The environmental impact of the Dutch chemical Industry

Report
Delft, September 2012

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Publication Data

Bibliographical data:
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The environmental impact of the Dutch chemical Industry

Delft, CE Delft, September 2012

Publication code: 12.2797/3452.67

CE publications are available from www.cedelft.eu

Commissioned by: NL Agency (*Agentschap NL*), in association with VNCI.

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CE Delft's solutions are characterised in being politically feasible, technologically sound, economically prudent and socially equitable.

Preface

Background
At the VNCI's 2010 annual stakeholder dialogue, participants expressed a desire to gain a better understanding of the ecological footprint of the Dutch chemical industry. The sector itself is also keen to improve insight in this respect, in order to identify 'hotspots' where improvements can be made, set priorities accordingly and discuss the options with stakeholders. Because the VNCI's Energy and Climate taskforce has already taken various initiatives in the realm of supply chain management and LCA thinking, this project is a joint exercise of theirs together with the Responsible Care taskforce, and companies from both taskforces have been brought together in an expert advisory group.

Methodology
Proceeding from the knowledge available at VNCI, this report outlines the chemical processes currently operated in the Netherlands, gives an indication of the production capacities involved and explains the interrelationships between these processes with reference to the production chains of which they are a part. This yields an approximate picture of the various chemical flows within the Netherlands and the volumes involved. The next step was to assess the ecological impact of these flows. For this purpose the ReCiPe methodology was adopted, with weighted average and absolute volume flows being employed to calculate and compare the ecological impact of the flows identified. One noteworthy result to emerge is that while the so-called 'high volume chemicals' have a relatively low impact per tonne of product, they prove to score relatively high when it comes to their absolute impact due to their volume.

Position of chemicals in the supply chain and daily used products
In general we see that the most attention is given on the energy consumption in the production phase of (half) products. The importance of chemical products for society becomes more clear when further examining endproducts and their supply chains. To provide more insight 4 supply chains have been selected:
styrene, sulphuric acid, nitric acid and fatty acids. For each of these, the range of downstream products derived from them is discussed. The effects of these materials on the greenhouse gas emissions in the use phase should be taken into account as wel as part of a total life cycle approach. In many cases the amount of greenhouse gas reduction i.e. through better insulation or lighter materials exceeds the initial greenhouse gas emissions in the production phase. Also the specific functionality of the resulting products should be taken into account, can our society do without these products or can we create alternatives. This report creates more insight and awareness of the role the chemical industry fulfils in the total life cycle.

Link with activities at company level
In tandem with the present study a project was started to help chemical companies get a better handle on the role they play in product(ion) chains. To this end a number of experienced member companies were first surveyed to establish the methodologies currently used in this context and the reasons for adopting them. These experiences have been laid down in a preliminary paper from which a 'goal and scope document' is to be developed. This will enable companies to make a considered choice as to whether to have just a carbon footprint calculated, for example, or a more extensive LCA, based on the specific questions they or their contractors or customers have.

In the context of negotiated agreements with Dutch industry (the 'Multi-Year Energy Agreements' MJA3 and MEE) there are already numerous activities around the themes of energy and climate that are geared to supply chain optimisation. All these activities have been dovetailed together in a logical manner in the 'Energy and Climate Road Map towards 2030'.

Responsible Care
The present ecological footprint project fits seamlessly into the Responsible Care philosophy of continual process improvement and supply chain optimisation. Under the Responsible Care management system, companies report annually on the progress made in a number of areas including energy and the environment.

Context
This report has been prepared with the support of NL Agency (*AgentschapNL*) and CE Delft. It consists largely of technical descriptions of the chemical processes operated in the Netherlands and the assumptions and methodology used to elaborate a number of issues the VNCI is keen to discuss with stakeholders. An important word of warning is in order, though, for while this report provides a good indication of chemical flows in the Netherlands, it makes no pretence at being complete. The same holds for the assumptions and methodology employed. The report is therefore emphatically not intended to be read in isolation or be quoted from. Follow-up actions emerging from a stakeholder dialogue will be elaborated through Responsible Care channels and via the Energy and Climate Route Map for 2030 and will be duly reported on the VNCI website.

Colette Alma, Reinier Gerrits and Arnout Schikhof, VNCI

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Summary

Introduction

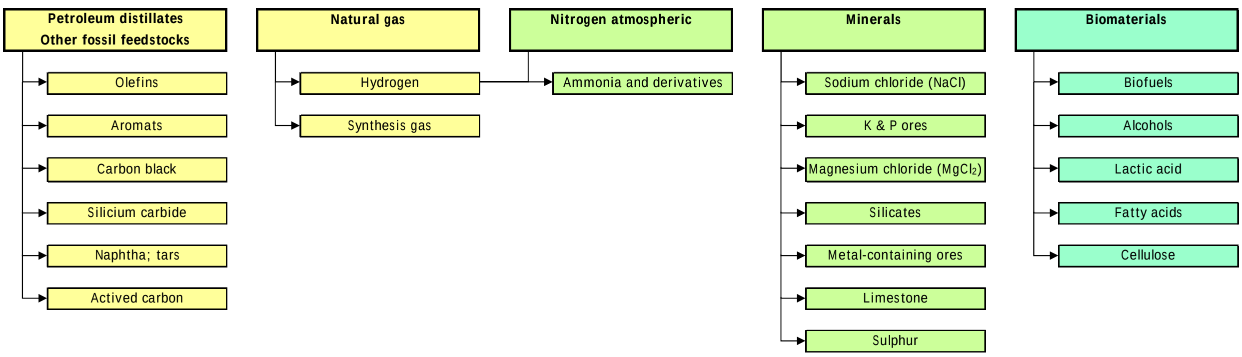
Following its annual dialogue with stakeholders, the Association of the Dutch Chemical Industry, VNCI, stated that it wished to gain a better understanding of the ecological footprint of the Dutch chemical industry. The companies in the sector are themselves also keen to improve insight in this respect, in order to identify 'hotspots' where improvements can be made, set priorities accordingly and discuss the options with stakeholders.

Proceeding from VNCI's knowledge of the chemical processing plant currently operated in the Netherlands, in this report an indication is given of the production capacities involved and explains the interrelationships between these processes with reference to the production chains of which they are a part. This yields an approximate picture of the various chemical flows within the Netherlands and the volumes involved. The next step was to assess the ecological impact of these flows, cradle-to-gate, which was carried out using the Ecoinvent database. For this purpose the ReCiPe methodology was adopted, with weighted average and absolute volume flows being employed to calculate and compare the ecological impact of the flows identified. One noteworthy result to emerge is that while the so-called 'high volume chemicals' have a relatively low impact per tonne of product, they prove to score relatively high when it comes to their absolute impact.

A number of supply chains were then selected for further examination, gate-to-gate. Besides the flow with the greatest calculated absolute impact, three others were selected, to provide insight into the breadth and complexity of the chemical industry. The flows concerned are styrene, sulphuric acid, nitric acid and fatty acids. For each of these, the range of downstream products derived from them is discussed.
Finally three chains of products were assessed cradle-to-grave, in order to analyse the whole impact through the chain.

The flows of high volume chemicals are thus the main focus of this study. These are shown in Figure 1.

Figure 1 Feedstocks for the chemical industry in the Netherlands



Methodology and approach

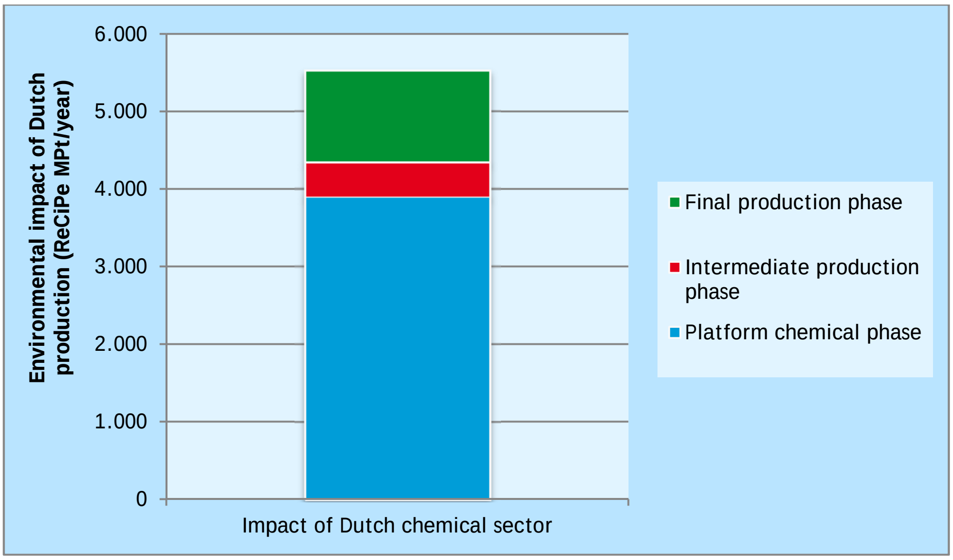
From the overall spectrum of chemicals produced within the Dutch chemical industry, 36 key high volume chemicals were selected for analysis. For these, the ecological impacts were assessed, based on the production capacity currently installed in the Netherlands.

The ReCiPe method provides a means of weighing up these environmental impacts according to their potential damage to three 'endpoints': damage to human health, damage to ecosystem diversity and damage to resource availability. These endpoints are themselves weighted to enable an overall environmental assessment to be made in the form of a combined single score indicator. The ReCiPe single score indicator is expressed in points, or Pt (in this study also in megapoints, or MPt). For example, Dutch electricity production currently stands at around 120 TWh per year, which (in a rough calculation) has an overall impact score of around 7,600 MPt.

Results, impact of Dutch chemical industry

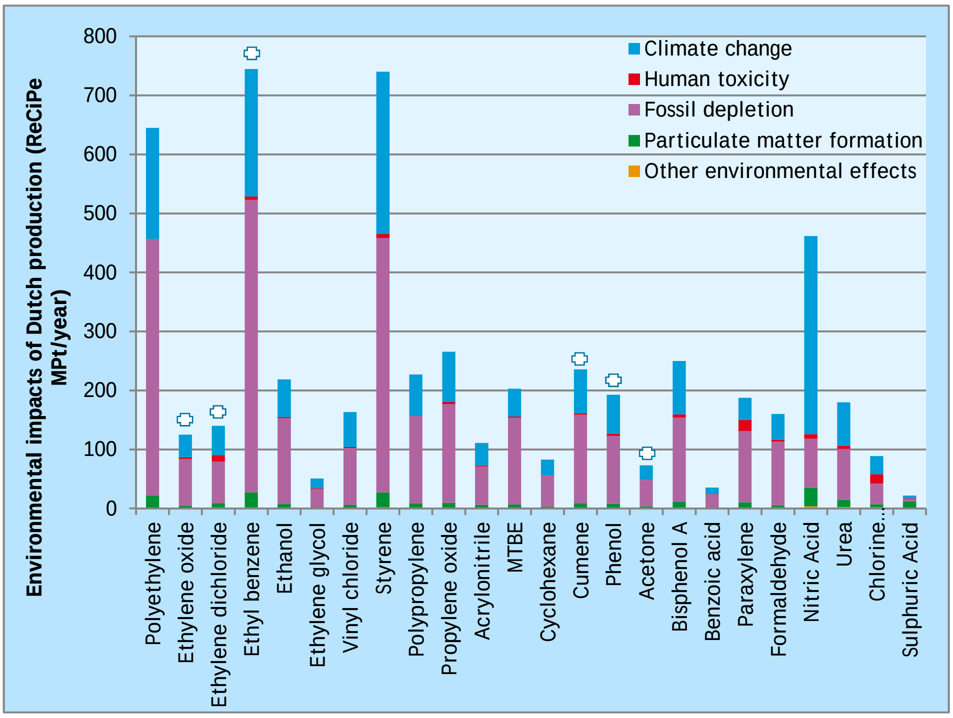
Figure 2 shows the total impact of the Dutch chemical industry derived in this study, expressed in ReCiPe MPt/year. The total impact of the three recognized phases is app. 5,500 MPt/year. This is lower than the impact of the Dutch electricity production. It should be noted that in this comparison there is a double count for the electricity used by the chemical industry.

Figure 2 Total impact of Dutch production of all 36 key high-volume chemicals selected



For the most important of these high volume chemicals, the contribution of the various individual environmental impacts is shown in Figure 3. As can be clearly seen, for this group of chemicals climate change and fossil depletion are the dominant environmental impacts.

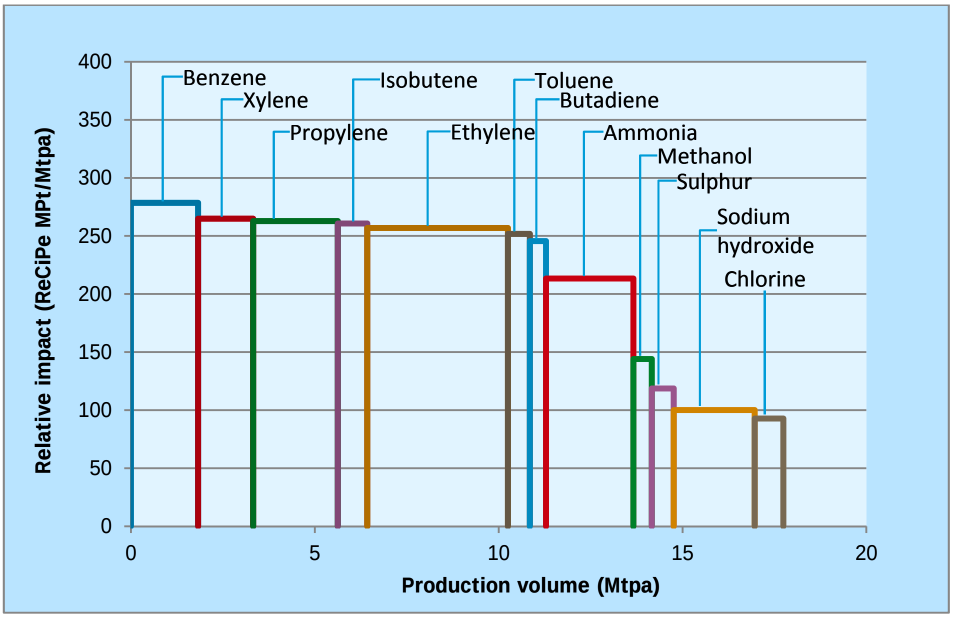
Figure 3 **Impact of Dutch production of high volume chemicals, broken down according to environmental theme**



Note: The impacts of these chemicals are not independent, as six products (indicated) are also feedstocks used in production of other high volume chemicals, and this figures shows cradle-to-gate impacts. Impacts may not be summed.

Figure 4 shows the overall environmental impact per unit mass and in relation to annual production capacity. The area of each column represents the impact of the chemical concerned. It is clear that the group of petrochemicals all have approximately the same annual impact per tonne.

Figure 4 **Impact per unit of mass vs. production capacity**



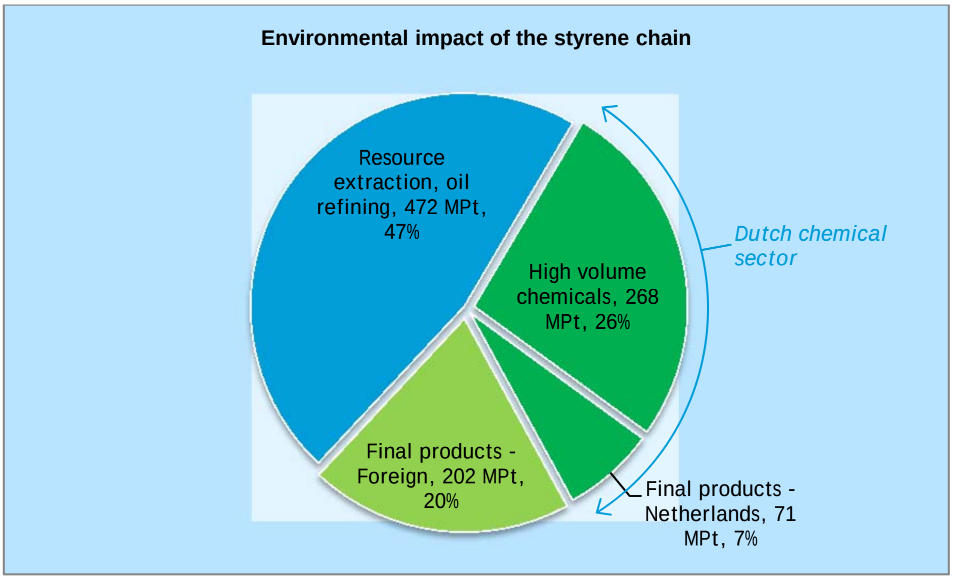
Partly because of the high production volumes involved, bulk petrochemicals account for a substantial share of the ecological footprint of the Dutch chemical industry. The petrochemical platform chemicals are responsible for 76% of the total impact of the platform chemicals within the Dutch chemical sector.

Results chain assessment styrene

An environmental impact assessment was then carried out for four selected production chains to gain deeper insight into the impact of final chemical products. The purpose of this assessment is to indicate the potential impact of final products not examined in the assessment of high volume chemicals.

Figure 5 shows the situation for styrene, produced from a number of bulk chemicals that have a knock-on effect on its ecological impact.

Figure 5 **Environmental impact of the styrene chain (in ReCiPe MPts/year; final products allocated to styrene according to mass)**

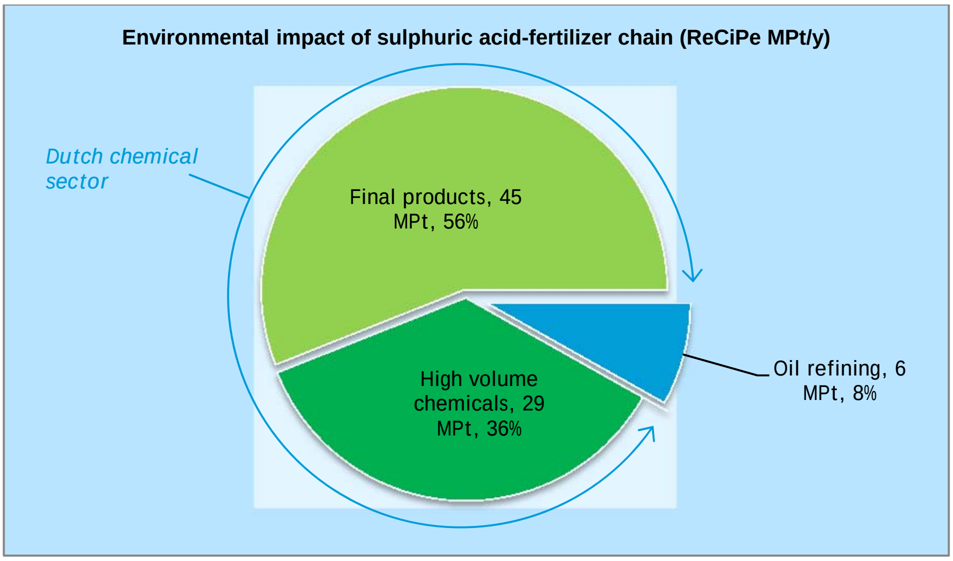


As can be seen, production of the final products derived from Dutch-produced styrene has a significant environmental impact. However, because the majority of this production takes place abroad, the contribution of final chemical production in the Netherlands is relatively minor. Within the Dutch chemical sector the impact of final production of styrene-derived products is about 20%.

Results chain assessment fertilizers

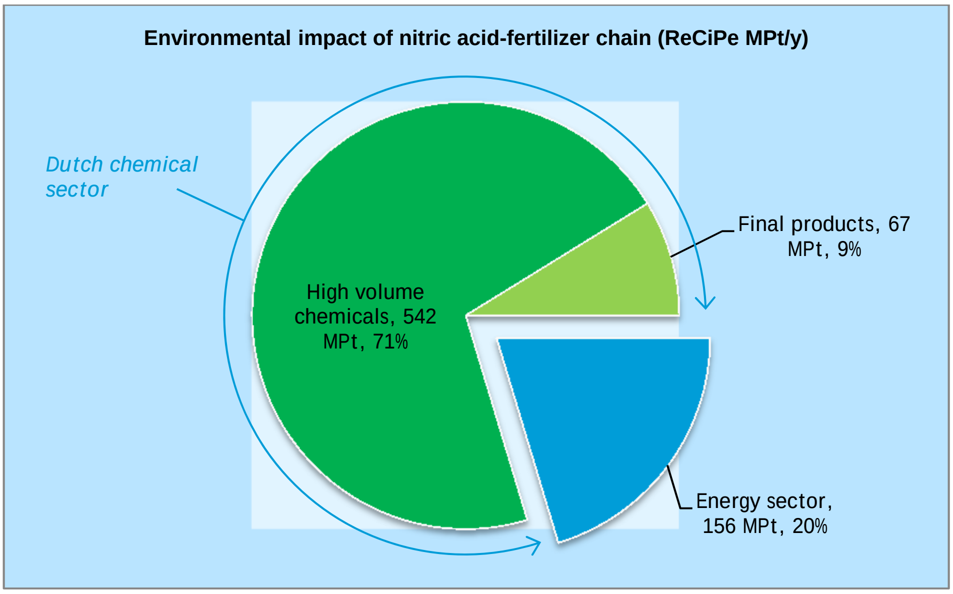
The next production chain considered was that of fertilizers produced by the sulphuric acid route.

Figure 6 **Environmental impact of the sulphuric acid - fertilizers chain (in ReCiPe MPt/year; final products allocated according to mass)**



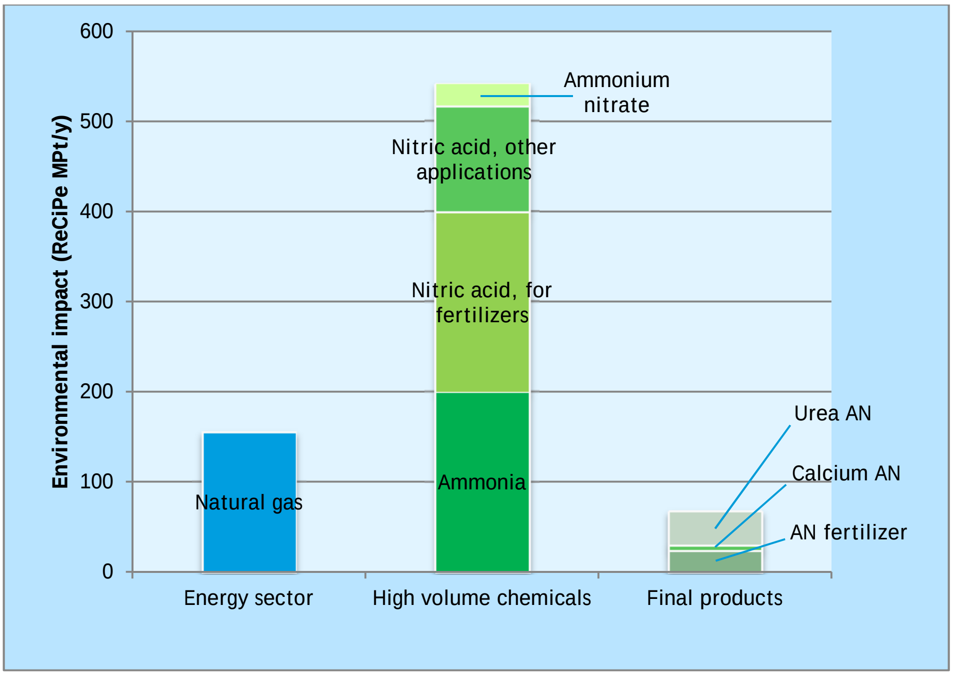
In this production chain the supply chain upstream of the chemical industry has a surprisingly low impact. This is because it involves secondary sulphur, arising as a by-product in oil refining processes. As refinery operations yield numerous products of high economic value, the allocation[1] of impacts to this sulphur is low.
The third chain examined was the nitric acid used in fertilizer production, particularly for nitrogenous fertilizers.

Figure 7 **Environmental impact of the nitric acid - fertilizers chain (in ReCiPe MPts/year; final products allocated according to mass)**



1 Economical allocation is used in LCA's to derive the impact when different product are produced simultaneously.

Figure 8 **Substances incorporated in the nitric acid - fertilizers chain impact analysis (ReCiPe MPt/a for production volumes, unique impacts of steps)**



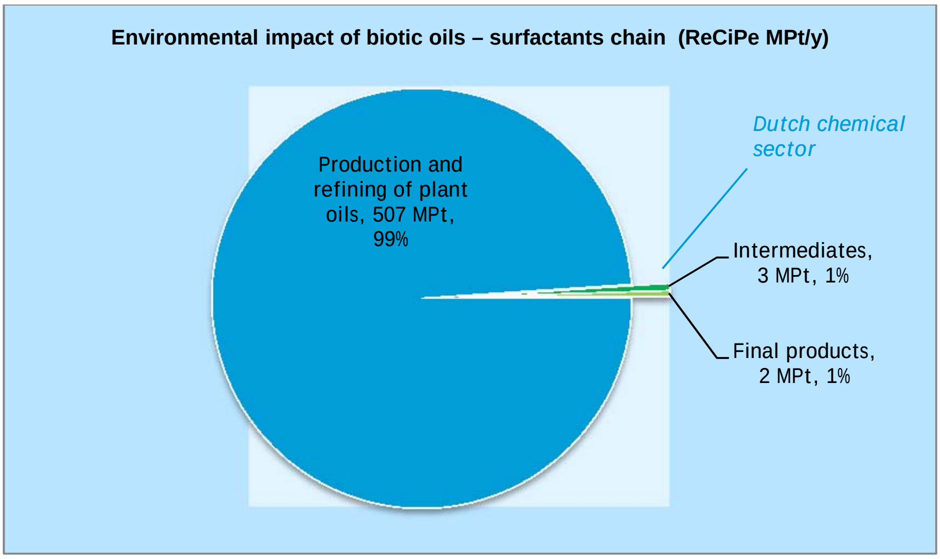
In this production chain, the high volume chemicals clearly account for the bulk of the overall environmental impact. While the impact of the upstream supply chain is not low, it is overshadowed by the high impact of the high volume chemicals (ammonia and nitric acid).

The impact of final production of the nitrogen fertilizers represents only a small fraction of the overall impact of the chain, and is conspicuously low compared with the case of phosphate fertilizer production. In the nitrogen fertilizer production chain, final production is responsible for only 9% of the overall environmental impact, or 11% of that of the chemical part of the chain. This is due to the high impacts of the high volume chemical production phase.

Results chain assessment fatty acids and oils

The fourth production chain analysis examined the application of biotic fatty acids and oils in detergents. Figure 9 shows clearly that the environmental impact is dominated by the agricultural phase of the biotic oils. This is mainly due to the land-use and land transformation from tropical rainforests. The impact of the actual chemical processing is marginal compared to this.

Figure 9 Environmental impacts of the fatty acids chain (plant oils to detergents) (in ReCiPe MPt/year)



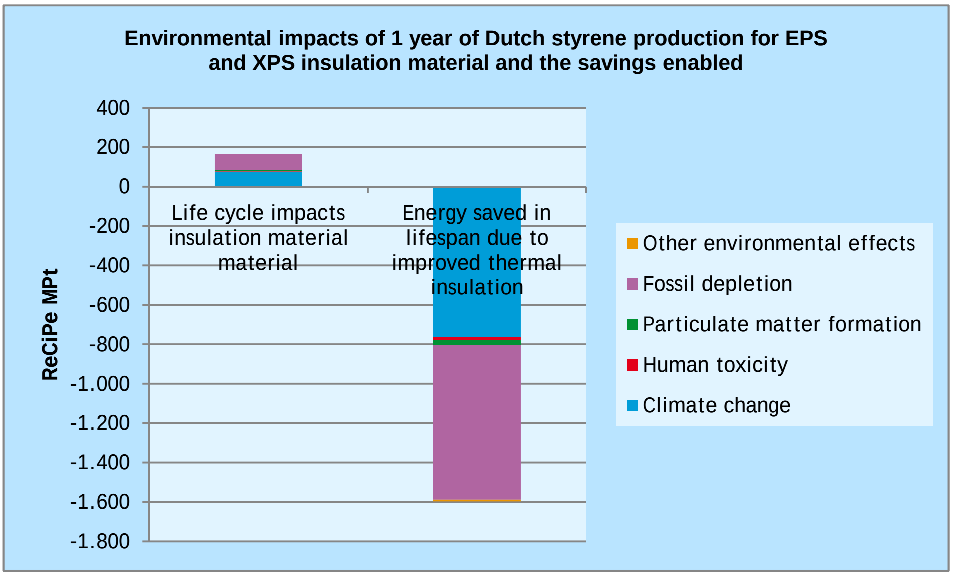
Potential environmental gain in application of three chemical products

In this study not only the cradle-to-gate impacts of chemical products have been assessed but also three examples of application and use of chemical products. The intention with the analyses is to show the potential for an environmental gain that is associated with the use of these products. These gains are not representative for the average chemical products but show the relevance to include the use phase, when routes for further improving the environmental performance in the chemical production chains are sought.

Application of EPS and XPS from styrene as insulation material in housing

Styrene is used to produce numerous products, many of which are polymerized. A familiar example used in high volumes is polystyrene insulation material, EPS or XPS. Application of such products leads to energy savings in homes and elsewhere. Figure 10 shows how the environmental impact of polystyrene production compares with the energy savings and savings on fossil fuel consumption resulting from its use.

Figure 10 **Comparison of lifecycle impacts of insulation material and lifecycle impacts of prevented energy consumption**



Application of N-fertilizers in agriculture

As Figure 11and Figure 12 show, synthetic nitrogen fertilizers have major net benefits for the environment. Without N-fertilizers, per-hectare crop yields would be about 17% lower on average. The gross environmental savings attributable to the use of Dutch N-fertilizers are greater than the lifecycle impacts of their production and use. This ratio, termed the 'X-factor', is between 1.4 and 1.8, depending on the figure adopted for N_2O process emissions during nitric acid production.

Figure 11 **Environmental impacts of nitrogen fertilizer lifecycle vs. savings enabled**

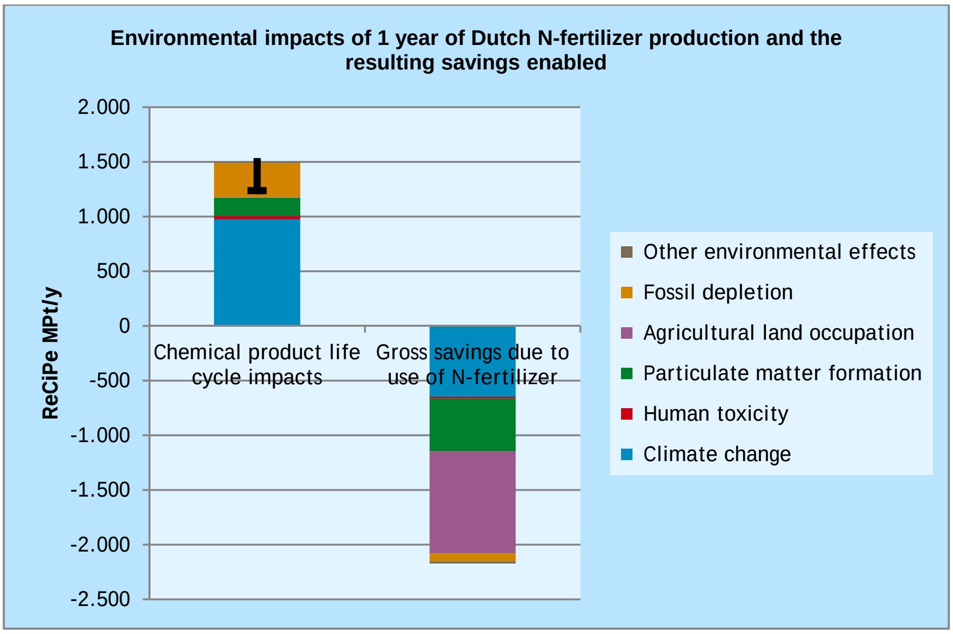
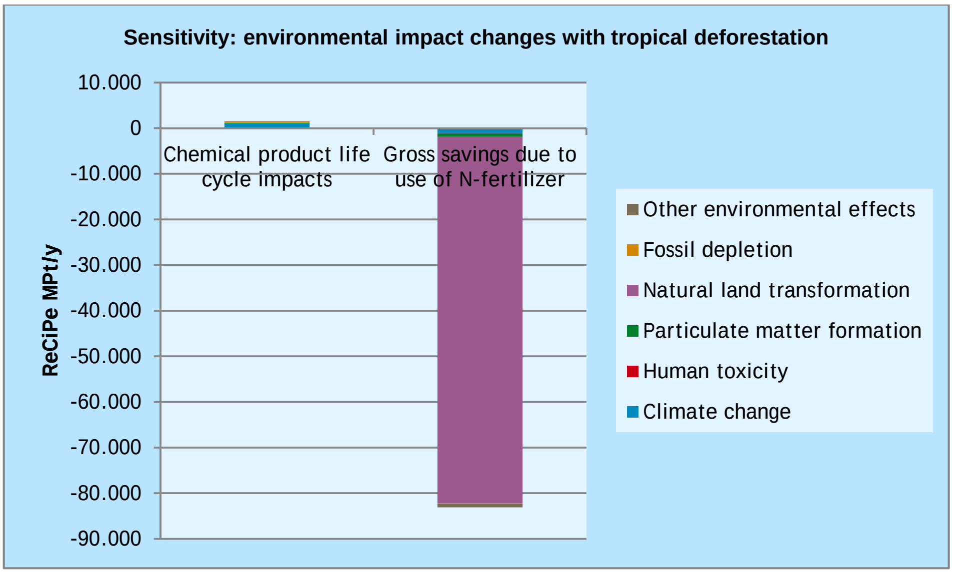


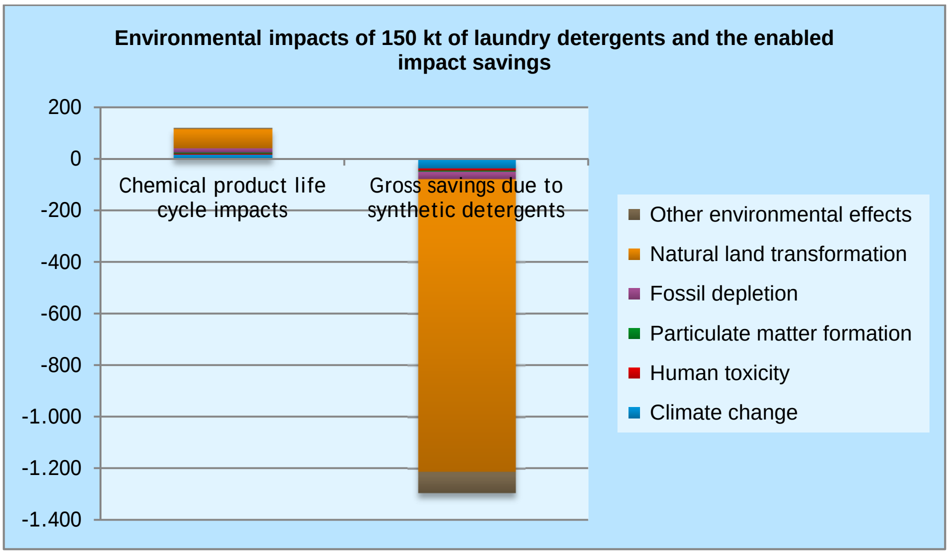
Figure 12 **Environmental impacts of nitrogen fertilizer lifecycle vs. savings enabled for the case of extra land use leading to tropical deforestation (clear-cutting of primary rainforest in Brazil for extra farmland)**



Land use changes can cascade down to tropical regions, where the potential environmental impacts are greater. If N-fertilizers cannot be used and the related amount of extra land needed (1.86 million ha) were provided by clear-cutting of tropical rainforest, this would lead to far higher environmental impacts. Quantifying this as a worst-case scenario, the X-factor expressing this effect would be 55 to 67.

