental Energy Technologies Division, Berkeley.

SUMMARY AND CONCLUSIONS

Introduction and scope

The last couple of decades have been a period of growing concern about the sustainability of the increasing demand for energy. On the global level, the enhanced greenhouse effect caused by anthropogenic greenhouse gas (GHG) emissions is nowadays the major environmental issue related to the energy system. The use of fossil fuels is the major source of these emissions. For a proper assessment of the past, current and future impacts of global energy use on the climate system, consistent and reliable monitoring of energy use, energy related GHG emissions and energy efficiency developments is of vital importance. This also holds for the design and evaluation of policies aiming to reduce this impact. This recognition forms the starting point for this thesis in which the focus is on the industrial sector. The central research question for this thesis is:

How can the monitoring of energy use, CO₂ emissions and energy efficiency for the industrial sector be improved?

The specific goals of the thesis are:

- To contribute to improved energy statistics for the chemical industry by studying in detail historical energy statistics for the Netherlands at the company level and to draw lessons for improvement of the Dutch and international energy statistics for this industry.
- To develop and apply a methodology to account for CO₂ emissions originating from the feedstock use and other non-energy use of fossil fuels that can be used as crosscheck for national GHG emission inventories.
- To develop and apply a methodology to study energy efficiency trends in the industrial sector based on publicly available physical production and energy use data.
- To develop a bottom-up energy model for the petrochemical sector and to assess theoretical energy saving potentials in the Dutch, European and global petrochemical industry at the level of individual production processes.

These goals fulfill a number of research needs in the monitoring of energy use, energy related GHG emissions and energy efficiency developments. We briefly introduce these research needs below.

For the evaluation of energy efficiency and GHG intensity of the industrial sector, reliable energy statistics are of key importance. An industrial sector for which the compilation of energy statistics is particularly challenging is the chemical industry. In the chemical industry, energy commodities are used not only for energy purposes, but also as feedstock for the production of chemicals. Various conversions take place between energy commodities, but also between energy commodities and chemicals. There are indications that this results in quality and consistency problems in national and international energy statistics for the chemical industry. Therefore, there is need for further analyses on the quality of energy statistics for this important sector of industry.

The use of energy commodities as feedstock and for other non-energy purposes imposes not only challenges for the compilation of energy statistics, but also for monitoring carbon dioxide (CO₂) emissions. The national emission inventory guidelines that are currently used contain a methodology to determine emissions from non-energy use. The methodology is based on constant storage fractions that are used to calculate the amount of carbon stored in synthetic organic chemicals. Various authors point at weaknesses in this methodology such as the failure to take into account trade in synthetic organic chemicals. Given these weaknesses, there is need for independent checks of national GHG emission inventories related to feedstock and other non-energy use of fossil fuels.

For mitigating GHG emissions via improved energy efficiency or by reducing the demand for energy intensive activities, a clear view on the amount of energy that is needed for a certain activity is required. Energy efficiency improvements can be defined as using less energy for producing the same amount of service or product. It is widely accepted that for the industrial sector, the use of physical rather than economic indicators of activity offers a better understanding of energy efficiency developments. Several of the studies using methods based on physical indicators of activity stress the continued need for further methodological development, addressing issues such as (public) data availability, data quality and cross-country comparisons.

Given the long-term scope of the climate problem, a clear view is needed on theoretical energy efficiency potentials. These can be defined as the difference between the theoretical minimum energy use required for a certain activity (based on thermodynamic laws) and the current energy use. For sectors where chemical conversions between raw materials and products take place like the chemical industry, the energy effect of reaction is an important

part of the energy balance. It is therefore of key importance to take these effects into account when determining (theoretical) energy efficiency potentials. Surprisingly, these energy effects of reaction are often not explicitly dealt with in studies on energy use and energy efficiency potentials for the chemical industry, calling for a systematic, sector-wide analysis.

Summary of the results

In Chapter 2, the methodology of the NEAT (Non-energy use Emission Accounting Tables) model is presented. The model tracks the final fate of the carbon embodied in the fossil fuels used for non-energy purposes by means of a carbon flow analysis. Emissions from solvent and other product use are estimated by modelling the conversion routes from 22 basic chemicals to 55 intermediate and final products. Part of the carbon embodied in the fossil fuels used for non-energy purposes is also directly emitted as CO₂ in a number of industrial processes. These industrial process emissions from the production of lower olefins, ammonia, methanol, carbon black and certain metals and inorganic chemicals are estimated based on specific emission factors. Independently from energy statistics, the model generates estimates for the total non-energy use of the country studied and the carbon storage in synthetic organic chemicals. The model can be applied as valuable crosscheck and tool for improvement of the non-energy use emission accounting methodology used for the official national GHG inventories. Major drawback is the substantial data requirement, especially for the carbon flow analysis that is used to estimate solvent and other product use emissions. The country analyses conducted with the model (e.g. the one for the Netherlands presented in Chapter 3) show that it is in principle possible to collect the necessary data. Still, we conclude that a useful addition could be to develop a more simplified model using independent or generic estimates for solvent and other product use emissions. Such a simplified model could be of use for countries with a more limited data availability.

In Chapter 3, we apply the NEAT model to the Netherlands for the period 1993 – 1999 making use of confidential production and international trade statistics provided by Statistics Netherlands for the purpose of this project. For the period studied, we estimate the total non-energy use in CO₂ equivalents in the Netherlands to vary between 26.1 and 30.2 Mt CO₂ per year. Of this total, 4.6 – 6.6 Mt CO₂ is emitted in industrial processes and during product use. The remainder is stored in synthetic organic chemicals, resulting in an overall storage fraction of approximately 80%. We also calculate storage fractions by type of fuel. For natural gas and oil products, together responsible for approximately 90% of the non-energy use in the Netherlands, storage fractions of respectively 27 – 39% and 87 – 93% were found. Given the uncertainties involved, it was not possible to identify clear trends for the years of study. We show that the use of either a gross definition of non-energy use (including the parts of the

feedstock that are used directly or indirectly as fuel) or a net definition (excluding these parts) has a significant influence on the calculated storage fractions.

