Comparative life cycle assessment of polyethylene based on sugarcane and crude oil

CHRISTIN LIPTOW
ANNE-MARIE TILLMAN

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
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SE-412 Göteborg
Sweden
Telephone + 46 (0) 31 772 1000

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1. Summary

The goal of this study was to assess the environmental performance of low density polyethylene (LDPE) based on Brazilian sugarcane ethanol and compare it to LDPE based on crude oil and to answer the question if it is environmentally preferable in the production of goods and packaging in Europe. The production routes were compared in a life cycle perspective.

The investigated life cycles start with the cultivation of sugarcane in Brazil and extraction of crude oil in the Middle East, followed by the production of LDPE in Brazil and Europe, respectively. The LDPE was assumed to be used in Europe for both alternatives. A generic waste treatment scenario was applied, incineration, with recovery of the released heat to electricity. The assessment method used was life cycle assessment (LCA) in its two methodological approaches – consequential and attributional LCA. The two approaches were consistently applied in parallel to investigate the impact of methodological choices on the outcome of the LCA.

Use of fossil fuels and release of greenhouse gases were considered to be the two most important types of environmental impact in the study. As may be expected, the use of fossil fuels proved to be much lower for the sugarcane based LDPE.

The results for global warming show that, if effects of land use change are disregarded, the sugar cane route comes out much better than the oil based route. However, there *are* greenhouse gases released as a consequence of the rapid land use changes taking place in Brazil. It has not been possible to quantify the extent of these emissions with any degree of certainty, but the available data indicate that the effects of land use changes may be significant. The emissions may even be in the order of magnitude to flip the ranking between the oil based and the sugarcane based route to LDPE. But again, the data are too uncertain to allow for any ranking of the alternatives with respect to global warming potential.

What may be said though is that if the feed-stock were to come from some type of biomass that does not imply land use changes, LDPE based on ethanol is probably an environmentally much better alternative than LDPE based on oil.

In summary, polyethylene based on ethanol uses significantly less fossil fuels than the oil based alternative, and has the potential to significantly reduce emissions of greenhouse gases. However, as long as the ethanol is based on sugarcane, the cultivation of which leads to land use changes, there is considerable risk that the positive effect on greenhouse gas emissions is overturned by emissions resulting from land use changes.

The *dominance and sensitivity analyses* showed that the surrounding technical systems, such as electricity production system and waste management system have a large influence on the results. This was most clearly demonstrated by placing the oil-based route in a Swedish context (oil from North Sea, Swedish electricity production mix). The effect was a dramatically reduced environmental impact, particularly in terms of acidification, eutrophication and photochemical oxidant formation. Shorter transport distances also drastically reduced acidification, and to a lesser extent eutrophication and formation of photo-oxidants.

The project has revealed extensive knowledge gaps regarding environmental impacts resulting from land use change. Research is needed not only to generate data on the size of the emissions, but also into methodology on how to use such data in LCA.

2. Introduction

The increasing industrial interest in renewable materials has lead to the development of new plastics via biological routes. However, due to differing material properties their integration into existing plastics applications is restricted. This restriction has initiated a rethinking of the production of conventional plastics, such as the polyolefin polyethylene (PE), and launched the planning, and realization of production processes using biomass as raw material.

Different PE producers are pushing this development and started respectively announced the start of constructions of PE plants in Brazil running and sugarcane-based ethanol. However, despite this rush into renewable materials by PE producers, companies using PE in their products are aware that renewable does not necessarily mean environmentally preferable, in all respects.

Two companies sharing this awareness are Tetra Pak and Trioplast in Sweden. Both apply LDPE for their various products, and in relation to the current developments in the production of plastic, they raised the question, ‘Is the production of LDPE from a renewable feedstock like sugarcane environmentally preferable in comparison to the crude oil based alternative’.

In the course of this project, which was partly financed by Tetra Pak and Trioplast, this question was answered by investigating and assessing the environmental impact of LDPE production from sugarcane based ethanol in Brazil and from crude oil in Europe.

The difference between those two routes is not only raw material but also process wise. For example, the production of the cane based LDPE starts with the cultivation of the cane. This involves the use of fertile land, as it is an agricultural process. During the last decade and still now, this agricultural process expanded and the use of land by sugarcane increased (Sparovek et al., 2009). The reason for this expansion is the increasing demand of ethanol. It is accompanied by an increased change in land use – (change from one form of land use to another form) - whose consequences needed to be investigated for this study.

Further impacts relevant to the assessment of the sugarcane based LDPE were the resource consumption and the related release of emissions. They were investigated for all steps in the sugarcane route, starting from the cultivation of the cane, to the production of the LDPE resin in Brazil, and the final incineration of the LDPE containing product in Europe. The production of a final product containing the LDPE, and the use of this product were excluded. They would be the same for both material alternatives, causing no difference in their environmental performance.

The result of the investigation was used to assess the potential impact of the sugarcane based LDPE on the following impacts:

- Global warming,
- Photochemical ozone creation,
- Ozone depletion,
- Acidification
- Eutrophication
- Total primary energy consumption, renewable and non-renewable

Resource consumption and emission release were also investigated for the crude oil based LDPE. The investigation included all steps from the extraction of the crude oil in the Middle East, over its refining and polymerization in Europe until its final incineration (again, the use segment was not included due to the already stated reasons). The results of the investigation were used to assess the potential impact of the oil-based material on the already stated impact categories. The evaluation method was Life Cycle Assessment (LCA) for the oil, as well as, for the sugarcane route.

LCA assesses the environmental impact of a product by investigating its resource consumption and the emissions released during its production, use and waste treatment (ISO, 2006).

Two methodologically differing approaches can be applied for this.

- One approach is **attributional LCA**. Attributional LCA sets out to describe a state and answers question like 'What environmental impacts are associated with LDPE based on crude oil and on sugarcane ethanol?'

- The other is **consequential LCA**. Consequential LCA answers question like 'What would be the environmental consequence if the production of the product 'x' changes from crude oil based PE to cane based PE?' or 'What would be the environmental consequences if the demand for cane based ethanol increases due to the production of cane based PE?'

In this study, both approaches were applied. This was done to investigate the impact of methodological choices on the result of the assessment. The result of this investigation is intended to increase the knowledge about the environmental impact of cane based LDPE for the commissioner, as well as a wider audience. Furthermore, the consistent application of attributional and consequential LCA is expected to shed further light on the application of the two methodologies, on a concrete case study basis.

3. LCA Methodology

Life cycle assessment (LCA) is the quantitative assessment of the environmental performance of a product in a ‘cradle to grave’ perspective (ISO, 2006) . Whereby the ‘cradle’ is the extraction of the raw materials used. It is followed by the production of the product, its use phase, and finally its disposal.

There are two fundamentally different methodological approaches in LCA. One is attributional LCA; the other is consequential LCA (Baumann and Tillman, 2004). Consequential LCA is change oriented and answers questions like ‘What would be the environmental consequence if the production of the product x increases or decreases?’ It uses marginal data for the environmental assessment, as possible changes in the production affect the directly, and indirectly related marginal suppliers and competing products. Attributional LCA, on the other hand, assesses the environmental impact of a state, which can be a past, present or envisioned future state. It applies average data to answer questions like ‘What environmental impact may be associated with the product x?’

As can be seen in Figure 1, the two approaches also differ (next to the data) in how they account for multi functional operations – how environmental burdens are allocated for multi functional operations, or in methodological terms in how system boundaries are drawn.
The ISO 14044 gives an order of preferences between different ways to deal with allocation, whereby system expansion is preferred over partitioning (ISO, 2006). Our position in this study is rather that partitioning reflects an attributional approach and system expansion a consequential one, and that these give answers to different questions (Baumann and Tillman, 2004).

For the allocation issues in this study, the system is made virtually multifunctional in the case of attributional LCA. This means that in the case of multiple functional operations the environmental loads of the operation are allocated (partitioned) between the function/ product studied and the other functions (outputs) (Baumann and Tillman, 2004). In the consequential approach, however, the environmental load is not allocated. Instead, all outputs are traced to their alternative production and the system is then credited with the avoided environmental loads.

In Figure 1 the multiple functional process is the incineration. Its functions are 1) the disposal of the product after the use phase and 2) the generation of surplus heat, which can be fed into the district heating system. In the attributional approach, the environmental burdens resulting from the incineration are allocated between the surplus heat and the product studied. In the consequential approach, on the other hand, the full burdens of the incineration are accounted for. At the same time, the surplus heat is traced to the production of the alternative fuel that would have been used instead – so- called system expansion. The system is then credited with the avoided environmental loads from the alternative production of the same amount of heat.

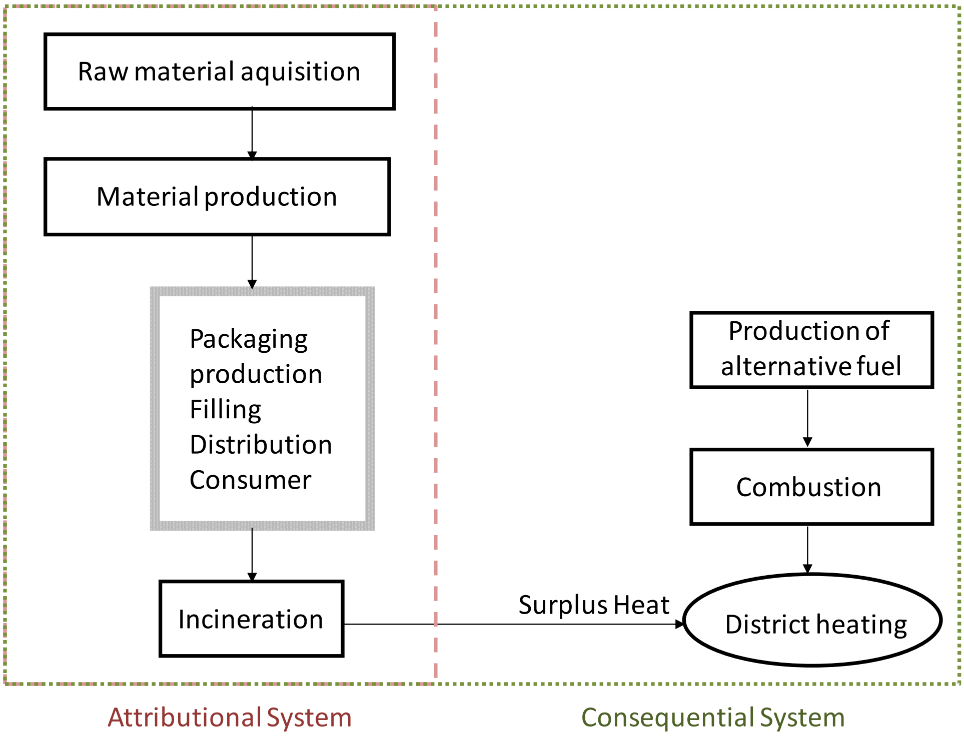


Figure 1: Comparison between an attributional system and a consequential system according to Baumann & Tillman (2004)

Independent from the approach an LCA according to ISO 14044 (2006) consists of four phases as can be seen in Figure 2.