Application of fatty acid in synthetic low temperature washing detergents

Figure 13 **Environmental impacts of modern laundry detergents and the impact savings they enable**



The analysis of synthetic detergents shows that the savings enabled by their use – the X-factor - are 11 times higher than the lifecycle impact of the chemical production chain, in the baseline case. However, there is considerable uncertainty in the assessment due to the inventory adopted as a reference, as the plant oils used to produce natural laundry soap may be more or less sustainably produced. The uncertainty was modelled with adjustments in the inventory for the laundry soap, yielding a lower and upper limit for the X-factor: a savings ratio of 4 versus 15. In all the scenarios assessed, synthetic laundry detergents have lower environmental impacts than the natural soap-based reference.

Overall conclusions
The aim of this study was to assess the environmental impact of the Dutch chemical sector and the share it contributes to the chemical product production chains of which it is a part. The main conclusions are as follows:
1. The high volume chemicals (12 platform chemicals and 24 derivative high volume chemicals) produced by the Dutch chemical sector account for the bulk of the environmental impact of this sector in the Netherlands.
2. The contribution of final chemicals production by the Dutch chemical sector to its aggregate environmental impact varies considerably depending on the end product. Based on four key production chains, this share can be estimated at between 10 and 50%.
3. Within the various production chains, the contribution of the different phases is clear and can be used for improvement.
4. Given the environmental benefits that can be gained from their use, the products made from the chemicals assessed in the chain analysis enable a significant decline in net environmental impact.

1 Introduction

1.1 Programme

The Responsible Care and Energy and Climate taskforces of the Association of the Dutch Chemical Industry (VNCI), together with NL Agency (*Agentschap NL*), have expressed a desire for the environmental or ecological footprint of the chemical industry in the Netherlands to be assessed. This task was commissioned to CE Delft by NL Agency and the results of the study are presented in this report.

1.2 Goal

The main goal of this study is to provide an overall assessment of the environmental impact of the Dutch chemical industry. This was done by analysing the flows of chemical products in the Netherlands and assessing the environmental consequences of the activities of the chemical sector.

The main goal was addressed by way of the following research questions:
1. Following assessment of the high volume chemicals produced by the Dutch chemical industry, how can we express, in quantitative terms, the environmental impact of the Dutch chemical industry?
2. Assessing the entire production chains of final products of the chemical sector, what is the sector's share in the impact thereof, and how does this relate to the analysis of high volume chemicals?
3. Assessing the impacts that chemical products have in other sectors, what net environmental gains are enabled by the use of the products involved?

These questions have been answered in three research phases, as detailed in the present report.

1.3 Approach

In the initial phase of the research, the first research question was answered by mapping the most important flows of chemicals and chemical products in the Netherlands in terms of volume and/or environmental impact and determining the related ecological impact for the Netherlands as a whole.

The impact of these flows was determined by means of a general assessment of the environmental impact of the Dutch chemical sector as a whole. The emphasis was thus on the overall impact of the sector. Because of the enormous variety of chemical products, in practice it is unfeasible to assess them all. For pragmatic reasons (data availability) such an exercise is only possible for high volume chemicals (cradle-to-gate).The assumption has been made, however, that these high volume chemicals, including their supply chains, are responsible for the vast bulk of the environmental impact of the Dutch chemical industry. In this phase of the research, then, only these high volume chemicals were included. In a later phase the viability of this assumption was examined, to identify the potential contribution of low volume/high impact chemicals and assess the added impact of the production of the chemical end products derived from the high volume chemicals.

To answer research question 2, in the second phase a number of interesting product chains within the chemical sector were assessed in their entirety. This enabled an assessment of the entire impact of the chemical sector and its share in the overall production chain. It also permitted assessment of what fraction of the environmental impact of the production chain is associated with production of high volume chemicals and what fraction with production of final chemical products like polystyrene insulation foam or a bar of toilet soap. In this way the relative impact of the chemical industry in the overall chain could be quantified.

The following production chains were analysed:
- styrene;
- sulphuric acid;
- nitric acid;
- fatty acid derivatives.

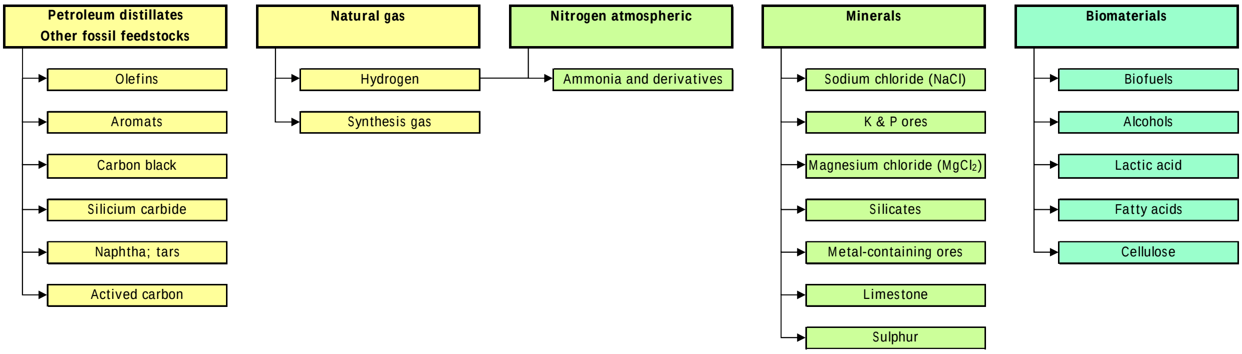
The third phase of the research was concerned with the positive environmental impacts deriving from the use of chemical products and the functions they provide to society. For this purpose three of the four production chains analysed in the second phase were taken. The associated environmental benefits are reported in relation to the environmental impacts of the chemical product's overall lifecycle.

2 Chemicals in the Netherlands

2.1 Main feedstocks

The main flows of chemicals in the Netherlands can be described under the headings of five basic feedstocks: petroleum distillates, natural gas, nitrogen, minerals and biomaterials, from which all further chemical products are derived (VNCI, 2011). Figure 14 provides an overview, showing the most important categories of basic chemicals produced from each feedstock.

Figure 14 Feedstocks for the chemical industry in the Netherlands



From these feedstocks a huge number of chemicals are made, some of them in very high production volumes. Table 1 shows the production capacities for the 27 highest volume chemicals in the Netherlands, derived from VNCI (2011).

Table 1 **Production capacity of the 27 highest volume chemicals in the Netherlands in megatonnes per year (Mtpa) (VNCI, 2011)**

#	Chemical	Production capacity (Mtpa)	#	Chemical	Production capacity (Mtpa)
1	Ethylene	3.8	15	Chlorine	0.8
2	Styrene	2.7 [2]	16	Sulphur	0.6
3	Ethyl benzene	2.6 [3]	17	Vinyl chloride	0.6
4	Propylene	2.5	18	Toluene	0.6
5	Benzene	2.4	19	MDI	0.6
6	Nitric acid	2.4	20	Methanol	0.5
7	Ammonia	2.2	21	Paraxylene	0.5
8	Sodium hydroxide	2.2	22	Ethylene oxide	0.5
9	Xylene	1.5	23	Butadiene	0.43
10	Ethanol	1.2	24	Bisphenol A	0.4
11	Formaldehyde	1	25	Soda ash[4]	0.3
12	Propylene oxide	1	26	Ethylene glycol[5]	0.3
13	MTBE	0.9	27	Carbon black[6]	0.2
14	Sulphuric acid	0.8			

In this study the chemicals in Table 1 are considered high volume chemicals if production capacity is 0.3 Mtpa or more.

2.2 Classification

Some of the high volume chemicals in Table 1 are used as a feedstock for other high volume chemicals. Figure 15 provides a simplified scheme of the relationships between the high volume chemicals and other key chemicals derived from them.

2 Styrene capacity is now likely about 2.2 Mtpa, as one plant has closed. Furthermore, actual output will be lower than ethyl benzene production, as the ethyl benzene has a higher molar mass than styrene and there conversion is not 100%.

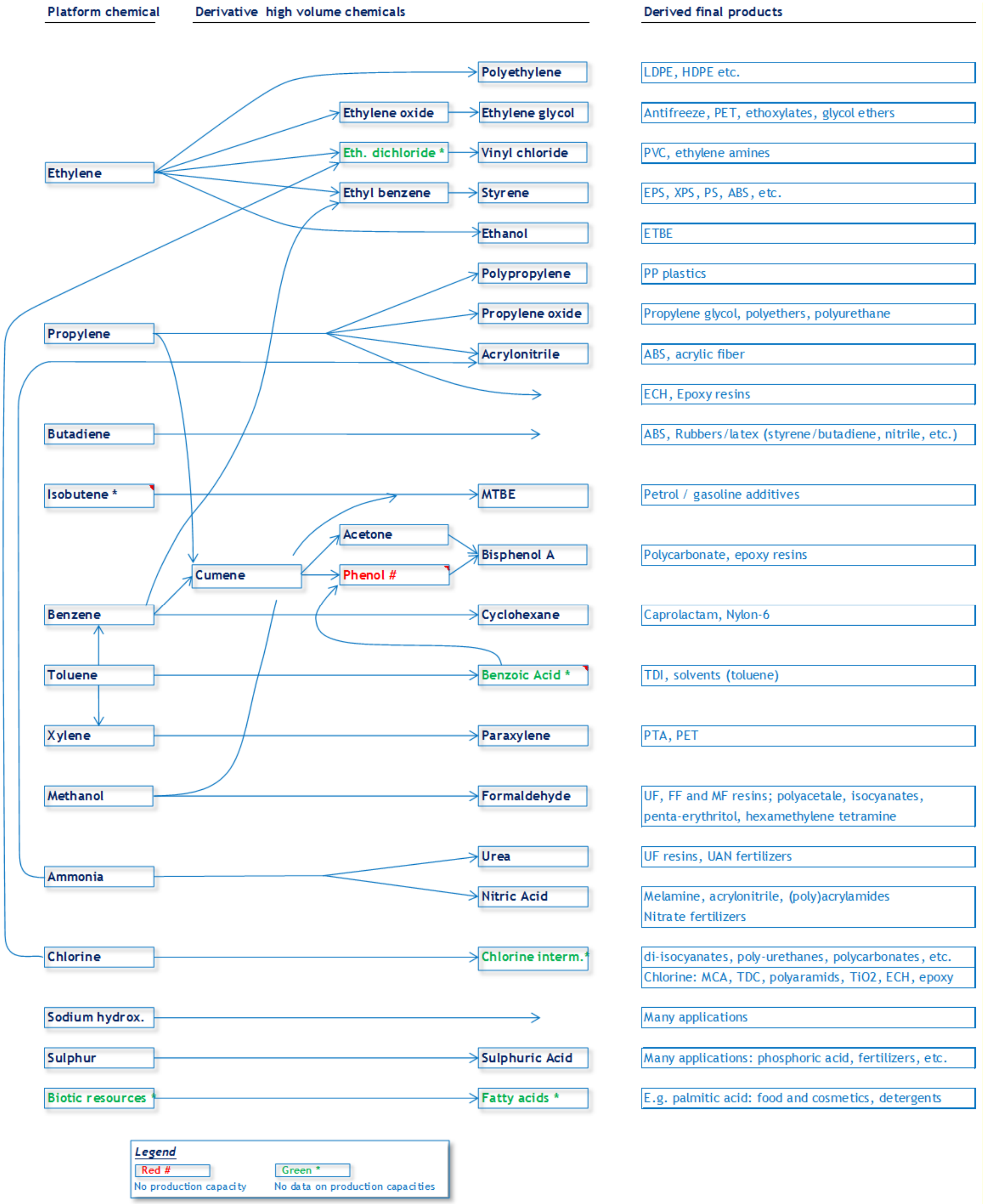
3 Ethyl benzene capacity is somewhat lower than the value reported, as one plant has closed. However, the value in the table is lower than the indicated capacity for styrene. This is not logical as ethyl benzene has a higher molar mass compared to styrene and the conversion is not 100%. Based on 2.2 Mtpa of styrene capacity, Dutch ethyl benzene capacity can be expected to be in the range 2.4–2.6 Mtpa depending on the conversion.

4 Soda ash production at Delfzijl has been discontinued; as no other producers remain, it has not been analysed further.

5 Ethylene glycol has been taken into account at the capacity shown. However, current remaining capacity is lower, as production at Terneuzen has been discontinued.

6 While one production site remains, carbon black is no longer ‘high volume’ and is not analysed further.

Figure 15 Relationships between high volume chemicals



Based on the relationships in the figure, the chemicals can be classified as *platform chemicals* or *derivative high volume chemicals*.

Platform chemicals

The chemicals in the first column of the figure are so-called platform chemicals: key high volume chemicals that are used as feedstocks for other chemicals, the derivatives indicated in the second and further columns.

Derivative high volume chemicals

These are high volume chemicals produced from platform chemicals that can be used either as a final product or as a feedstock for other derivatives. The chemicals indicated in red in the figure are intermediate chemicals for which there is currently no production capacity in the Netherlands. Since they form a basis for chemical production that does occur here, however, they have been incorporated in the figure and in the analysis.

Final products

To the right is a non-exhaustive list of derivate chemicals that reflect the huge range of final products of the chemical sector, many of which are produced in the Netherlands. According to our definition, these are often not high volume. A number of these product chains will be assessed in Chapter 5.

The chemicals cited in the boxes in the left-hand columns of Figure 15 will be analysed in Chapter 0. They include those intermediate and final derivatives with a large production volume in the Netherlands.

3 Methodology

3.1 Introduction

The main goal of this study is to determine the overall impact of the Dutch chemical sector, its supply chains and its indirect impact through export to chemical sectors abroad. The chemical sector is one of the most diverse sectors of the economy and one of the most complex in terms of product range, with platform chemicals tying in with production of numerous intermediate and final chemical products. Given the scope of the present study, a detailed and comprehensive impact assessment of each of these products is neither feasible nor necessary. As a pragmatic approach covering most of the impact of Dutch chemical production and upstream supply chains, the analysis has been broken down into two parts: one oriented towards all high volume chemicals produced in the Netherlands, the other focusing on four selected chains with the aim of providing greater insight into the impact of chemical end products.

The first part of the analysis focuses on those high volume chemicals that represent the bulk of the Dutch chemical sector's output. While these may not have the highest environmental impact per tonne produced, they are still likely to represent the bulk of that impact because of their large production volumes. Besides platform chemicals like ethylene and benzene, these high volume chemicals also include many of the intermediate chemicals derived from them, such as ethyl benzene.

In the second part of the analysis the impact of four selected chains is examined more closely. The purpose of this assessment is to indicate the potential impact of final chemical products, which were not examined in the first step. By determining the impact of final product production relative to the impact of upstream links in the supply chain, both within and outside the Dutch chemical sector, an indication is given to what extent final chemical production contributes to the sector's overall impact. For this purpose the chains of styrene, sulphuric acid, nitric acid and fatty acids were selected, as these cover a very wide range of final products and are among the largest volume chemicals produced in the Netherlands and worldwide. Fatty acids have been specifically chosen as a relative outsider for which the environmental impacts are relatively unknown because of the wide range of resources that can be used to produce them.

It is important to draw clear system boundaries for the Dutch chemical sector. Thus, the chemical sector does not include resource extraction, which according to Dutch industry classification SBI-2008 B is part of the oil refining sector, category C19. Our definition of the chemical industry includes all activities subsumed under category C20A. A more detailed explanation of the system boundaries adopted in this study is given in Annex B1.

To assess the environmental impact of production of each of the high volume chemicals and the four selected production chains the LCA impact assessment method ReCiPe was used.

3.2 Impact assessment: the ReCiPe method

ReCiPe is the most up to date LCA impact assessment method available and was therefore adopted for our assessments (ReCiPe, on-going). In this method 18 different environmental effects are assessed at 'midpoint' level (see Table 2), providing detailed information on each specific environmental issue. On its own, however, this does not yet give a clear picture of the total environmental impact, because the impacts per environmental effect cannot simply be added but must first be weighted.

In the ReCiPe method the individual environmental effects are weighed up according to their potential damage to three 'endpoints', viz. damage to human health, damage to ecosystem diversity and damage to resource availability. These endpoints are themselves weighted to enable an overall environmental assessments to be made in the form of a combined single score indicator, which is expressed in points, or Pt (in this study also in megapoints, or MPt). For example, Dutch electricity production currently stands at around 120 TWh per year, which (in a rough calculation) has an overall impact score of around 7,600 MPt. Per capita of the Dutch population this translates to around 473 Pt.

In this study we generally consider environmental impacts at the endpoint level expressed as a single score indicator and using the most common 'European/Hierarchist' perspective (ReCiPe, on-going). In certain cases the relative share of the 18 separate environmental effects to the total impact score will also be reported.

Annex B.3 provides further details of the ReCiPe methodology and the relationships between assessment and indicators at midpoint and endpoint levels and the single score indicator. For further information on the ReCiPe method the reader is referred to http://www.lcia-recipe.net/ (ReCiPe, on-going).

Table 2 The 18 midpoint environmental effects distinguished in the ReCiPe method

Nr	Effect
1	Climate change (CC)
2	Ozone depletion (OD)
3	Terrestrial acidification (TA)
4	Freshwater eutrophication (FE)
5	Marine eutrophication (ME)
6	Human toxicity (HT)
7	Photochemical oxidant formation (POF)
8	Particulate matter formation (PMF)
9	Terrestrial ecotoxicity (TET)
10	Freshwater ecotoxicity (FET)
11	Marine ecotoxicity (MET)
12	Ionising radiation (IR)
13	Agricultural land occupation (ALO)
14	Urban land occupation (ULO)
15	Natural land transformation (NLT)
16	Water depletion (WD)
17	Mineral resource depletion (MRD)
18	Fossil fuel depletion (FD)

3.3 Analysis of high volume chemicals

Most chemical products are produced from a relatively small number of platform chemicals produced in high volumes. As there are no clear statistics available on the actual annual output of the chemicals produced by all the companies comprising the Dutch chemical sector, as a proxy our assessment was based on production capacities instead. The capacities used in this study were taken from a report by the VNCI describing the Dutch chemical industry (VNCI, 2011). Working with nameplate production capacities means an overestimation of the actual production taking place and therefore of the environmental impact, too, since many production plants will not always operate at full capacity. As nameplate capacities are here consistently used, however, the relative impacts will still be generally valid.

Table 3 lists the most important high volume chemicals produced in the Netherlands along with their nameplate production capacities and environmental impacts according to the ReCiPe single score lifecycle impact assessment methodology and data on production processes from the Ecoinvent LCI database (Ecoinvent, 2011). The impacts show the 'cradle to factory gate' impact. This means that for each of the chemicals listed the environmental impacts of the production chain from resource production through to product output from the chemical plant are covered. The use phase and end of life phase of the final products are thus not included.

Table 3 Cradle-to-factory gate environmental impact of high volume chemicals (ReCiPe single score, in Megapoints per Mtpa production)

Chemical	Mtpa	ReCiPe score, MPt/Mtpa
Ethylene	3.8	256.9
Styrene	2.2	476.8
Ethyl benzene	2.6	327.2
Propylene	2.5	262.7
Benzene	2.4	278.6
Nitric acid	2.4	200.3
Ammonia	2.2	213.4
Sodium hydroxide	2.2	100.1
Xylene	1.5	264.9
Ethanol	1.2	197.1
Formaldehyde	1	186.0
Propylene oxide	1	552.0
MTBE	0.9	226.8
Sulphuric acid	0.8	27.2
Chlorine	0.8	92.8
Sulphur	0.6	118.7
Vinyl chloride	0.6	267.8
Toluene	0.6	251.8
MDI	0.6	446.2
Methanol	0.5	144.1
Paraxylene	0.5	288.4
Ethylene oxide	0.5	267.9
Butadiene	0.43	245.5
Bisphenol A	0.4	617.3
Soda ash	0.3	108.5
Ethylene glycol	0.3	221.3

Note that we cannot simply multiply and sum all the impact figures in Table 3 to calculate an aggregate environmental impact of the Dutch chemical sector, since the list includes platform chemicals *as well as derivatives produced from them*. Summing them without prior correction would mean double counting certain parts of the derivative supply chains and also include upstream effects such as resource extraction and transport.

To avoid double counting, the mass flows of the platform chemicals and derivatives were mapped according to the scheme shown in Figure 15. This provides a complete mass balance of the high volume chemicals produced by the Dutch chemicals sector. For the platform chemicals the cradle-to-gate impact has been assessed and for the derivatives the 'gate-to-gate' impact. In this way double counting is avoided. In Annex B.3 a calculation example is provided to show how this procedure was applied.

Based on this list of 27 substances a total of 12 true platform chemicals and 24 derivative high volume chemicals were analysed. The derivatives may be either final derivatives or intermediate derivatives derived from the platform chemicals.

3.4 Analysis of selected production chains

The chemical sector has a very wide range of final products, many of them produced in relatively small amounts. As explained, then, four chemical production chains were therefore selected for further assessment, to identify the potential impact of the final products concerned, as these were not examined in the initial assessment of high volume chemicals. These chains were selected on the basis of several criteria. Styrene and nitric acid were chosen because of their large production volumes in the Netherlands. Sulphuric acid was selected as a key element in numerous final products and because it is the chemical with the largest global production volume. The fatty acid chains were selected because that they can be produced from either bio-based chemicals or petrochemicals and are used in a wide range of applications like washing soaps. They therefore represent a group of products for which the impacts are expected to be very diverse.

The selected chains were mostly assessed based on the LCA data of the final chemical products. In some cases it was necessary to find additional data to translate the LCA data to the Dutch situation.

The known Dutch production volumes of the various chemicals were put into a mass balance for the entire production chain, allowing conclusions to be drawn about the likely fraction of final chemical production occurring abroad to make up for the production capacity lacking in the Netherlands.

In many cases the production chain examined was not the only input for production of the final chemical product concerned. In these cases the environmental impact of the final chemical production step was allocated on a mass basis to the various upstream chains involved. Although this allocation method is scientifically valid, financial allocation would have been preferable. This allocation method was chosen nonetheless because financial data suitable for financially adjusted allocation was lacking. However, there were no cases in which major mutual differences in financial value are to be expected, so that the results of mass-based allocation are not likely to deviate substantially from those of financial allocation.

3.5 Low volume, high impact chemicals

In our approach to assessing the environmental impact of the Dutch chemical sector, one potential blind spot might be the existence of low volume chemicals with a very high environmental impact. To assess the risk of missing such instances, all the chemicals included in the Ecoinvent LCA database were screened for their potential to be a low volume, high impact chemical with the potential to influence the outcome of the overall assessment. To this end their environmental impact per tonne was assessed and compared with that of a tonne of bisphenol A, the large volume chemical with the highest impact per tonne of the group of such chemicals assessed here. By normalising the large group of substances from the LCA database to this reference, a critical production volume for each of the substances could be calculated as a measure of the production volume of the substance that would have the same environmental impact as the total production of bisphenol A. Following this calculation, the likelihood of a substance being produced in amounts close to the critical volume was assessed. None of the substances assessed in this way emerged as a potential candidate. The most likely candidates were heavy metals, which have a high environmental impact and are produced in considerable volumes. Within the chemical sector, however, heavy metals are clearly used in smaller amounts than the critical volumes calculated.

Since LCA databases focus on substances known for their potential to cause environmental harm during and after production, it is unlikely that any substance not included in such databases would pass the test described. Our conclusion is therefore that low volume, high impact chemicals are unlikely to make any significant contribution to the aggregate environmental impact of the Dutch chemical sector.

3.6 Data sources

The Dutch chemical sector is very dynamic, with expansion of production capacity and plant closure occurring regularly. The primary source of data on the flows of chemical products in the Netherlands used here is an internal report of the VNCI (VNCI, 2011) which addresses the most important flows of chemicals and production capacities in the Netherlands. In general, developments in plant capacities that have taken place since data gathering for the cited study have not been incorporated in the present analysis. The data in this report should thus be taken as valid for base year 2010.

The primary data source used for the production processes and related environmental issues is the Ecoinvent lifecycle inventory (LCI) (Ecoinvent, 2011). Ecoinvent is the most advanced and elaborate lifecycle inventory commercially available and combines many LCIs constructed by sector organisations, academics and others. The LCI data in Ecoinvent is generally inventoried for several geographical regions and locations, with a focus on Europe. The data are valid for average production processes in the European Union and reflect technology levels of the latter 2000s. Ecoinvent is an active project with regular updates.

Where required, additional data on production processes were taken from a range of wider literature sources. Where literature data has been used, the values adopted and the modelling choices made are clearly documented in this report.

DISCLAIMER

This study encompasses a large group of chemical industries with complex production systems and a very diverse range of products that is changing constantly, both in production volume and type. With this study we do not have the goal nor the pretention to accurately describe the environmental impact of the Dutch chemical sector, the production chains and the applications of these products. The goal and intention is merely to sketch a general picture of the over all impact of the production chains that the Dutch chemical sector belongs to and how the different steps in the supply chain are contributing to this impact. Below are the most important limitations of this study given:

Quick scan

- The assessments in this study are quick scans and by no means full LCA studies according to ISO 14040. No review has been conducted.
- The production volumes are estimated based on installed production capacities, not on actual production volumes.
- Only high volume chemicals and their largest derivatives have been assessed.
- General LCA databases for European processes have been used to describe Dutch processes and have only been adapted if clear differences with the Dutch situation were known.
- Although a single score indicator has been used for convenience, it must be pointed out that this holds several uncertainties. More certain conclusions can be drawn on midpoint level (e.g. on level of environmental effects, like greenhouse effect), but would lead to more incomplete judgements.

The overall impact

The intention of the overall impact assessment was to create a general reference base. Only large volume chemicals have been assessed for this assessment. This was done on a cradle-to-gate and not a gate-to-gate bases to allow for a proper public discussion of the overall impacts of the produced chemical products. The Dutch chemical sector only represents a part of their production chains, next to other sectors like resource extraction and oil refining sectors, within and outside The Netherlands. Although a quick scan of low volume/high impact chemicals has been conducted, which shows no large contribution to the overall impact of the Dutch chemical sector, we can not exclude the possibility that there might be such chemical(s) that does have a relevant contribution to this total

The researched chains

Only a limited group of four high volume chemical production chains have been assessed more thoroughly, to include assessments of the major chemical final products. This was done to show, only by example, how the additional impact of the final production steps within the Dutch chemical sector can contribute to the overall impact. This does not give a certain or definite answer to what the actual contribution of the final chemical production steps are within the Dutch chemical sector.

The researched example applications

Also the three cases to show the potential benefits of the application of chemical products are only exemplary. They do not represent the average range of applications of chemical products. They are chosen merely to show the potential environmental benefit of products, derived from typical chemical high volume chemicals, can result to. This only supports conclusion regarding potential environmental benefits and in what directions the chemical sector can further extent and develop the environmental performance of their products. It can not support any conclusions regarding the average environmental benefit in the application of the current average chemical production.

All results and conclusions from this study must be read in the light of these limitations.

4 Results for high volume chemicals

In this chapter we present the results for 12 fully analysed platform chemicals and 24 derivative high volume chemicals: a total of 36 high volume chemicals that together are responsible for the bulk of the environmental impact of the Dutch chemical sector. As mentioned earlier, since the 12 platform chemicals as well as 6 of the intermediate derivatives are feedstocks used in downstream processes like styrene production, the associated impacts are not independent and cannot simply be summed. Only by summing the impact of production of the final products can the environmental impact of the Dutch chemical sector be calculated without double counting.

4.1 Total impact of the Dutch chemical sector

The overall cradle-to-gate impact of the 36 high volume chemicals produced in the Netherlands amounts to just over 5,500 ReCiPe MPt per year. As explained in Section 3.3, the underlying calculation avoids any double counting of feedstock production. This figure can be put into perspective by comparing it with the estimated environmental impact of Dutch electricity production. Today this stands at about 120 TWh a year, which translates (in a rough calculation) to an impact score of around 7,600 MPt (0.0641 Pt/kwh). According to our calculations, the overall impact of the high volume chemicals produced by the Dutch chemical sector is approximately 25% lower.

The impact of platform chemicals production accounts for 70% of the aggregate impact (Figure 16), with the remainder due to the added impact of later production phases. The impact of final production accounts for 22% of the total, that of intermediate production for the remaining 8%.

Figure 16 Total impact of Dutch production of all 36 key high volume chemicals selected, broken down according to production phase

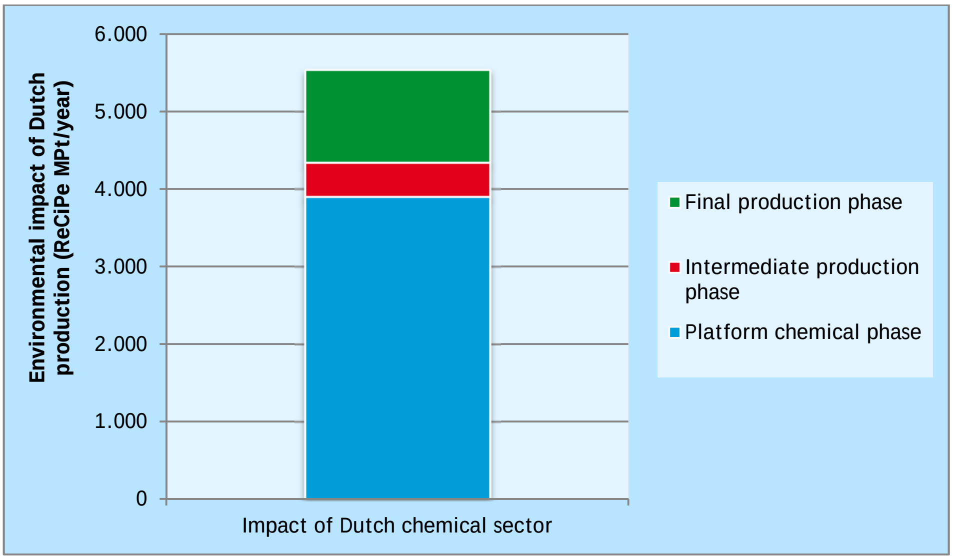
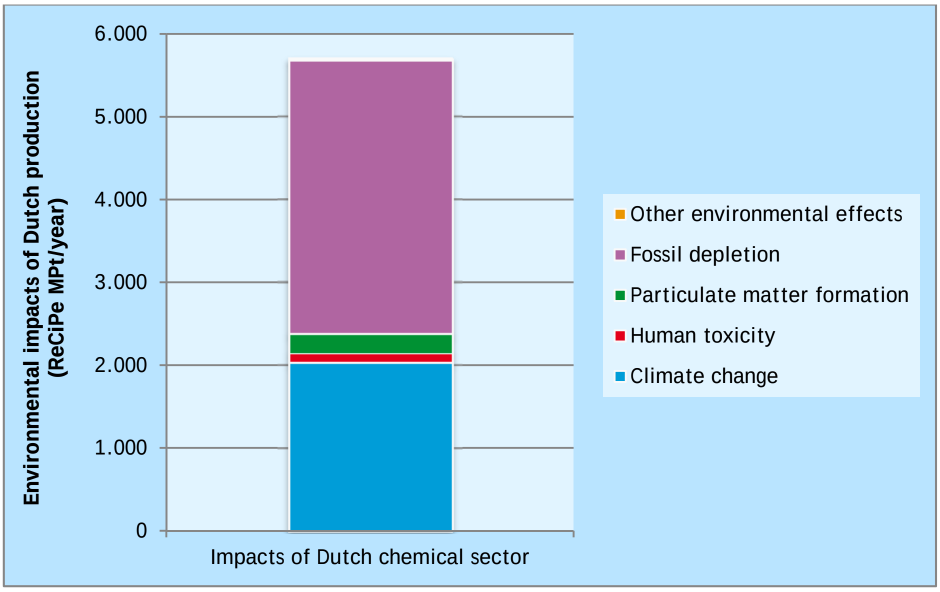


Figure 17 again shows the cradle-to-gate impact of the high volume chemicals produced by the Dutch chemical sector, but now broken down according to the contributing environmental effects. Fossil depletion is the main contributor, with 58%, while climate change is responsible for 36% of the total impact. The climate change impact is due to 42.9 Mt CO_2 eq. of greenhouse gas emissions. For comparison, the cradle-to-gate CO_2 emissions of Dutch electricity production are around 81 Mt CO_2 eq.