We also compare the results with the official Dutch national GHG inventory published in 2004. The carbon storage published in that report is 5 – 9 Mt CO₂ lower compared to the NEAT result. We show that these differences can partly be explained by a methodology in the inventory that allocates some emissions from product use abroad to the Netherlands (~2 Mt CO₂) and partly by not taking into account the export of anodes from the Netherlands. The remainder of the difference can be explained by problems associated with the non-energy use figures in the Dutch energy statistics and their direct use for CO₂ emission accounting. The non-energy figures in the Dutch statistics are shown to be low compared to the estimates according to the NEAT model, resulting in an underestimation of carbon storage. The underestimation of carbon storage in the national GHG inventory compared to our study suggests that total fossil CO₂ emissions in the inventory are overestimated. We therefore strongly recommend adapting the emission inventory methodology for emissions from non-energy use in the Netherlands making use of the results of this study.

In Chapter 3 and in work that finally resulted in Chapter 5 of this thesis, we found irregularities in the Dutch energy statistics for the chemical industry. In order to identify causes for these irregularities, we study in Chapter 4 the company data that form the basis of the energy statistics in the Netherlands between 1995 and 2004. We show that certain chemical products have occasionally, but not systematically, been included in the energy statistics. Furthermore, we found that lack of guidance in the survey for the complex energy conversions in the chemical industry resulted in large fluctuations for certain energy commodities. Also the complexity of the petrochemical industry with respect to the energy flows has been insufficiently acknowledged in the statistical process. As a result, errors once made, could remain unnoticed for a long time before being discovered. The exact methodologies used by Statistics Netherlands to come to an overall energy balance have also not always been reported adequately. As a result, a rigorous analysis of the observed problems was not possible. We could, however, quantify the error made by the occasional inclusion of chemical products in the energy statistics. We show that this has resulted in an annual underestimation of feedstock use in the energy statistics by 33 – 75 PJ in the period 1995 – 2004, which is 14 – 28 % of the reported non-energy use and 1 – 2% of the total energy use in the Netherlands in this period.

We used the results of our analysis to develop a new improved survey for the chemical industry that is in use by Statistics Netherlands since 2007. In this survey, better guidance is given on the system boundaries of the statistics in order to avoid inclusion of chemical products in the energy statistics. In the new survey also the reporting of energy conversions

has been simplified and clarified. Making use of the Dutch experience, we also looked at the annual oil products questionnaire used for the international energy statistics. We show that this questionnaire can result in comparable problems as those observed for the Netherlands. We recommend to include the important energy conversions in the chemical industry in a more explicit manner in the international energy statistics and to address chemical residual gas as separate energy commodity in the annual questionnaire. Within the chemical industry, various conversions between energy commodities and chemicals take place. In general terms, we conclude that for good quality energy statistics for the chemical industry, it is essential to define clearly how the energy conversion processes are included in the statistics, to clearly define which products are regarded energy commodities and which are seen as chemicals (i.e. to define the system boundaries) and to acknowledge the complexity of the chemical industry by involving expert knowledge in the statistical process.

In Chapter 5, we study energy efficiency trends for the paper, fertilizer, chemical, building materials and basic metals industry in the Netherlands between 1995 and 2003. We use specific energy consumption data from open literature and physical production data originating from open literature and partly from data made available by Statistics Netherlands for this project. We found that since the middle of the nineties, significant energy efficiency improvements have been made in the industrial sector. We estimate the annual primary energy efficiency improvements in this period at 1.3% on average, with the individual sectors ranging between -0.1 and 1.5%. Energy efficiency improvements with respect to electricity, fuels/heat and non-energy use have been monitored separately and are shown to differ significantly (for the sum of the sectors studied: 1.9% for electricity, 2.6% for fuels/heat and -0.1 % for non-energy use respectively). We combined our results with those from a previous study for 1980 – 1995 using a comparable methodology and show that over the full time period, primary energy efficiency improvements of approximately 1.0% per year have been achieved on average. This estimate excludes the chemical industry for which no reliable data for the period 1980 – 1995 were available. The efficiency improvement is low compared to the more ambitious goal of 2% efficiency improvement recently advocated both at the national and European level.

We quantitatively assessed the effect uncertainties in the input data. This uncertainty analysis reveals that data uncertainties make it difficult to draw robust conclusions on energy efficiency developments from year to year. Instead, a longer time period should be analysed. We show that there are still substantial differences between the energy use according to the energy statistics and the energy use according to the official monitoring reports of the long-term agreements on energy efficiency. We found, however, a good match between the development of the physical production according to the long-term agreement and our study. Based on this comparison and the detailed uncertainty analysis, we conclude that we

developed a reliable top-down monitoring framework for studying energy efficiency trends in the industrial sector for the Netherlands based on data that is available for research purposes.

In Chapter 6, we developed a bottom-up energy model for the petrochemical industry by preparing energy and carbon balances for 68 processes in the petrochemical industry for Western Europe, the Netherlands and the world. We analyse the sum of all energy inputs (both process energy use and the energy content of the raw materials of the processes) that do not end up in the useful products of the process, but are lost primarily as waste heat to the environment. The total energy loss thus identified can be regarded as a good approximation of the theoretical energy saving potential of the processes analysed. For the analysis, we use, where possible, datasets that most likely represent Western Europe in 2000. We estimate the energy loss in Western Europe in the year 2000 at 1620 PJ of final energy and 1936 PJ of primary energy, resulting in a total of 127 Mt CO₂ emissions. For the Netherlands and the World, we estimate the loss at 282 and 10092 PJ of primary energy, respectively. We show that process energy use and energy effects of reaction often have an equal share in the overall energy loss of the processes studied and we recommend addressing reaction effects, which are not directly visible in energy statistics, explicitly in energy efficiency studies. The processes with large energy losses in relative and absolute terms are recommended for more detailed analysis taking into account further thermodynamic, economic, and practical considerations to identify technical and economic energy saving potentials. Such analyses will for example require more detail at the level of unit operations and need also to take into account the second law of thermodynamics. We show that in many cases the efficiency potential from implementing Best Available Techniques offer already a large energy efficiency potential (up to 50%).

Conclusions, applications, and the way forward

We are glad that several of the results of the work described in this thesis have found useful applications in monitoring and evaluation methodologies of relevant energy and climate policies. The studies described in Chapter 2 and 3 have been used to improve the Dutch methodology for calculating emissions related to non-energy use. In the new methodology, in use since 2005, the link in the energy statistics between non-energy use on the one hand and energy use on the other hand is better acknowledged. The more systematic way of approaching the use of fossil fuels for non-energy use purposes is also included in the new 2006 Guidelines for national GHG inventories that will be the basis for the preparation of national GHG inventories post 2012. The studies described in Chapter 2 and 3 of this thesis provided an important input into these new guidelines. In the 2006 Guidelines, countries are recommended to ensure via material flow analyses that emissions are neither double counted

nor omitted from the national inventory. The analysis of carbon flows as incorporated in the NEAT model could be further extended into a complete model for countrywide tracking of carbon embodied in products over time. Such a model could quantify how much fossil carbon enters and leaves the country in the form of chemical products and based on this make an estimate of the stock of carbon in products and the potential future CO₂ emissions from these products.