They are:

- Goal and Scope definition
- Inventory Analysis
- Impact Assessment
- Interpretation

In the goal and scope definition, the purpose of the study and hence the question to be answered with the assessment is determined. This also involves the decision on the LCA approach as it decides on the scope of the study. Next to the determination of the scope, the functional unit is chosen. It is the basis for all calculations and the assessment of the impacts. The selection of these impacts is the final part of the goal and scope definition.

The inventory analysis starts with the construction of the process flowchart according to the model assumptions set in the goal and scope definition. It includes the functional unit, represented in the form of the reference flow. The next step in the inventory analysis is the collection of all data necessary to determine the material and energy inputs and the emission and waste outputs of all processes included in the flow chart. Finally, these collected data are calculated in accordance to the functional unit.

The results of the inventory analysis are further processed in the impact assessment.

This involves the relation of the inventory results to the chosen impacts – so called classification. It is followed by the characterization, in which the results are multiplied with set equivalency factors and finally summed up into the different impacts.

The impacts can be further condensed by different weighting methods e.g. Ecoindicator’99 or EDIP. They result in a single number, which enables a faster communication of the LCA result. However, this might also lead to the missing of crucial details as all impacts are summarized into one number. In this study, weighting was not applied.

During the assessment, modeling assumptions are made and data from different sources are used. However, data can have poor quality or might not even available. This introduces uncertainties for which the assessment needs to be tested. Two ways of testing – analyzing the quality of data – are uncertainty analysis and sensitivity analysis. In the uncertainty analysis, the ranges in which data can vary are determined. In the sensitivity analysis the robustness of assumptions and data are investigated by systematically changing them until the result of the assessment changes.

For this study, different scenarios for testing the sensitivity of the assessment were applied.

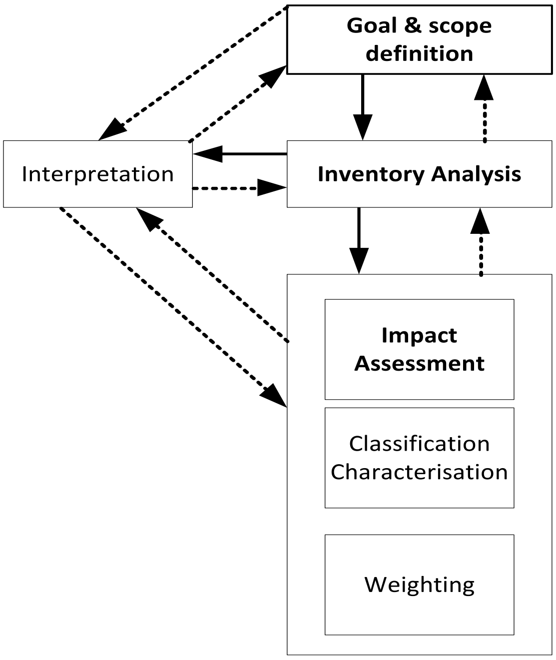


Figure 2: The 4 phases of an LCA according ISO 14044 (2006)

4. Goal and scope definition

4.1 Goal definition

The goal of this study is to answer the question, is the use of sugarcane based LDPE in the production of goods and packing in Sweden environmentally preferable to crude oil based LDPE.

The question can be reformulated:

1. What is the environmental impact of sugarcane based LDPE in comparison to crude oil based LDPE?
2. What would be the environmental impact if the production changes from crude oil to sugarcane based LDPE?

As described above, in LCA the first question corresponds to an attributional LCA method and evaluates the current environmental impact of the two alternatives. The second question evaluates the consequences of a future possible change. This corresponds to a consequential LCA method. For this study, both questions were evaluated, to investigate the impact of the choice of approach on the results of the LCA.

The following section describe, the models developed to assess the environmental performance of sugarcane and oil based LDPE.

4.2 Scope definition

The two scenarios analyzed were sugarcane based LDPE produced in Brazil and crude oil based LDPE produced in the EU. These scenarios were varied in a sensitivity analysis to sugarcane based LDPE originating from Morocco and oil based LDPE produced in Sweden. The life cycle assessment for both materials and all scenarios did not include the use phase, since it would be the same for both materials.

The waste treatment scenario chosen was incineration with production of electricity from the incineration heat. The treatment was changed to landfill storage in the sensitivity analysis.

4.3 Functional unit

The functional unit chosen is 1 kg of LDPE. All impacts were calculated in relation to the functional unit.

4.4 System boundaries

Crude oil based LDPE

Figure 3 and Figure 4 show the life cycle flowcharts for the oil based LDPE in the attributional and consequential perspective, respectively. Both charts display the process chain involved in the production of the oil based LPDE including in- and outputs.

Processes accounted for were the crude oil extraction and all intermediate processes until the LDPE. Energy consumed along the process chain was traced back to the extraction of the energy carriers (fuels) needed for its generation. Data for energy consumption was based on current Swedish production under the assumption that there is no significant difference in the production of LDPE in different European countries. Moreover, both LCAs (attributional and consequential) used the same data set under the assumption that the operations are independent from demand changes.

The following operations were not included: 1. production and maintenance of capital goods form buildings and machinery (their impacts were set to be insignificant), as well as, 2. Operations including personnel employment, like supply with housing, food, etc., is not counted since this would be out of the scope of this study.

Attention needs to be paid that for the generation of electricity different data sets were applied for the two LCA approaches. In the attributional approach, data for the average EU electricity production were used, whereas the consequential approach applied data representing marginal EU electricity production.

Outputs accounted for in this study were by-products and emissions released to air. Water emissions were omitted, because of data unavailability for some parts of the sugarcane route.

In addition to the processes, the charts display the locations of the processes. They were set to be in the EU, apart from the crude oil extraction, which was located in Saudi Arabia, for this study.

A process omitted in the process chain is the use phase – (see scope definition). However, the final step in the life cycle of the LDPE, the waste treatment, is included. This was modeled as waste incineration with generation of electricity from the recovered heat – as a generic scenario. A comparison between the two flowcharts reveals a difference for this last step. The reason is its multi functionality. Waste incineration removes the LDPE waste, and generates electricity at the same time. Relative to the two different LCA approaches, the burdens related to the multi functional incineration were treated differently. In the attributional approach, they were allocated (partitioned) between the two functions, waste removal, and energy production (see section 4.5 Allocation). In the consequential approach, they were fully accounted for. However, simultaneously, the system was credited with emissions and energy consumptions avoided from the alternative production of the same amount of electricity. In the flowchart, this is shown by the inclusion of the production of coal electricity – so called system expansion. The coal electricity was assumed to be replaced by incineration electricity.

Figure 3: Flowchart attributional approach oil based LDPE

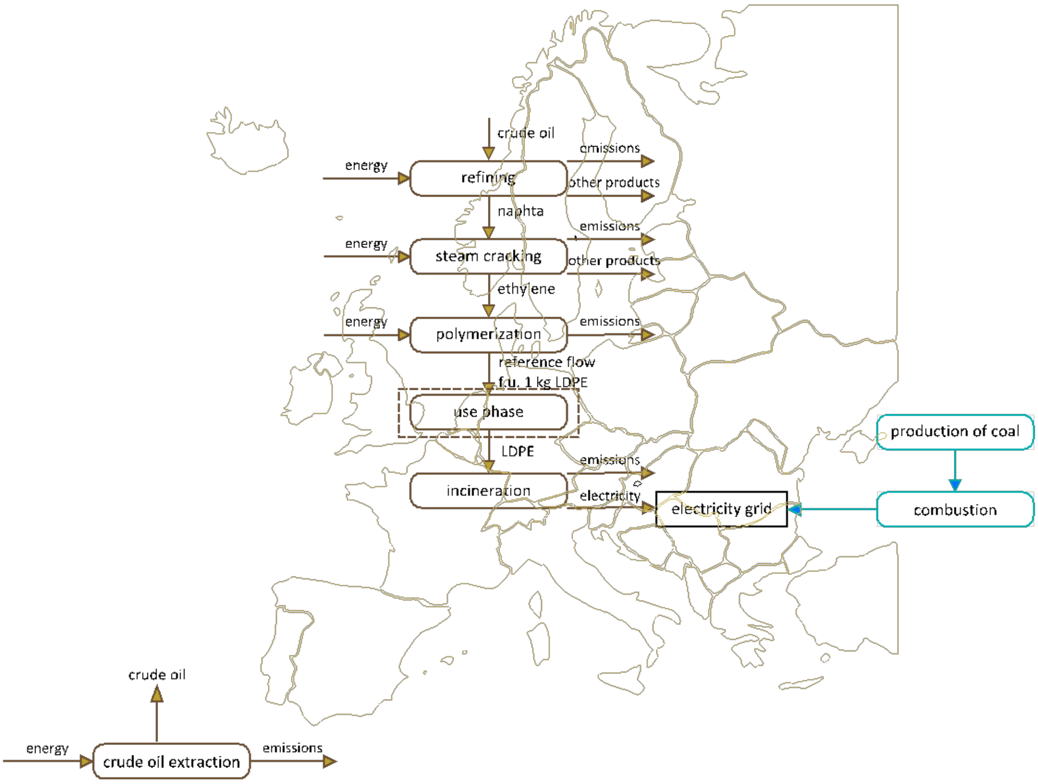


Figure 4: Flowchart consequential approach oil based LDPE

Sugarcane based LDPE

Figure 5 and Figure 6 show the life cycle flowcharts of the sugarcane based LDPE in an attributional and a consequential perspective, respectively.

Both charts display the process chain involved in the production of the sugarcane based LPDE including in- and outputs. Processes accounted for were the cultivation of the sugarcane and all intermediate processes until the LDPE. Energy consumed along the process chain was traced back to the extraction of the energy carriers (fuels) needed for its generation. Whereby, the ethanol mill operation generated its own energy by combusting bagasse.

The following operations were not included: 1. production and maintenance of capital goods form buildings and machinery (their impacts were set to be insignificant), as well as, 2. Operations included in personnel employment, like supply with housing, food, etc., is not counted (this would be out of the scope of this study).