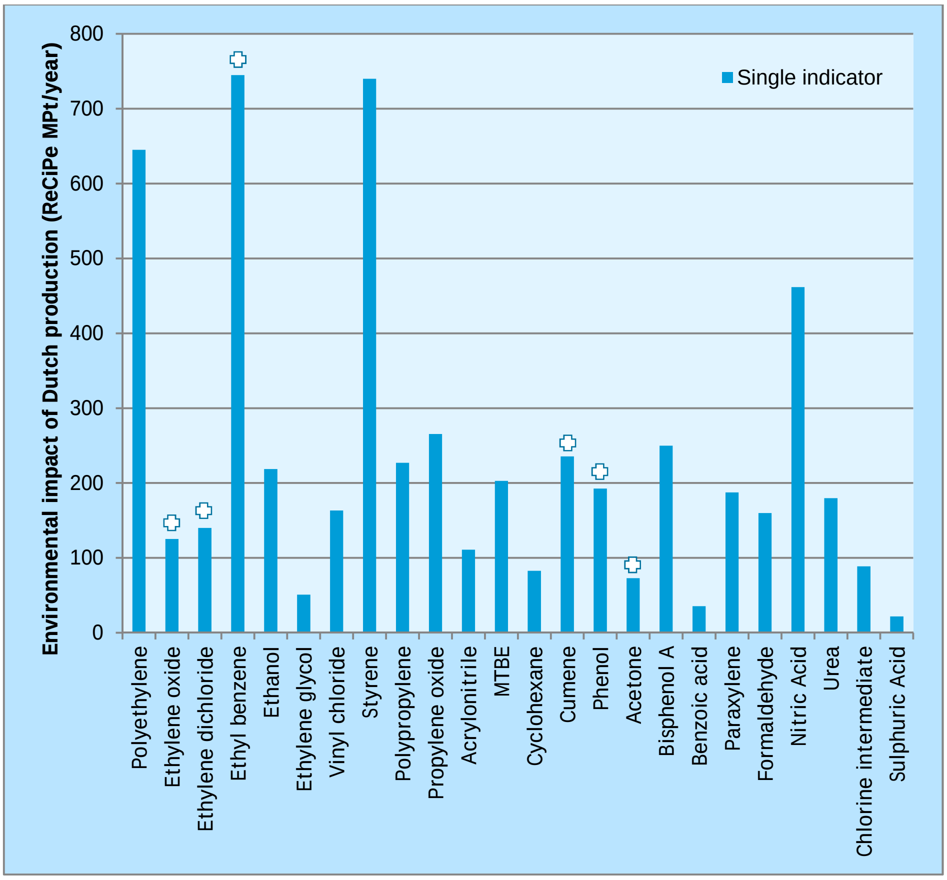
Figure 17 Total impacts of Dutch production of all 36 selected key high volume chemicals, broken down according to environmental theme



4.2 Intermediate and end products

The total single-score impact of Dutch production of 24 selected key high volume intermediate and end products is shown in Figure 18. For the relationships between intermediate and end products, see Figure 15.

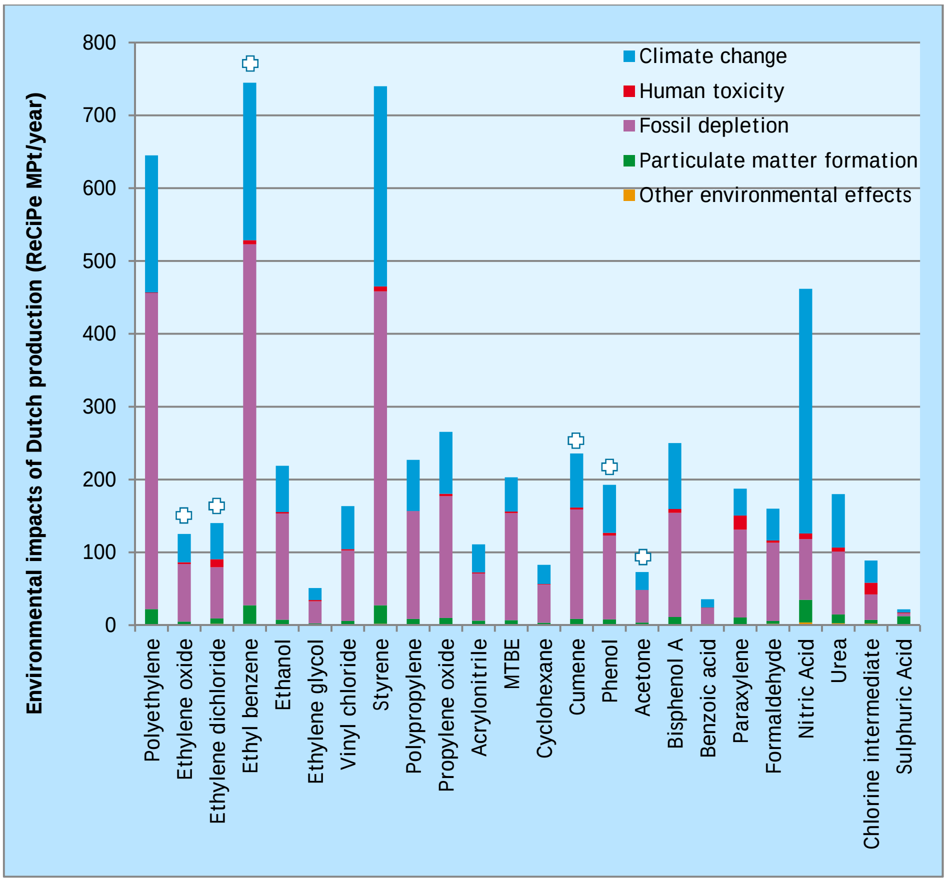
Figure 18 Total impact of Dutch production of 24 selected key high volume chemicals



Note: The impacts of these chemicals are not independent, as 6 products (indicated: ethyl benzene, cumene, phenol, ethylene dichloride, ethylene oxide and acetone) are also feedstocks used in production of other high volume chemicals, and these figures are cradle-to-gate. Impacts are therefore not independent and may not be summed.

Figure 19 shows the impact of Dutch production of the key high volume chemicals, broken down according to environmental theme. As can be seen, fossil depletion is the main contributor, with climate change coming in second. Particulate matter formation and human toxicity are minor contributors. None of the other environmental themes make any appreciable contribution.

Figure 19 Impacts of Dutch production of 24 selected key high volume chemicals, broken down according to environmental theme

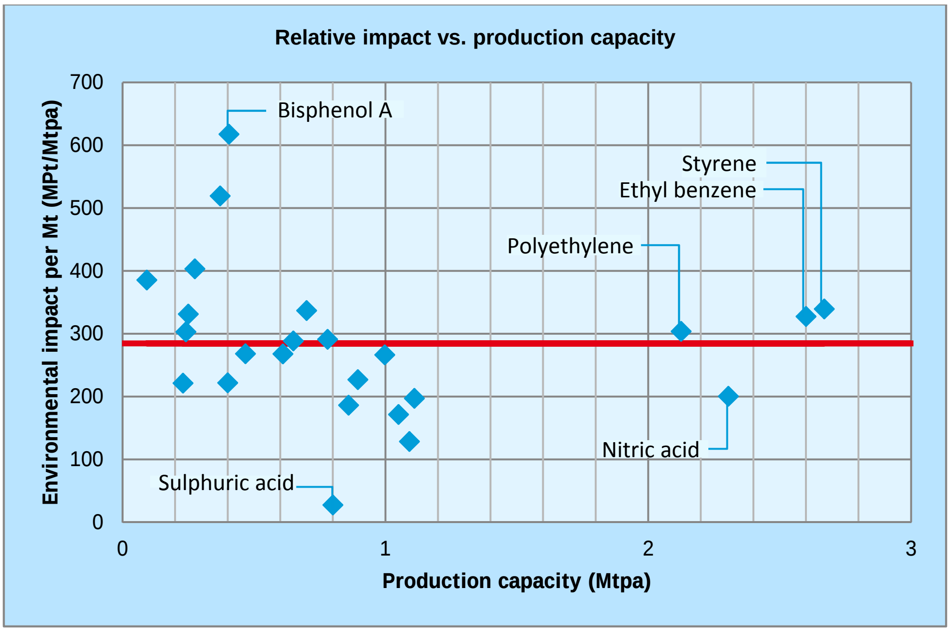


Note: The impacts of these chemicals are not independent, as 6 products (indicated: ethyl benzene, cumene, phenol, ethylene dichloride, ethylene oxide and acetone) are also feedstocks used in production of other high volume chemicals, and these figures are cradle-to-gate. Impacts are therefore not independent and may not be summed.

The production of certain end products – notably polyethylene, ethyl benzene, styrene and nitric acid - has a more substantial impact than that of others. This is due mainly to the large production volumes of these chemicals: over 2 Mtpa. Figure 20 is a scatter diagram in which the high volume chemicals are plotted according to production capacity on the x-axis, with the environmental impact per tonne on the y–axis. It thus shows the environmental impact of the chemical relative to its production capacity. The average, 285 MPt/Mtpa, is indicated by a red line.

Two groups of chemicals can be identified: a small group with a very high volume of over 2 Mtpa and an environmental impact concentrated around the average impact line between 200 and 350 Pt per tonne, and a far larger group produced in volumes between 0.3 and 1.2 Mtpa, but with a far wider ranging per-tonne impact of between 620 Pt/t for bisphenol A and about 20 Pt/t for sulphuric acid.

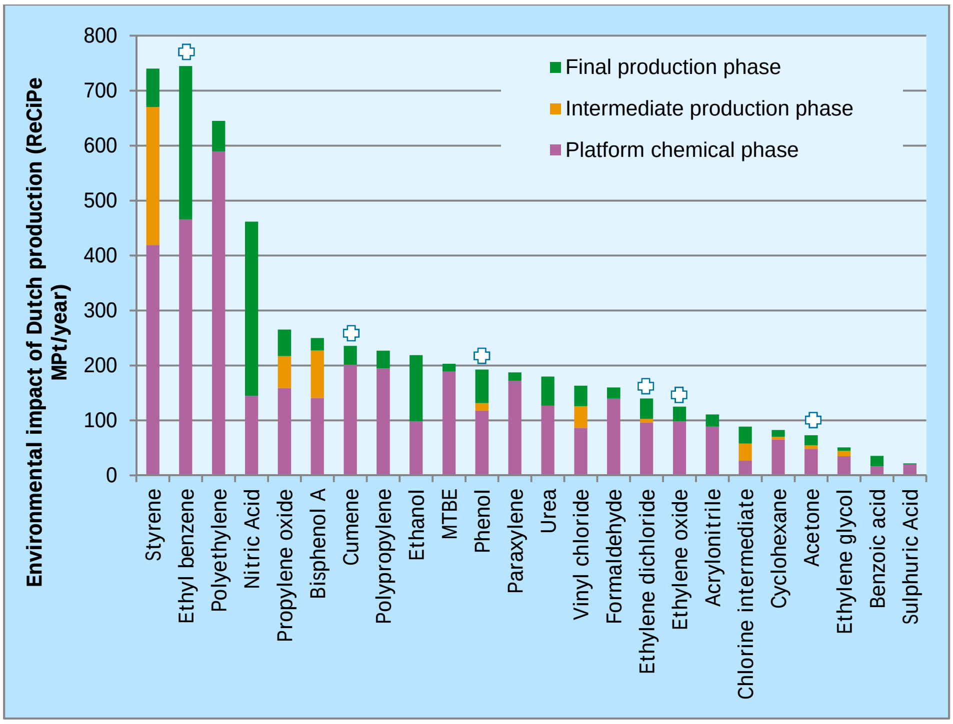
Figure 20 Impact per unit mass versus production capacity



4.3 Share of production phases in overall impact

Figure 21 shows the respective contributions of production of platform chemicals, intermediate feedstocks and final products to the overall environmental impact of the 24 high volume chemicals reviewed, sorted in descending order of aggregate impact.

Figure 21 **Respective contributions of production of platform chemicals, intermediate feedstocks and final products to overall environmental impact of 24 key high volume chemicals (sorted)**



Note: The impacts of these chemicals are not independent, as 6 products (indicated: ethyl benzene, cumene, phenol, ethylene dichloride, ethylene oxide and acetone) are also feedstocks used in production of other high volume chemicals, and these figures are cradle-to-gate. Impacts are therefore not independent and may not be summed.

The average share of platform chemicals production in the overall cradle-to-gate impact of the end products is around 68%, that of intermediate production around 9% and that of the final production phase of the chemical in question around 24%.

4.4 Platform chemicals

The impact of Dutch production of the 12 selected platform chemicals is shown in Figure 22 and Figure 23. As can be seen, the impact of these chemicals is clearly dominated by fossil depletion, owing to the petrochemical feedstock from which they are produced. Climate change also makes a considerable contribution. Particulate matter formation and human toxicity play a small but still relevant role in the production of some of these chemicals.

Figure 22 Total impact of Dutch production of 12 selected platform chemicals

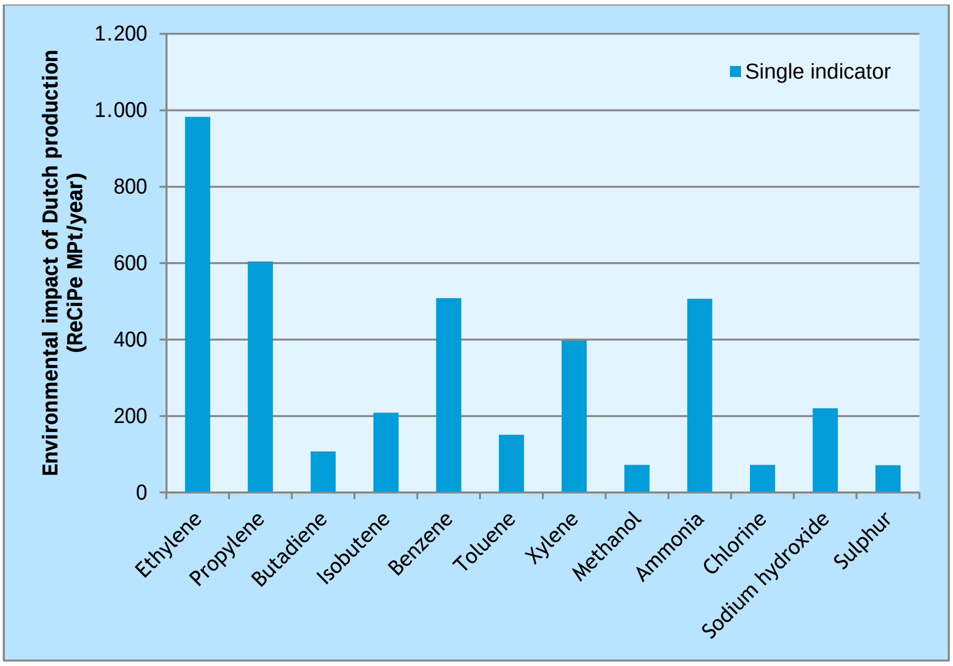
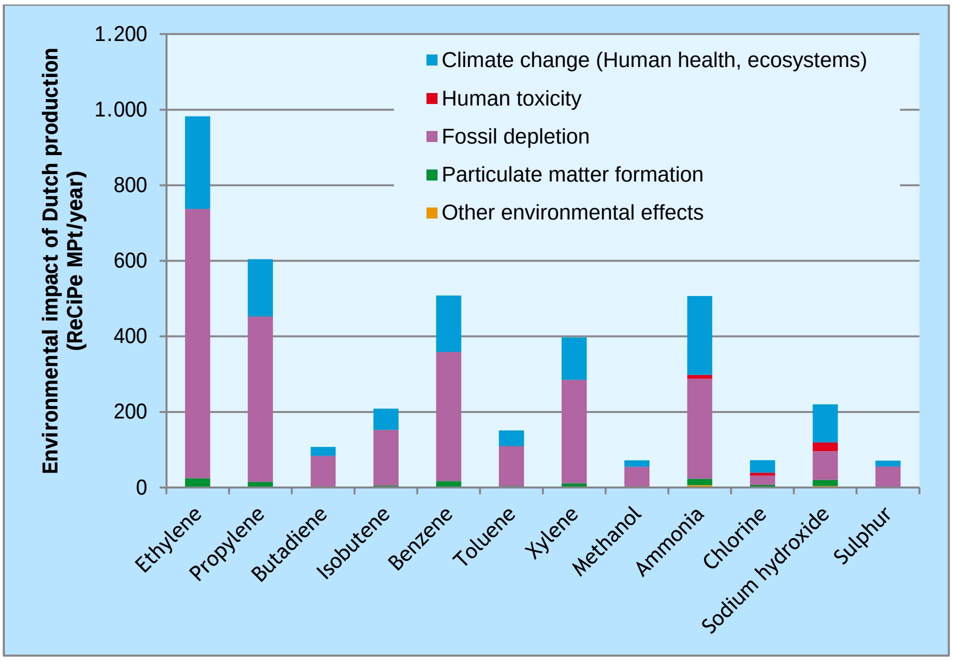
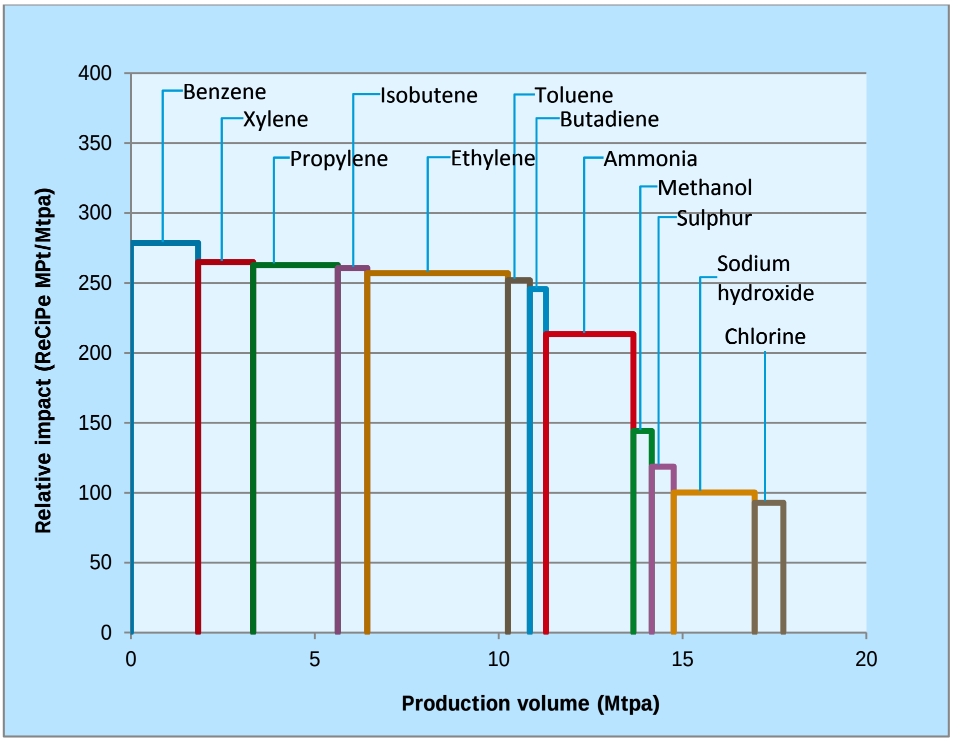


Figure 23 Breakdown of impact of Dutch production of platform chemicals according to environmental effect



The relative impact of these platform chemicals is shown in Figure 24. It can be seen that aromatic hydrocarbons and olefins have similar environmental impacts, which are higher than those of products derived from natural gas feedstock (ammonia, methanol), which are in turn higher than in the case of mineral feedstock-based products (sodium hydroxide, chlorine). The relatively minor impact of sulphur is due to it being derived from oil desulphurisation.

Figure 24 Impact per unit mass vs. production capacity



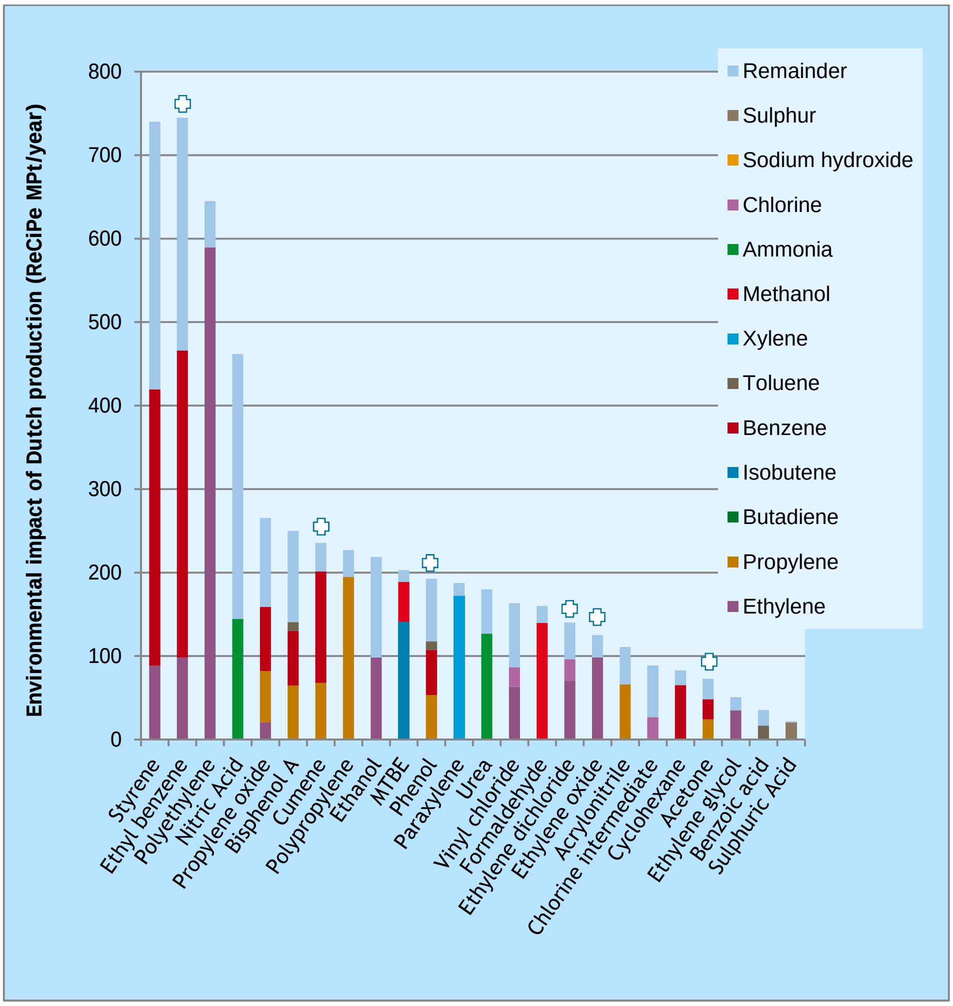
From Figure 24 it can be concluded that there is a distinct group of platform chemicals produced in an aggregate volume of around 11 to 12 Mtpa that has a very similar environmental impact per tonne production of between 250 and 270 Pt per tonne per year. These are the petrochemicals. The overall environmental impact of these platform chemicals is dominated by petrochemical refining of the feedstock, leading to a virtually identical impact per tonne. The petrochemical platform chemicals are responsible for 76% of the total impact of the platform chemicals within the Dutch chemical sector.

The remaining 7 to 8 Mtpa of aggregate output has an increasingly lower environmental impact per tonne, ranging from 220 to only 100 Pt per tonne per year. This wider range is due to the different origins of the respective feedstocks (natural gas; sulphur; salt) and the consequent differences in chemical processing.

4.5 Share of platform chemicals production in overall end product impact

It is interesting to examine the contribution of the platform chemical production phase to the overall environmental impact of the end products. Figure 25 shows the results for the various derivative high volume chemicals.

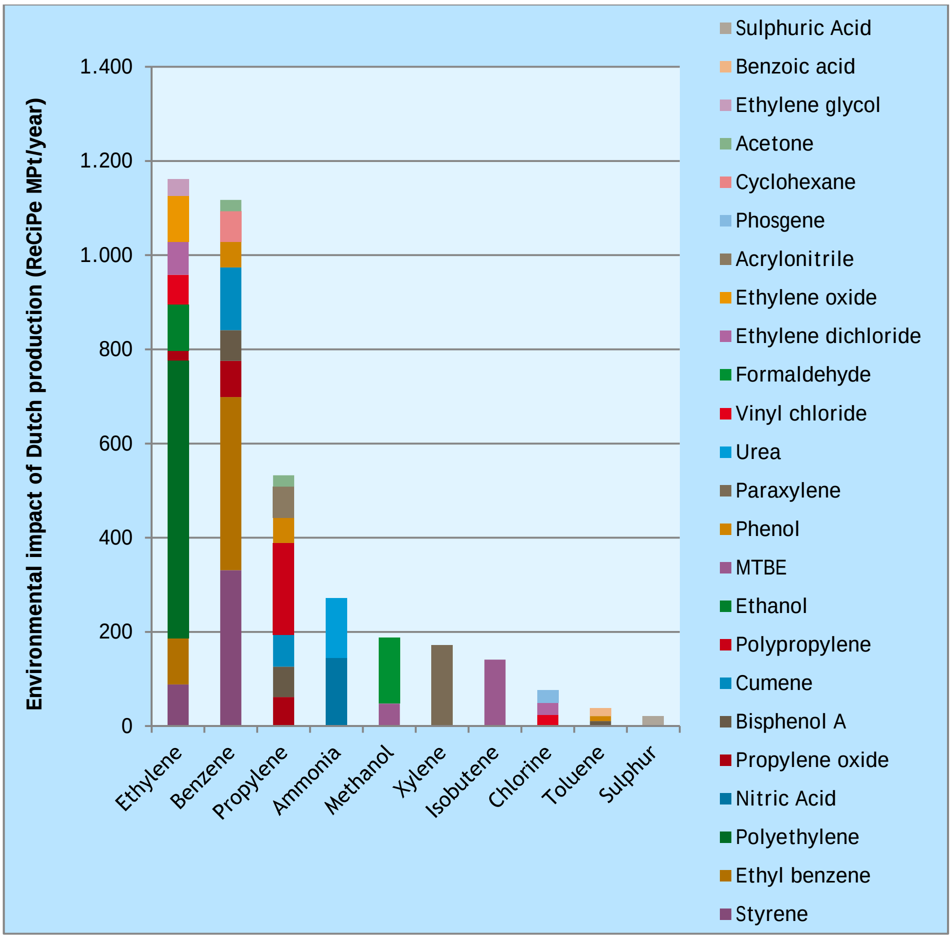
Figure 25 Share of platform chemical production in the impact of the various end products



Note: The impacts of these chemicals are not independent, as 6 products (indicated: ethyl benzene, cumene, phenol, ethylene dichloride, ethylene oxide and acetone) are also feedstocks used in production of other high volume chemicals, and these figures are cradle-to-gate. Impacts are therefore not independent and may not be summed.

As a corollary, Figure 26 shows the share of the total environmental impact of the platform chemical phase attributable to each high volume chemical.

Figure 26 **Share of the impact of each platform chemical attributable to each high volume chemical**



Note: These impacts may not be summed as that would lead to double counting of impacts.

5 Analysis of selected chemical production chains

5.1 Introduction

For more insight into the specific impact of final chemical products, four production chains were selected for a dedicated environmental impact assessment. The aim of this assessment was to provide an indication of the potential impact of the end products not examined during assessment of the high volume chemicals in Chapter 0. By calculating the impact of production of these final products relative to the impact of earlier stages in the supply chain, both within and outside the Dutch chemical sector, an indication is given of the extent to which final production contributes to the overall impact of the sector. For this purpose the production chains of styrene, sulphuric acid, nitric acid and fatty acid derivatives were taken.

Styrene was selected because it is a key intermediate chemical worldwide, but particularly in the Dutch chemical industry, because in this country it is the chemical with the largest production volume. Sulphuric acid was chosen because at 255 Mtpa it is by far the highest volume chemical produced worldwide, although at 0.8 Mtpa Dutch production is relatively modest. Since sulphuric acid has the lowest per-tonne environmental impact of all the high volume chemicals considered, it was interesting to assess whether or not products derived from it have a similarly low impact. Nitric acid is an inorganic chemical that is very important in the fertilizer chain and is also one of the highest volume chemicals produced in the Netherlands. The fourth chain selected for analysis is that of biotic fatty acids and oils used in the production of detergents. Detergents can be derived from either plant oils or petrochemical feedstock, and it was interesting to see how bio-based products perform compared with petrochemical products fulfilling the same function.

For each of these production chains an assessment was made of the contribution of the high volume chemicals in selected final products. In this way the specific impacts of the final products can be added to those of the production chain of the selected high volume chemicals.

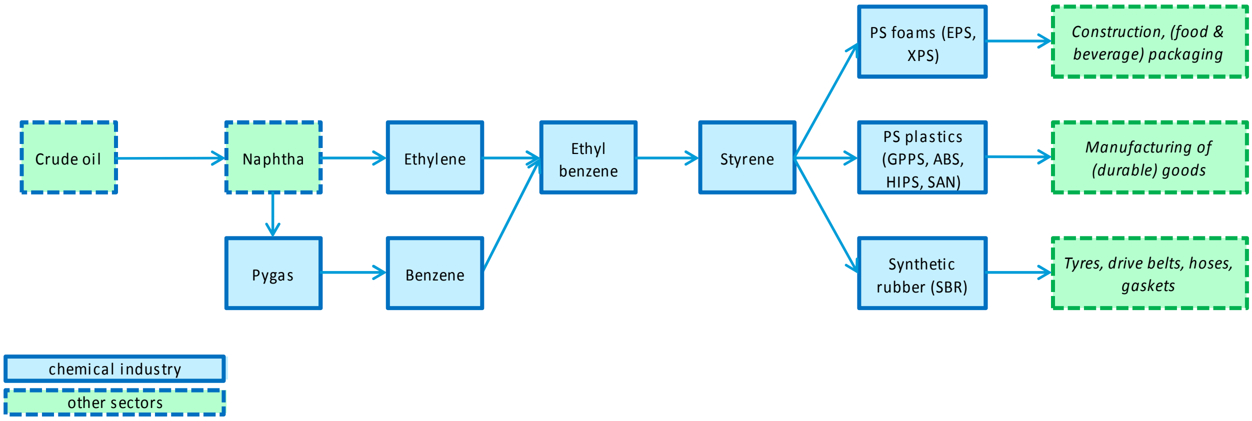
For the purpose of the assessment, the production chain was broken down into four parts: 1) the non-chemical supply chain, 2) the production chain of platform and derivative high volume chemicals within the Dutch chemical sector, 3) the production of final chemical products within the Dutch chemical sector, and 4) the same production of final chemicals, but now outside the Netherlands. In this way a clear picture can be obtained of the environmental impact of the Dutch chemical sector within the respective production chains and the contribution of final chemical production within the Dutch chemical sector.

5.2 Styrene chain

5.2.1 Overview

Styrene is an key intermediate chemical from which a multitude of chemical products are derived. An overview of the styrene chain is given in Figure 27.

Figure 27 The styrene chain



The styrene production chain starts with crude oil being refined to yield a naphtha fraction. This naphtha is cracked, yielding (among other products) ethylene and benzene (via pygas). From these chemicals – considered *platform chemicals* in this study - ethyl benzene is produced, which is then converted to styrene. Styrene is produced at four locations in the Netherlands, by a process using only ethyl benzene as a feedstock (direct dehydrogenation) or, alternatively, ethyl benzene and propylene in a joint process with co-production of propylene oxide. The intermediate styrene is a product that can self-polymerise, but under a protective atmosphere it is traded in the world market. Styrene is polymerised to create a wide range of materials (foams, plastics, resins and rubbers), yielding an even larger range of applications in end products.

5.2.2 Applications of styrene

Styrene is used primarily to make different kinds of foams, plastics and rubbers. In these cases the styrene monomer is polymerised. Polymerisation can also be performed incorporating other feedstocks, yielding a range of substances with various useful properties.

Foams made using polystyrene include *expandable polystyrene* (EPS; Dutch production 210 ktpa) and *extruded polystyrene* (XPS). EPS is used extensively in the building sector as an insulation material as well as a packaging material. There are 12 manufacturers of EPS products in the Netherlands (branch organisation: Stybenix). Among other applications, XPS is used for beverage containers (Styrofoam cups) and as an insulation material.

Plastics using polystyrene include *general purpose polystyrene* (GPPS) and *high-impact polystyrene* (HIPS) (combined Dutch production approx. 180 ktpa), and a number of copolymers with different characteristics: *acrylonitrile-butadiene-styrene* (ABS; Dutch production 163 ktpa) and *styrene-acrilonitrile* (SAN; Dutch production approx. 30 ktpa).

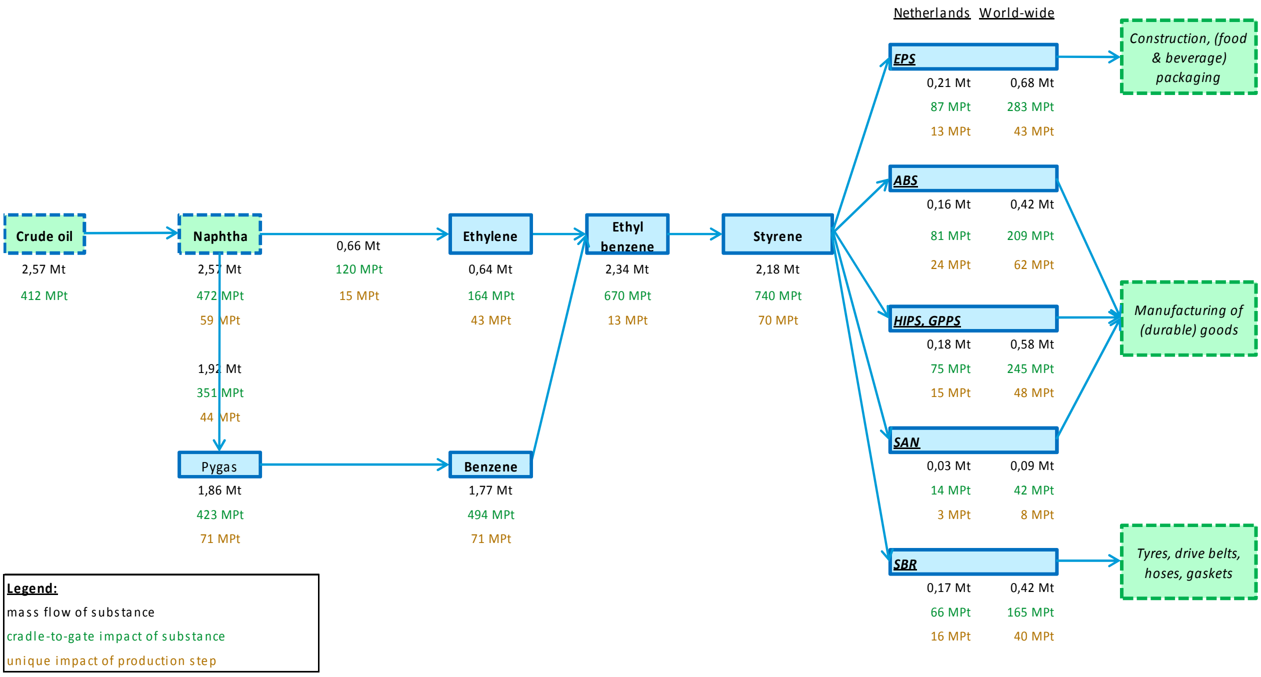
These plastics are used in a vast number of applications in a wide range of goods and products, both short-lived and durable, ranging from flower pots to plastic toys, and CD 'jewel cases' to encasings for electronics. In addition, PS also has a number of applications in films, including PS/PE packaging films.