Energy statistics as such do not get much attention in (scientific) literature. Yet, they form the basis for an uncountable number of research efforts in research fields like energy and climate modelling, energy analysis and evaluation of energy policy. If the analysis described in Chapter 4 makes one thing clear, it is that a sufficient quality of international and national energy statistics can never be taken for granted, even in countries with a good 'energy data reputation' like the Netherlands. The prerequisites of good energy statistics for the chemical sector summarized in Chapter 4 (involvement of sufficient specific expertise, clear guidance on system boundaries and the treatment of conversion processes) are equally valid for energy statistics of other industrial sectors. It would be worthwhile to check the statistical systems that are used on the national and international level with these three prerequisites in mind and, where needed, to improve the methodologies used. The recommended changes in the international statistics for the chemical industry (inclusion of chemical residual gas and of energy conversions in the published statistics) could be a step towards possible future publication of carbon statistics based on the current energy statistics. There is an increasing need for such carbon statistics given the necessity of crosschecks for fossil fuel based CO₂ emissions, but also as a consequence of the implementation of carbon storage and sequestration and the transition to bio-based fuels and materials. Making use of the insights from Chapter 2 and 3 of this thesis, these statistics would allow to adequately reflect which part of fossil fuels are initially stored in products that are not used as energy commodity.

An important future improvement to energy statistics for the industrial sector would be to publish more information on energy end uses on a regular basis, i.e. specified by unit operations. This information would be a very useful input into the further analyses at the level of unit operations recommended in Chapter 6. Currently, information on energy end uses is scarce with the only data available being based on incidental ad-hoc analyses, e.g. on the electricity use for motor applications or studies on heat use by temperature level. Collection of end use data is time-consuming and can also be difficult in view of the confidentiality of certain data. Extrapolation of survey results from a limited number of sample companies could, however, be a first towards systematic publication of information on energy end uses. This would substantially advance the research field studying energy efficiency potentials and it would allow deriving more solid policy recommendations.

The main achievement of the work presented in Chapter 5 is the development of a reliable top-down monitoring framework for industrial energy efficiency monitoring in the Netherlands based on data that are publicly available for research purposes. The methodology has been used since 2004 for the calculation of annual energy savings in the Netherlands according to the so-called “protocol monitoring energy savings”. Based on our analysis, we identify two important ways forward for this kind of analysis. Given the fact that the same data sources are available for other countries in the European Union, we conclude that the methodology could also be applied there. The methodology could therefore contribute to a consistent, reliable and independent cross-country comparison of energy efficiency levels. This would represent an important tool in view of the ever-increasing importance of common European energy efficiency policies. A second area for future work is the introduction of regular checks of all energy and energy-efficiency related data flows from individual companies to the government (as part of e.g. environmental reports, production statistics, emission trading etc.). These checks could be used to detect inconsistencies in data at the lowest aggregation and avoid problems in future evaluation of energy related policies.

Analyses combining various data sources can also contribute to detailed analysis of energy efficiency trends for individual companies. Combination of financial and physical activity data at the lowest aggregation level could, for example, give insight in the relation between economic and physical growth of the economy. The studies performed in this thesis (Chapter 3 and 5) show that these confidential data can be made available for research purposes.

This thesis analyses data and methods that are used in the design and evaluation of energy and climate policy. Data at various aggregation levels has been combined in a number of ways. This thesis shows that this kind of analysis can reveal weaknesses in the methodologies used. It also became clear that official statistics sometimes contain significant errors that can be detected and eliminated rather easily via detailed analysis. Finally, this thesis shows that there is a risk of inconsistencies across the various data sources that are used in policy evaluations. Based on these findings, the conclusion is that independent checks of the methodologies used in energy and climate policies are absolutely indispensable. In these checks, all available data should be combined in a clever way. Adequate attention needs to be given by policy makers to these activities if (more stringent) energy and climate policy is supposed to be credible, reliable and effective.

SAMENVATTING EN CONCLUSIES

Introductie en doelstellingen

In de laatste decennia is er een toenemende bezorgdheid over de duurzaamheid van de groeiende energievraag. Het versterkte broeikaseffect veroorzaakt door antropogene broeikasgasemissies is op mondiaal niveau het belangrijkste milieuprobleem gerelateerd aan het energiesysteem. De voornaamste bron van deze emissies is het gebruik van fossiele brandstoffen. Voor een goede beoordeling van de invloed van het mondiale energiegebruik op het klimaatsysteem is het monitoren van energiegebruik, van energiegerelateerde broeikasgasemissies en van ontwikkelingen in energie-efficiëntie van vitaal belang. Dit geldt ook voor het ontwerpen en beoordelen van beleidsinstrumenten die tot doel hebben deze invloed te verminderen. Deze constatering vormt het uitgangspunt van dit proefschrift, waarbij de focus ligt op de industrie. De centrale onderzoeksvraag van dit proefschrift is:

Hoe kan het monitoren van energiegebruik, CO₂ emissies en energie-efficiëntie voor de industrie worden verbeterd?

Het proefschrift heeft de volgende specifieke doelstellingen:

- Bij te dragen aan verbeterde energiestatistieken voor de chemische industrie door in detail historische statistieken voor Nederland op bedrijfsniveau te bestuderen en hieruit lessen te trekken voor de verbetering van de Nederlandse en de internationale energiestatistieken.
- Een methodiek te ontwikkelen en toe te passen om CO₂ emissies resulterend uit het niet-energetisch gebruik van fossiele brandstoffen te bepalen en de methode te gebruiken als controle voor nationale broeikasgasemissie-inventarisaties.
- Een methodologie te ontwikkelen en toe te passen om energie-efficiëntie trends in de industrie te bestuderen gebaseerd op openbaar toegankelijke fysieke productie en energiegebruik data.
- Een bottom-up energiemodel voor de petrochemische industrie te ontwikkelen en theoretische energiebesparingpotentiëlen vast te stellen voor de Nederlandse,

Europese en mondiale petrochemische industrie op het niveau van individuele productieprocessen.