Outputs accounted for in this study were by-products and emissions released to air. Water emissions were omitted, because of data unavailability for some parts of the sugarcane route.

The assessment of the energy consumptions was based on data from currently used technologies. However, the assumptions regarding how the system interacted with the energy system differed between the attributional and consequential approach.
The attributional approach used electricity data representing average Brazilian electricity production, while the consequential method used data originating from marginal electricity production.

A comparison of the flowcharts between the oil and the sugarcane-based routes reveals an extra emission category for the sugarcane route. This ‘category’ is LUC emissions. It is caused by the expansion of the sugarcane, as will be described in the following section 5 Land Use Change. Their released quantity differed between the consequential and attributional approach due to the use of average and marginal data – see section 5 Accounting for land use change.

In addition to the processes, the charts contain the locations of the processes. They were Brazil (Sao Paolo) and Europe. The use phase and the final waste treatment were therefore assumed to take place in Europe. Brazil and its state Sao Paolo were chosen as the production site of the sugarcane based LDPE since Brazil is the world’s main sugarcane producers with Sao Paolo as the main cultivation area (Zuurbier and van de Vooren, 2008).

The production process of the sugarcane based LDPE in Brazil started with the cultivation of the sugarcane and its subsequent harvest. The harvesting techniques and the resulting environmental impact were modeled in different ways in the consequential and attributional approach – see section 5 Land Use Change. For the consequential approach, mechanical harvesting was assumed, while manual harvesting was assumed for the attributional approach – see section 5 Accounting for land use change. The harvested sugarcane is then transported to the ethanol mill. In the ethanol mill, the sugarcane is converted to ethanol. The environmental assessment of this process is based on data from currently applied process technologies.

Subsequently to the ethanol mill, the ethanol is dehydrated to ethylene. This process has not yet been demonstrated on an industrial scale. For this reason, estimated future industrial production values were used. The values were obtained from simulation scaling factors (for details see Appendix).

The ethylene is finally polymerized to LDPE. The data for this step were based on current Swedish process technology. This was valid under the assumption that production conditions do not differ between the Swedish and Brazilian processes. However, Brazilian conditions for energy carriers including electricity were applied. The finished LDPE resin is then shipped to a customer in Europe. Therefore, a transport from Sao Paolo (in the state Sao Paolo) to Europe (Sweden) was evaluated. The subsequent use phase was omitted. However, the final step in the life cycle of the LDPE – the waste treatment in the form of incineration, was included.

A comparison between the two flowcharts reveals a difference for this last step. The reason is its multi-functionality. It removes the LDPE waste, and generates electricity at the same time. In the two LCA method approaches, the burdens related to the multi-functional incineration were treated differently – see above in crude oil description.

Another multi-functional process assessed in the study is the ethanol mill process. It produces its own renewable energy carrier – the bagasse. However, not all of it is needed for the ethanol mill process. Therefore, a surplus of bagasse energy is produced. In the attributional and consequential flowcharts, this surplus is accounted for differently. In the attributional approach the environmental burdens were allocated between ethanol and the electricity generated from the surplus bagasse – see section 4.5 Allocation. In contrast, the consequential approach counted for the full burden. However, the system was credited with emissions and energy consumptions avoided from the production of an equal amount of electricity elsewhere – based on natural gas, as this is the marginal electricity source in Brazil.

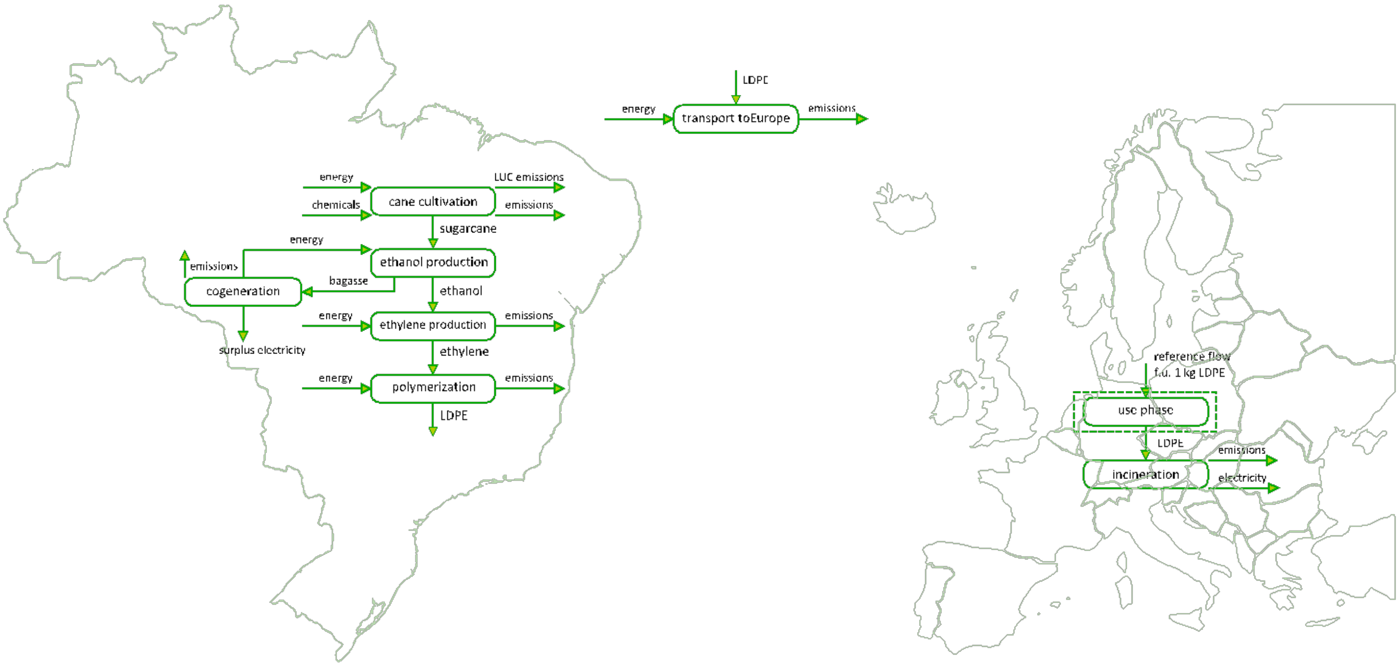


Figure 5: Flowchart attributional approach sugarcane based LDPE

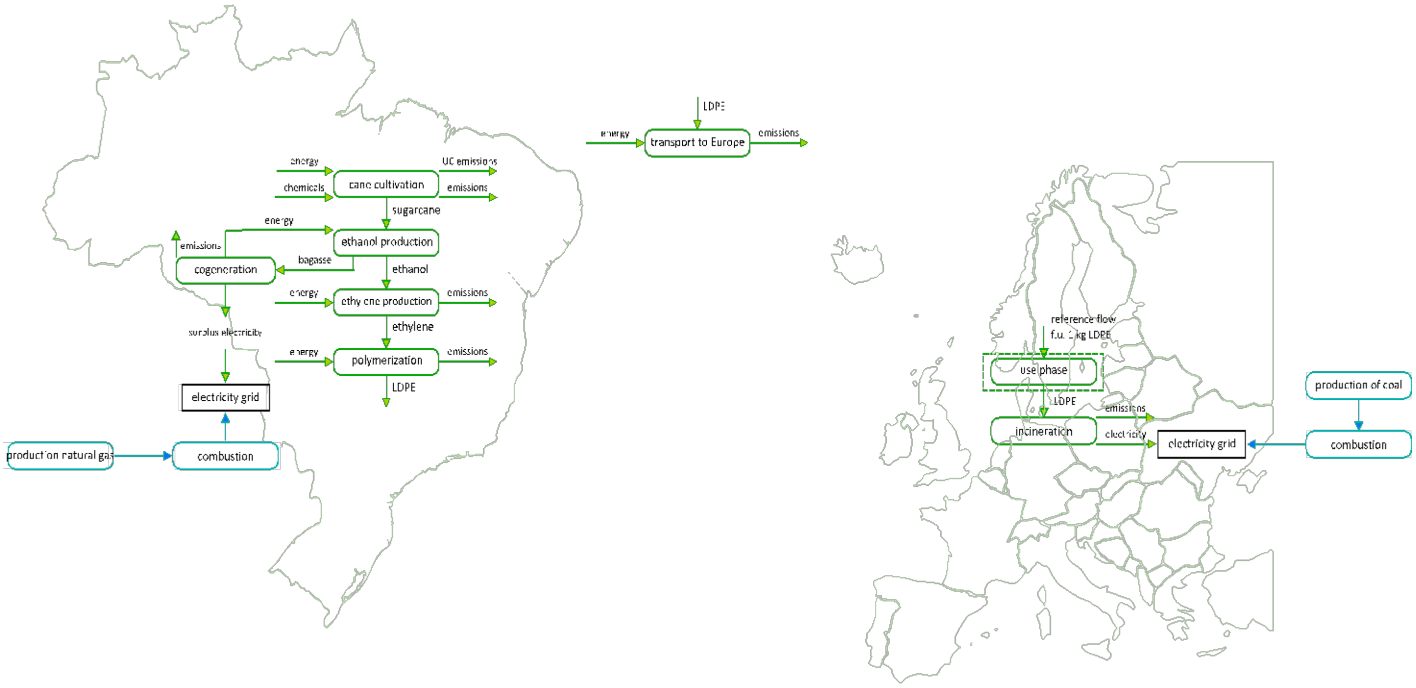


Figure 6: Flowchart consequential approach sugarcane based LDPE

4.5 Allocation

Crude oil based LDPE

Attributional approach

As already stated, in the attributional approach the environmental burdens were allocated through partitioning multi-output operations. The ISO 14044 suggests different allocation bases like physical properties or economic value (ISO, 2006).

For the oil route, almost all processes are multifunctional. They either produce various materials in the same operation or fulfill various functions, e.g., the refinery does not only produce naphtha, but also diesel, etc. or as in the case of incineration not only is the waste disposed, but also the generation of electricity from the waste occurred. For these multiple outputs, the environmental burdens needed to be allocated between products/functions relevant for the study and other products/functions. The allocation bases were as follows:

- Weight for all products in the refinery process
- Energy content of the natural gas and the oil in the case of extraction
- Weight for all products in the steam cracking process
- Economical value for the incineration; i.e. cost of waste treatment in relation to the price paid for electricity.