Synthetic rubbers made from styrene include *styrene-butadiene rubber* (SBR; Dutch production 170 ktpa). This rubber is used in large volumes in tyre manufacture. Rubber makes up some 50% of a typical car tyre by weight, of which around 50% is synthetic rubber. SBR rubber is also used in durable flexible applications like drive belts and gaskets.

5.2.3 Styrene chain analysis

Figure 28 shows the complete mass balance of the styrene chain, with the estimated annual production volume of each step indicated in Mt. For each step the accumulated environmental impact and the 'unique contribution' of the step to that impact is also given for the production volume in question, expressed in MPt (ReCiPe single score).

Figure 28 Styrene chain: styrene-related mass flow and environmental impact per production step



Note: The 'unique impact' of each step reflects the styrene-related impact of that particular step, corrected for feedstock. These figures do not sum to a cradle-to-gate total. Non-styrene feedstocks are not included in the figure.

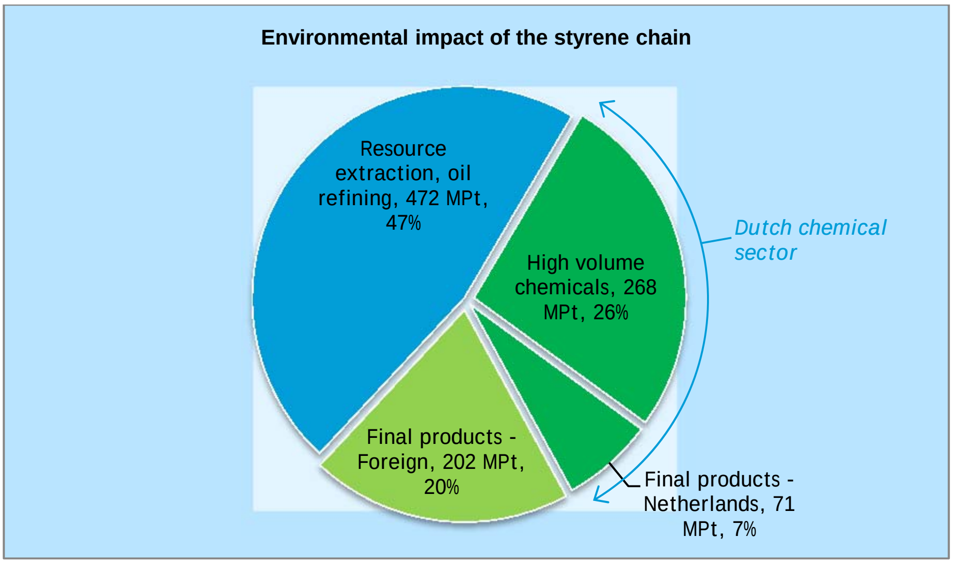
The overall environmental impact of the styrene chain is depicted in the pie chart of Figure 29.

– The blue slice indicates the impacts of the part of the chain *upstream* of the Dutch chemical sector: extraction and processing of natural resources and oil refining. These are activities undertaken both in and outside the Netherlands.

– The two dark green slices indicate the impacts of the activities performed within the chemical industry in the Netherlands: processing of the naphtha from oil refineries to create the platform chemicals, production of derivative high volume chemicals from these platform chemicals, and production of the styrene-derived final products like foams and plastic and rubber products.
– As a significant share of Dutch styrene production goes to the chemical industry in other countries, a light green slice indicates the impacts associated with Dutch styrene used outside the Netherlands for production of chemical final products elsewhere.

In the impacts of the styrene-derived end products, allocation of the styrene part of the impacts of end materials production is on a mass basis.

Figure 29 Environmental impact of styrene chain (in ReCiPe MPt/year; final products allocated to styrene according to mass)



In Figure 30 the same results are presented as a bar chart.

Figure 30 **Impact of styrene chain along sectoral boundaries: resource extraction/oil refining sector and chemical sector per type of product (platform chemicals & derivatives vs. final products, domestic and foreign)**

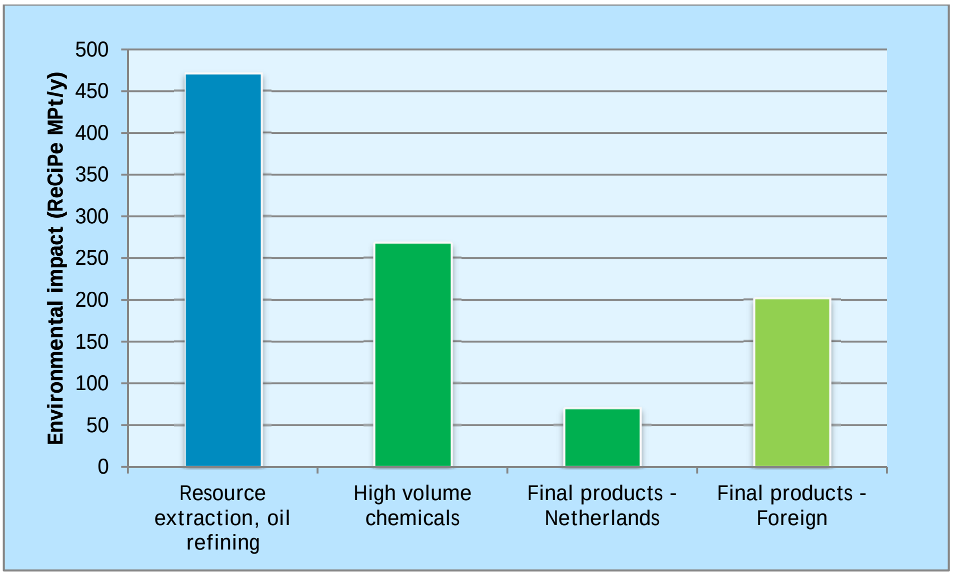
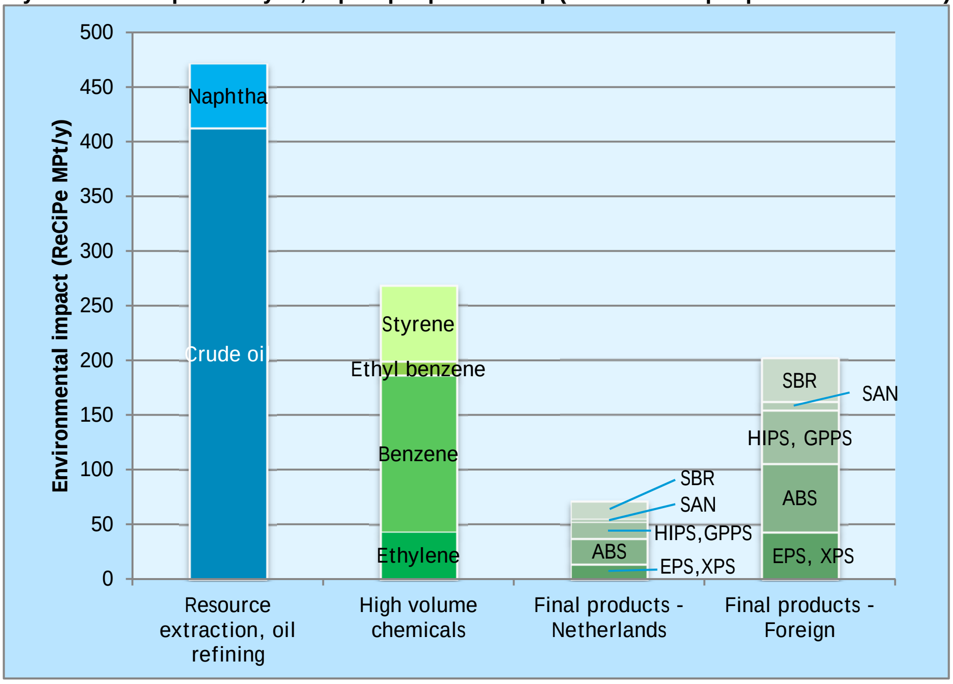


Figure 31 breaks down this overall impact, assigning it to the different substances produced in the styrene production chain according to their production volume. The volume data for the various styrene applications have been estimated based on worldwide production capacities (VNCI, 2011).

Figure 31 **Styrene chain impact analysis, impact per process step (ReCiPe MPt/a per production volumes)**



In the first phase of the chain, resource extraction of oil predominates. The impact of the second phase, production of high volume chemicals, is slightly less than that of the first. In this phase the production of styrene from ethyl benzene from benzene and ethylene is a relative large contributor.

5.2.4 Conclusion

The production of final chemical products from Dutch-produced styrene has a significant environmental impact. However, because the bulk of this production takes place abroad, the contribution of final chemical production in the Netherlands is relatively small. Within the Dutch chemical sector the impact of final production from styrene is about 20%.

Detailed remarks on data processing for the calculation of these results are given in Annex A.2.

5.3 Sulphuric acid chain

With global annual production at 255 Mtpa, in volume terms sulphuric acid is the world's most important chemical by far. Dutch production is relatively minor, however, totalling no more than 0.8 Mtpa. Sulphuric acid is used in a very large number of applications in the chemical industry and other sectors, as a feedstock, reactant and catalyst. In terms of volume, the most important application is fertilizer production. In addition to these numerous chemical processes, sulphuric acid also has important applications in the refinery sector, in leaching processes in the mineral extraction sector and in pulp and paper making (Moulijn *et al*., 2001).

5.3.1 Production

Table 4 lists the main feedstocks for sulphuric acid production. The most important is elementary sulphur, which today is entirely a co-product of crude oil refining. Other sources are sulphur dioxide (SO_2) from the metallurgical industry, where it is generated in roasting and smelting processes involving metal sulphide-containing ores. Here, too, the sulphur feedstock is a by-product. A smaller fraction derives from re-generation of spent and impure sulphuric acid.

In the manufacturing process from elementary sulphur, the sulphur is first burned to create SO_2 (an exothermal process). This SO_2 is then oxidized to form sulphur trioxide (SO_3), which is absorbed in water to yield sulphuric acid (H_2SO_4). These process steps are again exothermal, allowing a significant amount of steam to be generated. The sulphuric acid has a concentration of 96-99%. A concentration of over 100% is possible by dissolving SO_3 in the pure H_2SO_4, yielding oleum.

Table 4 Sources of sulphur for sulphuric acid production

Source	
Elementary sulphur	70%
SO_2 from the metallurgical industry	20%
Spent sulphuric acid catalysts	10%

Source: Davenport and King, 2006.

5.3.2 Applications

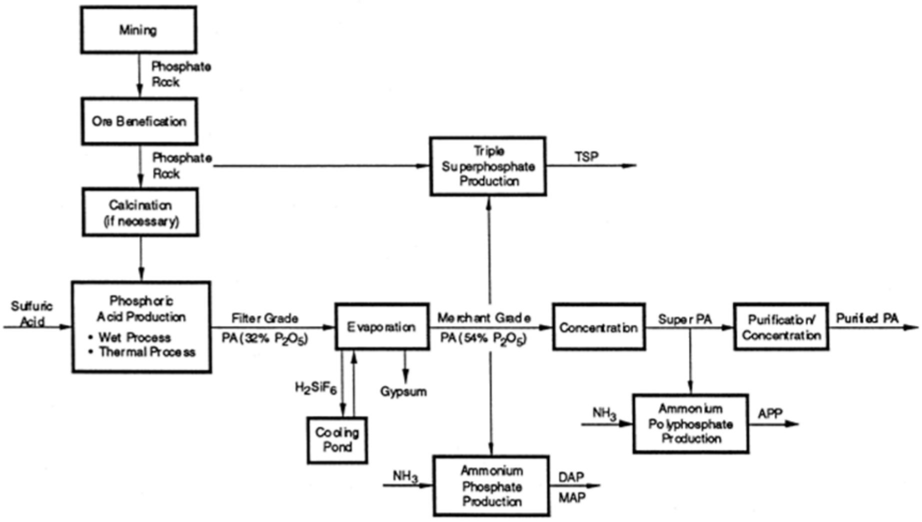
Sulphuric acid is used in a very large number of applications (Wikipedia, 2012; DKL Engineering, 2012; Ecoinvent, 2011). The most important of these, with their approximate share, are as follows:

- production of inorganic fertilizers, largely phosphor-based (60%):
  - single superphosphate;
  - via phosphoric acid to triple superphosphate, ammonium phosphate and ammonium sulphates.
- a range of other processes in the chemical industry (20%):
  - titanium oxide production (sulphate process, 2.5%, not in the Netherlands, NL);
  - hydrofluoric acid production (0.6%);
  - yellowcake (uranium concentrate) production (0.7%, not in NL);
  - chlorine drying (0.7%);
  - pulp en paper industries: aluminium sulphate (alum) production;
  - detergents production, e.g. linear alkylbenzene sulphonate;
  - concentration of nitric acid;
  - explosives (oleum).
- alkylation at petroleum refineries (high-octane motor fuel from lower olefins and i-butane) (10%, not in NL).
- metallurgical and steel industry (10%):
  - leaching processes for copper, nickel and uranium ores (copper: 3 Mtpa -20% of world copper production - is produced using the sulphuric acid leaching processes (Dreier, 1999; Index Mundi, 2009));
  - iron/steel pickling.
- electrolytes for batteries.

5.3.3 Chain analysis

The production of phosphate fertilizers is the single most important application of sulphuric acid, with synthesis of phosphoric acid from phosphate rock constituting a pivotal process in the P-fertilizer chain (Figure 32). In wet-process phosphoric acid production, sulphuric acid is reacted with phosphate rock to form phosphoric acid and gypsum. The production of single superphosphate (SSP) is not shown in the figure, but the process is similar.

Figure 32 Phosphoric acid (PA) production route yielding different fertilizer grades and phosphates



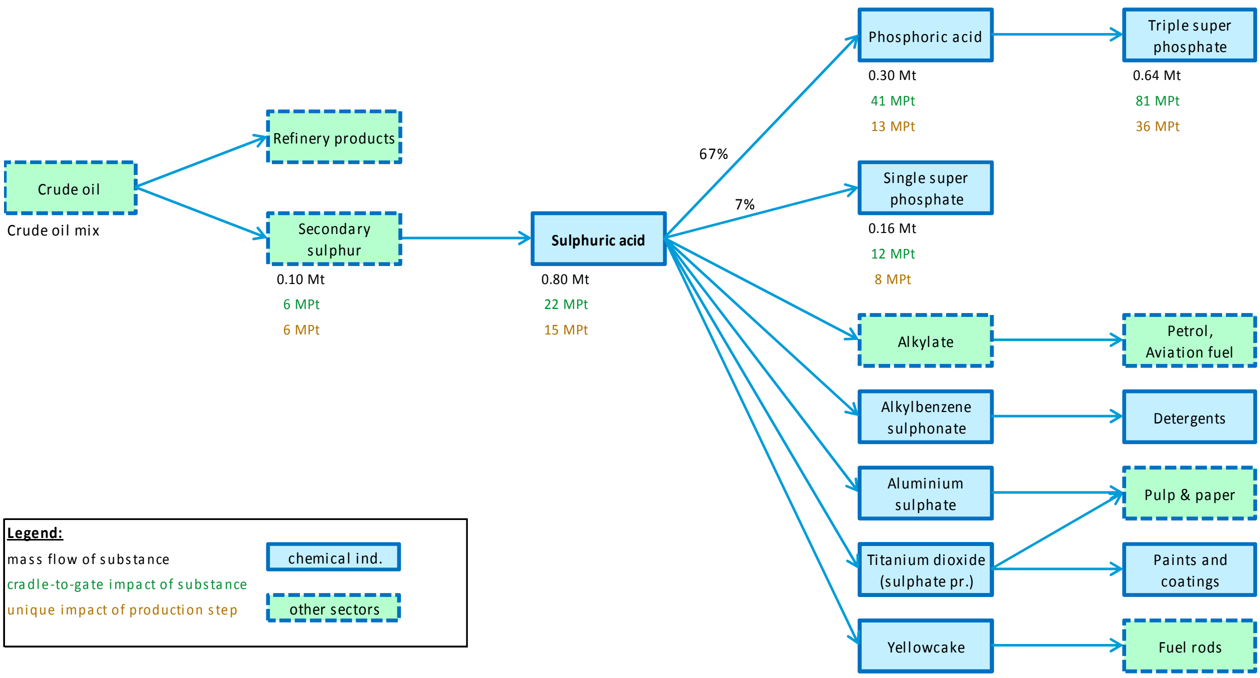
Source: EPA (1993).

Around 70% of the sulphuric acid produced the Netherlands is used in P-fertilizer production and for this reason we have limited the scope of the chain analysis to fertilizers. Dutch manufacturers produce a range of P- and mixed fertilizers, but for this analysis we focus on the pure P-fertilizers (SSP and TSP). It is not anticipated that this will lead to a significant underestimation of impacts.

The chain overview with the resulting mass flows are shown in Figure 33. For each step the estimated annual production volume is indicated in Mt. Also the accumulated environmental impact and the 'unique contribution' of each step to the accumulated environmental impact is given for that production volume, expressed in MPt (ReCiPe single score). Total P-fertilizer production in Netherlands is 0.8 Mt/y; we assumed a 20%/80% split between SSP and TSP, with the larger share attributed to TSP to reflect the relative importance of fertilizers derived via phosphoric acid (PA). TSP was used as a proxy for other PA-derived fertilizers. Total Dutch production of sulphuric acid is 0.8 Mtpa, over 70% of which is used in P-fertilizers manufacturing.

For detailed remarks on data processing for the calculation of these results, see Annex A.2.

Figure 33 Sulphuric acid chain: mass flow and environmental impact per production step



Note: The 'unique impact' of each step reflects the sulphuric acid-related impact of that particular step, corrected for feedstock. These figures do not sum to a cradle-to-gate total. Non-sulphuric acid feedstocks are not included in the figure. Mass flows for secondary sulphur and PA are indicated at the level used in the chain analysis and do not reflect total production figures.

Combining the impacts and classifying the SSP and TSP as final products yields the picture shown in Figure 34 and Figure 35. As can be seen, the high volume chemical production phase, to which the production of phosphoric acid is also allocated, and the upstream part of the chain (oil refining) have lower impacts than the latter part of the chain, the steps towards final products. Figure 33 shows the impacts attributable to the chemical sector. For P-fertilizers, the environmental impact of the high volume chemical production phase represents only a minor part of the overall impact.

Figure 36 provides a breakdown of the environmental impact according to the unique impacts of each step in the chain. As can be seen, the relatively large impact of final production is due mainly to TSP.

Figure 34 **Environmental impact of sulphuric acid - fertilizer chain (in ReCiPe MPt/year; final products allocated according to mass)**

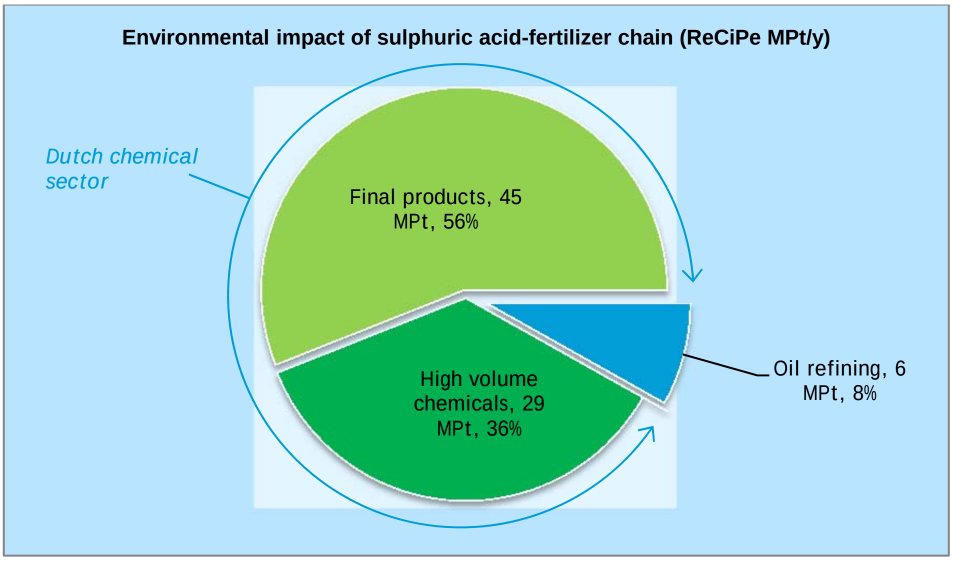


Figure 35 **Impact of sulphuric acid - fertilizer chain along sectoral boundaries: oil refining sector and chemical sector per type of product (platform chemicals & derivatives vs. final products)**

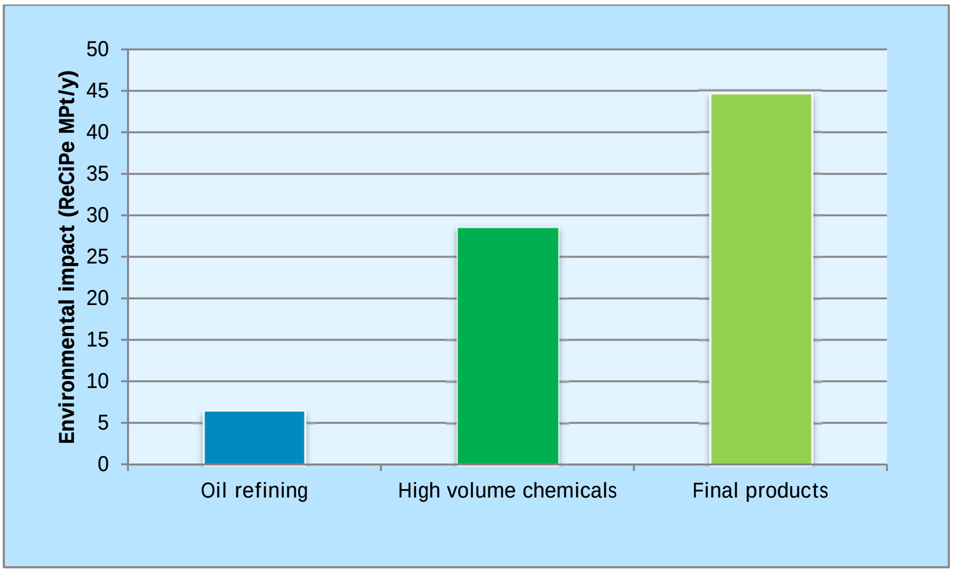
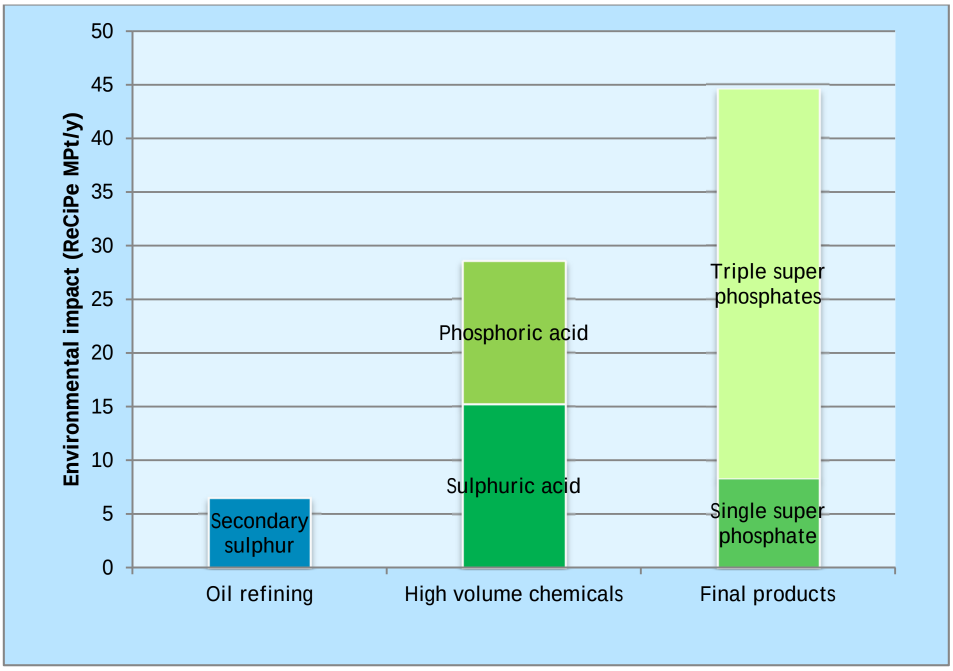


Figure 36 **Substances included in the sulphuric acid - fertilizer chain impact analysis (ReCiPe MPt/a per production volume, unique impacts of steps)**



In this production chain, the supply chain outside the chemical industry has a surprisingly low impact. This is due to the fact that this involves secondary sulphur, derived as a by-product in the oil refining process. As oil refining produces numerous products of high economic value, allocation of impacts to this sulphur is low.

Sulphuric acid production from elementary sulphur is also a relatively easy and energy-extensive process. In contrast, the production of final product Triple Super Phosphate (TSP) is very energy-intensive. Another reason why TSP production has a disproportionate impact is the relatively high contribution of the transport processes associated with import of phosphate ores. Transportation generally makes a 5-10% contribution to the overall environmental impact of a production process. For this particular stage, though, it is over 35%. However, over the production chain as a whole, transport is still close to 10% of the total impact.

5.3.4 Conclusion

In the sulphuric acid to fertilizer chain, final products contribute 56% to the total environmental impact of the production chain. This relatively large share is due to three circumstances:

- the high volume (intermediate) production phase is of low environmental impact (not energy-intensive);
- the final production phase to TSP is energy-intensive;
- transport impacts are relatively large.

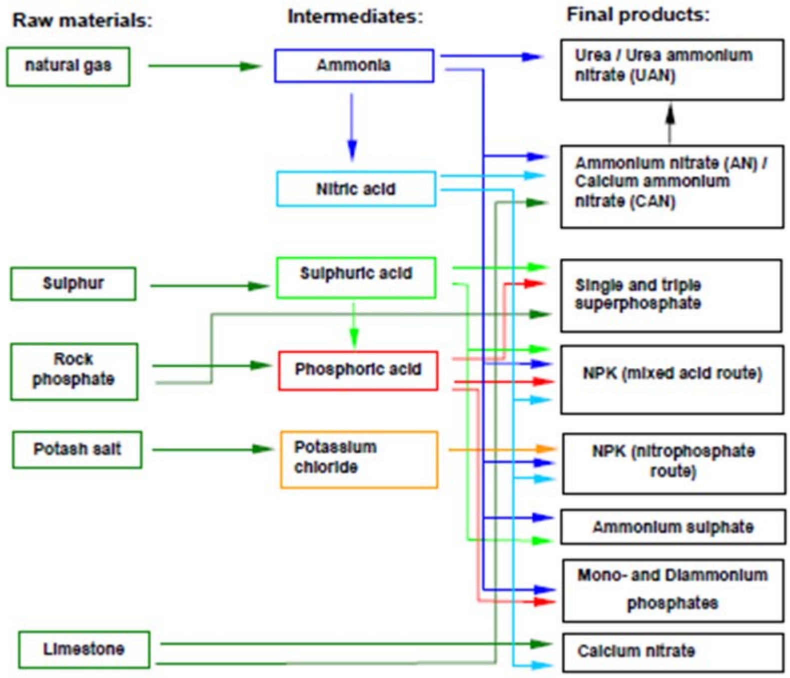
Furthermore, with annual production figures of 0.3 Mtpa for phosphoric acid and 0.8 Mtpa for P-fertilizers, these should really be considered high volume chemicals.

This example shows that in some cases the impact of the end-product production step can be quite high and indeed exceed that of the previous steps. Since sulphuric acid scores low in terms of both Dutch production and impact per tonne, however, the additional impact of the final products is still limited, in the light of the overall Dutch chemical sector, too.

5.4 Nitric acid chain

Nitric acid is an inorganic chemical that plays a central role in the production chain of many types of fertilizer, as illustrated in Figure 37. Key for the Netherlands are ammonium nitrate, calcium ammonium nitrate and urea-ammonium nitrate fertilizers, which are produced at four locations.

Figure 37 Key chemicals in the production routes of various mineral fertilizers



Source: Nemecek *et al.*, 2007

5.4.1 Production

Nitric acid production is a three-stage process. First, ammonia is catalytically burned to yield a wet gas mixture of nitric oxide. This is then further oxidized by adding air at low pressure, and then compressed and absorbed in water to yield nitric acid. The ammonia is produced from nitrogen-containing syngas from a wide range of sources, although natural gas is most commonly used.

5.4.2 Applications

Around 5 million tonnes of nitrogenous fertilizers are produced in the Netherlands each year, a far larger amount than in the case of the P-fertilizers discussed above in the analysis of the sulphuric acid-fertilizer chain.

Besides the many applications in N-fertilizer production, nitric acid is also used in numerous other industrial processes. Important among these are nitration processes, used for example to produce nitrobenzene from benzene and nitric acid. (Nitrobenzene is a precursor of aniline, a feedstock for isocyanates and aramid fibres, both of which are relevant in the Dutch chemical industry; aniline is not produced in the Netherlands, however.) Nitric acid is also used in relatively minor quantities in uranium enrichment, metals processing (chromium steel rolling), anodization of aluminium, herbicide and fungicide production (approx. 1-5 ktpa for the Netherlands) and explosives production.

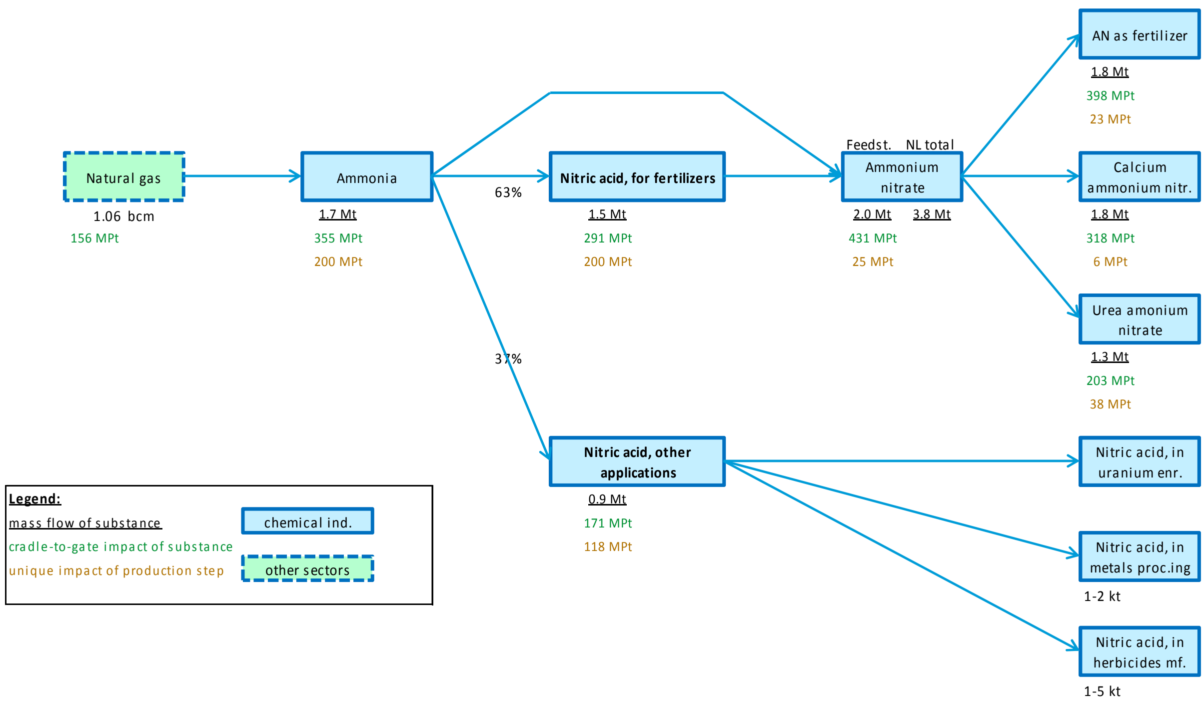
5.4.3 Chain analysis

Because fertilizer production is the predominant use of nitric acid, we limit the scope of our chain analysis to N-fertilizers.

An mentioned, the main products of the Dutch N-fertilizer industry are ammonium nitrate (AN), calcium ammonium nitrate (CAN) and urea-derived fertilizers like urea ammonium nitrate (UAN). In assessing the environmental impact we treat all N-fertilizers as belonging to these categories, a simplification that will still yield an accurate picture of the relative impacts of N-fertilizer production. Dutch manufacturers also supply mixed, NP-fertilizers, i.e. fertilizers containing both nitrogen-based and phosphorus-based nutrients. The impacts of the phosphorus fertilizers have already been analysed in the chain analysis of sulphuric acid, and combining those results with those of the present chain analysis will yield an accurate picture for those products supplied by Dutch manufacturers that is not an underestimate.

The nitric acid production chain is shown in Figure 38, with the estimated annual production volume of each step indicated in Mt. Again, the accumulated environmental impact and 'unique contribution' of each step to that impact is shown for the production volume concerned, expressed in MPt (ReCiPe single score). In the chain analysis we proceeded from the total production capacity of nitric acid, dividing this into nitric acid for fertilizers and for other applications. Furthermore, AN is used both directly in fertilizer applications and in CAN and UAN applications. Additional information on the data processing for this analysis is provided in Annex A.2.

Figure 38 Nitric acid chain: mass flow and environmental impact per production step



Note: The 'unique impact' of each step reflects the nitric acid-related impact of that particular step, corrected for feedstock. These figures do not sum to a cradle-to-gate total. Non-nitric acid feedstocks are not included in the figure.

From Figure 38 we see that ammonia production and nitric acid production are both important steps with significant environmental impacts. Those associated with ammonia production derive from energy-intensive process steps, while with nitric acid production it is largely N_2O and NO_x emissions that are reflected in the ReCiPe score. By contrast, the impact of the steps towards final products is relatively limited; these reactions are exothermic, generating significant amounts of heat.

Two remarks are in order concerning the environmental impacts expressed in the ReCiPe scores.
- In the score for nitric acid, 57% is due to N_2O emissions. In the data source used, the Ecoinvent LCI, these are cited as 8.39 kg per tonne of nitric acid, reflecting average European production. However, according to one manufacturer these emissions have meanwhile been considerably reduced. IPCC (IPCC, 2000, p.3.35) indicates that this value may be a factor of around four too high for plants equipped with non-selective catalytic reduction (NSCR) technology.
- Although the Ecoinvent LCI inventory notes the generation of waste heat, it does not explicitly incorporate steam generation using this heat. If heat is economically applied for steam generation, which is the case in the large integrated fertilizer plants where nitric acid as well as ammonium nitrates are produced, one could envision even lower or negative environmental impacts of the final production steps.