Deze specifieke doelstellingen komen voort uit een aantal onderzoeksbehoeften in de monitoring van energiegebruik, van energiegerelateerde broeikasgasemissies en van ontwikkelingen in energie-efficiëntie in de industrie. Deze onderzoeksbehoeften worden hieronder kort geïntroduceerd.

Betrouwbare energiestatistieken zijn belangrijk voor het evalueren van de energie-efficiëntie en de broeikasgasintensiteit van de industrie. De chemische industrie is een sector waarvoor het maken van energiestatistieken in het bijzonder uitdagend is. In de chemische industrie worden energiedragers niet alleen voor energiedoeleinden gebruikt (warmte, elektriciteit), maar ook als grondstof voor het vervaardigen van bijvoorbeeld plastics. Er vinden verschillende omzettingen plaats tussen energiedragers, maar ook tussen energiedragers en chemische producten. Er zijn indicaties dat de verschillende omzettingen en het gebruik als grondstof resulteren in problemen in zowel nationale als internationale energiestatistieken voor de chemische industrie. Er is daarom behoefte aan verdere analyses van de kwaliteit van de energiestatistieken voor deze sector.

Het gebruik van energiedragers als grondstof en voor ander niet-energetisch gebruik brengt daarnaast ook uitdagingen met zich mee voor het monitoren van koolstofdioxide (CO₂) emissies. De handleiding voor nationale broeikasgasemissie-inventarisaties, die momenteel gebruikt wordt, beschrijft een methode voor het bepalen van emissies uit dit niet-energetische gebruik. De methode is gebaseerd op opslagfactoren, die worden gebruikt om de hoeveelheid koolstof te berekenen die wordt opgeslagen in synthetische organische producten zoals plastics. Verschillende auteurs wijzen op zwakke punten in deze methodiek. De internationale handel in organisch-chemische producten kan bijvoorbeeld niet goed worden meegenomen. Met het oog op deze zwakke punten is er voor wat betreft de emissies uit niet-energetisch gebruik van energiedragers behoefte aan onafhankelijke controle van nationale broeikasgasemissie-inventarisaties.

Om broeikasgasemissies te reduceren door het verbeteren van energie-efficiëntie of door het verminderen van de vraag naar energie-intensieve producten, is het nodig inzicht te hebben in het energiegebruik van verschillende economische activiteiten. Het verbeteren van energie-efficiëntie kan worden gedefinieerd als het gebruik van minder energie voor het leveren van dezelfde hoeveelheid diensten of nuttige output. Het gebruik van fysieke in plaats van economische activiteitsindicatoren kan bijdragen aan een beter begrip van energie-efficiëntie ontwikkelingen in de industrie. Verschillende studies die methodes gebaseerd op fysieke indicatoren gebruiken, benadrukken dat er behoefte is aan verdere methodische verbeteringen.

Hierbij zouden bijvoorbeeld de (publieke) beschikbaarheid van data, de kwaliteit van de data en vergelijkingen tussen landen aan bod kunnen komen.

De lange termijn focus van het klimaatprobleem vraagt om inzicht in theoretische energie-efficiëntiepotentiëlen. Deze potentiëlen kunnen worden gedefinieerd als het verschil tussen het minimale energiegebruik nodig voor een bepaalde activiteit (gebaseerd op thermodynamische wetten) en het huidige energiegebruik. Voor sectoren waar chemische omzettingen plaatsvinden tussen grondstoffen en eindproducten is het energie-effect van de reacties een belangrijk onderdeel van de energiebalans. De chemische industrie is hier een duidelijk voorbeeld van. Het meenemen van deze reactie-effecten is van groot belang voor het bepalen van (theoretische) energie-efficiëntiepotentiëlen. Verassend genoeg wordt dit echter vaak niet expliciet gedaan in studies die zich richten op het energiegebruik en energie-efficiëntiepotentiëlen van de chemische industrie. Er is dus behoefte aan een overzichtsstudie waarin deze reactie-effecten wel worden meegenomen.

Samenvatting van de resultaten

In hoofdstuk 2 wordt het NEAT (Non-energy use Emission Accounting Tables) model gepresenteerd. Het model gaat door middel van een analyse van koolstofstromen na wat er uiteindelijk gebeurt met de koolstof in fossiele brandstoffen, die voor niet-energetische toepassingen worden gebruikt. Emissies uit productgebruik worden geschat door het modelleren van de conversieroutes van 22 basischchemicaliën naar 55 intermediaire en finale producten. Een deel van de koolstof in de fossiele brandstoffen die voor niet-energetische toepassingen worden gebruikt, wordt direct als CO₂ geëmitteerd in een aantal industriële processen. Deze industriële procesemissies in de productie van ethyleen en propyleen, ammoniak, methanol, carbon black en bepaalde metalen en anorganische producten worden geschat op basis van specifieke emissiefactoren. Onafhankelijk van de energiestatistieken komt het model tot schattingen van het totaal niet-energetisch gebruik en van de koolstof opslag in synthetische organische producten. Het model kan worden gebruikt als een belangrijke controle op de methodiek voor het bepalen van emissies van niet-energetisch gebruik zoals die in de inventarisatie wordt gebruikt. Het kan dienen als een handvat om deze inventarisatie te verbeteren. Het belangrijkste nadeel van het model is de hoeveelheid benodigde data, in het bijzonder voor de koolstofstroomanalyse die wordt gebruikt om de emissies van productgebruik in te schatten. De analyses die met het model gedaan zijn tonen aan dat het in principe mogelijk is de benodigde data te verzamelen. Toch zou het een nuttige aanvulling zijn om een gesimplificeerd model te ontwikkelen dat gebruik maakt van onafhankelijk bepaalde of generieke schattingen voor emissies van productgebruik. Zo'n

gesimplificeerd model zou dan kunnen worden gebruikt door landen waarvoor maar beperkte gegevens beschikbaar zijn.