Consequential approach

The consequential approach in principal should apply system expansion to all multi-functional processes. However, system expansion was not used for extraction, refining, and steam cracking in this study. The resulting complexity of the system model would be outside the scope of this study. For this reason, allocation instead of system expansion was used for these processes.

The only exception is in the case of incineration where the system is expanded. The replaced electricity was traced back until the mining of the coal for the avoided coal electricity.

Sugarcane based LDPE

Attributional approach

The sugarcane cycle has two multi output operations – the ethanol mill process with its ethanol and electricity production and the incineration with its waste disposal and electricity generation.

The burdens of these operations were allocated in the following bases:

- Energy content i.e. of electricity generated from surplus bagasse in relation to energy content of ethanol
- Economical value for the incineration; i.e. cost of waste treatment in relation to the price paid for electricity.

Consequential approach

The consequential approach fully accounted for environmental load associated with the electricity generated by surplus bagasse. In the same way, it also accounted for the electricity produced during incineration. The electricity was then traced back until the extraction of the natural gas for the avoided Brazilian natural gas electricity and until the mining of the coal for the avoided coal electricity in Europe.

4.6 Data quality

For all operations, the following types of data were collected:

- Raw material
- Energy consumption
- Emission to air
- Distance and transportation mode

The following data sources were used for this collection:

- Environmental reports
- Manufacturers
- Scientific articles/literature
- Databases
- Model calculations

Whenever available, recent data from the last 5 years were applied for calculating the environmental impact of the operations. A more detail description of the data origins and their dates is given in the Inventory section.

Quantitative data for emissions to water was not available for all operations in the sugarcane route. For this reason, water emissions, and consumptions were not evaluated quantitatively. However, qualitative data on the water consumption, and pollution caused by sugarcane cultivation, and sugarcane processing in the ethanol mill was available, and are described in the section non- quantified impacts.

Another factor not quantitatively assessed is the impact of the sugarcane route on biodiversity. A quantitative assessment is not possible due to the lack of biodiversity indicators. It is assessed only in a qualitative manner.

4.7 Choice of impact categories

The sugarcane life cycle releases different greenhouse gases like CH_4 and N_2O during its agricultural operations. Moreover, it consumes energy in its various operations like transport, ethylene production, and polymerization. These operations do not only release global warming effective (like CO_2), but also acidifying, photochemical ozone creating and eutrophying effective emissions like SO_2 and NO_x. The same goes for the crude oil life cycle. It consumes raw materials and energy whose productions release various emissions like CO_2, NO_x, SO_2, potentially effecting the environment in different ways.

For these reasons, the following environmental impact categories were chosen to assess and compare the potential environmental impact of the two materials:

- Global warming potential – GWP 100 (kg CO_2 eq/kg LDPE)
- Acidification potential (g SO_2 eq/kg LDPE)
- Photochemical ozone creating potential – high NO_x POCPs (g ethylene eq/kg LDPE)
- Eutrophication potential (g PO_4/kg LDPE)

As an indicator of resource consumption, total primary energy consumption in 'MJ/kg LDPE', divided into renewable and non-renewable was chosen.

5. Accounting for land use change and its impact on global warming

Land Use Change (LUC) and the accompanying emissions are a possible environmental issue related to feed-stocks produced on land.

They become especially important when comparing the environmental impact of a product based on renewable feed-stocks, originating from an area with rapid LUC, with one based on non-renewable feed-stock. The reason is the impact of LUC and its emissions on especially the global warming and the biodiversity.

Agricultural operations, such as the cultivation of sugarcane, imply the use of land, and in the case of expansion of the areas used for a certain culture, this is accomplished by changes in land use. This may have a significant environmental impact, not at least in terms of climate change.

Sugarcane had such an expansion in the last decade, and moved, and still does, into areas that were not used for sugarcane cultivation before (Sparovek et al., 2009). The result is land use change, which can be divided into direct (DLUC) and indirect land use change (ILUC) (Zuurbier and van de Vooren, 2008).

DLUC is directly caused by the movement of sugarcane into a new area. For example, if the sugarcane moves into areas previously used for other agricultural operations, the change from the other operation to sugarcane causes direct land use change. ILUC is a consequence of the DLUC. It is caused by the movement of the replaced agricultural operations into other areas.

Both forms of land use change can cause emissions of greenhouse gases (GHG) due to changing operations, and clearing measures. Their quantity and sort depends largely on the soil conditions and the land management practice (Egeskog and Gustafsson, 2007), (Zuurbier and van de Vooren, 2008).

From an LCA point of view, there is so far no established methodology on how to include emissions related to LUC, although there is growing awareness of the need to do so. There is also considerable uncertainty regarding the extent of emissions originating from LUC, both because data are lacking or are scare and because there is large variability in emissions from LUC.

The following paragraphs will give an overview into how a set of regulatory instruments account, or plans to account, for LUC, a section on how GHG emissions related to harvesting techniques, and following that how LUC and the related emissions were accounted for this study.

Overview on the accounting for LUC in regulatory instruments

LUC and its environmental impact gain a steadily growing awareness also among regulating organizations and a number of regulations and standards on how to account for the LUC are already released, or under development.

The following table gibes an over-view over this development. The purpose is to increase the awareness about this regulatory development and to show that LUC is an environmental issue that cannot be ignored, although methods to account for it in different contexts is not yet fully established.

Organization	DLUC	ILUC	Comments
British Standard Specification for the assessment of the life cycle greenhouse gas emissions of goods & services	X	(X)	* dealing with goods and services * currently ILUC not included * ILUC inclusion after development of proper methods * DLUC – change from non-agricultural land to agricultural land
European Union Renewable Energy Directive/Fuel Quality Directive	X	X	*dealing with biofuels (includes ethanol) * DLUC & ILUC shall be included in GHG emission calculations * currently: analysis how to include ILUC factor into GHG emissions
Cal/EPA Proposed Regulation to implement low Carbon Fuel Standards Volume I, Staff Report: Initial Statement of Reasons	X	X	* dealing with fuels including ethanol from Brazilian sugarcane * calculation of GHG from DLUC & ILUC by GTAP model

X stands for ‘accounted for’

Used methodology and assumptions

To sum up, no established methodology exists for how to account for LUC in LCA, and existing data is uncertain. As effects of LUC were considered potentially significant, they were included in this study, never the less. It should be recognized that both the methods and data used, described in the following paragraphs, are tentative.

Attributional approach

In the attributional approach, the LUC was assessed in a retrospective manner. For this purpose, data related to the expansion and emissions that occurred in the past 20 years were applied. The data were annualized which relate to 1m3 respectively 1MJ ethanol.

The past expansion of sugarcane occurred mainly along the borders of the already settled cultivation areas in the main growing regions - Sao Paolo state, and Mato Grosso do Sol state. These expansion areas were mainly pasture (displayed as cow icon in Figure 7), according to Sparovek et al. (2009) and therefore no direct deforestation and consequently no release of emissions, due to sugarcane cultivation occurred. Zuurbier and van de Vooren (2008) even state the accumulation of carbon into the soil of former pasture, when displaced by sugarcane harvested mechanically, without burning (see box regarding harvesting techniques).

However, the predominant harvesting technique was and is manual harvesting (Egeskog and Gustafsson, 2007), which instead of accumulating carbon, might have lead to its release. Since the investigated literature pointed in different directions, in this study zero emissions for DLUC were assumed. It must however be pointed out, that this assumption is highly uncertain.

The expansion of sugarcane into former pasture did not only have direct effects, but might have been accompanied by indirect effects, too. For example, Sparovek et al. (2009) state there are indications (though no definite proof) that the indirect effect was migration of pasture into virgin areas like the Amazonas, resulting in the cut down of the natural vegetation, an extensive soil processing (Cederberg et al., 2009) and the release of greenhouse gas emissions. In Figure 7 this is depicted as the movement of the cow icon, which stands for pasture, into the area of the bird icon, which symbolizes virgin area.

Although there is uncertainty if sugarcane or the expansion of other agricultural operation, such as soy bean production, was the main driver for pasture movement, in this study, the effects of ILUC were attributed to sugarcane. In this respect, the way ILUC was represented in this study may be regarded as a worst case scenario.

The applied methodology follows the conclusion of a recent workshop with invited European LCA experts, on Greenhouse emissions in the food chain (Den Haag, June 5, 2009), which recommended inclusion of effects of ILUC, also in attributional LCA studies, in cases where the raw material comes from agriculture with rapidly changing land use practices, and that the effects of this change is attributed to the product studied.

Data availability is limited. Estimates according to Zuurbier and van de Vooren (2008) and California EPA (2009) were used for this study.

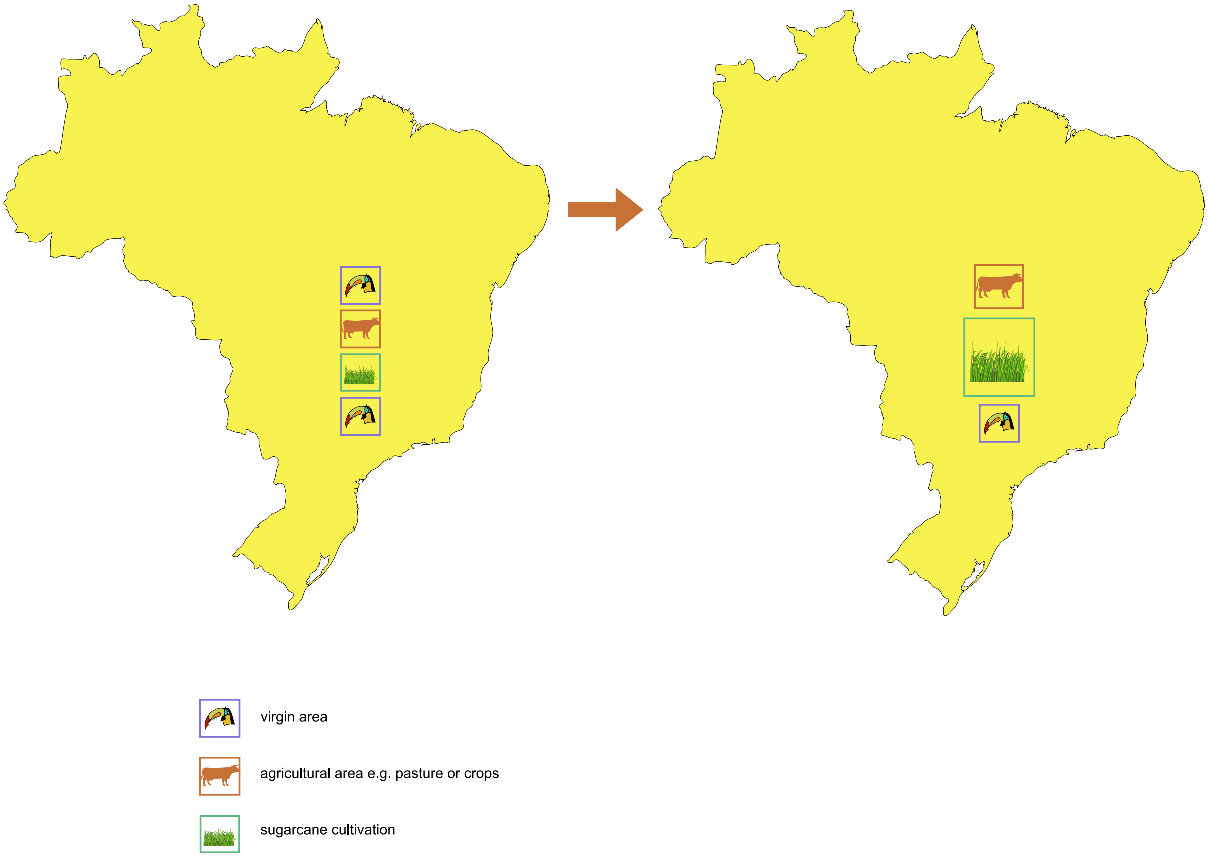


Figure 7: Visualization of the LUC for the attributional approach – note: the location and quantity of expansion is not true to scale