The impacts of the various links in the chain shown in Figure 38 are depicted more simply in Figure 39, Figure 40 and
Figure 41. In these figures we see that the bulk of the impacts are associated with the high volume chemicals, while the contribution of the final products produced in the chemical sector is limited. The contribution of the energy sector is also considerable (20% of the total), but nevertheless limited.

Figure 39 Environmental impact of nitric acid - fertilizer chain (expressed in ReCiPe MPts/year; final products allocated according to mass)

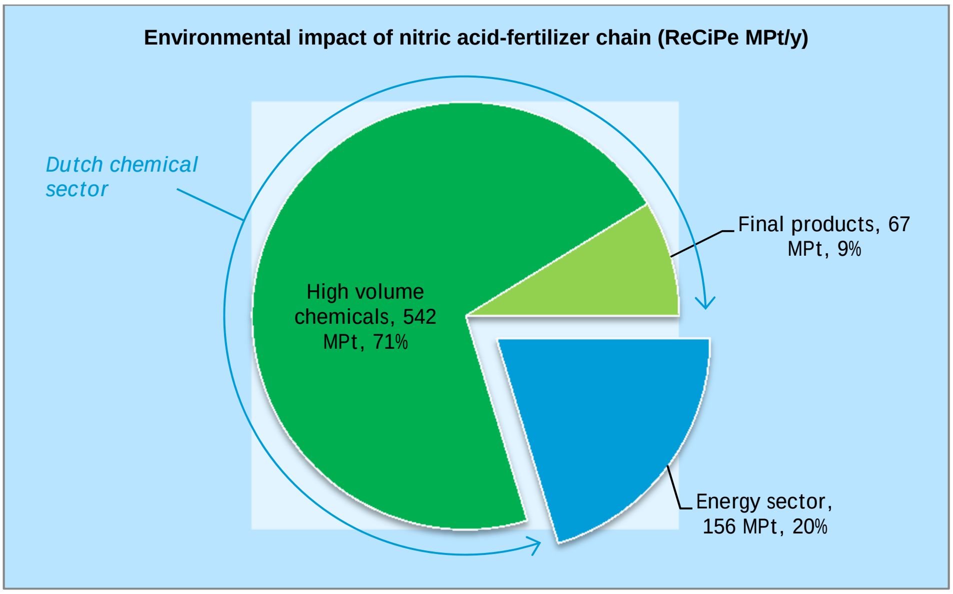


Figure 40 **Impact of nitric acid - fertilizer chain along sectoral boundaries: energy sector and chemical sector per type of product (platform chemicals & derivatives vs. final products)**

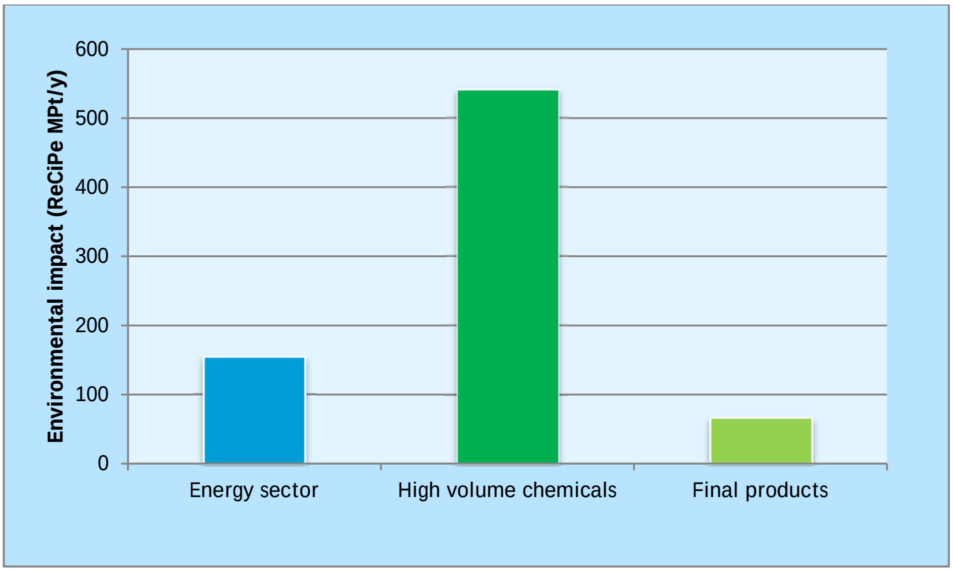
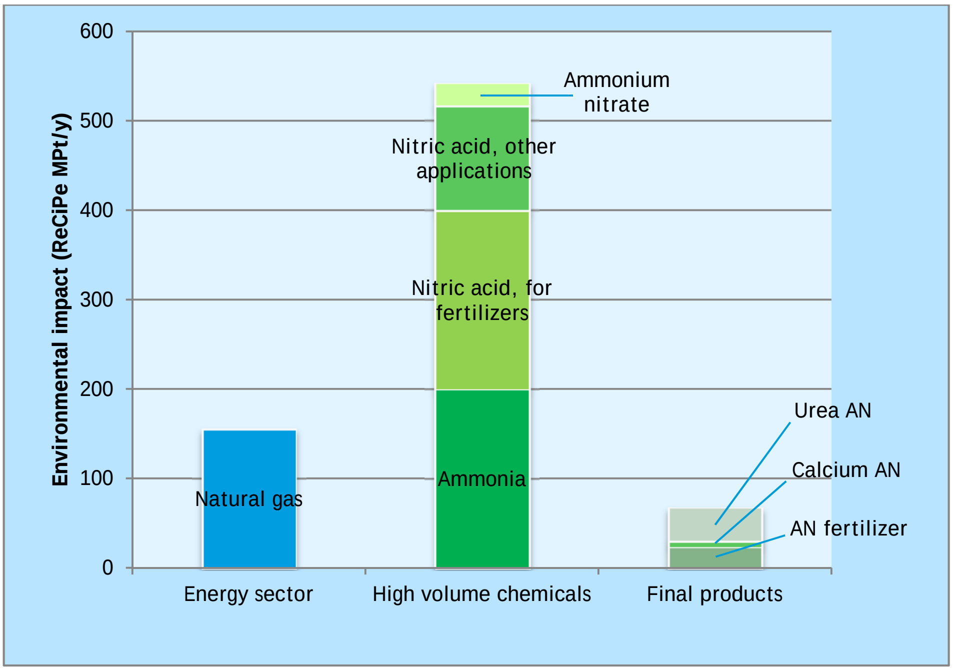


Figure 41 **Substances incorporated in nitric acid - fertilizer chain impact analysis (ReCiPe MPt/a per production volume, unique impacts of steps)**



In this production chain it is clearly high volume chemicals (ammonia and nitric acid) that are the main contributors to the overall environmental impact. The impacts associated with the upstream supply chain are not low, but are still overshadowed by the high impact of the high volume chemicals. Production of the final products, nitrogen fertilizers, contributes least to the chain impacts. The impact of these final steps is particularly low in comparison with final production of phosphate fertilizers (cf. Section 5.3).

5.4.4 Conclusion

In the nitrate fertilizer chain, final production is responsible for only 9% of the overall environmental impact of the production chain, or 11% of the chemical part of the chain. This is due to the substantial impact of the high volume chemical production phase. The nitric acid chain contributes significantly to the aggregate impact of the Dutch chemical sector.

5.5 Fatty acids product chains: from bio-oils to detergents

The fourth production chain analysis is concerned with the application of biotic fatty acids and oils in detergents. Detergents are composed of tensides, builders, bleaches and auxiliaries, and the analysis focuses on the tensides, the surface-active compounds (surfactants). These are molecules that have a polar and non-polar component and can thus interface between fat and water and achieve a washing effect. They can be derived from either plant oils or petrochemical feedstocks.

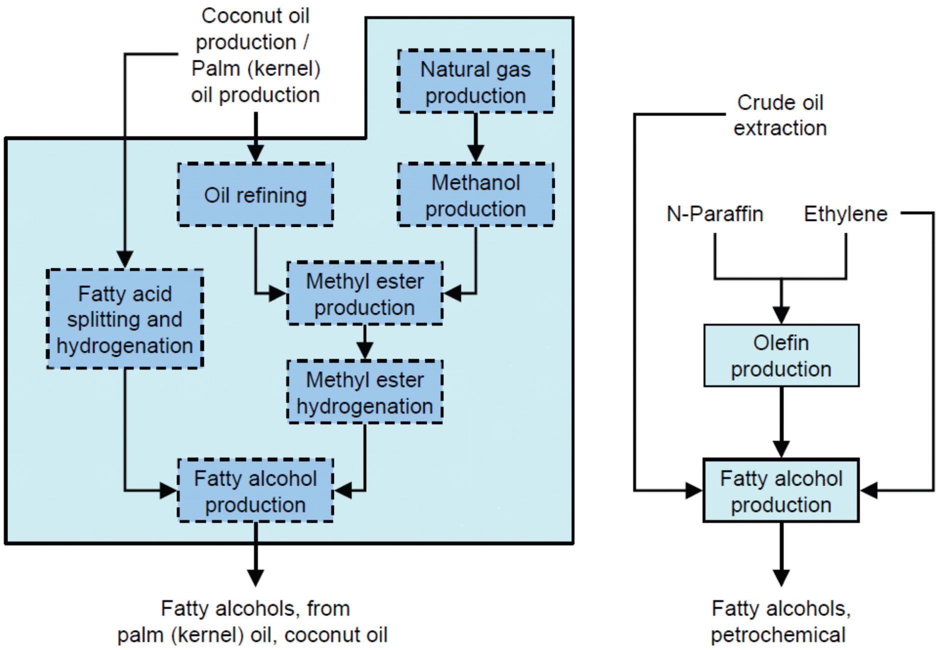
There are numerous bio-oils, including soybean, palm, palm kernel, coconut, sunflower, rapeseed and olive oil, each with a different typical distribution of carbon chain lengths in the molecule. De-esterification is applied to yield a wide range of fatty acids; each kind of plant oil has a typical distribution of fatty acids that can be used in different derived products. For the surfactants used in detergents, coconut, palm kernel and palm oil are important.

- In both coconut oil and palm kernel oil, a major constituent fatty acid is lauric acid (chain length C_{12}), constituting up to 48% by mass of these oils (Combs, 1985). Lauric acid is used to manufacture surfactants such as sodium laureth sulphate (SLES), sodium lauryl sulphate (SLS) and ammonium lauryl sulphate (ALS): fatty alcohol sulphates that are important, very commonly used ingredients in shampoos, conditioners and cosmetic lotions.
- One of the major constituent fatty acids in palm oil is saturated palmitic acid (chain length C_{16}), constituting up to 44% by mass (Wikipedia). Palm oil is used in surfactants and is an important ingredient in (natural) soap production. Palm oil is regarded as the bio-oil with the highest per-acre oil yield: 5 tonnes per acre per year (FAO, 2002) and it is consequently also widely used as a fuel (biodiesel) and in foodstuffs and for cooking. Palmitate, the tri-ester of palmitic acid, is also used as an emollient in cosmetic lotions and creams.

5.5.1 Production

Production of soap from plant oils is carried out by hydrolysis of the fat triglycerides using caustic soda, yielding a mixture of sodium salts of fatty acids and glycerine, which is separated off. Soap produced in this way is not as important as it was historically, owing to the rise in use of synthetic surfactants, which are specifically tailored combinations of fatty acids that are processed into fatty alcohols and then to surfactants. These synthetic detergents can be derived from either biotic or fossil feedstocks. Figure 42 depicts the oleochemical and petrochemical production pathways for fatty alcohols that can be applied in surfactant production.

Figure 42 Biotic and fossil routes for fatty alcohol production



Source: Zah and Hischier, 2007.

In the chain analysis of the plant oils - surfactants chain, we focus on the groups of soaps, fatty alcohol sulphates and alcohol ethoxylates, key surfactants used in detergents.

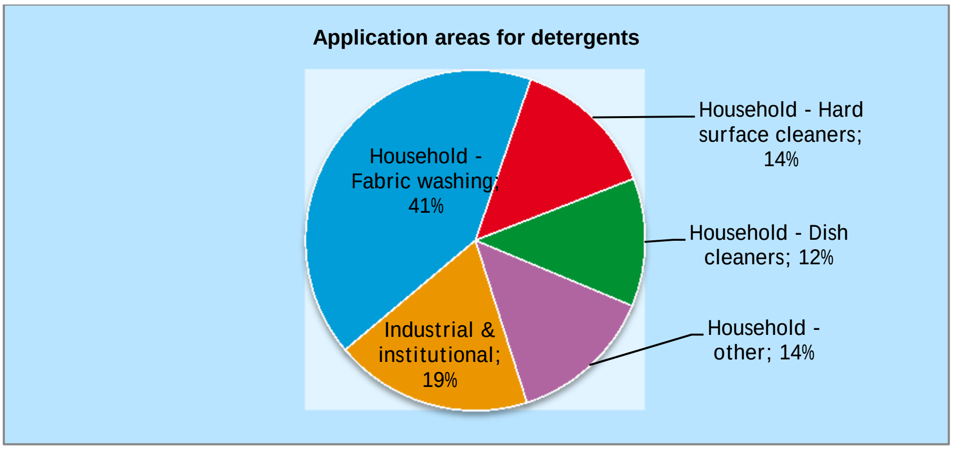
- fatty alcohol sulphates are a group of anionic surfactants incorporating SLES, SLS and ALS, and are produced from fatty alcohols that are sulphonated;
- alcohol ethoxylates are a range of large molecules of varying structures that can effectively surround fat and soil impurities.

Surfactants produced from palm kernel and coconut oil (acid carbon chain length C_{12}-C_{15}) are effective at low temperatures, while those produced from longer carbon chain acids (palm oil) are more effective at higher temperature.

5.5.2 Applications

Soaps and detergents are used by households for clothes washing, house cleaning and dish cleaning, and in cosmetics and toiletries. In addition, detergents are used in numerous applications in institutions and industry. The following figure shows the market sizes of the various application areas in the EU-27, based on information from the International Association for Soaps, Detergents and Maintenance Products (A.I.S.E., 2011).

Figure 43 **Application areas for detergents based on market size. The total for the EU-27 + Switzerland and Norway for 2010 is 35 bln. € (adapted from A.I.S.E.)**



For the chain analysis of specifically the surfactants, as we have no data on Dutch production capacities we estimated the total Dutch detergent market and the relative share of surfactants in it, and based our analysis on this volume of chemicals. In the Netherlands 150 ktpa of detergents are used by households in textile washing applications (MilieuCentraal, 2012). This equates to 10 kg/person per year. Based on this figure and the cited A.I.S.E. data we estimate the minimum size of the Dutch detergent market at 360 ktpa. The total European market for detergents is around 6 Mtpa (RPA, 2006)[7].

To estimate the size of the surfactants market, we based ourselves on information derived from a selection of product safety data sheets for a variety of detergents from several manufacturers (Table 5).

Table 5 **Composition of detergents**

	% Anionic surfactants	% Non-ionic surfactants
Fabric washing	13%	6%
Hard surface cleaners	-	5%
Dish cleaners	7%	8%
Weighted average	**11%**	**6%**

This leads to an estimate of the Dutch market for anionic surfactants of 40 ktpa and for non-ionic surfactants of 22 ktpa. The implications of these data are assessed in the next section.

5.5.3 Chain analysis

Surfactants are complex molecules with a molecular structure specifically tailored to the application in which they are used. The Ecoinvent LCI provides the following processes for aggregate groups of non-ionic and anionic surfactants:

– fatty Alcohol Sulphates (FAS) (anionic);
– linear Alkylbenzene Sulphonates (LAS) (anionic);
– alcohol Ethoxylates (AE) (non-ionic);
– soap (anionic).

7 The derived figure for the Netherlands is in line with the magnitude of the Dutch economy relative to the EU-27.

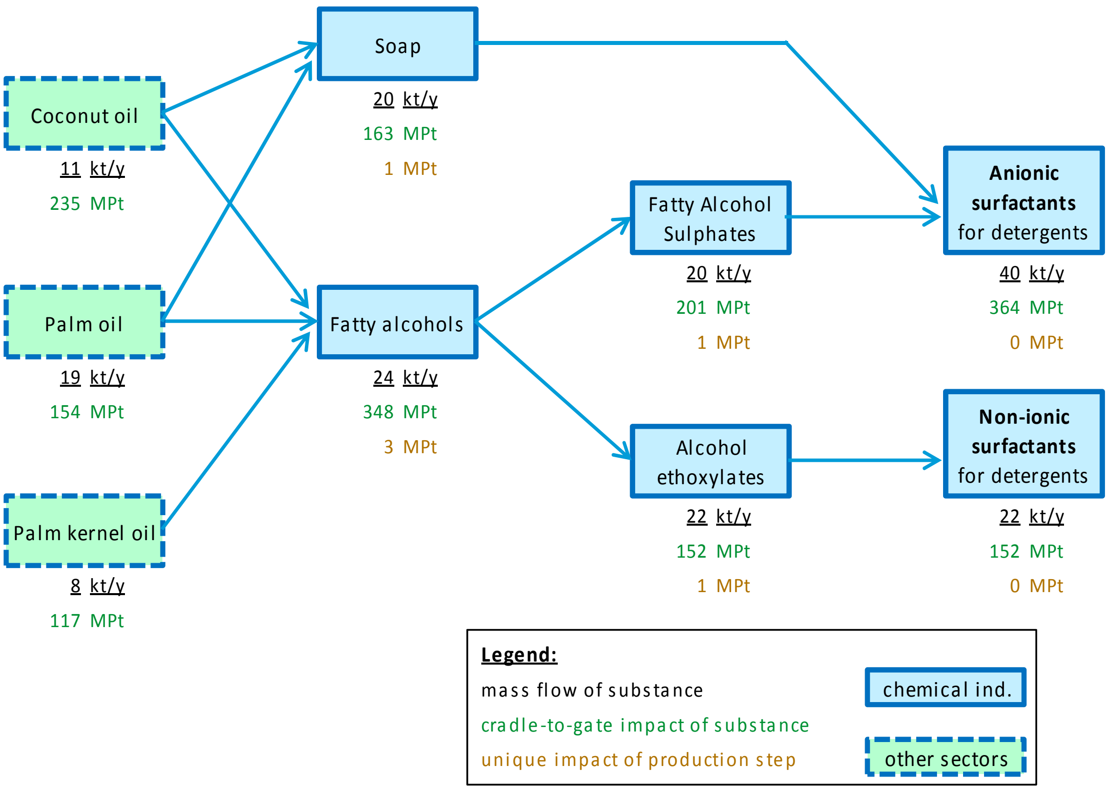
Of these, LAS are of petrochemical origin, soap is largely oleochemical, while FAS and AE may be either oleochemical or petrochemical.

There are no publicly available data on Dutch surfactant production capacity, but Patel (1999) provides German production figures and from these it can be derived that around 60% of surfactant production is from biotic feedstocks. Within the group of anionic surfactants, soap makes up 34%, petrochemical-derived surfactants (e.g. LAS) 37% and oleochemical synthetic surfactants (e.g. FAS) 29%. Within the group of non-ionic surfactants, AE comprises up to 90% of the total.

To assess the plant oil-surfactants chain, we assume that all surfactants are made from oleochemical feedstock and then assess the impacts. Pragmatically adapting the Patel figures for the chain analysis, we assume that the non-ionics can be represented fully by AE, and the anionics by 50% soap and 50% FAS. So as not to ignore the petrochemical feedstock, we also calculate the impacts of a petrochemical surfactant and use these figures for comparison.

The steps in the biotic oil – surfactant production chain are shown in Figure 44, with the cradle-to-gate impacts of each step indicated for the production volume involved as well as the accumulated impact.

Figure 44 Biotic oil - surfactant chain: mass flow and environmental impact per production step



Note: The 'unique impact' of each step reflects the impact of that particular step, corrected for feedstock. These figures do not sum to a cradle-to-gate total. Non-fatty acid feedstocks are not included in the figure.

As can be seen, the unique impact of the production steps in the chemical sector (indicated in light blue) are minimal compared with the impacts in the plant oil production and refining sectors. The results are summarised in chart form in Figure 45, Figure 46 and Figure 47.

Figure 45 Environmental impact of fatty acids chain (plant oils to detergents) (in ReCiPe MPts/year)

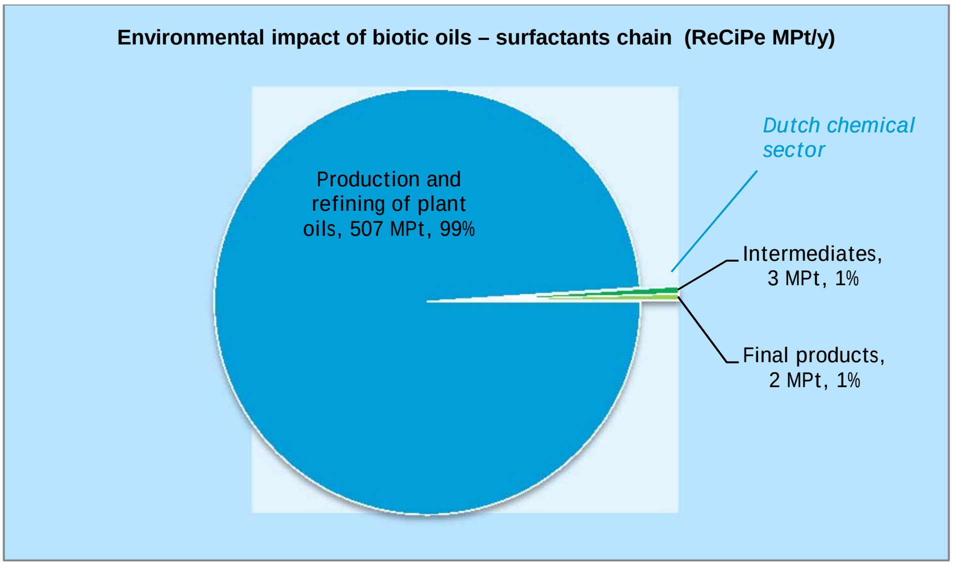
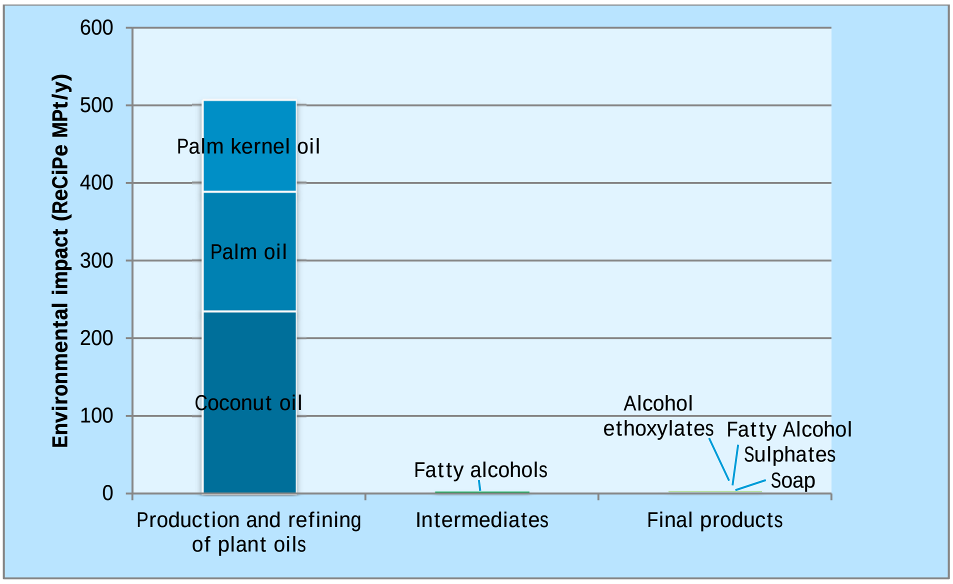


Figure 46 Chain impact per sector/product type, with share of product indicated

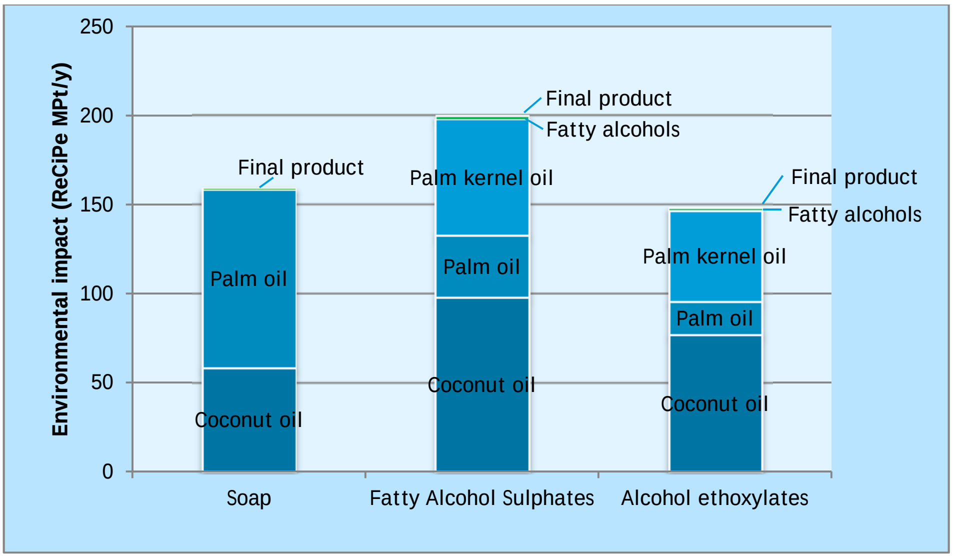


As is immediately apparent from these two figures, in the case of surfactants the production steps in the chemical sector have an extremely small impact compared with that of the upstream supply chain outside the sector.

Figure 47 shows the impacts of the analysed final products: soaps, fatty alcohol sulphates and alcohol ethoxylates. Allocation of the feedstock to the final products is on a mass basis. The final products reflect product groups that should be taken as aggregates for a very large number of specific final products with specific molecular formulae used by manufacturers. In the case of FAS and AE, for the composition of the aggregates we lacked precise data

on the shares of the different specific feedstocks (palm, palm kernel, coconut) and therefore assumed equal percentages for each, following the Ecoinvent approach (see also Annex A.2).
It is important to note that a combination of data sources (including secondary data) was used in this assessment, so the presented range of plant oil feedstocks should not be taken to reflect the actual amounts used in the Dutch chemical industry.

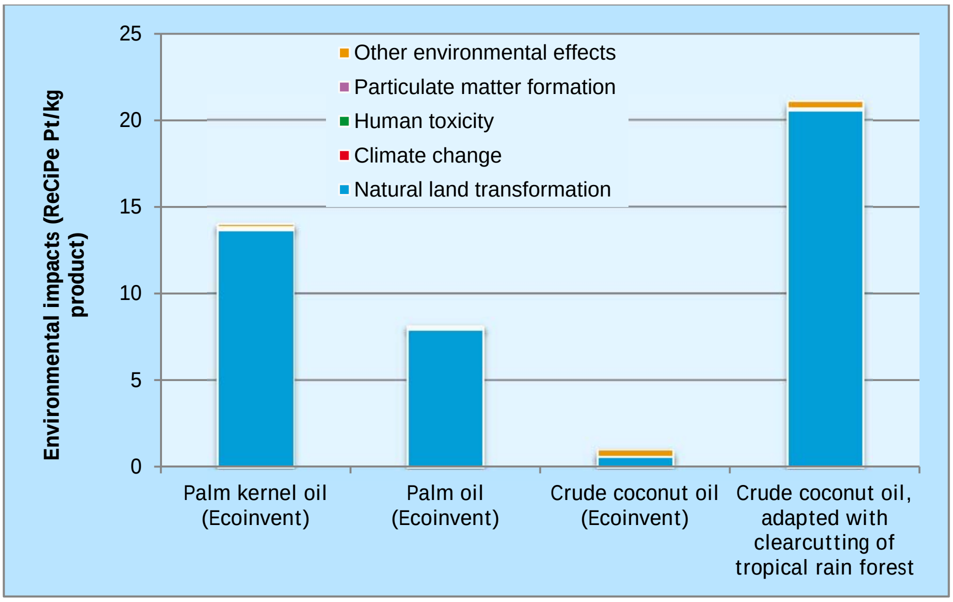
Figure 47 Chain impact per final product



As can be seen in Figure 48, showing impact scores for the environmental effects of the various oils, the high impact of tropical plant oils production is due almost entirely to the transformation of natural land for palm and coconut plantations, causing major biodiversity losses and releasing carbon and pollutants into the atmosphere. The clear-cutting of tropical rainforests for oil plantations is particularly damaging in these respects.

Internationally, there is attention for this issue. Since 2004 the Roundtable on Sustainable Palm Oil (RSPO) has been certifying palm oil producers on a number of sustainability criteria, including the prevention of clear-cutting.
A growing number of importers in the EU are switching to RSPO-certified palm oil.

Figure 48 **Environmental impacts of different tropical oils**



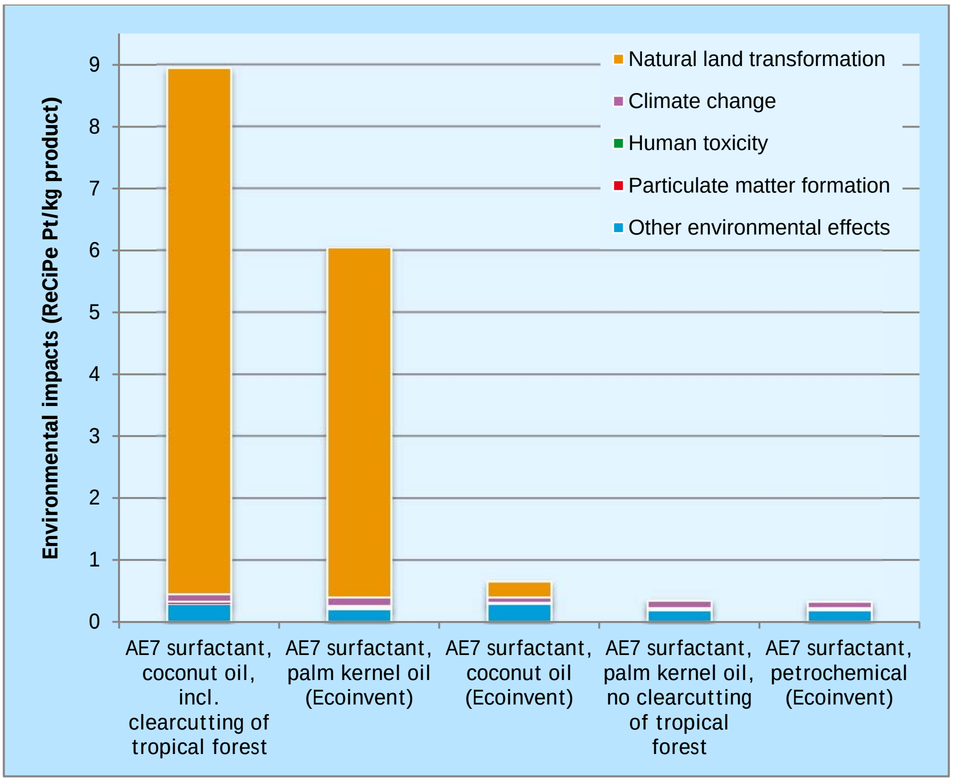
To more accurately assess the effects of clear-cutting, the Ecoinvent inventory for palm oil and palm kernel oil has been updated in Ecoinvent v.2 using information from FAO (FAOSTAT, 2006, in Zah and Hischier, 2007). However, this has not been done for coconut oil production, for which the inventory is still based on early 1990s data from the Philippines, with a lower assessment of clear-cutting[8]. As coconut plantations are also established in tropical rainforest areas, for this study the Ecoinvent process for coconuts was adapted to include clear-cutting in the same manner as done by Ecoinvent for palm and palm kernel oil.

The effects of sustainable (e.g. RSPO-certified) plantations have not been assessed quantitatively. As yet, the global market for uncertified palm oil is far larger (WWF, 2011), so such an exercise is indeed difficult. We can, however, give an indication of the effect of sustainable plantations by adapting the processes to remove the effect of clear-cutting, providing an idea of the range of feasible outcomes. Also, given the land transformation issues associated with plant oils, it is relevant to assess how petrochemical feedstock compare.

For the alcohol ethoxylate surfactant AE7 (i.e. AE with ethylene oxide chain length 7) the results of this analysis are reported in Figure 49 below, showing the environmental impacts per kg surfactant for the various alternative feedstocks relevant for AE7: petrochemical, coconut and palm kernel. For the two biotic feedstocks the effects of tropical clear-cutting are indicated. For coconut oil, an adapted process was created that includes clear-cutting of primary forest (this is also the coconut oil process used in the analysis in this chapter). For palm kernel oil, in the adapted process this clear-cutting is removed, to mimic the possible impact of sustainably produced oil.

8 See remark in Annex A.2.

Figure 49 **Comparison of feedstock effects for alcohol ethoxylate (AE) surfactants**



Note: Annex A.2 contains the same graph with ReCiPe 'World normalization' (as opposed to 'European normalization') .

As can be seen, if clear-cutting is avoided, e.g. through responsible plantation certification systems, environmental impacts are very substantially reduced, by at least 90%, compared with the present situation. It is also clear, furthermore, that petrochemically derived surfactants have far lower impacts on ecosystems than palm (kernel) oil and coconut oil if the plantations involve clear-cutting of tropical forest. Petrochemically derived surfactants score about the same as sustainable biofeedstocks.

5.5.4 Conclusion

The conclusion from the analysis of the fatty acids–detergents chain is that this is a sector characterized by relatively low-volume chemicals having a high environmental impact. However, the impacts are in the sector 'production of vegetable and animal oils and fats' (Dutch SBI C.10.4), outside the scope of the Dutch chemical sector. The contribution of the chemical part of the surfactants chain to the overall impact of the Dutch chemical sector is very minor: the impact of the intermediates and final products is approx. 5 MPt (0.08% of the Dutch chemical sector).

As our exploratory calculations show, however, different feedstocks have widely differing upstream environmental impacts. Depending on how oil plantations have been established (i.e. sustainably, or with clear-cutting of primary tropical forest), the environmental impacts of the supply chain can be very large. Through their procurement policies, chemical companies can have a major influence on these issues. Our analysis indicates that the supply chain impacts of Dutch detergent consumption could be as high as 516 MPt if all the detergents derived from plant oils from unsustainable tropical agriculture.