In hoofdstuk 3 wordt het NEAT model toegepast voor Nederland in de periode 1993 – 1999 waarbij gebruik gemaakt wordt van vertrouwelijke productie en internationale handelsstatistieken die door het Centraal Bureau voor de Statistiek (CBS) voor dit doel beschikbaar zijn gesteld. Voor de bestudeerde periode varieerde het totale niet-energetische gebruik in CO₂ equivalenten van 26.1– 30.2 Mt CO₂. Van dit totaal werd 4.6 – 6.6 Mt CO₂ geëmitteerd in industriële processen en tijdens productgebruik. Het overige deel werd opgeslagen in synthetische organische producten, resulterend in een opslagfactor van ongeveer 80%. Ook zijn opslagfactoren voor de individuele brandstoffen berekend. Voor aardgas en aardolieproducten, samen goed voor ongeveer 90% van het niet-energetisch gebruik in Nederland, zijn opslagfactoren gevonden van respectievelijk 27 – 39% en 87 – 93% voor de periode 1993 – 1999. In verband met onzekerheden was het niet mogelijk een duidelijke trend te onderscheiden voor de bestudeerde jaren. Het gebruik van een bruto definitie van niet-energetisch gebruik (inclusief het deel van het grondstofgebruik dat direct of indirect als brandstof wordt gebruikt) of juist een netto definitie (waarbij het gebruik als brandstof niet worden meegeteld) blijkt een belangrijke invloed te hebben op de opslagfactoren die worden berekend.

De resultaten zijn ook vergeleken met de nationale broeikasgasemissie-inventarisatie voor Nederland gepubliceerd in 2004. De koolstofopslag in dat rapport is 5 – 9 Mt CO₂ lager in vergelijking met de NEAT resultaten. De verschillen kunnen gedeeltelijk verklaard worden door de methodiek, die gebruikt is in de nationale inventarisatie. Hierin worden sommige emissies van productgebruik in het buitenland aan Nederland toegewezen (~ 2 Mt CO₂). Ook wordt de export van anodes uit Nederland ten onrechte niet meegenomen in de berekende koolstofopslag (~ 1 Mt CO₂). Het restant van het verschil kan worden verklaard door problemen met de getallen voor niet-energetisch gebruik zoals die in de Nederlandse energiestatistieken gevonden worden en het directe gebruik van deze getallen voor CO₂ emissie berekeningen. De getallen voor niet-energetisch gebruik in de Nederlandse energiestatistieken zijn erg laag als ze vergeleken worden met de schattingen met het NEAT model. Als gevolg hiervan wordt ook de koolstofopslag in producten onderschat. De onderschatting van de koolstofopslag in de nationale inventarisatie maakt het waarschijnlijk dat de totale fossiele CO₂ worden overschat in de inventarisatie. Het verdient daarom aanbeveling om de resultaten van deze studie te gebruiken om de methodiek voor het bepalen van emissies van niet-energetisch in de nationale broeikasgasemissie-inventarisatie aan te passen.

In Hoofdstuk 3 en in het werk dat uiteindelijk in Hoofdstuk 5 van dit proefschrift heeft geresulteerd, werden onvolkomenheden gevonden in de Nederlandse energiestatistieken voor de chemische industrie. Om oorzaken voor deze onvolkomenheden te vinden worden in hoofdstuk 4 bedrijfsdata bestudeerd die de basis vormen voor de energiestatistieken in Nederland tussen 1995 en 2004. In het maken van energiestatistieken is het belangrijk een goed onderscheid te maken tussen energiedragers die zijn opgenomen in de statistiek en andere producten (hieronder chemische producten genoemd), die niet in de energiestatistieken zijn opgenomen. De bestudering van de bedrijfsdata bracht aan het licht dat in aantal gevallen chemische producten ten onrechte wel zijn opgenomen in de energiestatistieken. Daarnaast werd duidelijk dat de manier waarop de complexe energieomzettingen in de chemische industrie zouden moeten worden opgegeven, gebrekkig was beschreven in de vragenlijst. Dit heeft geresulteerd in grote fluctuaties in de energiestatistieken voor sommige energiedragers. Ook is de complexiteit van de petrochemische industrie met betrekking tot energiestromen onvoldoende onderkend in het statistische proces. Daardoor konden fouten, eenmaal gemaakt, lang doorwerken zonder ontdekt te worden. De methodes die het CBS gebruikt om te komen tot een totale energiebalans zijn bovendien niet altijd adequaat gerapporteerd. Als een gevolg hiervan was een volledig kwantitatieve analyse van de gevonden problemen niet mogelijk. Wel was het mogelijk de fouten te kwantificeren, die gemaakt zijn door af en toe chemische producten in de energiestatistieken op te nemen. Dit heeft geresulteerd in een onderschatting van het niet-energetisch gebruik van brandstoffen van 33 – 75 PJ in de periode 1995 – 2004, wat neerkomt op 14 – 28% van het gerapporteerde niet-energetische gebruik en 1 – 2% van het totale energiegebruik in Nederland in die periode.

De resultaten van de analyse zijn gebruikt om een nieuwe verbeterde vragenlijst voor de chemische industrie te ontwerpen die sinds 2007 door het CBS gebruikt wordt. In deze vragenlijst wordt een betere beschrijving gegeven van de systeemgrenzen in de statistieken om te voorkomen dat chemische producten als energiedragers worden opgegeven. In de nieuwe vragenlijst is eveneens de wijze van rapporteren van energieconversies versimpeld en wordt deze duidelijker beschreven. Gebruik makend van de Nederlandse ervaringen is ook naar de jaarlijkse vragenlijst voor olieproducten gekeken die wordt gebruikt voor het maken van de internationale energiestatistieken. De vragenlijst blijkt te kunnen resulteren in vergelijkbare problemen als die in Nederland werden gevonden. Om deze situatie te verbeteren, verdient het aanbeveling om de belangrijke energieomzettingen in de chemische industrie expliciet in de internationale energiestatistieken op te nemen en chemisch restgas als een aparte energiedrager op te nemen. Binnen de chemische industrie vinden zoals gezegd verschillende omzettingen tussen energiedragers en chemische producten plaats. In algemene zin kan worden geconcludeerd dat het voor goede energiestatistieken voor deze sector essentieel is om duidelijk te definiëren hoe de verschillende energieconversies in de statistieken worden opgenomen, om duidelijk aan te geven welke producten als energiedrager

en welke producten als chemisch product worden gezien en om de complexiteit van de petrochemische industrie te erkennen door voldoende specifieke expertise in het statistische proces te betrekken.