Consequential approach

In the consequential approach, the goal is to assess the annualized LUC caused by the marginal expansion of the sugarcane in a prospective manner. This means it intends to assess the expansion of the sugarcane that could be caused by a future change in sugarcane demand.

To get a better understanding for this marginal expansion, the marginal expansion occurring in the past and until now is described in the following paragraph. A visualization of this can also be found in Figure 8.

In contrast to the average expansion of sugarcane cultivation, the marginal expansion is the movement of mechanically harvested sugarcane into regions that are adjacent to the major growing areas, e.g. Cerrado, as well as into distant regions like the Amazonas (Zuurbier and van de Vooren (2008) and Sparovek et al. (2009)). For both regions types, the already stated LUC due to sugarcane expansion is observed, whereby its extent depends on the specific conditions found in the expanding areas.

ILUC and its related emissions might have occurred when the area of expansion was already used for other operation, as was the case for some part of the stated regions, e.g. Cerrado. For other parts however, no former land use existed, and, therefore, the sugarcane expanded directly into virgin areas, directly causing the release of greenhouse gases (Sparovek et al., 2009).

In Figure 8 this movement is visualized by the movement of the sugarcane into ‘cow’ (pasture area) and ‘bird areas’ (virgin areas) that are adjacent, as well as, distant from the original ‘green plants’ areas.

The above statements describe the current marginal sugarcane expansion, and it is not certain that the development in the future will follow the same pattern. Sparovek et al.(2009) and Zuurbier et al. (2008) state that in the near future (approx. the next 5 years) the major expansion will mainly occur into pasture and other croplands, which is why, a direct effect on virgin areas, at least in the near future, is unlikely.

However, these statements include an uncertainty as they say ‘mainly’. To account for this uncertainty, in this study it was assumed that 5% of the ethanol origins from sugarcane that is grown on virgin area, while 95% of the sugarcane is grown on former pasture. This assumption is based on a deforestation rate stated by Sparovek et al. (2009).

The related DLUC was assessed using data from Zuurbier and van de Vooren (2008). However, in contrast to the attributional approach, which used data for manual harvest sugarcane, the consequential approach used data for mechanically harvest sugarcane. This decision was based on the assumption that recently issued laws about harvesting will be implemented in the near future – see box regarding harvesting techniques. The ILUC was assessed by applying data from the California EPA (2009).

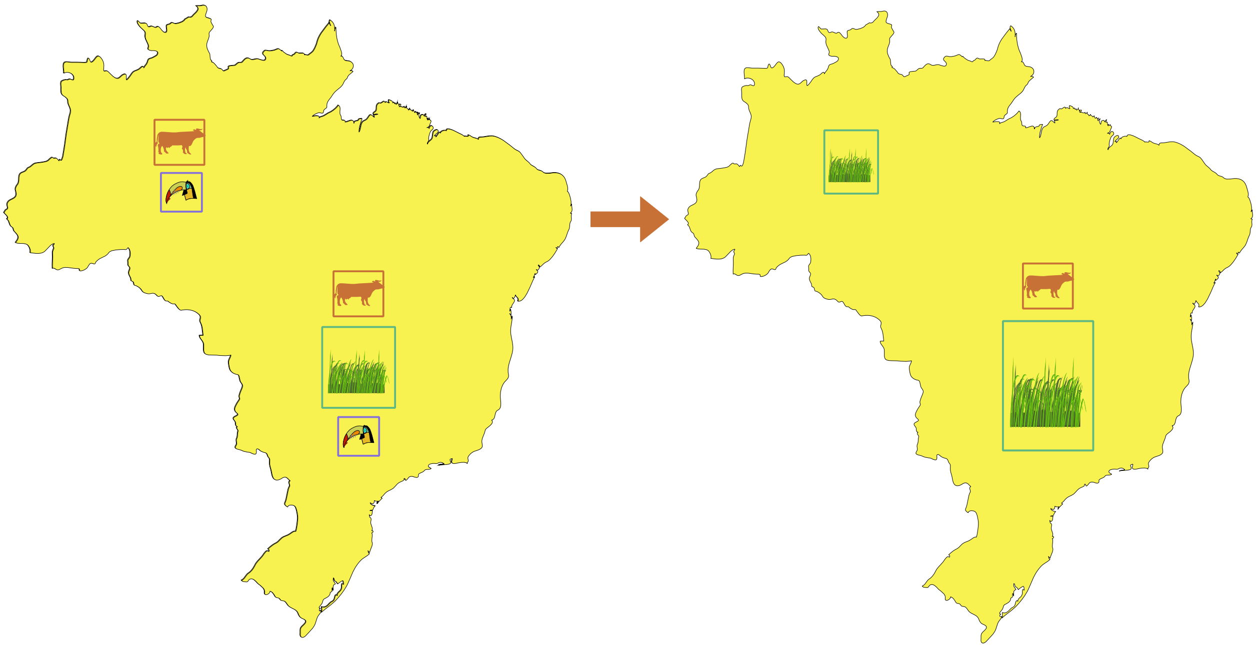


Figure 8: Visualization of the LUC for the consequential approach – note: the location and quantity of expansion is not true to scale

Note on data sources

It has already been stated that the data used for the emissions resulting from ILUC are highly uncertain. In particular the model applied by the California EPA has been criticized, by among others the Brazilian Sugarcane Industry Association – UNICA. Their main critique on the Californian model can be summarized as (Unica,(2009).

- the model is not specific enough for geographical conditions in Brazil
- the model does not consider technology changes/improvements e.g. intensification of cattle production
- the model does not take legislative measures like phase-out of pre-burning into account
- the model uses too low carbon accumulation values for sugarcane
- the model accounts too high emissions resulting from indirect land use change

We are aware of this critique exists and the uncertainty of the data.

.

6 Inventory and Impact Assessment

The following factors were applied to calculate the impact potentials of the routes. They are according to the data stated in the calculation aid released by CML Institute of Environmental Sciences (Leiden University)(2009).

	global warming factors GWP 100 [kg CO2 eq/kg emi]	**photochemical ozone creation potential high NOx POCPs** [kg ethy eq/kg emis]	**acidification** [kg SO2 eq/kg emis]	**eutrophication** [kg PO4eq/kg emis]
CO2	1	0	0	0
NOx	0	0	0,7	0,13
SO2	0	0,048	1	0
HFC	0	0	0	0
HC	0	0,15	0	0
CO	0	0,027	0	0
CH4	25	0,006	0	0
N2O	300	0	0	0,27
NMVOC	0	0,15	0	0

Table 1: Emission Factors

Note for VOC and NMVOC:

Data were found in different formats. Some data sources stated CH_4 and other volatile organic compounds separately. For these cases, volatile organic compounds were assessed under NMVOC emission factors. Other data sources did not state CH_4 and other volatile organic compounds separately. For those cases, volatile organic compounds were treated as $CH_{4.}$

Note for raw data and data sources:

The full data including data sources and assumptions set are given in the appendixes.

6.1 Crude oil route

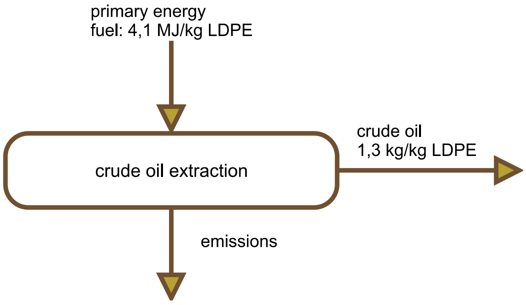
Offshore exploration of crude oil in Saudi Arabia

Process Description

The technique used to explore crude oil offshore depends on the pressure in the oil well. High pressures make the exploration easier, and therefore simpler primary methods can be applied. One method is to use the natural pressure in the well. If the well pressure is high, the oil rises without any further assistance. This high pressure is caused by gas dissolved in the oil. If there is no gas or the pressure is not sufficient pumps are used to transport the oil to the surface (Erdöl-Vereinigung, 2003). If gas is present but cannot be economically explored, it is pressured into the surrounding ground. This increases the pressure on the oil and it is pushed out of the well. As the exploration proceed and the well ages, the pressure in the well will decrease. At this stage, secondary exploration measures, like water injections to push the oil out of the ground, become necessary. When the oil in the well is very low, the last exploration measure, so-called tertiary exploration is used. In this method, steam or chemicals are injected to decrease the surface tension of the oil. The decreased tension detaches the oil from the surrounding ground and it can be extracted (Erdöl-Vereinigung, 2003). The extracted oil is then transported to the refinery by pipelines or tankers.