6 Net positive impacts of three product chains

6.1 Introduction

6.1.1 Analysis of the use phase

So far, this analysis of the ecological impact of the Dutch chemical Industry has yielded two sets of research results. In the first phase the total environmental impact of the Dutch chemical sector was estimated through an analysis of 36 high volume chemicals. In the second phase four important chemical production chains were examined along their entire length, through to final product, to assess the share of the chemical sector in the overall impact.

In addition, the assessment thus far has focused on the various forms of environmental damage associated with the respective production chains. However, chemical products do not necessarily only have negative impacts. They may also help reduce environmental impacts in other sectors and thus have a net positive impact on the environment, by reducing energy consumption in the usage phase or reducing land use impacts, for example. In some cases the environmental impact of chemicals production may be far smaller than the positive environmental influence of application of the chemical product.

For this reason, the third and final part of the research focuses on these positive impacts of the application of chemical products, by examining several specific cases related to the production chains already investigated above. This is subject of the present chapter.

For each of the cases examined, the central question will be:

> *'How large are the quantifiable environmental impact reductions due to use of a chemical product in relation to the chemical product's own lifecycle impacts?'*

The following three examples have been investigated: *house insulation*; *fertilizer use for food production*; and *modern synthetic laundry detergents*. These have been selected to tie in with the production chains already investigated in the second phase of the study. The examples represent the principal product volumes of these production chains, respectively production of polystyrene (EPS and XPS) insulation materials from plastics, production of nitrate fertilizers (from nitric acid) and production of surfactants from biological and synthetic resources for use in washing powders.

6.1.2 Description of example cases

Saving energy by insulating houses
Numerous materials are on the market for insulating homes and other buildings. These include both chemically produced materials like expanded polystyrene and non-chemical products like rock wool and glass wool. Below, the environmental performance of these material will be assessed in the use phase, with reference to the thickness of materials providing equal insulation performance (the so-called R-value). In this way we can show the environmental benefit of the insulation material per R-value point of each material (equalling a number of centimetres of insulation material). The environmental benefit will be calculated per m^2 insulation material over the lifetime of an average house (usually set at 50 years) in our north European climate (giving the average difference in temperature inside and outside the house). This will be compared with the environmental impact of the production of the insulation materials (both production and end of life phase). To show the aggregate performance of these materials, the total number of m^2 insulated in northern Europe with chemically produced insulation materials will be roughly assessed.

Increased yield due to use of fertilizers (reduction of land use)
Thanks to a range of innovations in agriculture, crop yields have been growing for decades. The single biggest innovation has been the introduction of synthetic fertilizers, specifically N-, P- and K-fertilizers, which administer these minerals in the specific amounts required for each crop, giving optimal yields. By comparison, organic farming, in which no synthetic fertilizers are applied, gives considerably lower yields: to produce the same volume of crop a larger area of land must be cultivated. Especially in the tropical areas where crops like soy are grown, there is major pressure to transform forests into arable land. This is typically the case in a country like Brazil. While in Europe this type of impact due to increased land use is not to be expected, land occupation is still a relevant issue. The comparison we make here is between production of key crops like wheat, corn and potatoes by conventional means, with application of synthetic fertilizers, and organic farming of the same crops. The difference in environmental impact will be calculated for the annual output of nitrate fertilizers (based on nitric acid) by the Dutch chemical sector, per crop type and in an average mix. By way of sensitivity analyses, a shift of land use towards unsustainable soy production in Brazil will also be considered, to illustrate a worst case scenario in which increased land use for organic farming is compensated with production outside Europe.

Reducing energy consumption with laundry detergents
Laundry detergents are one of the oldest chemical products in use. Both synthetic and bio-based surfactants - the main active substance in washing powders - are used for the cleaning process. Thanks to several chemical innovations it has become possible to reduce the temperature of the washing process from 60 degrees to a more modest 30 degrees, and even lower still. In particular, surfactants with shorter molecular chains are suitable for low temperature washing. Below we assess the environmental impact of the amount of modern detergents required per wash cycle and compare this with the saved energy consumption due to low temperature washing and the replaced production of natural soaps. To demonstrate the performance of the total amount of detergent used on a yearly basis, the assessment is scaled to the number of wash cycles performed annually in the Netherlands. As it is unclear what types of surfactants are produced by the Dutch chemical sector

and in what quantities, a direct link to production volumes cannot be made at present.

6.1.3 Methodology
For the assessments and comparative screening LCAs performed in this study, the scope and assumptions of the ICCA report 'Innovations for greenhouse gas reductions' (ICCA, 2009) have been followed as closely as possible. For the savings enabled by a chemical product – the subject of the present chapter - a key concept introduced by ICCA is the so-called X-factor. Here, this factor will be used express the ratio of environmental impact saved by the application of a chemical product relative to the chemical product's own full lifecycle. The chemical product's lifecycle will be a cradle-to-grave assessment, whereas the 'savings' will be quantified by analysing the differences from a (non-chemical) reference case.

A description of the report and methodology of the approach followed is provided in 0.

6.2 Insulation material

6.2.1 Introduction
Insulation is a clear example of an area where use of a chemical product can result in major net benefits to the environment. Insulation greatly reduces the heat lost by buildings, thus vastly reducing the energy required for space heating. Similarly, building insulation also greatly reduces the energy required for cooling.

In the construction sector numerous insulation materials are used, some deriving from the chemical sector, some from other sectors. For the present analysis we focus on styrene-related insulation materials (EPS and XPS foams), an important class of insulation materials which are products of the chemical sector. These materials are used in a wide range of applications[9].

This analysis focuses on the question: *How can we quantify the potential environmental benefits of the chemical insulation material in the use phase, compared with the impact of production of this material?*

To answer this question, the benefits of insulating the existing Dutch building stock to the level of current construction standards for newly built houses will be assessed. The benefits of this insulation will then be compared with the impact of the production chain of the polystyrene insulation product.

The approach followed is similar to ICCA (2009). However, as the authors of ICCA follow a multi-case study approach on North American, Asian and European houses and did not publish the underlying data on the cases calculated, we here construct a case proceeding from Dutch construction standards. To this end we incorporate an assessment of current average insulation levels, which are expected to be far higher than those of the average North American home. The environmental impacts are assessed for the volume of insulation material produced annually by the fraction of Dutch

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9 Besides chemical insulation materials, non-chemical insulation materials are also used in large volumes. Inorganic insulation materials include glass wool, stone wool and foam glass. Organic materials include materials like cellulose, flax and hemp fibres. These materials have different properties and applications to which they are most optimally suited. For the purpose of this analysis, an assessment of the chemical insulation materials suffices; assessment of the relative advantages of each material vis-à-vis the others is beyond the scope of this study.

styrene production capacity attributable to manufacturing of EPS and XPS insulation materials (both domestic and abroad).

Because there are several different production processes for EPS and XPS insulation materials, we also perform a sensitivity analysis to see how their lifecycle impacts compare.

6.2.2 Size of the insulation market

Polystyrene insulation materials can be divided into expanded polystyrene (EPS) and extruded polystyrene (XPS). An assessment of the quantity of insulation material deriving annually from Dutch styrene production capacity is given below.

The total European market for styrene applications is currently estimated at 4.6 Mtpa, of which 1.6 Mtpa is for EPS and about 0.3 Mtpa for XPS (Styrene Producers Association, 2012).[10] It is unknown what fraction of this is for building insulation materials, but for these applications ICCA (2009) provides figures for Europe (Table 6). Combining these figures yields the insight that around 27% of the total European styrene market should relate to polystyrene (EPS, XPS) insulation applications.

Table 6 Annual volume of installed styrene-derived insulation materials, for Europe

Insulation material	Amount (ktpa)
XPS	110
EPS	404
Total, EPS+XPS	514

Source: Tecnon, SRI, GUA; cited in ICCA, 2009.

Manufacturer Kingspan (2008) gives data for the European insulation market (1.6 billion m^2, based on data from IAL consultants). An assessment of the amount of polystyrene insulation material relative to the total insulation material market cannot be precise, as compositions, thicknesses and densities are not given in this aggregate figure and vary depending on the insulation product. Assuming an average thickness of 4 cm, the amount of 514 kt of polystyrene insulation material would equal about 27% of the EU insulation market, so polystyrene is very relevant indeed.

As reported in Section 5.2, above, Dutch production capacity for styrene associated with foams (EPS and XPS) was found to be about 0.9 Mtpa (Netherlands and abroad). This would be about 57% of the European market for EPS and XPS when related to the figure of the Styrene Producers Association. Multiplying this by the share of insulation materials in the overall European market for EPS and XPS (27%), it follows that around 0.24 Mtpa of worldwide production capacity for EPS and XPS insulation materials is associated with Dutch styrene production capacity. This annual output is sufficient to fully insulate to a good standard all the hard/closed surfaces of about half a million average Dutch houses.

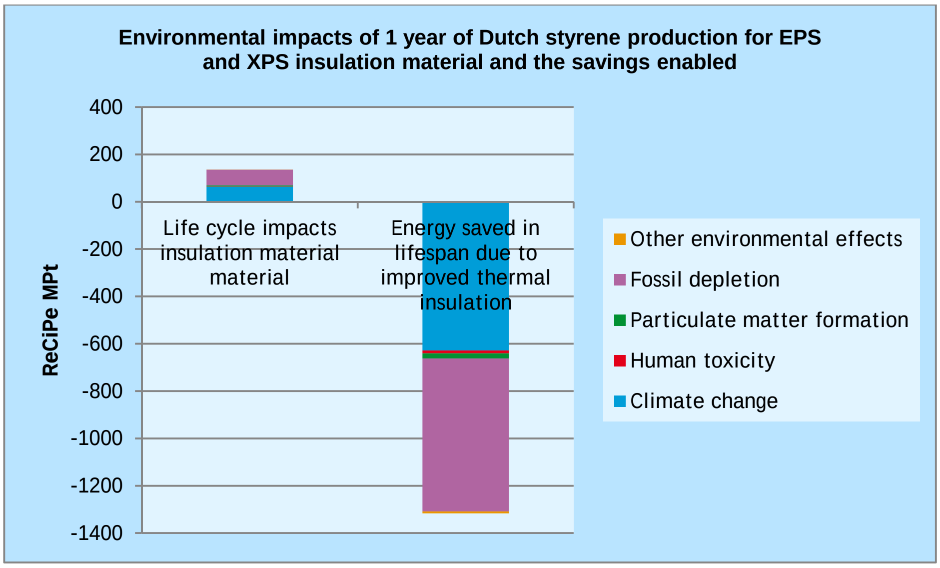
10 Note that the market size refers to produced styrene. Dutch styrene manufacturers have a large share in this, although according to VNCI (2011) actual European production capacities are significantly larger than the figure cited above. In this study for the Netherlands we only have data on Dutch capacities. This may lead to an overestimate of the importance of the Dutch chemical sector relative to the European market.

6.2.3 Environmental benefits of insulation

To assess the environmental benefits of the use of polystyrene insulation materials, we analysed the existing building stock and assessed the amount of energy that could potentially be saved if the buildings were better insulated using the amount of polystyrene insulation material associated with Dutch styrene production. The assumptions employed in these calculations are detailed in the following section.

The results are presented in Figure 50, which shows the lifecycle impacts of the insulation material alongside the impacts of prevented energy consumption. The figures are for the relevant share of Dutch styrene production, i.e. that used in manufacturing EPS and XPS insulation materials.

Figure 50 Comparison of lifecycle impact of the insulation material and of prevented energy consumption



From the figure we see that the amount of environmental impact 'saved' due to energy savings far exceeds the lifecycle impacts of the chemical insulation material. It can thus be concluded that **one unit of environmental impact due to the manufacturing and disposal of polystyrene insulation material results in 10 times greater savings in the environmental impact of the house itself due to lower energy use.**

This answers our question: the benefits of the chemical product far outweigh the impacts of production of the material concerned.

The net environmental impact of the full lifespan of insulation materials, for a year of production of the materials, is about -1,180 ReCiPe MPt/year. This is a major positive environmental contribution equal to about a quarter of the annual direct impacts of the Dutch chemical industry, as established in Chapter 0.

Savings on energy consumption

The resulting savings in average energy consumption for space heating due to better insulation of the closed surfaces of the houses are calculated to be 17%.

6.2.4 Calculation assumptions

This assessment is based on the following assumptions:

- For the insulation material we combined EPS and XPS according to their respective current European market share. The EPS assumes virgin feedstock, while the XPS is based on the average mix of blowing agents (50/50% CO_2 and HFC-134a/152a).
- The following steps in the material lifecycle were analysed: cradle-to-gate production chain of material, decommissioning/removal, final disposal with energy recovery and electricity generation.
- A functional life of 50 years is assumed, according to ICCA (2009), but also equal to the amortization periods commonly used in the housing sector.
- For the energy saved, only heating was assessed, on the basis of a high efficiency, low NO_x, modulating fan boiler and using natural gas as an input. If cooling were also assessed, the energy savings would be even higher.
- For a 'good insulation level' the Dutch building code was taken as a standard. For the building envelope, a heat resistance value of R_c = 3.5 m^2.K/W is prescribed (Bouwbesluit, 2012). As of 2012, newly built and renovated houses need to be at this level.
- As the reference case, we took the average insulation level of homes in the Netherlands. The current average thermal insulation of Dutch houses was determined by assessing the existing building stock and insulation levels. The average heat resistance value of existing houses is R_c = 1.6 m^2.K/W (for derivation, see Annex D).
- Heat losses were assessed for flooring, flat roofs, inclined roofs, front and back façade (closed surfaces) and side façade (closed surfaces); in the reference case these surfaces are responsible for about 35% of heat loss from homes.
- Heating requirements were assessed using the average of weighted degree days at De Bilt from 1970-2011. For a base temperature of 18°C, this is 3040 K·d, (KWA Bedrijfsadviseurs 2012).
- It is assumed that 50% of spaces are heated.
- Insulation materials are available in a range of insulation values and mass densities. For XPS the range is particularly wide as there are many different applications requiring higher or lower rigidity of the material, which influences both these aspects. The parameters used for density and insulation properties are given in Table 7. These have been derived from the Ecoinvent processes and were checked against the available literature.

Table 7 Insulation material parameters

	Thermal conductivity (W/m.K)		Density (kg/m^3)	
	Ecoinvent	Value adopted	Ecoinvent	Value adopted
Glass wool	0.04	0.04	40	40
EPS	0.035-0.040	0.038	28-30	29
XPS	0.035-0.040	0.038	25-45	35

6.2.5 Explorative analysis: screening different insulation materials

There are a number of processes for EPS and XPS insulation materials.
To assess the influence of the production methods on the lifecycle impacts of the insulation material, in this section the impacts of a number of process improvements are discussed. A comparison with an inorganic insulation material, glass wool, is also made.

Production methods for EPS and XPS insulation material

If recycled material can be used as a feedstock, this generally lowers the environmental impact of a unit of final product. To show the effect of this kind of material efficiency improvement, for EPS we consider a process with 45% recycled content. This process is available in the Ecoinvent LCI.

Similarly, production of styrene in combined styrene and propylene oxide units is significantly more energy-efficient than in conventional EBSM units. Although this is already partly incorporated in the analysis (which encompasses EPS and XPS from a mix of 21 European production sites using both processes), styrene exclusively from PO/SM processes may score almost 45% better than the European average. The impact of this on the overall environmental impact of the EPS may be very sizeable and comparable to the score for recycled content, although a more elaborate assessment will need to be done to know this for sure.

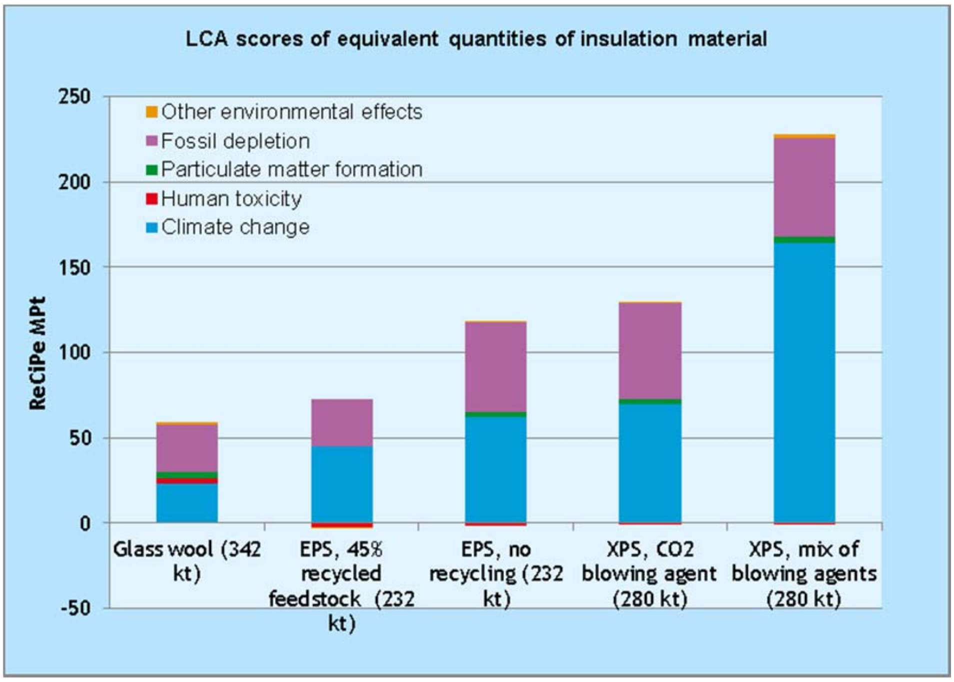
For XPS, the choice of blowing agent is very relevant for the environmental impact. Some of the traditional blowing agents like HFC-134a and HFC-152a have very marked climate change effects, but these are now gradually being replaced by alternatives with lower global warming potentials. The Ecoinvent process for 'Polystyrene, extruded (XPS)' used in the above assessment has the following shares of blowing agents: 50% CO_2, 25% HFC-134a and 25% HFC-152a. In 2005 over 50% of companies in Europe were already using CO_2 instead of HFCs as a blowing agent (Kellenberger *et al.*, 2007). To show the effect of using CO_2, an XPS process using only this blowing agent is also analysed.

Comparison with glass wool

It is also interesting to know how chemical products compare with a non-chemical insulation material. For comparison, glass wool was selected, a mineral wool widely used in the insulation applications examined here.

In Section 6.2.2 it was derived that 0.24 Mtpa of XPS and EPS insulation material is produced using the relevant fraction of Dutch styrene capacity. With the parameters from Table 7 above, this is sufficient for insulating 72 mln. m^2 of hard surfaces at a level of $R_c = 3.5\ m^2{\cdot}K/W$. To compare different insulation materials over their lifecycle we shall take this amount as the functional unit. With the technical parameters of Table 7, different amounts of material are needed for this amount of insulation: 342 kt of glass wool equates to 232 kt of EPS or 280 kt of XPS. Figure 51 shows the resultant outcomes for the lifecycle environmental impacts of these different insulation materials. Since the assessment is for functionally equivalent amounts of insulation material, the use-phase energy savings are by definition equal for all the cases investigated.

Figure 51 **Impacts of production chain of different insulation materials**



From Figure 51 follows that the lifecycle impact of the EPS production chain is indeed substantially reduced if use is made of recycled content. Furthermore, the lower climate change impact of the XPS with CO_2 blowing agent is evident: the score for this impact is much lower than for the process with HFCs used as a blowing agent. It can also be seen that EPS insulation material has lower environmental impacts than XPS.

Glass wool insulation material has even lower lifecycle environmental impacts, due largely to lower climate change impacts compared with EPS. The score of EPS with 45% recycled feedstock is in the vicinity of that of glass wool. From this it may be concluded that by greatly increasing the share of styrene from PO/SM co-production to achieve similar eco-efficiency, EPS insulation material can approach the eco-performance levels of glass wool.

The above assessment illustrates only the material lifecycle environmental impacts of approximately *functionally equal* amounts of insulation material (only in terms of insulation value). In actual functionality these materials are very different with different applications. Given this approach, the environmental impact savings enabled in the use phase in the form of energy savings are by definition equal for all materials. For all the materials the impact savings in the use phase are relatively greater than those of the lifecycle of the material itself: the corresponding 'X-factor' is 22 for glass wool, 19 for EPS with 45% recycling, 11 for average EPS, 10 for XPS with CO_2 blowing agent and 6 for XPS with a mix of blowing agents.

Although, based on this assessment, one would be tempted to conclude that lifecycle impacts of polystyrene insulation material (EPS or XPS) are worse than that of glass wool, or that EPS is better compared to XPS, however these kinds of conclusions cannot be drawn from this analysis. Whereas, in terms of insulation level, the functional equal amounts of material have been used in the figure, in terms of real world application XPS, EPS and glass wool materials are very different, since they are used in different insulation applications. For instance the structural strength of EPS allows for different applications where other materials are less applicable. For this reason, they are not functionally equal, and we cannot compare them to draw conclusions on the relative environmental scores.

6.2.6 Conclusions

From this analysis of chemical insulation materials the following conclusions can be drawn:

1. Insulation is a clear example of an area where the use of a chemical product results in very large overall benefits for the environment.
2. The environmental benefits due to the use of the chemical insulation material outweigh the direct lifecycle impacts of the product lifecycle by an 'X-factor' of 10 (based on 50 years of better insulated houses).
3. The fraction of Dutch styrene going to EPS and XPS insulation materials would enable 0.5 million average houses to be fully insulated annually to a good level. With this insulation, these houses' heating energy bills would be lowered by an average of 17%, resulting in major benefits to consumers.
4. The environmental impacts of EPS can be improved if use is made of recycled feedstock. Similarly, improvements in the energy efficiency of styrene production (e.g. PO/SM co-production) lead to lower overall environmental impacts of both EPS and XPS.
5. The environmental impacts of XPS can be substantially improved if CO_2 is used as a blowing agent instead of HFCs.

6.3 Fertilizers

6.3.1 Introduction

A number of innovations in agriculture have contributed to an impressive growth in crop yields over the past century. The single biggest innovation has been the development of artificial fertilizers. Today, fertilizers are tailor-made to contain specific doses of the three primary nutrients (N, P and K minerals) to precisely match the requirements of each crop and soil type. Mineral bookkeeping supports fertilizer dosage in such a way that yields are high while effectiveness is optimised by aiming for maximum uptake by the crop.

Conventional farming can be compared with organic farming. While organic farming has a number of benefits with respect to resource conservation, lower ecotoxicity and higher biodiversity, one disadvantage is that it generally has considerably lower yields. A key reason for this is that the use of synthetic fertilizers is prohibited in this kind of farming. For the same crop yield, in organic farming a larger area of land must therefore be cultivated.

The popularity of synthetic fertilizers in conventional farming has made them one of the chemical industry's most important products. In the Dutch chemical sector, too, fertilizers are an important product, produced at a number of large production sites. This chapter assesses the amount of agricultural output enabled through application of the N-fertilizers produced by the Dutch chemical industry and estimates the net gains in environmental impact to which they give rise.

Approach

First the environmental impacts of the full lifecycle of synthetic N-fertilizers will be assessed. This includes the following:

- the cradle to factory gate impacts resulting from manufacture of the N-fertilizers produced in the Netherlands (calculated in Section 5.4 above);
- the environmental effects of the fertilizers in the use phase, specifically emissions to air and water.

These impacts will then be compared with the environmental savings due to fertilizer application. The following savings are assessed:

- Savings in the use phase, by comparing farming with and without synthetic N-fertilizers, by looking at differences in NO_x, N_2O, ammonia and nitrate emissions to air and water.
- Yield improvements with synthetic N-fertilizers. Use of these fertilizers results in extra agricultural output with the same production factors. The extra output per hectare can be viewed as a 'replaced production' of organic farming and can be viewed as an environmental impact saving.

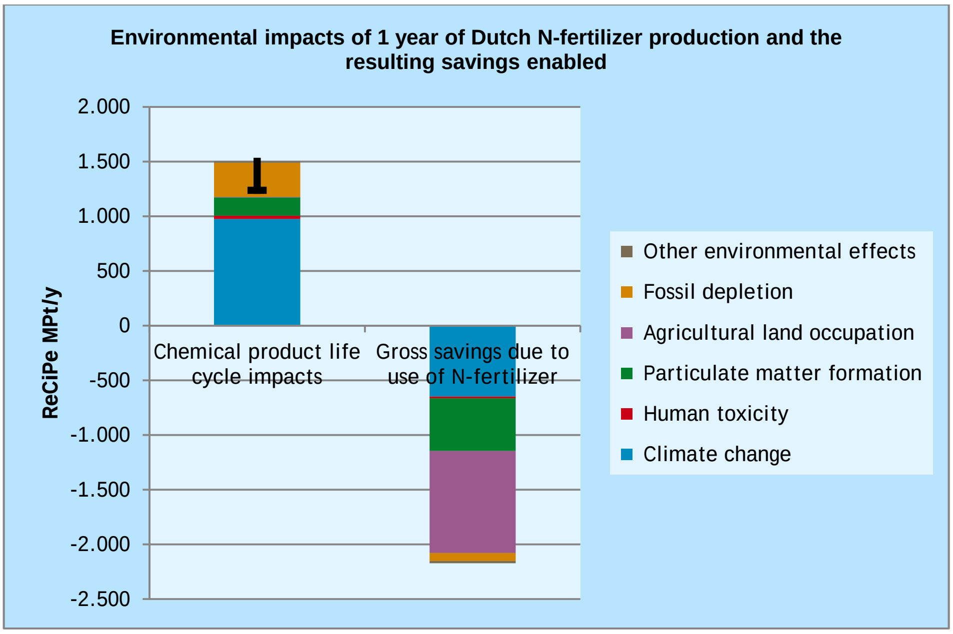
Uncertainty

There is uncertainty regarding the environmental impact of organic farming relative to improved conventional farming. We attempted to minimize this by analysing a number of important crops (barley, maize, potato and wheat) and using the state of the art Ecoinvent lifecycle inventory (Nemecek *et al.*, 2007). However, it is important to note the uncertainty and bear in mind that the yield of organic farming can perhaps be improved in the coming decades.

6.3.2 Environmental benefits of synthetic fertilizers

The analysed lifecycle impacts and difference in environmental savings are depicted in Figure 52.

Figure 52 Environmental impacts of N-fertilizer lifecycle versus savings enabled



In Figure 52 the uncertainty regarding the precise N_2O emission levels of current nitric acid production compared with the Ecoinvent dataset is expressed by a black 'error bar' for 'chemical product lifecycle impacts'. This bar represents the total environmental impact of the product lifecycle if N_2O emissions are 2 kg/tonne nitric acid rather than the Ecoinvent value.

As the figure clearly shows, the gross emission savings attributable to the use of N-fertilizers are greater than the lifecycle impacts of their production and use. The 'X-factor' expressing this ratio is 1.4 or 1.8, depending on how nitric acid production is factored in. Further details on the calculation are given in the following section.

6.3.3 Calculation of effect of N-fertilizer use

In this section we detail the calculations of the effects attributable to Dutch N-fertilizers. The question of how much crop production is attributable to the amount of N-fertilizers produced by the Dutch chemical sector depends on assessment of a number of factors:

- for each key crop: currently applicable areas of land, crop yield and specific N-fertilizer dose;
- crop yield reduction if fertilizers are not used (organic farming);
- share of N-fertilizers in the above yield reduction.

Applicable land areas

In Section 5.4 it was found that the N-fertilizer production capacity of the Dutch chemical industry is approximately 3.8 Mtpa. This was modelled as three N-based fertilizers: ammonium nitrate (AN), calcium ammonium nitrate (CAN) and urea ammonium nitrate (UAN). The total amount of N in these fertilizers is 1.34 Mt per year.

By assessing data from the United Nations' FAO on fertilizer use and other statistics (see Table 8), it can be derived that the volume of N-fertilizers concerned is sufficient for the N-requirements of 64% of the combined production of 5 European countries (the Netherlands, Belgium, Germany, France and the United Kingdom) of 4 key crops (barley, maize, potato and wheat).

Table 8 N-fertilizer dose, area cultivated and N-consumption for the Netherlands, Belgium, Germany, France and United Kingdom

	Average fertilizer dose	Area cultivated	N-consumption	Production
	kg N/Ha	x 10^6 Ha	Mtpa	Mtpa
Barley	132	4.7	0.63	28.4
Maize	164	2.2	0.36	20.3
Potato	79	1.8	0.14	78.5
Wheat	167	5.7	0.95	42.1
Total			**2.09**	28.5
Netherlands' N-fertilizer production share:			**64%**	

Source: Adapted from FAO, 2012a. The figures reflect, per crop, combined weighted averages and totals, respectively, for 5 countries: the Netherlands, Belgium, Germany, France and the United Kingdom. The data for the column 'Production' are from FAO, 2012b.

Fertilizers and crop yield

The reduction in crop yield resulting if synthetic fertilizers are not used is a parameter that is hard to quantify and that will vary considerably depending on the crop, existing soil composition and nutrients content, precipitation and many other factors. ICCA (2009) pragmatically assumes a figure of 50% yield reduction for both fertilizers and pesticides. Given the number of factors influencing this figure, this seems rather arbitrary. Instead of working with this figure, a crop-specific parameter was derived from the Ecoinvent inventory. For the four crops of barley, maize, potato and wheat, Ecoinvent has inventories for modern conventional methods (integrated production) as well as for organic farming processes.

The crop yield reduction is attributable to both fertilizers and pesticides. For this demarcation problem, use has been made of ICCA data. One quoted source in ICCA (2009, p. 61) estimates a yield reduction of 50% for only fertilizers versus 66% for both fertilizers and pesticides. Taking these two figures, it can be deduced that whatever the yield reduction due to organic farming, 75% can be allocated to fertilizers and 25% to pesticides.

On this basis, Table 9 reports the figures calculated for the reduced yield of organic farming due to differences in the use of both fertilisers and pesticides.

Allocation to N-fertilizers

The last column of Table 9 reflects the allocation to N-fertilizers. Allocation of yield gains was done by dose on a mass basis, based on the average fertilizer dose for the 4 crops assessed according to FAO (2012a). This allocates 60% of the yield due to fertilizers to N-fertilizers, as these are the most important by weight. For the 4 crops assessed, the weighted yield reduction without N-fertilizers is about 17%.

Table 9 Crop outputs and estimates of yield reduction if no N-fertilizers are applied

Crop	Yield depending on farming method (t/ha) (Ecoinvent)		Yield reduction, no fertilizers or pesticides	Yield reduction, no fertilizers	Yield reduction, no N-fertilizers
	Conventional farming	Organic farming			
Barley	9.08	5.36	41%	31%	**19%**
Maize	7.53	6.30	18%	14%	**8%**
Potatoes	30.59	18.03	41%	31%	**19%**
Wheat	8.46	5.22	38%	29%	**17%**

Source of yield data: Ecoinvent.

Amount of extra production and land use prevented

The above parameters permit calculation of the amount of land use prevented by the Dutch chemical industry's N-fertilizers and the extra production enabled. The results are shown in Table 10.

Table 10 Results for extra production and yield due to Dutch N-fertilizers

	Area cultivated	Total production	Extra production due to Dutch N-fertilizers	Land use prevented by Dutch N-fertilizers
	x 10^6 Ha	Mt/y	Mt/y	x 10^6 Ha·y
Barley	4.7	28.4	3.4	0.69
Maize	2.2	20.3	1.1	0.13
Potato	1.8	78.5	9.4	0.27
Wheat	5.7	42.1	4.7	0.77

Source of production data: FAO, 2012b.

For the comparison, the extra production (fourth column in Table 10) is used in the gross savings assessment to calculate the environmental impacts of the yield improvements due to synthetic N-fertilizers. The N-fertilizers replace organic production at the calculated amounts. The land use is used in the sensitivity assessments of the effect of indirect land use change (ILUC) (Section 6.3.4).

In-use emissions

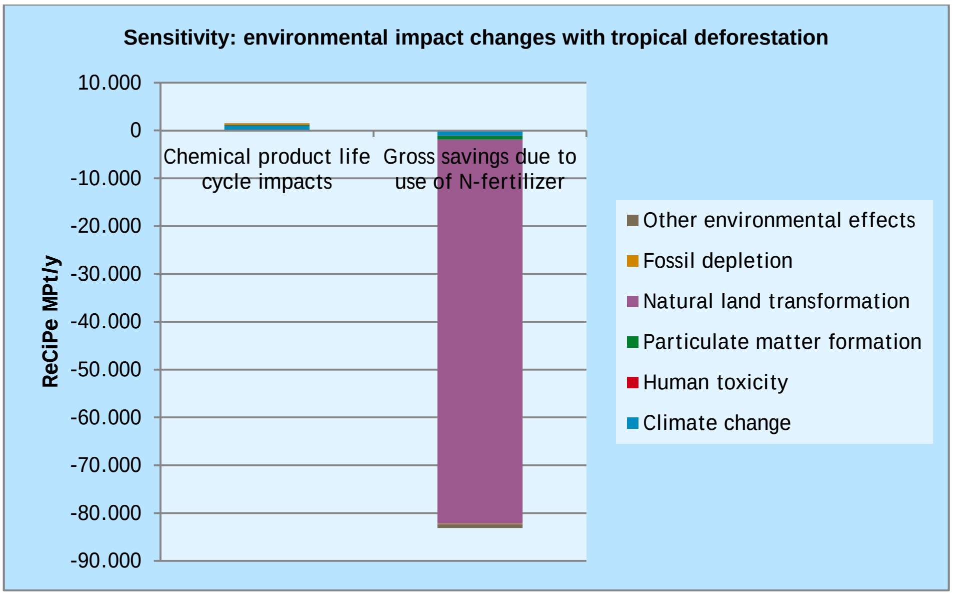
In assessing the chemical N-fertilizer product lifecycle, in-use emissions are also taken into account. These emissions relate to leaching to water of nitrates and emissions to air of NO_x, N_2O and ammonia. These emissions are inventoried in the appropriate Ecoinvent processes. Per tonne of produce, the emissions are similar or lower compared to organic farming, contributing to the net impact savings due to the use of synthetic N-fertilizers.

6.3.4 Sensitivity: tropical deforestation

As agricultural land is a scarce resource, extra land use for agricultural production in Europe or the Netherlands may cascade down to land use in tropical regions. This extra demand for farmland (indirect land use change, ILUC) may lead to deforestation. Because tropical deforestation is an important environmental issue leading to loss of biodiversity and other environmental and social impacts, in this section we assess the related potential effects.