In hoofdstuk 5 worden ontwikkelingen in de energie-efficiëntie bestudeerd in de Nederlandse papier, kunstmest, chemische, bouwmaterialen en basismetaal industrie tussen 1995 en 2003. Hiervoor zijn gegevens over specifiek energiegebruik uit de open literatuur gebruikt en fysieke productiedata, die gedeeltelijk op de open literatuur zijn gebaseerd en gedeeltelijk door het CBS beschikbaar zijn gesteld. De resultaten geven aan dat er sinds het midden van de jaren negentig significante verbeteringen zijn opgetreden in de energie-efficiëntie van de industrie. De jaarlijkse verbetering in de primaire energie-efficiëntie is gemiddeld ongeveer 1.3% geweest, waarbij de verbeteringen in de individuele sectoren variëren tussen -0.1 en 1.5%. Voor de onderscheiden typen van energiegebruik verschillen de resultaten aanzienlijk. Voor de som van de sectoren werden verbeteringen van 1.9% gevonden voor elektriciteitsgebruik, 2.6% voor het gebruik van brandstof en warmte en -0.1% voor niet-energetisch gebruik. De resultaten zijn gecombineerd met een studie voor 1980 – 1995 die ongeveer dezelfde methode volgt. Hieruit blijkt dat over de totale tijdsperiode een jaarlijkse primaire efficiëntie verbetering van gemiddeld ongeveer 1.0% werd gehaald. In deze schatting zijn de resultaten voor de chemische industrie niet meegenomen, omdat voor deze industrietaak geen betrouwbare data voor de periode 1980 – 1995 beschikbaar waren. De gevonden verbetering in energie-efficiëntie is laag vergeleken met de meer ambitieuze 2% doelstelling, die recent zowel op nationaal als Europees niveau naar voren is gebracht.

In de studie is kwantitatief gekeken naar onzekerheden in de input data. Deze onzekerheidsanalyse geeft aan dat het moeilijk is robuuste conclusies te trekken over de ontwikkelingen in energie-efficiëntie van jaar tot jaar, maar dat altijd een langere tijdsperiode moet worden gekozen in de analyse. Een vergelijking met de monitoringsrapporten van de meerjarenafspraken energiebesparing laat zien dat er nog steeds behoorlijke verschillen bestaan tussen het energiegebruik volgens de energiestatistieken en het energiegebruik volgens de meerjarenafspraken. De ontwikkeling van de fysieke productie volgens de meerjarenafspraken komt wel goed overeen. Op basis van deze vergelijking en de gedetailleerde onzekerheidsanalyse wordt geconcludeerd dat een betrouwbare topdown monitoringsmethodiek is ontwikkeld om ontwikkelingen in energie-efficiëntie in de Nederlandse industrie te bestuderen gebaseerd op gegevens die openbaar voor onderzoeksdoeleinden beschikbaar zijn.

In hoofdstuk 6 wordt een bottom-up energiemodel voor de petrochemische industrie gepresenteerd. Het model is gemaakt door energie en koolstofbalansen op te stellen voor 68 processen in de petrochemische industrie in West Europa, Nederland en wereldwijd. De som

van alle energie die het proces ingaat (zowel het procesenergiegebruik als de energie-inhoud van de grondstoffen) en niet terecht komt in de nuttige producten van het proces is geanalyseerd. Dit totale energieverlies, dat voornamelijk verloren gaat als restwarmte naar de omgeving, kan worden beschouwd als een goede benadering van het theoretische energiebesparingpotentieel van het proces. Voor de analyse zijn, waar mogelijk, datasets gebruikt, die geldig zijn voor West Europa in het jaar 2000. Het energieverlies in West Europa in het jaar 2000 wordt geschat op 1620 PJ finale energie en 1936 PJ primaire energie. Dit komt overeen met een emissie van 127 Mt CO₂. Voor Nederland en de wereld zijn de verliezen geschat op respectievelijk 282 en 10092 PJ primaire energie. Het procesenergiegebruik en de energie-effecten van de reactie hebben vaak een vergelijkbaar aandeel in het totale energieverlies van de bestudeerde processen. Het verdient daarom aanbeveling de reactie-effecten, die niet direct zichtbaar zijn in de energiestatistieken, explicieter mee te nemen in studies naar energie-efficiëntie voor de chemische industrie. De processen met grote verliezen in relatieve of absolute zin zouden meer in detail kunnen worden geanalyseerd. Hierbij moet rekening worden gehouden met verdere thermodynamische, economische en praktische overwegingen om zo technisch en economisch haalbare energiebesparingpotentiëlen vast te stellen. Dit soort analyses zouden bijvoorbeeld meer in detail de verschillende onderdelen van het proces moeten bekijken en ook de tweede hoofdwet van de thermodynamica in de analyse moeten betrekken. De studie laat zien dat het implementeren van best beschikbare technieken al een fors energiebesparingpotentieel van soms wel 50% met zich meebrengt.

Conclusies, toepassingen en toekomstig werk

Het doet goed te zien dat veel van de resultaten beschreven in dit proefschrift een nuttige toepassing hebben gevonden. De studies beschreven in Hoofdstuk 2 en 3 zijn, zoals werd aanbevolen, inderdaad gebruikt om de Nederlandse methodiek voor het berekenen van emissies gerelateerd aan het niet-energetische gebruik van fossiel brandstoffen te verbeteren. In de nieuwe methodiek, in gebruik sinds 2005, wordt beter rekening gehouden met de link tussen niet-energetisch gebruik aan de ene en gebruik voor energetische toepassingen aan de andere kant. De meer systematische manier om naar het niet-energetisch gebruik van fossiele brandstoffen te kijken, is ook opgenomen in de nieuwe richtlijnen voor nationale broeikasgasemissie-inventarisaties gepubliceerd in 2006. Deze richtlijnen zullen gebruikt gaan worden voor het maken van nationale inventarisaties na 2012. De studies beschreven in Hoofdstuk 2 en 3 zijn hiervoor een belangrijke input geweest. In de nieuwe richtlijnen wordt aan landen geadviseerd om er via materiaalstroom analyses op toe te zien dat emissies niet dubbel worden geteld en ook niet worden vergeten. De analyse van koolstofstromen zoals die in het NEAT model is opgenomen, zou verder kunnen worden uitgewerkt tot een volledig

model voor het over de tijd volgen van de in een land opgeslagen koolstof in producten. Zo'n model zou kunnen kwantificeren hoeveel fossiele koolstof een land binnenkomt en uitgaat in de vorm van chemische producten om zo een inschatting te maken van de hoeveelheid opgeslagen koolstof in een land en de toekomstige potentiële CO₂ emissies uit deze voorraad.