Process Data

The crude oil was assumed to be extracted offshore in Saudi Arabia.
Data for this process were taken from Statoil Hydro (2007), a company extracting crude oil offshore, under the assumption that there is no difference between different companies.



flows – attributional and consequential approach

	GWP 100 [g CO$_2$ eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO$_2$ eq/kg LDPE]	EP [g PO$_4$eq/kg LDPE]
extraction	251,6	0	0,6	0,1

Table 2: extraction – environmental impact potentials; attributional and consequential approach

Electricity consumption

The following processes consume externally produces electricity in different amounts. The environmental impact of this consumption was assessed differently in the two LCA approaches. For the attributional assessment data from the EU electricity mix according to PE-

International GmbH (2002c) were applied, while in the consequential approach data for marginal coal electricity supply according to Markewitz et al. (2009) and Pe International (2002d) were used.

	electricity [g/MJ]
CO_2	217,5
NO_x	0,2
VOC	
SO_2	0,2
HFC	
HC	
CO	3,0E-02
CH_4	0,9
N_2O	5,8E-04
NMVOC	8,4E-03

Table 3: emissions related to electricity supply, marginal electricity

	electricity [g/MJ]
CO_2	155,0
NO_x	0,3
VOC	
SO_2	0,9
HFC	
HC	1,9E-05
CO	0,1
CH_4	0,3
N_2O	3,7E-03
NMVOC	4,9E-03

Table 4: emissions related to electricity supply, average electricity

Note for data origin of the following processes

For all following processes, data from Swedish producers were applied under the assumption that there is no difference in operation between European producers.

Refining – Production of Naphtha

Process Description

Before the refining can start, contaminants (water, inorganic salts or suspended solids) must be removed. This is done by desalting. There are two different desalting processes. One is chemical desalting. In this process, the crude oil is mixed with water and surfactants and heated up. This causes dissolving or attaching of the impurities to the water and finally their settle out. The other process is electrical desalting. It includes the exposure of the oil to high-voltage electrostatic charges, which promotes the concentration of impurities on the bottom of the storage tank (United States Department of Labor, 2003).

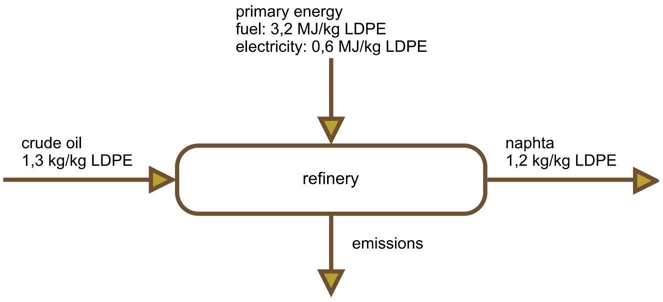
After this pretreatment the refining starts with the preheating of the crude oil up to 220-250ºC (in heat exchangers fed with recovered heat from the refining process). A further heating up to the column temperature (360-380ºC) follows in a furnace (crude heater) before the oil enters the column. In the column (atmospheric column) the partially vaporized oil is separated into, side and bottom products. Part of the top product is used as reflux for the column. The reminder goes to the naphtha hydrotreater. The other products go to the stripping columns, in the case of the side products resp. to the vacuum column for the bottom product (VCH Publishers., 1996).

The hydrotreatment is the removal of sulfur components in the top product. The later is mixed with hydrogen-rich gas, then heated up and lead through a catalyst bed. In the catalyst bed, the sulfur reacts with the hydrogen to hydrogen sulfide which is then separated in the subsequent separation steps (United States Department of Labor, 2003); (VCH Publishers., 1996).

The first step is a high pressure separation used to recover the not reacted hydrogen. The second step is a low pressure separation in which the hydrogen sulfur is removed. Finally, the hydrotreated top product is stabilized and the naphtha is separated from the rest of the top product in a gasoline splitter (VCH Publishers., 1996).

Process Data

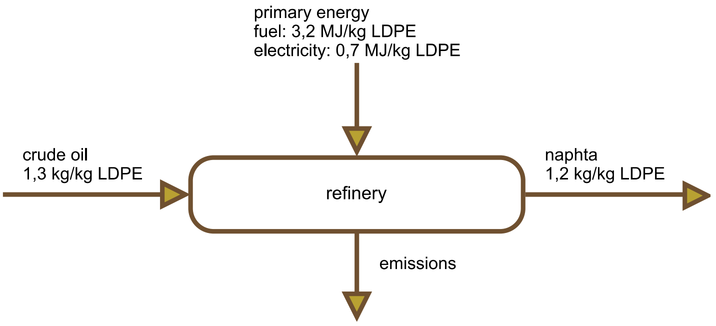
For the refining process, data for energy consumption and on-site emissions from the Shell Raffinaderi AB Göteborg (2007) were used. The environmental impact related to electricity supply was assessed using the already stated data – see section electricity consumption.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	**POCP** [g ethy eq/kg LDPE]x10	**ACP** [g SO_2 eq/kg LDPE]	**EP** [g PO_4eq/kg LDPE]
refinery	227,7	0,1	0,3	0,0

Table 5: refinery – environmental impact potentials; attributional approach



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	**POCP** [g ethy eq/kg LDPE]x10	**ACP** [g SO_2 eq/kg LDPE]	**EP** [g PO_4eq/kg LDPE]
refinery	242,4	5,7E-02	0,1	2,1E-02

Table 6: refinery – environmental impact potentials; consequential approach

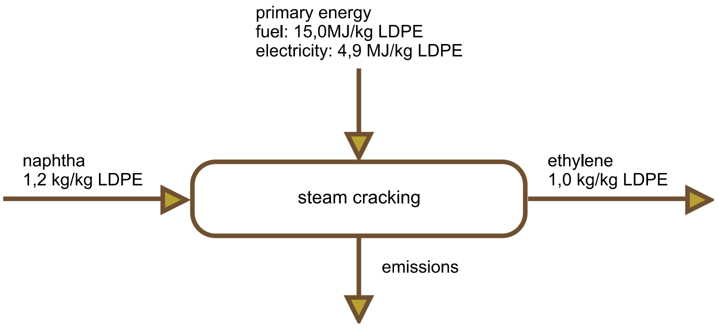
Steam cracking – Production of Ethylene

Steam cracking is the thermal cracking of saturated hydrocarbons into smaller hydrocarbons e.g. ethylene and other olefins, applying steam. In Europe and Asia, the primary raw material for the cracking is naphtha (fraction of the refinery boiling between 35 and 180°C) (VCH Publishers., 1996). For this reason, naphtha is chosen as cracker feed in the study.

The cracking process starts with the heating up of the naphtha in a countercurrent flow with flue gases. Then the naphtha is mixed with steam and further heated to 500-680°C. The temperature depends on its composition. After the heating, the mix flows into a fired tubular reactor. It is heated up to 750-875°C for 0,1-0,5s (while controlling residence time, temperature profile and partial pressure).The naphtha cracks into smaller hydrocarbons mainly ethylene, higher olefins and diolefins (VCH Publishers., 1996).Since this reaction is endothermic, the reaction products have a high temperature. To prevent subsequent reaction they are rapidly (0,02-0,1s) cooled down to 550-650°C, in the so-called quenching step. After the quenching, the products are separated, different separation steps and chemical treatments further purify the ethylene (VCH Publishers., 1996); (Chauvel and Lefebvre, 1989).

Process Data

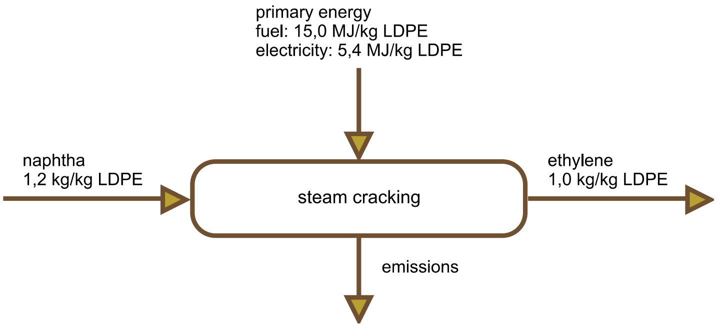
The steam cracking was assessed applying data from Borealis, Sweden (2008).
The assessment of the electricity supply was done using the already stated data. The consumption of external fuels (natural gas) in the process was assessed according to Bargigli (2004), taking the assumption that that it is Norwegian natural gas.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
steam cracking	919,0	0,8	1,9	0,1

Table 7: steam cracking – environmental impact potentials; attributional approach



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
steam cracking	1032,5	0,3	0,8	0,1

Table 8: steam cracking – environmental impact potentials; consequential approach

Polymerization of Ethylene – Production of LDPE

Process Description

Low density polyethylene (LDPE) is produced under high pressures (81-276MPa) and temperatures (130-330ºC) in either a tubular or stirring autoclave reactor. The products from this two reactor types differ mainly in their long chain branching composition due to differences in their backmixing. The result is shorter long-chain branching in stirring autoclave reactors, and longer in the tubular reactor (Kirk-Othmer, 2001).

The mechanism leading to the formation of the branched polymer is chain growth polymerization. It includes four reaction steps: initiation, propagation, branching and termination. The initiation starts with the decomposition of an initiator material, usually peroxides. When exposed to heat or irradiation, the peroxides, decompose releasing a free radical, which attacks the ethylene and starts the growth of the radical chain. In the next step, the propagation, an olefin radical chain attacks the double bonds of the surrounding ethylene monomers causing an addition reaction to occur and results in a longer chain (Kirk-Othmer, 2001).

In the process, the active center moves to the end of the new, longer chain and continues adding more monomers. The chain grows. However, the radical chain does not only react with double bonds in the monomers, but also with hydrogen from another polymer chain. The result is the termination of the first chain and a movement of the active center to the middle of the second chain, which now grows from there. This process is the called branching (Kirk-Othmer, 2001); (Ebewele, 2000).

The termination of the chain growth can be caused by different reactions. The two most important termination reactions are coupling and disproportionation. Coupling is the reaction of two polymer chains resulting in the formation of a long polymer molecule. Disproportionation is the transfer of a labile atom from one radical to another leading to two inert polymer chains (Kirk-Othmer, 2001); (Ebewele, 2000). A third termination mechanism is chain transfer. It involves the transfer of the active center of a polymer chain to a monomer or to a solvent, added to the mix to terminate the chain growth. In dependence of the reactivity of the newly formed radical, it might initiate the formation of a new polymer chain (Kirk-Othmer, 2001); (Ebewele, 2000).

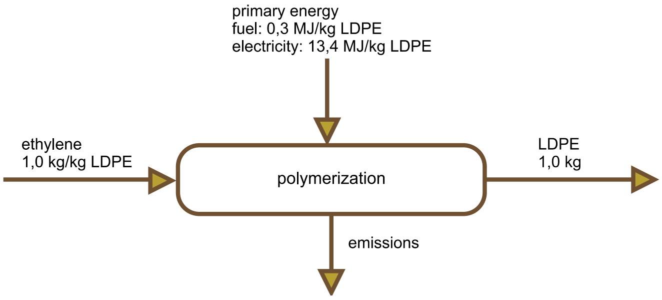
After the polymerization, the product stream passes through different separation steps to recover the not reacted ethylene gas for recycling and to remove waxes. The cleaned, molten polymer is then mixed with stabilizers and additives and finally made into pellets. In this last step, the polymer is forced through an extruder head to from the required shape and size of pellets. The pellets are usually cut under water and dried in a centrifugal drier (Kirk-Othmer, 2001); (Ebewele, 2000).