This is a worst-case scenario assessment, as the risk of the ILUC indeed having the extent assessed here is not fully known. Figure 53 reports the effects quantified for the 1.86 million ha agricultural land (see Table 10) 'saved' by the higher yield due to N-fertilizers.

Figure 53 N-fertilizer lifecycle impacts related to gross savings for the case of extra land use leading to tropical deforestation (clear-cutting of primary rainforest in Brazil for extra farmland)



In this approach, the Ecoinvent process 'provision, stubbed land/BR' was used, with the amount of clear-cut tropical forest allocated to 30 years of agricultural production. The related X-factor is 55, with an upper limit of 67. Clearly, the associated environmental impacts knock on very strongly in the overall assessment.

6.3.5 Conclusions

The following conclusions can be drawn from the analysis of N-fertilizers produced by the Dutch chemical industry:

1. Synthetic N-fertilizers contribute substantially to overall environmental benefits.
2. Without N-fertilizers, per-hectare crop yields would be about 17% lower on average.
3. The gross environmental savings attributable to the use of Dutch N-fertilizers are greater than the lifecycle impacts of their production and

use. The ‘X-factor’ expressing this ratio is 1.4 or 1.8, depending on the N_2O process emissions adopted for nitric acid production.

4. Land use changes can cascade down to tropical regions, where the potential environmental impacts are greater. If N-fertilizers cannot be used and the related amount of extra land needed (1.86 million ha) were provided by clear-cutting of tropical rainforest, this would lead to far higher environmental impacts. Quantifying this as a worst-case scenario, the related X-factor expressing this effect would be 55 to 67.

6.4 Laundry detergents

6.4.1 Introduction

The laundering of textiles is among the oldest human activities in which chemicals are used to achieve better results. Historically soap was used for this purpose, while today synthetic detergents have been developed comprising a carefully selected combination of active ingredients: surfactants, builders, enzymes and other auxiliaries. Today’s detergents achieve a far better washing result with less chemicals. In addition, several innovations in surfactants and enzymes have enabled the washing temperatures to be reduced from over 60°C down to 20-30°C.

In this section the environmental impact of modern detergents used for household laundry of fabrics is assessed by comparing the impacts of the synthetic detergent product lifecycle with the impact savings due to improved washing effectiveness and reduced energy consumption. Traditional soap, made from natural oils, will serve as the reference with which synthetic detergents are compared.

The level of analysis, or ‘functional unit’, is the annual number of wash cycles performed by Dutch households. As the detergents industry is an international business, it is not precisely known how much and which types of surfactants are produced by the Dutch chemical sector. This means that at present a direct link to the volumes produced in the Netherlands cannot yet be made.

6.4.2 Environmental benefits of modern detergents

The comparison of the environmental impacts of modern synthetic detergents relative to the savings they enable is shown in Figure 54.

Figure 54 Environmental impacts of modern laundry detergents and the impact savings they enable

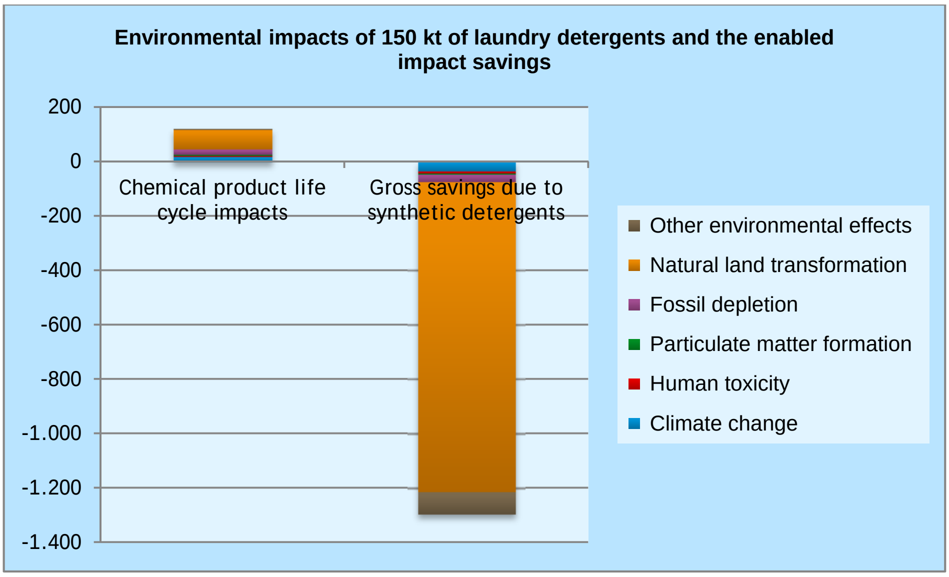


Figure 54 shows that the gross impact savings are far larger than the impacts of the synthetic detergents' lifecycle itself, with a related X-factor of 11. It is furthermore clear that the environmental impact 'natural land transformation' is dominant in the total impact. This holds not only for the soap reference, but also for the synthetic detergent. Natural land transformation is the environmental impact of the conversion of land from 'wild' natural land to land used other purposes. In this case it relates to the clear-cutting of tropical forest for palm and coconut oil plantations. There is an important uncertainty in this environmental effect, as discussed in Section 6.4.3.

Approach followed and data used

As far as possible, the approach adopted follows the ICCA (2009) assessment, taking the following into account for the chemical product lifecycle:

- A total of 150 kt/a of detergent is inventoried (MilieuCentraal), the amount used in 4 washing cycles per week for 7.2 million households in the Netherlands.
- Detergent composition: 18% surfactants, 50% builder, 15% bleaches, 10% filler and 7% auxiliaries. The composition used in the analysis is indicated in Table 11. Ecoinvent has lifecycle inventories for all the above substances except those in the table marked with (*), for which an average for the applicable group of ingredients was used. The detergent composition analysed includes other substances besides surfactants, which was the focus of chain in Section 5.5 above.
- The downstream impact on waste water was derived from ICCA data: 0.085 m^3 water treatment per cycle.

Table 11 Composition of modern laundry detergents (average)

Group	Ingredient	Composition (mass %)
Surfactants (18%)	Linear alkylbenzene sulphonates	6%
	Fatty alcohol sulphates	5%
	Alcohol ethoxylates	5%
	Soap	2%
Builders (50%)	Sodium silicate	3%
	Zeolites	27%
	Sodium carbonate	11%
	Sodium tripolyphosphate	3%
	other builders (*)	6%
Bleaches (15%)	Sodium perborate	15%
Filler (10%)	Sodium sulphate	10%
Auxiliaries (7%)	Carboxymethyl cellulose	1%
	Foam inhibitor (soap)	4%
	Enzymes (*)	1%
	Fluorescent whitening agent	1%

Data sources for the composition:
Nielsen and Skagerlind, 2007; Nemecek *et al.*, 2007; Wikipedia, 2012; manufacturer's specifications. Ecoinvent has lifecycle inventories for all the above substances except those marked with (*).

For the savings enabled by the replacement of a non-chemical alternative, the following were factored in:

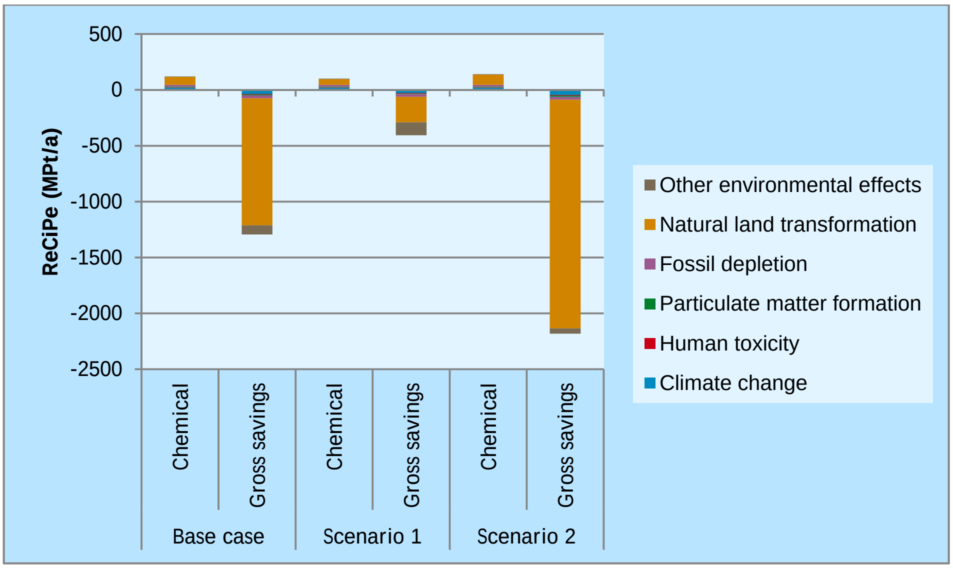
- Washing temperature for modern washing: 37°C, and for traditional washing with soap: 60°C, with related electricity requirements per cycle of 0.72 kWh for modern detergents versus 1.0 kWh traditionally (ICCA, 2009). The environmental impacts of this electricity consumption were calculated using the Dutch production mix with imports (electricity, low voltage, at grid/NL).
- Soap is less effective than modern detergents. According to ICCA (2009) three times more soap is needed for an equivalent washing result compared with modern detergents. This factor of three has been calculated for the sum total of all the active ingredients in synthetic detergents (surfactants, bleaches, builder, auxiliaries), which means that 405 ktpa of soap is assessed in total.
- The stated uncertainty regarding land use and land transformation impacts in the Ecoinvent inventory for soap was approached in the following way. The Ecoinvent process was duplicated with palm oil from unsustainable tropical plantations being replaced by tropical coconut oil and the average of the original Ecoinvent process and the thus adjusted process for soap then being taken.

6.4.3 Sensitivity

There is considerable uncertainty regarding impacts with respect to natural land transformation. In the Ecoinvent process for soap, the oil feedstock is inventoried as 0.61 kg of palm oil and 0.14 kg of crude coconut oil. Palm oil is inventoried for Malaysian palm oil plantations which, in the Ecoinvent inventory, has large natural land transformation environmental impacts due to clear-cutting of forest.

If plant oils are used with lower land transformation issues (e.g. coconut oil or RSPO-certified palm oil), then the total impacts of soap are substantially reduced. Palm, palm kernel and coconut oils are all very suitable for detergents (see Section 5.5). To express this uncertainty, Figure 55 shows the analysis results for different compositions of soap.

Figure 55 Sensitivity analysis of results



Alongside the base case (used in the analysis; soap is an average of the Ecoinvent process for soap and the adjusted process), scenario 1 shows the impacts if in the process for soap 0.61 kg of palm oil is replaced by 0.61 kg of crude coconut oil. Scenario 2 shows the results if the unadjusted Ecoinvent process for soap is used.

It is clear that the total environmental impacts are highly influenced by the type of oil used. The upper value of the X-factor (scenario 2) is 15, while the lower limit is 4 (scenario 1). In all cases, land transformation is a very relevant environmental impact, and the lifecycle impacts of synthetic detergent are clearly lower than in the reference case.

6.4.4 Conclusions

From the analysis of synthetic detergents the following conclusions can be drawn:

1. For detergents, the savings enabled by the use of synthetic detergents (the X-factor) are 11 times higher than the lifecycle impact of the chemical production chain, in the base case.
2. There is uncertainty in the assessment due to the inventory taken for the reference: natural laundry soap may be produced using more or less sustainably produced plant oils. This uncertainty was modelled by means of adjustments in the inventory for the laundry soap, yielding a lower and upper limit of the X-factor: a savings ratio of 4 versus 15.
3. In all the scenarios assessed, synthetic laundry detergents have lower environmental impacts than the natural soap reference.

6.5 Conclusions on net impacts of the three chains

For three example applications of chemical products, *insulation of houses*, *N-fertilizers in food production* and *modern synthetic laundry detergents,* the chemical lifecycle environmental impacts have been related to the savings enabled by use of the products. The savings relate to in-use performance differences and alternative production lifecycles. For all three cases the central question '*How large are the quantifiable environmental impact reductions due to use of a chemical product in relation to the chemical product's own lifecycle impacts*?' could be satisfactorily answered.

Insulation of houses

It was found that building insulation is a clear example of an area where use of a chemical product results in very large overall benefits for the environment, with a resulting X-factor of 10. (The X-factor is the normalised relationship between the environmental impact reduction due to the use of a chemical product and the impact due to the chemical product's own lifecycle). The fraction of Dutch styrene going to EPS and XPS insulation materials would enable 0.5 million average houses to be fully insulated annually to a high standard. This insulation would allow the heating bills of these houses to be lowered by an average of 17%, resulting in major benefits to consumers.

The lifecycle impacts of polystyrene insulation material (EPS or XPS) can be reduced as follows:

- for XPS, by use of CO_2 as a blowing agent instead of hfcs;
- for EPS, by use of recycled EPS to replace virgin material;
- for both EPS and XPS, through improved efficiency of styrene production.

N-fertilizers

In the case of N-fertilizers, it was found that these also contribute to overall environmental benefits. Assessing the key crops of barley, maize, potato and wheat, it was established that without N-fertilizers per-hectare crop yields would be about 17% lower on average. The environmental savings (X-factor) are 1.4 to 1.8 times the impact of fertilizer manufacturing. This range is due to what process emissions of N_2O are accounted for in nitric acid production. Thanks to the N-fertilizers produced by the Dutch chemical industry, some 64% of the area devoted to the analysed crops in Germany, France, the United Kingdom, Belgium and the Netherlands is fertilized, leading to an extra output of 30 Mt/y compared to organic farming. If these crops were produced using organic farming methods, some 1.86 million additional hectares of farmland would be needed. Land use change can have major environmental effects if it cascades down to tropical regions, where clear-cutting of tropical rainforest may occur. Assessing the possible consequences of this as a worst-case scenario, the resulting X-factor is between 55 and 67.

Laundry detergents
In the case of laundry detergents, the savings enabled by modern synthetic detergents are 11 times higher than the lifecycle impact of the chemical production chain, in the base case analysed. There is uncertainty in the assessment due to the inventory for the reference, as natural laundry soap may be produced from more or less sustainably produced plant oils. This uncertainty was modelled, yielding a lower and upper limit of the X-factor: a savings ratio of between 4 and 15. In all the scenarios assessed, synthetic laundry detergents have lower environmental impacts then the natural soap reference.

7 Conclusions

The aim of this study was to give more insight in the environmental impact of the Dutch chemical sector and its contribution to the overall impact of the production chains of chemical products. Due to the complexity of the Dutch Chemical sector a pragmatic approach has been taken to perform this assessment. This leads to several limitations to the accuracy of the results. All results and conclusions presented here, should be read in the light of these limitations (see also Chapter 3).

7.1 Main conclusions on the environmental impact

1. The high volume chemicals (12 platform chemicals and 24 derivative high volume chemicals) produced by the Dutch chemical sector represent the bulk of the environmental impact of this sector in the Netherlands.
2. The contribution of final production of chemical products within the Dutch chemical sector to its aggregate environmental impact varies considerably among end products. Based on four important chemical production chains, It can be estimated at between 10 and 50%.
3. In the application of chemical products there are clear examples where a substantial environmental gain can be achieved. In the assessed examples these gains can outweigh the environmental impact of the production of the applied chemical products with a factor of 1,5 up to 15 times the impact.
4. The overall impact of the analysed 36 high volume chemicals in the Netherlands amount to a total of approximately 5,500 ReCiPe MPt per year.
5. The impact of the platform chemicals accounts for 68% of that total. The remaining impact is due to the added impact of derivative production from these platform chemicals, with production of final high volume products accounting for 22% of the overall impact and production of intermediate high volume chemicals for a further 10%.
6. There is a clear group of platform chemicals produced in an aggregate volume of around 11 to 12 Mtpa that has a very similar environmental impact per tonne of production of between 250 and 270 Pt per tonne per year. The environmental impact of these platform chemicals is dominated by petrochemical refining of the feedstock, leading to very similar environmental impacts per tonne.
7. The remaining 7 to 8 Mt/a of aggregate output has an increasingly lower environmental impact per tonne, ranging from 220 to only 100 Pt per tonne per year. This wider range is due to the different origins of the respective feedstocks and the consequent differences in chemical processing.

7.2 Conclusions regarding the potential environmental gain

In the application of chemical products a potential environmental gain can be achieved when by this application an other environmental impact is avoided. For three example applications of chemical products, *insulation of houses*, *N-fertilizers in food production* and *modern synthetic laundry detergents,* the chemical lifecycle environmental impacts were related to the savings enabled by use of the products. The savings relate to in-use performance differences and alternative production lifecycles. For all three cases the central question

'*How large are the quantifiable environmental impact reductions due to use of a chemical product in relation to the chemical product's own lifecycle impacts*?' could be satisfactorily answered. Not with the intention to determine the overall environmental gain of the production of the Dutch chemical sector, but to show the potential for environmental gain that is correlated with the application of chemical products. The question if the gain can be attributed to the applied chemical product, is therefore not answered here.

Epilogue

This assessment has been executed in order to provide more insight in the environmental impact of the Dutch chemical industry. The VNCI will use this report accordingly:

1. As a basis for a dialogue with our stakeholders, they asked the VNCI to create more insight.
2. For our sector as a so called ‘hot spot’ analysis, it shows our members how their environmental impact relates to the total product(ion) chain.

This assessment focuses on fossil depletion and climate change as the main environmental impacts of our industry. These impacts have been a focal point for many years as part of the Long Term Agreements (now LTA3 and the LEE covenant) with a shift in the last years towards the whole production chain instead of solely focussing on the energy efficiency of our installations. Because the Dutch chemical industry is aware of it’s impact and key role in making our society more sustainable we have initiated a roadmap towards 2030 aiming at 40% greenhouse gas reduction compared to 2005 (www.routekaartchemie.nl). In this roadmap we show where we think that we can contribute with our sector in the years towards 2030. This report contributes to the roadmap that has been developed in parallel and will also be used for further action in involving companies in specific product(ion) chains.

On a wider level the VNCI members participate in the Responsible Care program in which we aim at continuous improvement of our sector on health, safety, environment, sustainable development and product stewardship.

Colette Alma, Reinier Gerrits and Arnout Schikhof, VNCI

Literature

A.I.S.E., 2011
International Association for Soaps, Detergents and Maintenance Products
Market and economic data
Website: http://www.aise.eu/go_withsub.php?pid=14&topics=4
Last accessed May 2012

Althaus et al., 2007
Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and A. Primas
Lifecycle Inventories of Chemicals : Final report Ecoinvent data v2.0 No. 8
Dübendorf : Swiss Centre for Lifecycle Inventories (Ecoinvent), 2007

Bouwbesluit, 2012
Decree of 29 August 2011 laying down rules concerning the construction, use and demolition of buildings (Dutch building codes 2012)
Website: http://wetten.overheid.nl/BWBR0030461/geldigheidsdatum_27-06-2012
Last assessed June 27th 2012

Combs, 1985
Durfee L. Combs
Processing for Industrial Fatty Acids – I
In : Journal of the American Oil Chemists' Society, Vol. 62, No. 2 (1985); p. 327-330

Davenport and King, 2006
W.G. Davenport, M.J. King
Sulfuric Acid Manufacture : Analysis, Control and Optimization, Volume 13
Oxford (UK) : Elsevier, 2006

DKL Engineering, 2004
Sulphuric Acid on the Web: Knowledge for the Sulphuric Acid Industry
Website: http://www.sulphuric-acid.com/techmanual/General/general.htm
Last accessed April 2012

Dreier, 1999
John Dreier
The Chemistry of Copper Heap Leaching: Web article 1999
Website: http://jedreiergeo.com/copper/article1/Chemistry_of_Copper_Leaching.html
Last accessed April 2012

Ecoinvent, ongoing
Ecoinvent LCI database v. 2.3 (current version)
S.l. : Ecoinvent Swiss Centre for Lifecycle Inventories
Website: http://www.Ecoinvent.org/database/
Last accessed November 2011

EPA, 1993
Thomas G. Walton, III
Phosphoric Acid and Phosphatic Fertilizers: A profile, draft
S.l. : U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, 1993

FAO, 2002
Kwasi Poku
Small-scale palm oil processing in Africa
In : FAO Agricultural Services Bulletin 148
Rome : Food and Agriculture Organization of the United Nations (FAO), 2002

FAO, 2012a
Fertilizer Use Statistics, 1996-200
Database, available online: http://www.fao.org/ag/agp/fertistat/fst_fubc_en.asp
Last accessed July 2012

FAO, 2012b
FAOStat - Production - Crops, data for the year 2000
Database, available online: http://faostat.fao.org/site/567/default.aspx#ancor
Last accessed July 2012

ICCA, 2009
International Council of Chemical Associations
Innovations for Greenhouse Gas Reductions - A lifecycle quantification of carbon abatement solutions enabled by the chemical industry, July, 2009

Index Mundi, 2009
Copper: World Mine Production, By Country
Website: http://www.indexmundi.com/en/commodities/minerals/copper/copper_t20.html
Lst accessed April 2012

IPCC
Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
Website: www.ipcc-nggip.iges.or.jp/public/gp/english/3_Industry.pdf
Montreal : IPCC, 2000

Kellenberger et al., 2007
Kellenberger D., Althaus H.-J., Jungbluth N. and T. Künniger
Lifecycle Inventories of Building Products : Final report Ecoinvent data v2.0, No. 7
Dübendorf : Swiss Centre for Lifecycle Inventories (Ecoinvent), 2007

Kingspan, 2008
Presentation to investors
Website: http://www.kingspan.com/kingspangroup/investors/fin_rep_pres/rep_pres2008/kingspaniday/kinginvday.pdf

KWA Bedrijfsadviseurs, 2012
Degree days the Netherlands (1970-2011)
Website: www.kwa.nl

Milieucentraal, 2012
Wasmiddelen
Website: http://www.milieucentraal.nl/themas/groen-en-comfortabel-wonen/schoonmaaktips/schoonmaakmiddelen/wasmiddelen
Last accessed: July, 2012

Ministry of Housing, Spatial planning and Environment, 2006
WoON 2006, Woononderzoek Nederland
Available online: http://vois.datawonen.nl/report/cow10_802.html
Website last accessed: July, 2012
The Hague : Ministery of Housing, Spatial Planning and Environment, 2006

Ministry of Housing, Spatial planning and Environment, 2011
Woningvoorraad – model SysWoV
Available online: http://syswov.datawonen.nl/
Website last accessed: July, 2012
The Hague : Ministery of Housing, Spatial Planning and Environment, 2011

Moulijn et al., 2012
J.A. Moulijn, M. Makkee and A. van Diepen
Chemical Process Technology
Chichester : John Wiley & Sons, 2001

Nemecek et al.,2007
T. Nemecek , T. Kägi and S. Blaser
Lifecycle Inventories of Agricultural Production System : Final report Ecoinvent v2.0 No.15
Dübendorf : Swiss Centre for Lifecycle Inventories (Ecoinvent), 2007

Nielsen and Skagerlind, 2007
P. Nielsen, P. Skagerlind, Novozymes A/S
Cost-neutral replacement of surfactants with enzymes
In : Household and Personal Care Today, 4/2007

Agentschap NL, 2011
Voorbeeldwoningen 2011: Bestaande bouw
Sittard: Agentschap NL, Energie en Klimaat

Patel et al., 1999
M.K. Patel, A. Theiß, E. Worrell
Surfactant production and use in Germany: resource requirements and CO_2 emissions
In : Resources, Conservation and Recycling, Vol. 25, Iss. 1 (1999); p. 61-78

ReCiPe, ongoing
RIVM, CML PRé Consultants, Radboud Universiteit Nijmegen, CE Delft
ReCiPe methodology for Lifecycle Impact Assessment S.l.: ReCiPe, v. 1.06 (current version)
Available online: http://www.lcia-recipe.net/
Website last accessed: May 2012

RPA, 2006
Non-surfactant Organic Ingredients and Zeolite-based Detergents, final report
London : Risk & Policy Analysts Limited (RPA), 2006

SimaPro v 7.3.3., ongoing
Pré Consultants
LCA software
Amersfoort; Washington DC: Pré Consultants, 2012

Styrene Producers Association, 2012
Eric Faes, PlasticsEurope Styrenics chain
E-mail communication: April, 2012

VNCI, 2011
Association of Dutch Chemical Industry
De Nederlandse Chemische Industrie: Internal document
Leidschendam : Association of Dutch Chemical Industry (VNCI), 2011

Wikipedia 2012
Online encyclopedia
http://www.wikipedia.org

WWF, 2011
Palm Oil Buyers' Scorecard 2011: Measuring the Progress of Palm Oil Buyers
Gland: World Wide Fund For Nature (WWF) (Formerly World Wildlife Fund), 2011

Zah and Hischier, 2007
R. Zah and R. Hischier
Lifecycle Inventories of Detergents: Final report Ecoinvent data v2.0, No. 12
Dübendorf : Swiss Centre for Lifecycle Inventories (Ecoinvent), 2007

Annex A Remarks on data processing for flow model

A.1 Remarks on data for high volume chemical analyses

There are a number of chemicals of relevance for this study with no production capacity in the Netherlands: phenol from the cumene process, for example. In cases where these substances are used as intermediate feedstocks, production levels have been calculated at the level needed for their present use as a feedstock and the environmental impacts have been attributed to these production levels. Although the impact of production does not physically occur within Dutch national borders, then, the associated impact of the production process has been incorporated in the present analysis.

Similarly, for methanol there is only limited production capacity in the Netherlands. Dutch formaldehyde and MTBE production require larger amounts of this feedstock than can be produced domestically and so the remainder is imported. The impacts of this methanol production have been incorporated in the present analysis, too, using environmental data applicable to European production. The impacts of the import itself (i.e. transport) have not been included in the analysis, though. While quantification of import/export levels of different feedstocks is also feasible, this did not form part of the analysis.

For certain chemicals there were no data available on production capacities in the Netherlands: isobutene and EDC, for example. In such cases pragmatic assumptions based on stoichiometry and assumed process conversion rates were adopted to resolve these data deficiencies. In the remainder of this annex we detail these assumptions and their consequences, with in many cases reference to the data cited in (VNCI, 2011), referred to further as 'the VNCI report'.

Ethylene, ethylene oxide, polyethylene

- The VNCI report assesses that 15% of Dutch ethylene production is used for Vinyl Chloride Monomer (VCM) manufacture, 15% for ethylene oxide and 50% for polyethylene. Based on production capacities, more accurate figures would seem to be: 10% - 10% - 60%. For the case of VCM production, the figure of 15% would amount to some 0.6 Mtpa, which is significantly more than Shin-Etsu needs for its production process in Botlek. It is illogical to assume that the ethylene from Dutch steam crackers goes to VCM production in Belgium and Germany as long as it follows from production capacities that the Netherlands is a net importer.

Ethyl benzene and styrene

- For ethyl benzene, there is some confusion in the text of the VNCI report: the table in Appendix 1 shows 2.57 Mtpa of production capacity for ethyl benzene in the Netherlands (Dow 1200 ktpa, Lyondell 720 ktpa, Shell 650 ktpa), whereas the table on p.10 shows no production capacity at LyondellBasel and 520 rather than 1,200 ktpa for Dow. In Terneuzen, ethylbenzene capacity is now officially 575 ktpa (Styron).
- For styrene, for the analysis we assumed a production capacity of 2.2 Mtpa of styrene (Styron 500 ktpa, Shell 450 ktpa, Ellba 550 ktpa, Lyondell/Bayer 640 ktpa).

- For the flow analysis we presumed that 90% of ethyl benzene goes to styrene manufacture and 10% goes to other uses. In the analysis, a capacity for ethyl benzene of 2.6 Mtpa is used.
- For styrene, the environmental impact used in the analysis is the weighted average of the impacts resulting from Ecoinvent data for styrene production via dehydrogenation of ethyl benzene (inventory from PlasticsEurope) and a multi-output process constructed for the SM/PO process employed at Maasvlakte and Moerdijk, with lower environmental impacts. For this multi-output process, see the remarks under propylene oxide.

Ethylene glycol

- The VNCI report mentions both 300 ktpa (p.37) (Shell and Dow) and 155 ktpa production capacity (Shell). The average was taken.
- Based on stoichiometry and the amount of ethylene oxide needed from Ecoinvent, 0.5 Mtpa of EtOx production capacity, 37% and not 60%, as stated in the VNCI report, was assumed to go to glycol production.

Ethylene dichloride (EDC) and vinyl chloride (VC)

- There are no data on EDC production capacity in the VNCI report. EDC production capacity is estimated at 1.1 Mtpa, of which we assumed that 90% is for VCM production, allowing for 0.62 Mtpa VCM production capacity and leaving around 0.1 Mtpa of EDC for other purposes.
- The following table shows the feedstocks for EDC and VCM from the two chlorination routes, with the associated feedstocks.

Table 12 Feedstocks for the two production routes towards EDC and VCM (stoichiometrically)

Chlorination, Mtpa	% share	VCM	EDC	Chlorine	Ethene	HCl
Direct chlorination	40%	0.24	0.39	0.28	0.11	0.14-
Oxychlorination	60%	0.37	0.58		0.16	0.21
Total		0.61	0.97	0.28	0.27	0.07

- While calculating the environmental impacts of VC and its constituent platform chemicals, it was established that there is a mismatch in the Ecoinvent LCI data for VCM production relative to the Ecoinvent LCI data for VCM's constituent platform chemicals such as EDC, HCl and chlorine. The ReCiPe single indicator for VCM amounts to 203 MPt/Mtpa, while it is 169 MPt/Mtpa for EDC. These results are contradictory since, combined with the above Mtpa values, it would attribute higher impacts to EDC (169 x 97) than to VCM production (203 x 61). For consistent analysis a correction to the LCI data was therefore necessary.
- The reason for the mismatch within the Ecoinvent LCI inventory is unknown. It could be due to different data sets being used. The LCI data for VCM are based on the Eco-Profile from PlasticsEurope (APME), whereas the LCI data for EDC are from Ecoinvent itself (Althaus *et al.*, 2007). Without pronouncing on the quality of either data set, we opted to take their 'average', as follows. The fraction of the environmental impacts of EDC production that is an 'overshoot' is attributed to VCM production, and removed from EDC production. This means the ReCiPe scores were multiplied by 0.76 for EDC and by 1.32 for VCM. This leads to the impacts resulting from the APME LCI data being applied to EDC production, and the impacts resulting from Althaus *et al*. (2007) being applied to VCM production.
- In Ecoinvent there are a number of processes available for the impact data of hydrochloric acid. The impacts are generally rather low, as most of the HCl used is a useful co-product of chlorinated hydrocarbon conversion processes and the allocation of impacts is then more towards the primary

product (e.g. because of allocation by economic value). For the impacts, the Ecoinvent process 'Hydrochloric acid, 30% in H2O, at plant/RER S' was therefore adopted, because this HCl stream is associated with isocyanides/ MDI production, which is representative for at least a significant part of the Dutch chlorine cycle. The impact level of this process is also approximately the average of the available processes for HCl within Ecoinvent.

Isobutene

- No production capacity for isobutene is cited in the VNCI report. Such a figure is needed to do the calculations on MTBE, however. It was estimated at 0.8 Mtpa, based on assumptions about naphtha cracking fractions: approx. 6% wt. for butenes, approx. 24% wt. for ethylene and 3.85 Mtpa total ethylene from naphtha cracking.

Polypropylene

- The VNCI report assesses that 40% of propylene is used for polypropylene (PP) production. This would mean a production of PP of 0.92 Mtpa. The Dutch PP production capacity is around 0.78 Mtpa, so, with a propylene feedstock requirement of 0.74 Mtpa, approximately 33% and not 40% of the Dutch propylene goes to polypropylene manufacturing in the Netherlands.

Propylene oxide

- In Ecoinvent the environmental data for the PO process is inventoried for the propylene oxide-chlorine (chlorohydrin) process. While this is a conventional production route, it is not representative of the route employed in the Netherlands, which is co-oxidation of propylene with isobutane or ethyl benzene. The combined SM/PO process is used by LyondellBasell (Maasvlakte), Shell and Ellba, and the TBA/PO process by LyondellBasell (Botlek).
- For this reason, new processes were set up in SimaPro reflecting the Dutch situation. The mass balance is given in the following table. Allocation of environmental impacts was done on a mass basis. For both propylene oxide and styrene monomer, the resulting weighted environmental impacts are significantly lower than the values reported in Ecoinvent.

Table 13 Feedstocks for co-production of styrene and propylene oxide, and for co-production of propylene oxide and MTBE

	In:			Out:		
	Propylene	Ethyl benzene	Isobutane	Styrene	Propylene oxide	MTBE
Molar mass (g/mol)	42	106	58	104	58	88
Dutch production capacities:						
PO/SM process, Mt/a	0.57	1.76		1.64	0.75	
PO/TBA process, Mt/a	0.19		0.41		0.25	0.59
Per kg PO:						
PO/SM process, kg/kg PO	0.76	2.36		2.20	1.00	
PO/TBA process, kg/kg PO	0.76		1.64		1.00	2.36

Acrylonitrile

- The VNCI report assesses that 15% of propylene goes to acrylonitrile production. This would be about 0.35 Mtpa, more than required for Dutch acrylonitrile production capacity. From stoichiometry and Ecoinvent it follows that around 0.25 Mtpa of propylene is used in acrylonitrile production, implying that 11% of propylene goes to this route.
- In addition, using data from Ecoinvent it follows that 0.11 Mtpa of ammonia is required.

MTBE

- To accommodate market needs, MTBE plants generally have a certain flexibility to produce either methyl tertiary butyl ether (MTBE) or ethyl tertiary butyl ether (ETBE). In this study, full capacity has been allocated to MTBE, not ETBE.
- As with the other processes, impacts were taken from Ecoinvent, as these are comparable with those computed from the customised PO/TBA process (see discussion under Propylene oxide).
- Using Ecoinvent data, methanol consumption was estimated at 0.33 Mtpa.

Phenol

- As there is no Dutch production capacity for phenol from cumene, we assumed an amount applicable to bisphenol A production. For 0.4 Mtpa of bisphenol A production, stoichiometrically and from Ecoinvent 0.37 Mtpa of phenol is needed. This is associated with 0.45 Mtpa of cumene production (approx. 50% of total cumene/approx. 10% of benzene) and approx. 0.04 Mtpa of toluene (unconventional production route).
- In the cumene process, phenol is co-produced with acetone. Allocation of feedstocks was based on mass flows, as shown in Table 14.