Energiestatistieken krijgen als zodanig niet veel aandacht in de (wetenschappelijke) literatuur. Tegelijkertijd vormen ze wel de basis voor energie en klimaatmodellering, energie analyse en evaluatie van energiebeleid. Als de studie gepresenteerd in Hoofdstuk 4 één ding duidelijk maakt is het wel dat voldoende kwaliteit van internationale en nationale energiestatistieken nooit een vanzelfsprekendheid is, zelfs niet in landen met een goede reputatie op het gebied van energiedata zoals Nederland. De gepresenteerde voorwaarden om te komen tot goede statistieken voor de chemische industrie (duidelijke systeemgrenzen, heldere richtlijnen voor het omgaan met energieconversies en het gebruik van voldoende expertise) zijn ook geldig voor andere sectoren. Het zou goed zijn de statistische systemen die op nationaal en internationaal niveau gebruikt worden in het maken van industriële energiestatistieken systematisch met deze voorwaarden in het achterhoofd tegen het licht te houden en waar nodig, verbeteringen aan te brengen. De voorgestelde wijzigingen in de internationale energiestatistieken voor de chemie (opnemen chemisch restgas en expliciet maken van energieconversies) zouden een stap kunnen zijn in de richting van een eventuele toekomstige publicatie van koolstofstatistieken gebaseerd op de huidige energiestatistieken. Dergelijke statistieken, die voor een belangrijk deel nu al gemaakt worden als onderdeel van nationale broeikasgasemissie-inventarisaties, zouden een belangrijke aanvulling kunnen zijn in het inzichtelijk maken van de bijdrage van verschillende energiedragers aan de uitstoot van CO₂-emissies. Er is een toenemende behoefte aan koolstofstatistieken vanwege de noodzaak voor controle op fossiele CO₂ emissie-inventarisaties, maar ook vanwege de implementatie van koolstof-afvang en opslag en de transitie naar brandstoffen en materialen uit biomassa. Gebruik makend van de inzichten zoals beschreven in Hoofdstuk 2 en 3 zou hierin ook duidelijk kunnen worden gemaakt welk deel van fossiele brandstoffen initieel wordt opgeslagen in producten die niet als energiedrager worden gebruikt.

Los hiervan zou een belangrijke toekomstige verbetering in energiestatistieken voor de industrie zijn om ook informatie over het eindgebruik van energie op een reguliere basis te publiceren. Deze informatie zou een belangrijke input zijn voor de in Hoofdstuk 6 aanbevolen verdere analyse van energiegebruik in de chemische industrie waarbij wordt gekeken naar energiegebruik per procesonderdeel. Op dit moment is informatie over eindgebruik van energie alleen beschikbaar op basis van incidentele specifieke studies, bijvoorbeeld naar elektriciteitsgebruik voor motortoepassingen of naar warmtegebruik per temperatuurniveau. Het verzamelen van data over het eindgebruik van energie is tijdsintensief en kan op bepaalde punten ook in verband met vertrouwelijkheid van gegevens moeilijk zijn. Toch zou

bijvoorbeeld door het extrapoleren van gegevens verzameld bij een gelimiteerd aantal bedrijven een eerste stap kunnen worden gezet richting het systematisch publiceren van gegevens over het energie-eindverbruik. Het onderzoeksveld dat potentiële voor energie-efficiëntieverbeteringen bestudeert zou er een stap verder mee komen.

De belangrijkste conclusie van Hoofdstuk 5 is dat er een betrouwbare topdown monitoring methodiek is ontwikkeld om ontwikkelingen in industriële energie-efficiëntie in Nederland te volgen, gebaseerd op data die publiek voor onderzoeksdoeleinden beschikbaar is. De methode wordt sinds 2004 gebruikt voor het berekenen van de jaarlijkse energiebesparing in Nederland volgens het ‘protocol monitoring energiebesparing’. Op basis van de analyse zijn twee belangrijke richtingen voor vervolgonderzoek te onderscheiden. Omdat het merendeel van de gebruikte data ook beschikbaar is in andere landen van de Europese Unie, kan de methodiek ook daar gebruikt worden gebruikt. De ontwikkelde methode kan dus bijdragen aan betrouwbare en onafhankelijke vergelijkingen van het niveau van energie-efficiëntie tussen landen. Met het oog op het alsmaar groeiende belang van gemeenschappelijk Europees energiebesparingsbeleid is dit een belangrijke conclusie. Een tweede richting voor toekomstig werk is om een reguliere controle te introduceren voor de verschillende energie en energie-efficiëntie gerelateerde datastromen van individuele bedrijven naar de overheid zoals bijvoorbeeld milieujaarverslagen, productiestatistieken en rapportages in het kader van de emissiehandel. De controles zouden kunnen worden gebruikt om inconsistenties in data op het laagste aggregatieniveau aan het licht te brengen en zo problemen in toekomstige evaluaties van energiebeleid te voorkomen.

Dit soort analyses waarbij verschillende soorten data worden gecombineerd zouden ook kunnen bijdragen aan gedetailleerde analyse van energie-efficiëntie trends bij individuele bedrijven. Combinatie van financiële en fysieke activiteitsdata op het laagste aggregatieniveau kan bijvoorbeeld inzicht verschaffen in de verhouding tussen de economische en fysieke groei van de economie. De studies beschreven in Hoofdstuk 3 en 5 van dit proefschrift laten zien dat dergelijke vertrouwelijke bedrijfsdata voor onderzoeksdoeleinden beschikbaar gemaakt kunnen worden.

Dit proefschrift analyseert data en methodes die gebruikt worden in het ontwerpen en evalueren van energie- en klimaatbeleid. Data op allerlei aggregatieniveaus werd op verschillende manieren met elkaar gecombineerd. Dit proefschrift laat zien dat dergelijke analyses zwakke plekken in gebruikte methodes aan het licht brengen. Daarnaast werd duidelijk dat er soms significante fouten zitten in officiële gepubliceerde statistische data, die door een goede detailanalyse eenvoudig kunnen worden opgespoord en verholpen. Ten slotte maakt dit proefschrift duidelijk dat er inconsistenties kunnen bestaan tussen verschillende databronnen gebruikt in beleidsevaluaties. Op basis van deze bevindingen luidt de conclusie

dat onafhankelijke controle van de methodes gebruikt in het energie- en klimaatbeleid noodzakelijk is en blijft waarbij op een goede manier gebruik gemaakt moeten worden van alle ter beschikking staande data. Beleidsmakers moeten voldoende aandacht geven aan dit soort activiteiten om toekomstig energie- en klimaatbeleid geloofwaardig, betrouwbaar en effectief te laten zijn.