Process Data

Process data for the polymerization originated from Borealis, Sweden (2008).

The electricity consumed, was assessed under marginal and average electricity supply – see section electricity consumption

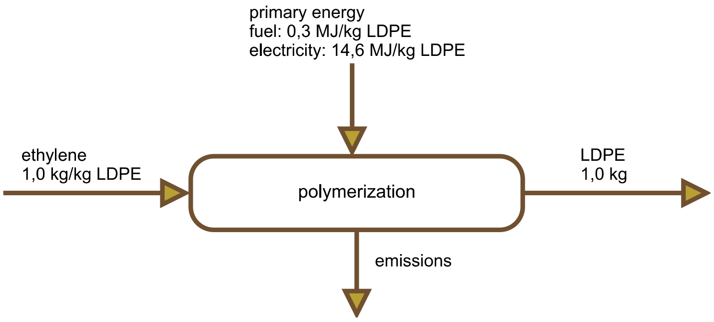
The environmental impact of external fuels consumed at the production site (consumption data according to Borealis (2008)) were assessed according emissions data from SPINE LCI (2008). External fuels were treated like diesel under the assumption that diesel and fuel oil have the same environmental impact during their production.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
polymerization	765,1	2,0	4,5	0,2

Table 9: polymerization – environmental impact potentials; attributional approach



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
polymerization	1073,2	0,5	1,4	0,1

Table 10: polymerization – environmental impact potentials; consequential approach

Incineration

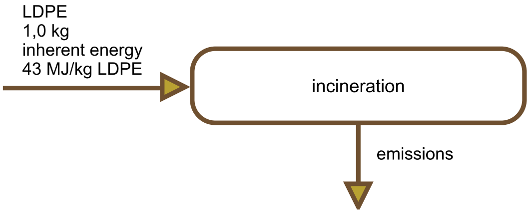
Process Description

As the incineration was not the process in focus for this study, it will only be shortly described.
In the incineration, the LDPE is combusted after its use phase. For the released heat, the assumption was set, that it was used to produce electricity.

During the incineration of the LDPE heat and electricity is generated according to Sundqvist et al. (1997) .To simplify, the heat was assumed to also be converted into electricity. The total electricity resulting from the incineration is the electricity generated from the heat plus the electricity that is already generated from the incineration – see appendix – Incineration 'European oil route'.

The heat generated from the incineration was assumed to be used for electricity generation with an efficiency of 0,12 (steam to electricity) (Global-Ecofuel-Solutions-S.L, 2009). The assessment of the resulting environmental burdens differs between consequential and attributional LCA. In the attributional LCA the environmental burdens were allocated between waste disposal and electricity generation, whereby Swedish data for LDPE incineration according to Sundqvsit et al. (1997) were used. As already stated in the Goal and Scope definition, prices were the allocation basis. They were set according to data from Energimyndigheten (2008) and Avfall Sverige (2007). In the consequential approach, the burdens were not allocated but fully accounted. The system was then credited with avoided coal electricity production – see Section 4 Goal and Scope definition.

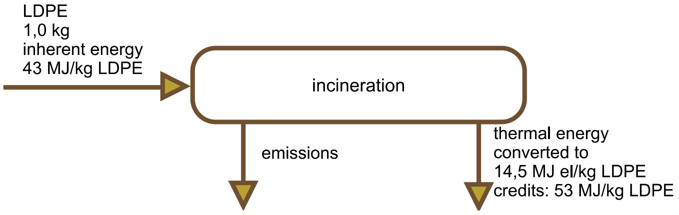
Coal electricity was assessed using data from Markewitz et al. (2009) and Pe International (2002d)



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
incineration	561,5	0,2	0,1	9,5E-03

Table 11: incineration – environmental impact potentials; attributional assessment



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
incineration	2440,0	0,9	0,2	4,1E-02

Table 12: incineration – environmental impact potentials; consequential approach

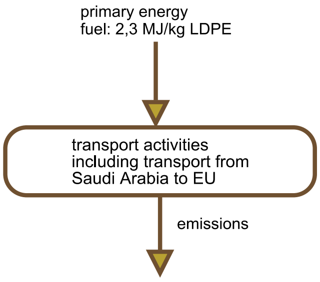
	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
crediting	-3497,8	-2,3	-4,9	-0,4

Table 13: emission crediting for avoided coal electricity generation

Transport Activities

The extraction of the crude oil is followed by its shipment from Saudi Arabia to Europe with an estimated transport distance of 7900 km. The distance for the shipment of the naphtha from the refinery to the steam cracker was set with 100km.

The emission release from these transport activities was assessed by data from NTM (2009).



flows – attributional and consequential approach

	GWP 100	POCP	ACP	EP
	[g CO_2 eq/kg LDPE]	[g ethy eq/kg LDPE]x10	[g SO_2 eq/kg LDPE]	[g PO_4eq/kg LDPE]
transport	200,8	1,8	6,7	0,7

Table 14: transport activities – environmental impact potentials; attributional and consequential approach

6.2 Sugarcane route

Sugarcane cultivation in Brazil

Process Description

The cultivation of sugarcane is a cycle consisting of one planting run and several ratoon runs. The planting run starts with an intensive soil preparation. It includes mechanical treatment like sub soiling and harrowing as well as chemical treatment in form of fertilizer application (Smeets et al., 2006). After that, the soil is furrowed, phosphate fertilizers and seed pieces are put into the furrow, which then is closed and another load of fertilizers and herbicides is applied. The furrowing and fertilizer application is repeated one to two times in the first year of cultivation. 12-18 months after the planting the cane is ready for harvesting. There are two different harvesting methods: manual harvesting, including the burning of the field before the harvest and mechanical harvesting not necessarily including pre-burning - see section 5 Land Use Change). From the field the harvested cane is transported to the mills and processed to ethanol (Smeets et al., 2006). Now the ratooning begins. Fertilizers and herbicides are spread and the cane starts re-growing from the left rootstock. Again, after 12-18 months, it can be harvested and a new ratooning starts. In total four ratoonings are done before the old cane is ploughed out (Cheesman, 2005). The ratooning is not done infinitely as the harvest decreases with every ratoon run.

Process Data

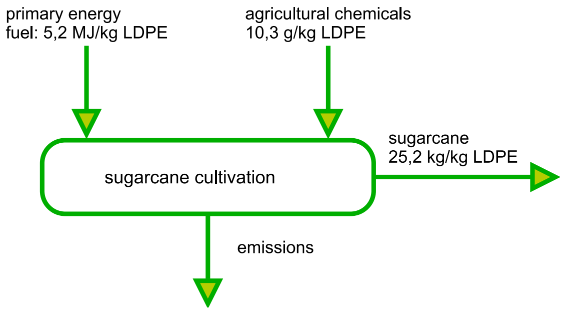
Data availability is a general problem of LCA and the cultivation of sugarcane in Brazil is no exception. Only few authors publish on this issue and the fact that practically all well-to-wheel studies are based on only one author (Macedo) out of these few further limits data diversity and availability. Another problem related to Brazilian sugarcane cultivation is the prediction of technical changes for agricultural operations. Although the Brazilian legislation released different laws concerning the cultivation of sugarcane and its processing (Egeskog and Gustafsson, 2007), it is uncertain to what extent they will be applied. For these reason, the attributional and consequential assessment of the sugarcane cultivation used the same data originating from a report published by Macedo in 2004.

Next to this report, data from Ometto et al. (2009) and Bernesson (2004) were used to assess the environmental impact of the production of fertilizer and pesticides, applied during the sugarcane cultivation.

The environmental impact of the consumed fuels (consumption data according to Macedo (2004)) was assessed, using data from the database SPINE LCI (2008) and NTM (2009) – these databases were also used for the environmental assessment of all processes' fuel consumption.

Emissions from Land Use change were assessed using data from the California EPA (2009) and Zuurbier and van de Vooren (2008) – see section 5 Accounting for land use change.

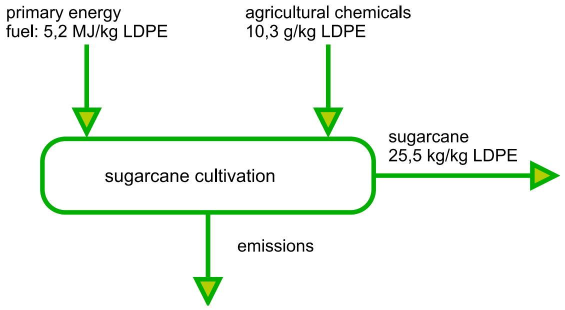
Attention must be paid that the assessed resource consumption and the resulting release of emissions differ between the attributional and consequential approach.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	**POCP** [g ethy eq/kg LDPE]x10	**ACP** [g SO_2 eq/kg LDPE]	**EP** [g PO_4eq/kg LDPE]
agri oper	217,5	0,1	0,5	0,1
fert/pest prod	203,7	0,2	0,4	0,1
emission DLUC				
emission ILUC	2517,3			
SUM	2938,4	0,3	0,9	0,2

Table 15: sugarcane cultivation - environmental impact potentials; attributional approach



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	**POCP** [g ethy eq/kg LDPE]x10	**ACP** [g SO_2 eq/kg LDPE]	**EP** [g PO_4eq/kg LDPE]
agri oper	290,5	0,2	1,1	0,2
fert/pest prod	205,6	0,2	0,4	0,1
emission DLUC	114,5	0,0	0,0	0,0
emission ILUC	2391,4	0,0	0,0	0,0
SUM	3002,0	0,4	1,4	0,3

Table 16: sugarcane cultivation - environmental impact potentials; consequential approach

Ethanol production from sugarcane

Process Description

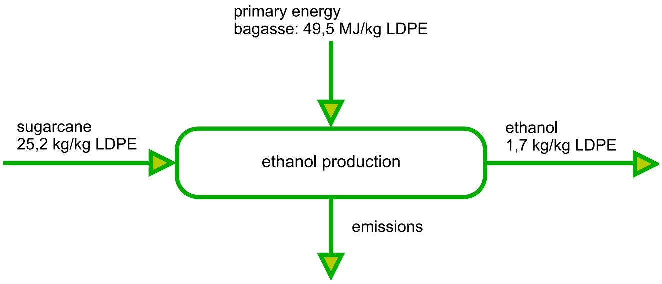
The production of ethanol from sugarcane consists of three processes: 1. pretreatment, 2. fermentation, 3. separation (Quintero et al., 2007). The pretreatment starts with the washing and the crushing of the cane. Afterwards, the cane is milled to extract its juice and to recover the bagasse, which is combusted to generate the energy needed in the ethanol production. The extracted juice is further treated. This includes a pH adjustment to an acidic pH, the removal of impurities and the sterilization of the juice before it enters the fermentation reactor. In the latter, the juice stays for 4-12 hours (Smeets et al., 2006). During that time, the added yeast, *S.cerevisiae,* metabolites its sugar to ethanol (8-11% w/w) and gases, mainly CO_2. At the end of the fermentation, these gases are removed by absorption. The remaining fermentation product is lead to a distillation column and the ethanol is concentrated to 63%. (The stillage produced as bottom product is used for irrigation in agricultural operations.) In a second column (rectification), the ethanol is then purified to 95%. The last purification step to produce anhydrous ethanol is azeotropic distillation using cyclohexane (Smeets et al., 2006). Finally, the ethanol is transported to the ethylene plant by trucks.