Table 14 Allocation of feedstocks for co-production of phenol with acetone

	In:			Out:	
	Cumene	**Oxygen**	**Propylene**	**Phenol**	**Acetone**
Molar mass (g/mol)	120	32	42	94	58,05
Per kg phenol (kg/kg)	1.34	0.36	0.47	1.00	0,65
Allocation of mass flows to end products					
To phenol	0.82	0.22	0.29	61%	
To acetone	0.53	0.14	0.19	39%	
Total	1.34	0.36	0.47	100%	

- Oxygen is not regarded as a separate platform chemical in our analysis. The impacts associated with an air separation unit are therefore counted in the impacts of the phenol production process.

Benzoic acid

- We took the percentage of toluene for ‘other derivatives’ (11%) as going to benzoic acid production. The environmental impacts of benzoic acid production were assessed as the average of the impacts of toluene (the feedstock) and of phenol. This approximates the production route of phenol from toluene in a two-step oxidation process via benzoic acid. Benzoic acid is also sold as an end product.

Nitric acid

- The VNCI report states that about 15% of ammonia output is associated with nitric acid production. However, based on the Ecoinvent figure of 0.29 kg ammonia input per kg nitric acid and Dutch production capacity, 0.7 Mtpa of ammonia goes to this route, which would be about 30% of the total.

A.2 Remarks on data for analyses of selected chains

A.2.1 Styrene

For assessing the impacts of crude oil production, the crude oil mix used in the Ecoinvent process for 'Naphtha, at refinery/RER' was analysed. Because of the impacts of transportation to the Netherlands, the origin of the crude oil is relevant. The composition of the crude oil mix used in this country is given in Table 15.

Table 15 Composition of crude oil used in the analysis

Origin of crude oil	Fraction
Russian Federation	18%
Latin America & the Caribbean	1%
Middle East	25%
Africa	11%
Nigeria	3%
Norway	23%
Great Britain	18%
Netherlands	0,3%

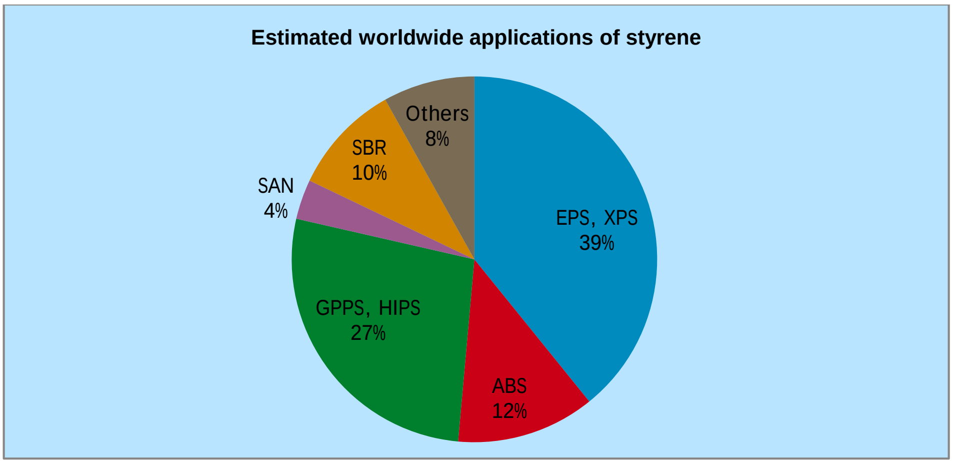
- The impacts of the benzene production step have been allocated on a 50/50 basis to the subsequent steps of pygas production and conversion to benzene.
- As processes for SBR are not available in Ecoinvent, 'Synthetic rubber/RER' was used instead.
- No process for HIPS is available in Ecoinvent. As it is available in the ELCD database, which reports impacts approximately equal to those of GPPS in Ecoinvent, the Ecoinvent process for GPPS was used in the impact analysis.
- The Ecoinvent process for EPS ('Polystyrene, expandable, at plant/RER') has lower environmental inputs associated with it than the styrene monomer process via dehydrogenation of ethyl benzene. Similarly to the flow analysis of high volume chemicals (Section 3.3), for styrene production we used a weighted average of the Ecoinvent data and a multi-output process constructed for the SM/PO process with lower environmental impacts.
- Feedstock inputs for the various production steps were derived from different processes, and where lacking in available databases (e.g. Ecoinvent), pragmatic estimates were made. The feedstock requirements are outlined in in matrix form in Table 16.

Table 16 Feedstocks of different products used in the styrene chain analysis

Product (1kg)	Amount of feedstock							
	Naphtha	Pygas	Ethylene	Benzene	Ethyl benzene	Styrene	Acrylonitrile	Butadiene
Ethylene	1.03							
Benzene		1.05						
Pygas	1.03							
Ethyl benzene			0.27	0.76				
Styrene					1.07			
EPS, XPS						1.04		
ABS						0.53	0.26	0.26
HIPS, GPPS						0.84		0.21
SAN						0.79	0.26	
SBR						0.41		0.64

The data sources and assumptions for Table 16 are:
- Refinery and naphtha cracking processes are multi-output processes. In the Ecoinvent LCI the process data are already allocated, on a mass basis. The underlying data are from PlasticsEurope and reflect data for around the year 1999.
- According to the Ecoinvent dataset, naphtha feedstock use per kg of ethylene is 1.03 kg/kg, implying an ethylene-attributable conversion loss of 3%.
- This figure of 1.03 kg/kg was also used for pygas production.
- Conversion of pygas to benzene is estimated to be accompanied by a loss of 5%.
- Figures for ethylene and benzene consumption for ethyl benzene production were taken from Ecoinvent.
- Conversion from ethyl benzene to styrene based on molar mass and 95% conversion.
- Use of feedstocks for the different styrene polymers, plastics and rubbers were estimated on a mass fraction basis, incorporating a 5% loss of material in production steps.
- For ABS, HIPS, SBR pragmatic assumptions were made regarding the styrene, acrylonitrile and butadiene feedstocks, reflecting averages of a range of possible values for the monomers (which in practice depend on the application concerned).
- As a starting point for global data on styrene applications, the global production data for the different materials from the VNCI report were taken, with an adjusted figure for SBR being incorporated by assessing the market for tyres. A subdivision of polystyrene into plastics (HIPS, GPPS) and expandable materials (EPS, XPS) was made by extrapolating from the Dutch breakdown, a rough-and-ready approach. The resulting use of styrene for different styrene-derived end materials is shown in Figure 56.

Figure 56 Approximate breakdown of styrene applications (global); total = 30 mtpa of styrene



A.2.2 Sulphuric acid chain

Dutch output of P-fertilizers was assessed based on the following information from the VNCI report:

Table 17 Dutch fertilizer manufacturers (manufacturer's names suppressed)

Manufacturer:	**Production**		**Description**
Manufacturer 1	320	ktpa	Supply of sulphuric acid for fertilizers
Manufacturer 2	550	ktpa	Phosphate fertilizers, from phosphate rock
Manufacturer 3	750	ktpa	Ureum fertilizers
Manufacturer 3	1,800	ktpa	Nitrate fertilizers
Manufacturer 3	1,350	ktpa	Ammonia
Manufacturer 4	2,200	ktpa	Base products, integrated with ammonia and nitric acid production
Manufacturer 4	945	ktpa	Nitric acid
Manufacturer 4	850	ktpa	Ammonia
Manufacturer 5	500	ktpa	Both P and N fertilizers
Total fertilizer production	5,800	ktpa	P and N fertilizers
Total P fertilizers	**800**	**ktpa**	

Regarding the importance of transport processes for Triple Super Phosphate (TSP), in the chain analysis we opted to subtract the impacts of the upstream parts of the process. This was done by assessing the impacts of the production of the *feedstock* for the process in question. By choice, for our impact analysis of the 'unique contribution' we did not subtract the heat inputs or transport processes associated with the production process. This leads to the higher than expected impacts of TSP.

A.2.3 Nitric acid chain

Aggregate Dutch N-fertilizer output (5 Mtpa) was interpreted as the sum of all the N-fertilizers sold to the agricultural sector. The feedstock part of AN (2 Mtpa) was therefore attributed to the share 'base chemicals and intermediates'.

A.2.4 Fatty acids chain: plant oils to detergents

To assess the plant oil-surfactants chain, we assumed that all surfactants are from oleochemical feedstock and then assessed the resultant impacts. The processes used were as follows:

- For the non-ionic surfactants Ecoinvent provides a mixed process using a range of Alcohol Ethoxylates (AE): equal mixes of AE3 and AE7 from palm kernel oil (PKO), coconut oil (CNO) and petrochemical feedstock. As the petrochemical route is not the focus of our assessment, however, the process was adjusted to comprise a mix of all the relevant oils, including palm oil (POI), as follows:

17%	AE3 - Palm kernel oil
17%	AE3 - Coconut oil
17%	AE7 - Palm kernel oil
17%	AE7 - Coconut oil
33%	AE11 - Palm oil

- Similarly, the Ecoinvent mix for anionic surfactants of the type Fatty Alcohol Sulphates includes a mix of oleochemic and petrochemic feedstocks. For our analysis a new process was created with the following composition:

33%	Fatty alcohol sulphate from POI
33%	Fatty alcohol sulphate from PKO
33%	Fatty alcohol sulphate from CNO

To validate the relative shares of plant oils, data on German surfactant production volumes for the year 1996 were taken; these are aggregated in Table 18.

Table 18 German production data for surfactants (Patel *et al*., 1999[11])

	Total surfactants (ktpa)	**Of which petrochemical (ktpa)**	**Of which oleochemical (ktpa)**	*Oleochemical PKO*	*Oleochemical CNO*	*Oleochemical pol*
Soap	129		129			
LAS	100	100	0			
SAS	40	40	0			
AS	30	18	12	9	3	
AES	80	24	56	16	40	
Total of anionics	*379*					
AE	165	33	132	28	10	94
APG	20		20	6	14	
Total non-ionics	*185*					
Others	305					
Total	869		349	59	67	94
	100%	**38%**	**62%**	**10%**	**12%**	**17%**

11 M.K Patel, A Theiß & E Worrell, Surfactant production and use in Germany: resource requirements and CO_2 emissions, Resources, Conservation and Recycling, Vol. 25, Iss. 1, January 1999, p. 61-78.

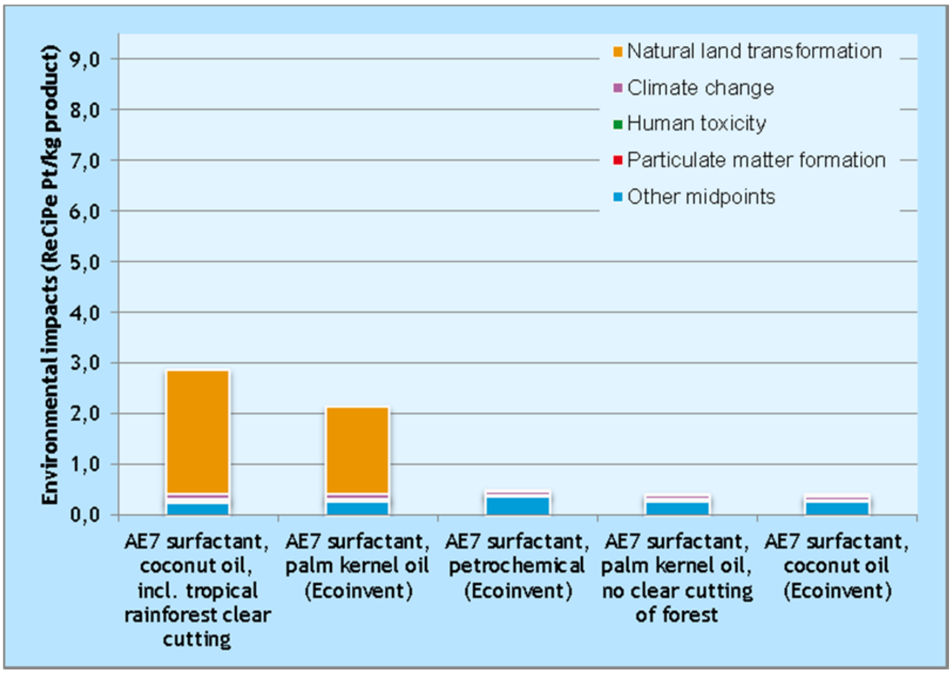
Coconut oil and land transformation

With regard to coconut oil, the inventory reported in the Ecoinvent database derives from the so-called ECOSOL study commissioned by the European Surfactants Association, CESIO. Although this does include land transformation, the assumption is that the forest was already in use for intensive clear-cutting. In the ReCiPe impact assessment with European normalization (see next paragraph), land transformation from (primary)tropical rainforest to plantation forest has a roughly thirty times greater impact, and this was adopted in the present study.

Land transformation and normalization

In Europe, degradation of primary forest is viewed considerably more critically than is generally the case in developing countries. To reflect this, the ReCiPe methodology gives users the option of adopting different perspectives and normalization methods. In this study we used the 'European' normalization. If 'World' normalization figures are used, the land transformation issue becomes less severe. Figure 57 is the same figure as Figure 49 but now with the world perspective.

Figure 57 Comparison of feedstock effects for alcohol ethoxylate (AE) surfactants, using ReCiPe 'World normalization'

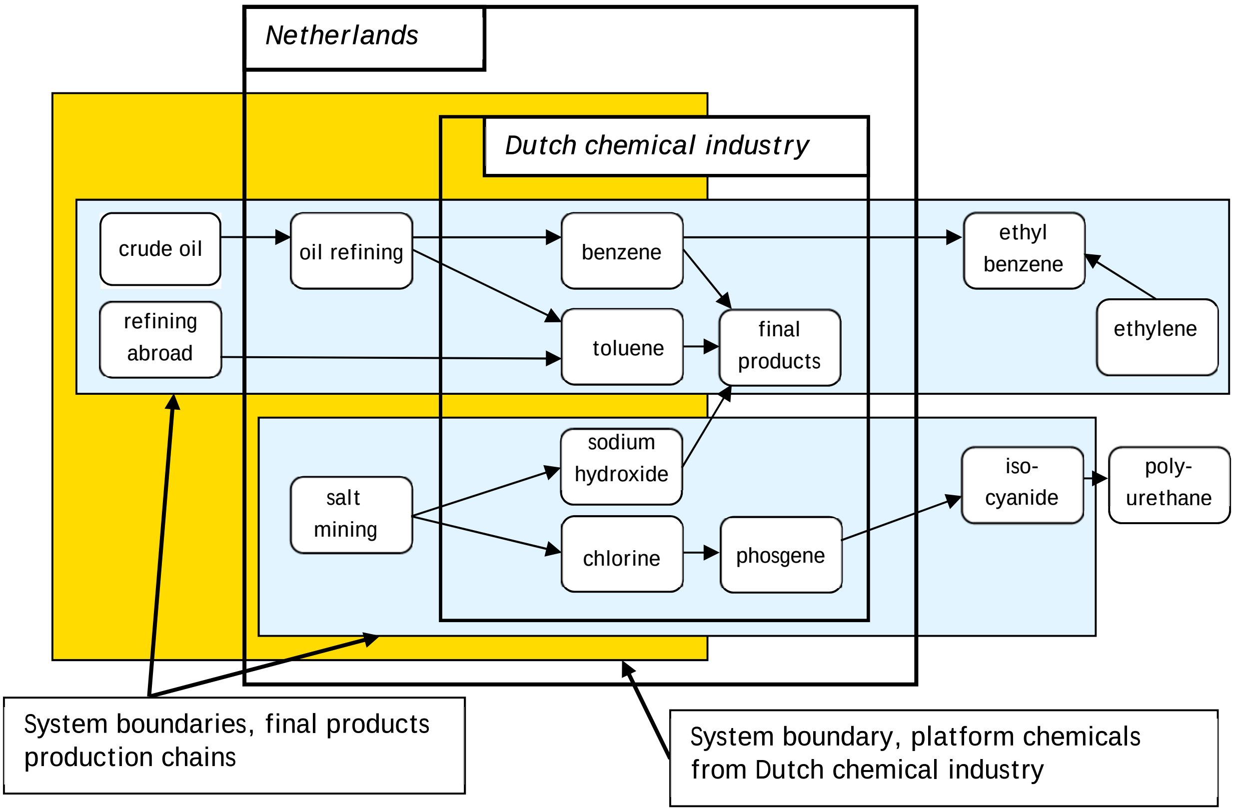


Annex B Impact assessment methodology

B.1 System boundary definition

Figure 58 provides a schematic overview of the system boundaries for the two main assessments performed in the present study and how they relate to processes inside and outside the Netherlands and the Dutch chemical sector. By way of illustration, two (fictitious) chains have been introduced, which help explain the approach adopted in this study.

Figure 58 Schematic overview of the system boundaries of assessments



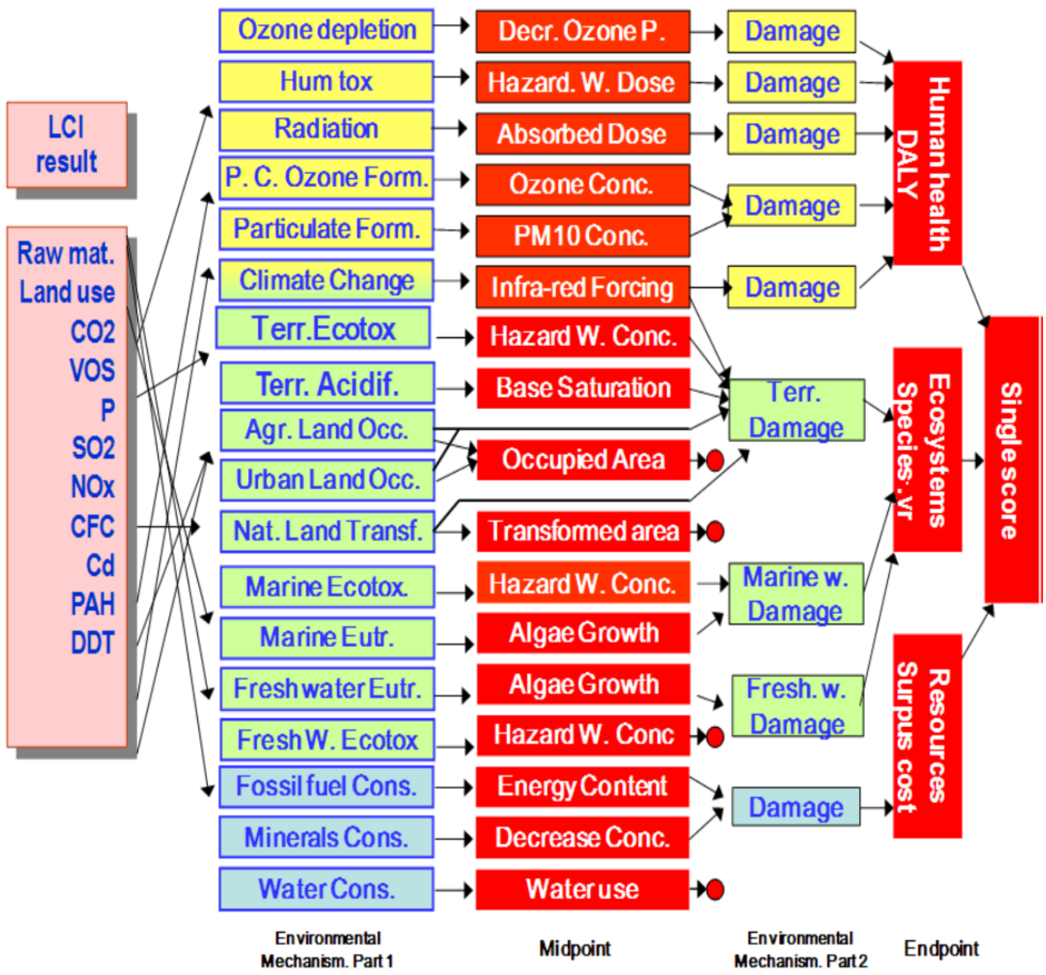
The system boundary adopted for assessing the platform chemicals produced by the Dutch chemical sector is given by the yellow box. In principle this includes all the chains passing through de chemical sector in the Netherlands, since almost all chemicals are based on platform chemicals. It includes all the resources and production processes required for producing these platform chemicals. However, it does not include the processes within the Dutch chemical sector for production of intermediates (e.g. MDI from chlorine) and final products. This was done intentionally to avoid double counting.

The platform chemicals are produced as separate products, for which the supply chains are clear and easy to separate. For products produced further down the chains, however, this is far less clear, and there is then a very real chance of double counting (part of) the supply chain. If, for example, ethyl benzene were counted as a platform chemical alongside benzene and ethylene, this would lead to double counting of the supply chain of benzene and ethylene. In this case it is obvious, but in other cases it is often much less clear. All high volume chemicals have therefore been placed in a mass balance for the entire chemical sector to avoid double counting.

B.2 ReCiPe impact assessment method

The ReCiPe impact assessment is built up around so-called midpoint and endpoint indicators, as summarized in Figure 60.

Figure 59 Relations between LCI results, environmental effects, midpoint indicators, assessment of environmental damage, and endpoint analysis weighed at single score level



B.3 Example: Allocating the environmental impacts along the mass flows

Demonstration of calculation method

To demonstrate the calculation method used for the flow analysis, as an example we work through calculation of the environmental impacts associated with production of ethylene oxide (EO) from ethylene. In this case the following data are required:

- production volumes of ethylene and ethylene oxide;
- the amount of ethylene going to ethylene oxide production;
- the environmental impacts of ethylene and ethylene oxide production.

Production volumes

VNCI (2011) assesses that 15% of Dutch ethylene production (by volume) goes to polyethylene, ethylene oxide, vinyl chloride, ethyl benzene and other derivatives. The VNCI report gives no actual volumes, however, citing production capacities instead. Throughout this study, therefore, it was opted to employ production capacity as a proxy for volume, regardless of actual output levels. Although the impact analysis flow tool permits adjustment to allow for actual production levels, for this study we assumed a level of 100% production.

Amount of ethylene for ethylene oxide production

Ethylene has a stated Dutch production capacity of 3.8 Mtpa (from steam crackers at Dow Terneuzen, Sabic Geleen and Shell Moerdijk). The allocation of this ethylene to the various end uses according to VNCI (2011) is shown in Table 19.

Table 19 Allocation of ethylene to derivative products

	Total	Polyethylene	Ethylene oxide	Vinyl chloride (via ethylene dichloride)	Ethyl benzene	Other ethylene derivatives
Fraction to derivatives	100%	50%	15%	15%	10%	10%
Ethylene (Mtpa)	3.8	1.9	0.6	0.6	0.4	0.4

A check on this allocation was performed for the different derivative products, with their different molar masses. For example, ethylene oxide has a molar mass of 44.1 g/mol and ethylene 28 g/mol. With the aforementioned figure of 0.6 Mtpa ethylene going to ethylene oxide production, based on stoichiometry and assuming full conversion, this would equate to 0.9 Mtpa of ethylene oxide.

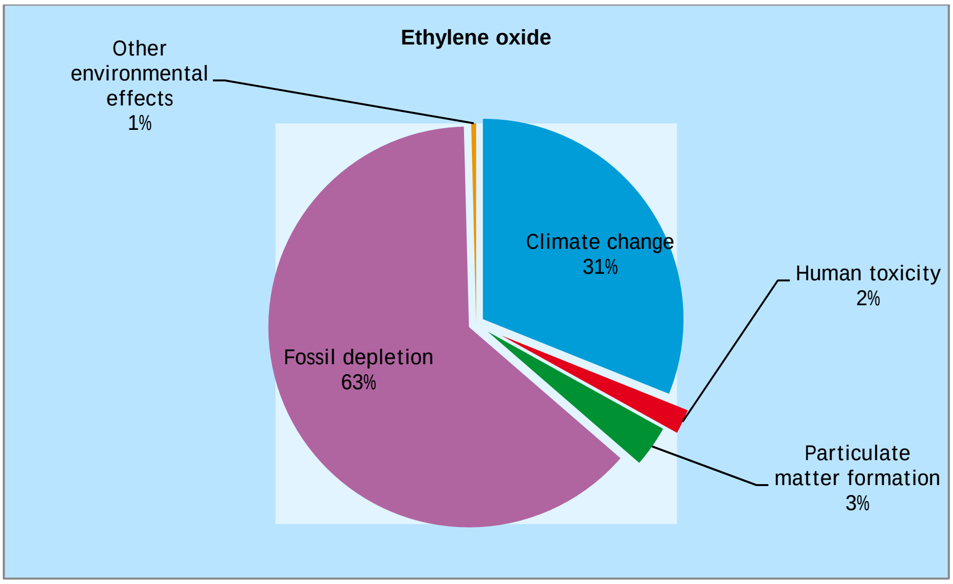
This figure seems high. Even allowing for lower conversion efficiencies, it is still significantly higher than Dutch ethylene oxide production capacity: 0.44–0.5 Mtpa. A comparison with the production levels of other derivative products leads to a revised estimate of the percentages of ethylene going to end products: 60% to polyethylene, 10% to ethylene oxide, 10% to ethylene dichloride and (unchanged) 10% to ethyl benzene and other derivatives. It was with these data on volumes and flows to ethylene oxide that environmental impacts were assessed.

Environmental impacts

For the environmental impact of ethylene production, the Ecoinvent process 'Ethylene, average, at plant/RER S' was taken. This process is representative of ethylene from steam crackers as produced in Europe, using LCI data from the Ecoprofiles of PlasticsEurope (APME), and is inventoried for 19 production sites (with a combined capacity of 7.8 Mtpa). The environmental impact of ethylene production from naphtha is 257 MPt/Mt. The unit of this impact is the aggregate single indicator ReCiPe score, scaled to a megatonne of ethylene at the pipeline. Assuming maximum production volumes from the available capacity, the impact of ethylene is 982 MPt/year, the highest figure for any platform chemical.

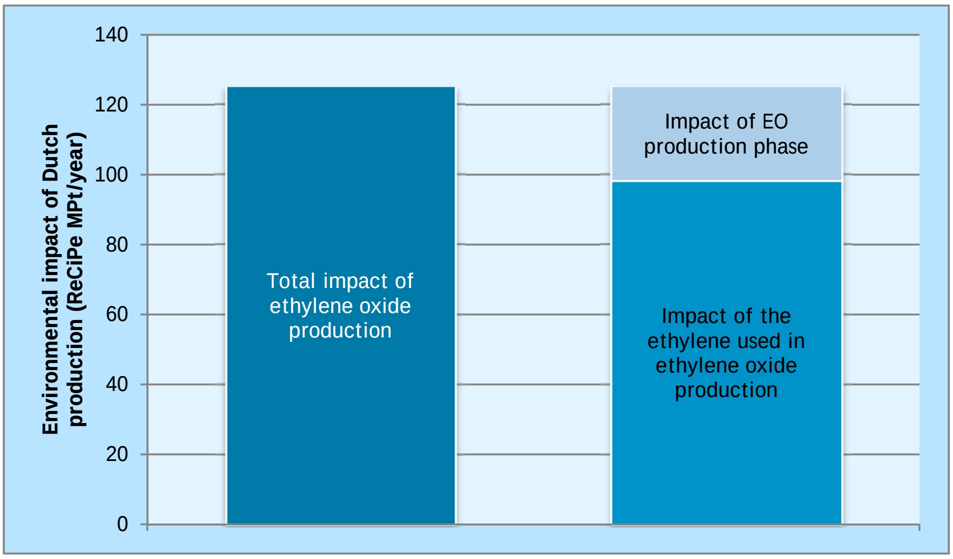
For the impact of ethylene oxide production, the Ecoinvent process 'Ethylene oxide, at plant/RER S' was used. This process holds for European production. The impacts amount to 268 MPt/Mt, or 125 MPt for total annual output. The impacts relate mainly to the environmental effects expressed as ReCiPe fossil depletion and climate change, as illustrated in Figure 60.

Figure 60 Environmental impacts of ethylene oxide production



In the calculation tool the impacts of ethylene oxide production can be computed with a breakdown into contributions from platform chemicals and intermediate chemicals. For EO this is illustrated in Figure 61, which shows on the right the relative contribution of the ethylene platform chemical.

Figure 61 Total impact of ethylene oxide production, with relative contribution of platform chemical



Annex C Methodology of ICCA report

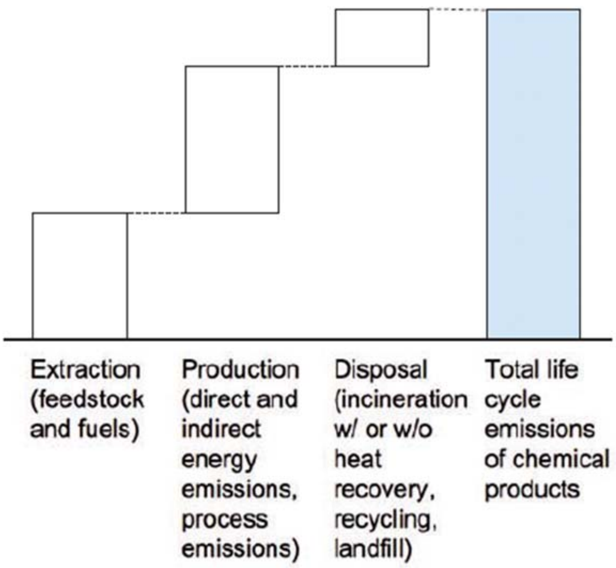
For the comparative screening LCAs performed in Chapter 6 if this study, the scope and assumptions of the ICCA report 'Innovations for greenhouse gas reductions' (ICCA, 2009) were followed as closely as possible. A brief description of this report is provided in the following text box.

The ICCA report on 'Innovations for Greenhouse Gas Reductions' (ICCA, 2009)
For the ICCA, McKinsey researched the global chemical industry's impact on greenhouse gas emissions by assessing the lifecycle impact of chemical products and the difference these chemical products make by preventing GHG emissions in their applications. In the ICCA report, the CO_2(-equivalent) emissions of a broad range of chemical applications were researched. The report compares the CO_2 lifecycle impact of the chemical product compared with the CO_2 impact of a non-chemical alternative fulfilling the same function and preserving the same lifestyle. The conclusion is that there are many applications where large savings in CO_2 emissions can be attributed to the use of chemical products. The three most important applications identified are:
- insulation materials for the construction industry;
- chemical fertilizers and crop protection;
- lighting solutions: the CFL.

Plastic packaging, marine antifouling coatings, synthetic textiles, automotive plastics, low-temperature detergents, engine efficiency and plastics for piping are also cited as important applications where large savings result.

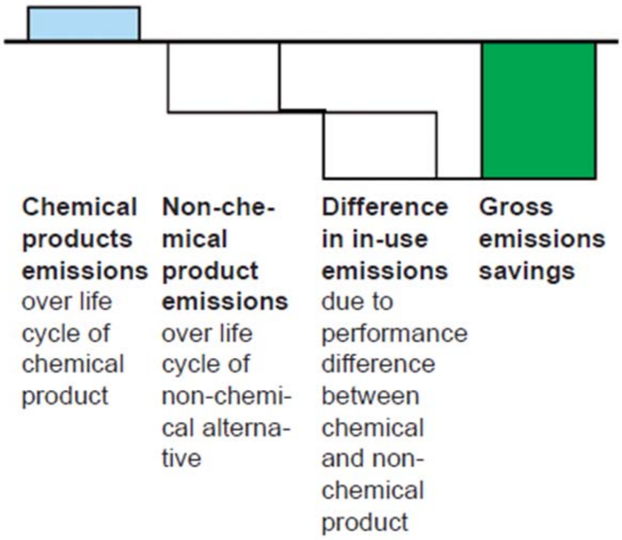
The results of the present report are presented according to the approach adopted in the ICCA report. In assessing the environmental impacts of a given chemical product, all the stages of its lifecycle are incorporated (cradle-to-grave), as illustrated in Figure 62.

Figure 62 Lifecycle emissions of products (ICCA, 2009)



In addition to the lifecycle emissions of a chemical product, a product can have use phase impacts that are either positive or negative. A positive use phase impact (i.e. an impact saving) can occur due to mitigated or prevented other impacts. In the ICCA study the reductions in environmental impact enabled by use of the respective chemical products were assessed by comparing the use-phase impacts of the chemical product with those of a realistic alternative reference involving use of a non-chemical product. There are often two types of savings, as schematically illustrated in Figure 63:
- savings due to higher lifecycle impacts of the non-chemical product;
- savings due to the in-use performance difference between the reference and the chemical product.

Figure 63 Calculation scheme for gross impact savings due to a chemical product (ICCA, 2009)



The gross impact savings arising through use of the chemical product can be normalized with respect to that product's lifecycle impacts, permitting a statement that by using the chemical product, for every unit of environmental impact resulting from its application, there are *impact savings* of X times that amount. This is referred to as the '**X-factor'** of the chemical product.

Annex D Derivation of average insulation level of Dutch dwellings

The Dutch government has data on a large number of houses in the country's building stock of currently 7.2 million houses (Ministry of Housing, Spatial planning and Environment, 2011). For the purpose of providing energy policy advice, thirty types of dwelling representative of all 7.2 million have been inventoried in detail (NL Agency, 2011). From this dataset the following data can be derived:

- the total amount of hard surface area that can be insulated (flat roof, inclined roof, ground level floor, closed front/back facade, closed side facade);
- the heat resistance value (r_c) per surface area for the thirty dwelling types;
- the combined weighted average heat resistance value of all Dutch houses.

The total amount of hard surface area of Dutch dwellings that follows from these data is shown in Table 20.

Table 20 Surface area of structural elements of Dutch houses (x10^6 m^2)

	Ground level floor	Flat roof	Inclined roof	Closed back/front façade	Closed side facade
Area	348	81	374	443	80
Total					1,325

The combined R_c for these areas based solely on this data source would be an underestimate, as many houses have retrofitted insulation, which is not incorporated in the data set. The actual level of insulation, including retrofitted measures, is an aspect that is being researched in the Dutch government's WoON survey (Ministry of Housing, Spatial planning and Environment, 2006). As of 2006, the percentage of dwellings with insulation measures applied to their various structural parts is as shown in Table 21.

Table 21 Percentage of dwellings with insulation measures applied to relevant structural elements

	Ground level floor	Roof	Wall
Number of dwellings with some degree of insulation of:	43%	76%	55%

Source: Ministry of Housing, Spatial planning and Environment, 2006.

Combining these data sources yields an average R_c value for all the hard surfaces of 1.6 $m^2 \cdot K/W$. This value can be used in calculations the scope still available for further insulation. Clearly, the value is lower than the Dutch building decree of 2012 (Bouwbesluit, 2012), which mandates a R_c of 3.5 $m^2 \cdot K/W$ for newly built houses and renovation projects.