DANKWOORD

Klaar! Tijd voor een dankwoord om iedereen te bedanken die aan de totstandkoming van dit proefschrift heeft bijgedragen.

In de eerste plaats Kornelis Blok en Martin Patel, mijn promotor en co-promotor. Kornelis, je hebt me altijd alle ruimte gegeven een eigen weg te volgen, maar wist op kritieke momenten wel die sturing te geven die ik nodig had. Met jou een artikel bespreken maakt een artikel altijd beter, enorm bedankt daarvoor. Martin, ook jou wil ik graag bedanken voor de ruimte die je me gelaten hebt om zelf dingen op te pakken en me verder te ontwikkelen. Tegelijkertijd was je altijd bereid in detail mee te denken met alle memo's, rapporten en artikelen, die ik op je tafel gooide. Je vriendelijkheid is bij iedereen bekend, ik bewonder je er enorm om. Bedankt voor de afgelopen jaren!

Inhoudelijk hebben nog veel meer mensen en organisaties bijgedragen aan de totstandkoming van de verschillende hoofdstukken van dit proefschrift. The international network on non-energy use and CO₂ emissions gave me a perfect start in writing Chapter 2 and 3 of this thesis. Next to Dolf Gielen, co-author of Chapter 2, I would like to thank also all the other members of the network. Het ministerie van Economische Zaken wil ik bedanken voor het beschikbaar maken van middelen om de problematiek rond de energiestatistieken voor de chemie in Nederland, beschreven in hoofdstuk 4 verder uit te zoeken. Zonder de samenwerking met het Centraal Bureau voor de Statistiek (CBS) was dat niet mogelijk geweest. Ik heb het leuk gevonden een paar maanden parttime bij het CBS rond te lopen. Hans Pouwelse, co-auteur van hoofdstuk 5, bedankt daarvoor. Ook de andere CBS-ers, hartelijk dank voor de samenwerking. De studie naar energiebesparing in de industrie is uitgevoerd voor het Platform Monitoring Energiebesparing. Piet Boonekamp, co-auteur van hoofdstuk 4, bedankt voor de mogelijkheid bij te dragen aan de jaarlijkse monitoring van de bereikte besparing in Nederland. Andrea, ik heb genoten van de goede discussies over data, methoden en onzekerheden en vind het erg leuk dat je co-auteur van dit hoofdstuk bent. Jacco Farla, bedankt voor het toegankelijk maken van jouw historische data, die het hoofdstuk een duidelijke toegevoegde waarde geeft. Het overzicht van energiegebruik en koolstof verliezen in de chemische industrie beschreven in hoofdstuk 6 is het resultaat van een onderzoeksproject voor de unit energie-efficiëntie in de industrie van het Energie

Onderzoekscentrum Nederland (ECN). Pieter Bach en Wim Haije, co-auteurs van hoofdstuk 6, dank voor de plezierige en goede inhoudelijke samenwerking.

De afgelopen twee jaar heb ik het afronden van mijn proefschrift mogen combineren met een leuke, uitdagende baan bij Ecofys. In het bijzonder Monique Voogt en Ernst Worrell wil ik bedanken voor deze mogelijkheid. Ik heb eigenlijk geen moment spijt gehad van de combinatie en zie er naar uit me nu nog iets meer op de Ecofys activiteiten te storten.

Alle (oud) - collega's, zowel bij NW&S als bij Ecofys, wil ik hartelijk danken voor de prettige werksfeer waarin ik altijd heb mogen werken. Kay, de jaren in het Centrum Gebouw Noord liggen al weer even achter ons, maar ik er denk er nog steeds met heel erg veel plezier aan terug. Martin, dank voor de fijne samenwerking in kamer 1003 in het van Unnik en voor het verzorgen van een elektronische koeriersservice tussen de universiteits- en Ecofysserver. Nog even en dan is het voor jou ook zover. Suzanne, dank voor de gezelligheid op de Kanaalweg.

Familie en vrienden, gelukkig word je niet echt jarenlang opgesloten in een kamertje om je proefschrift te schrijven. Lieve pa en ma, ik ben jullie intens dankbaar voor de basis die jullie mij gaven. Jullie hebben me altijd gestimuleerd bewust een eigen weg te kiezen en hebben me geleerd door te zetten in de dingen waar je aan begint. Zonder die basis was dit proefschrift er niet geweest, bedankt! Lieve schoonpa en ma, het is altijd genieten aan de Zeeuwse kust. Dank ook voor jullie steun, het is altijd fijn en goed om bij jullie te zijn en jullie bij ons. Jaap en Ardt, bedankt dat jullie mijn paranimfen willen zijn. Heerlijk om jullie achter me te hebben deze dag. Alle familie en vrienden, die ik hier niet bij name noem, bedankt voor alle steun!

Ten slotte, Elise. Het is niet te beschrijven fijn om iemand om me heen te hebben, die mij soms beter begrijpt dan dat ik dat zelf lijk te doen. Je maakt mijn beste, maar ook mijn slechtste kanten van dichtbij mee. Zoals dat eeuwige en naar nu blijkt inderdaad nodeloze gezeur over het niet afkomen van mijn proefschrift. Sorry daarvoor. Je bent geweldig, ik hou van je. Ik hoop minstens 100 met je te worden en kijk uit naar de toekomst van ons gezin.

CURRICULUM VITAE

Maarten Neelis was born in Rotterdam on 4 February 1977. In 1995, he finished secondary school in the same city and started his studies in Chemical Engineering at Delft University of Technology. In the last part of his studies, he focused on technology in sustainable development. He graduated cum laude in 2001 on an exergy analysis of hydrogen production and use in fuel cell vehicles. He conducted this study at Shell Global Solutions in Amsterdam. After working on two additional research projects at Shell, Maarten started in 2002 at Utrecht University as a teacher and researcher at the department of Science, Technology and Society. At Utrecht University, he conducted a number of research projects in the field of industrial energy use, energy efficiency and CO₂ emissions. A selection of these projects resulted in this thesis. Since 2006, he combines his position at Utrecht University with a position as consultant industrial energy use at Ecofys, a company offering consultancy and research services in the field of renewable energy and energy efficiency. Maarten is co-author of over 10 scientific journal papers and is lead author of the 2006 IPCC guidelines for national greenhouse gas inventories. He is married to Elise Caan and father of Leruo.