Note: The described operations are based on the production of fuel ethanol; however, for this study the high purity of fuel ethanol is not needed. For this reason, the environmental load of this operation might be overestimated.

Process Data

The data basis for the production of the ethanol was again the report from Macedo (2004).

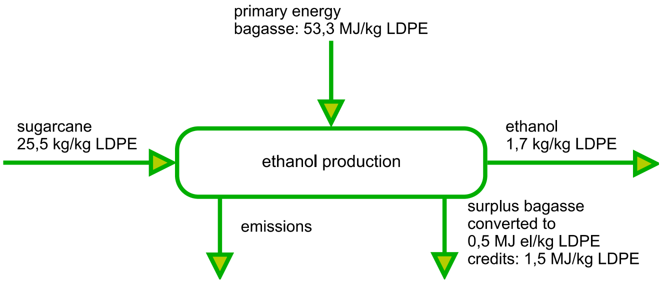
Also for this process, the resource consumption differs between the two LCA approaches, due to differences in system boundaries.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
mill oper	0,0	0,0E+00	2,7	0,5

Table 17: ethanol production- environmental impact potentials; attributional approach



flows – consequential LCA

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
mill oper	0,0	0,0E+00	2,7	0,5
crediting	-1,2	-6,1E-04	-2,1E-03	-3,9E-04
SUM	-1,2	0,0	2,7	0,5

Table 18: ethanol production – environmental impact potentials; consequential approach

Electricity consumption

The following processes consume externally produces electricity in different amounts. The environmental impact of this consumption was differently assessed in the two LCA approaches. For the attributional assessment data from an average Brazilian electricity supply according Coltro et al. (2003) were used, while marginal natural gas electricity supply data according to Bargigli (2004) for the extraction of the natural gas and according to Pilavachi (2009) for the generation of electricity from the natural gas; was applied in the consequential approach.

	electricity [g/MJ]
CO_2	149,1
NO_x	0,5
VOC	
SO_2	7,8E-04
HFC	
HC	
CO	1,1E-02
CH_4	1,5
N_2O	1,5E-04
NMVOC	5,4E-03

Table 19: emissions related to electricity supply, marginal electricity

	electricity [g/MJ]
CO_2	17,8
NO_x	0,6
VOC	
SO_2	0,1
HFC	
HC	7,5E-04
CO	0,1
CH_4	0,5
N_2O	1,1E-02
NMVOC	7,3E-03

Table 20: emissions related to electricity supply, average electricity

Ethanol Dehydration - Production of Ethylene from Cane based Ethanol

The following summarized description of the dehydration of ethanol to ethylene is in accordance to a patent held by Braskem (Barrocas and Lacerda, 2007), which was used to model the process in HYSYS and to thereby generate data. Figure 9 shows the process flowchart created in Aspen HYSYS.

The process starts with pumping the ethanol (at 13,73 bar) to the reactor. Before the reactor, the ethanol passes through two heat exchangers. In both exchangers, it is heated by a countercurrent flow of reactor product, which passes the exchangers before undergoing purification. However, before entering the second exchanger the ethanol is mixed with an ethylene-water vapor recycle from the reactor product. Leaving the second heat exchanger this mix is further heated to 481ºC in a furnace before entering the adiabatic reactor (at 481ºC and 11,93 bar). In the reactor, which is filled with alumina catalyst, the ethanol is dehydrated to ethylene. After an unspecified residence time the stream leaves the reactor and is split in the ratio 2:3 recycle flow to the flow of the end product. The remaining reactor product is further processed to remove impurities and receive PE grade ethylene.

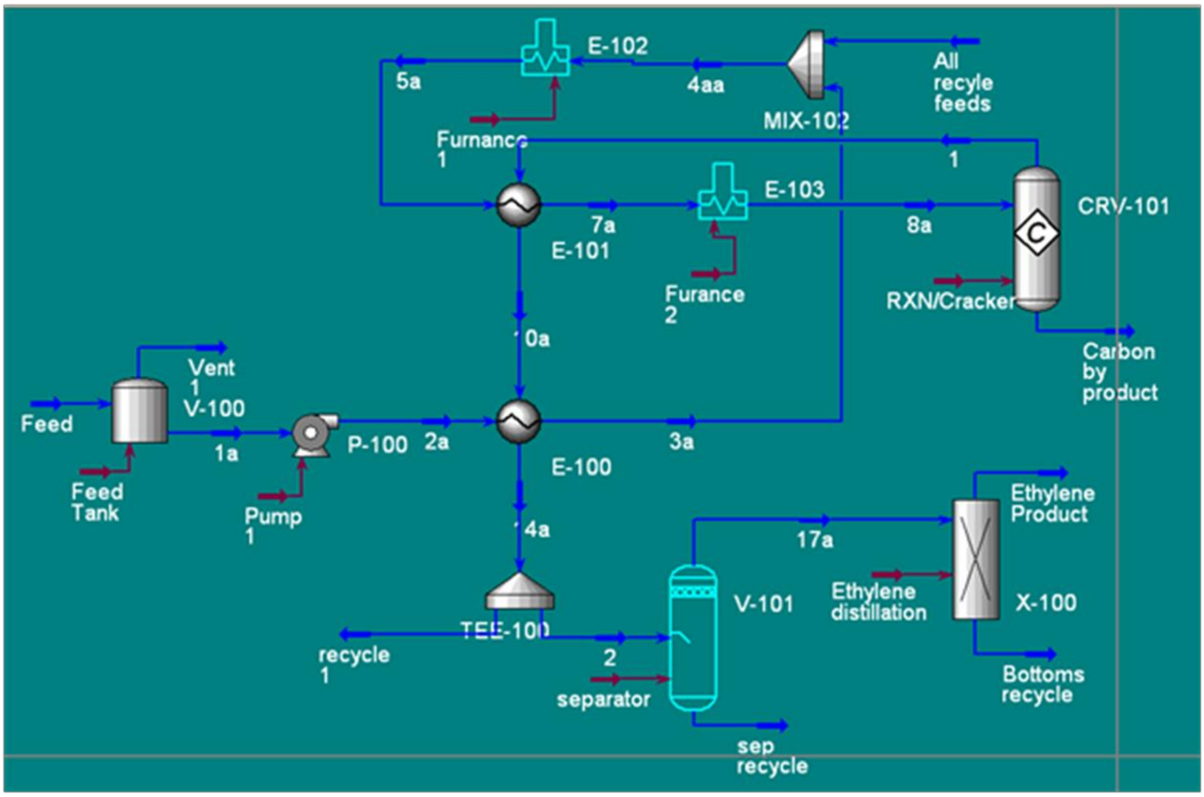
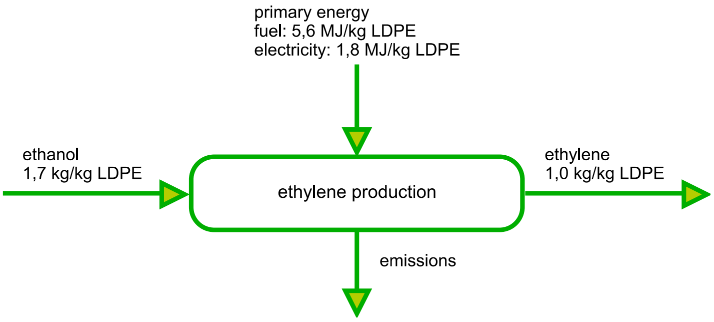


Figure 9: Process Flowchart for the dehydration of ethanol to ethylene in Aspen Hysys

Process Data

As already stated in the process description the data applied to assess this process partly originate from a patent held by Braskem (Barrocas and Lacerda, 2007). It was simulated in the process simulation program Aspen HYSYS. However, this patent does not include all steps up to the final purification of the ethylene. For this reason, the data generated from the process simulation were combined with data from a text released by Kochar et al. (1981). The text states the complete energy (in the form of electricity and fuels burned directly for the process) consumed to produce polymergrade PE as well as the specifications of the ethanol consumed – application of anhydrous ethanol.

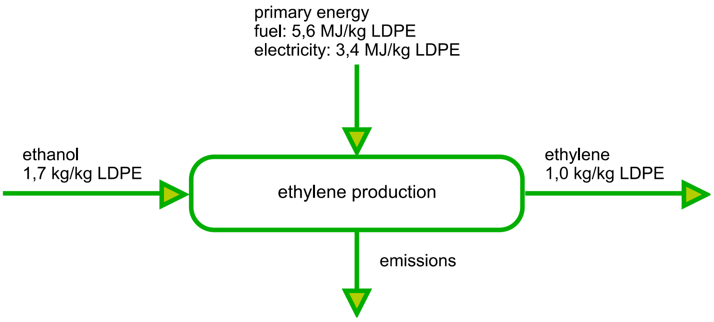
The energy consumed in the process is electricity and fuels directly burned for process purposes. Electricity consumed was assessed using the already stated data – see electricity consumption. All other energy carriers directly used in the plant were assumed to be natural gas. They were assessed according to data from Bargigli (2004) for the natural gas extraction and according to Baumann and Tillman (2004) for their combustion.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
ethy prod	367,8	0,2	1,2	0,2

Table 21: ethylene production – environmental impact potentials; attributional approach



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
ethy prod	538,8	0,2	1,0	0,2

Table 22: ethylene production – environmental impact potentials: consequential approach

Polymerization

Process Description

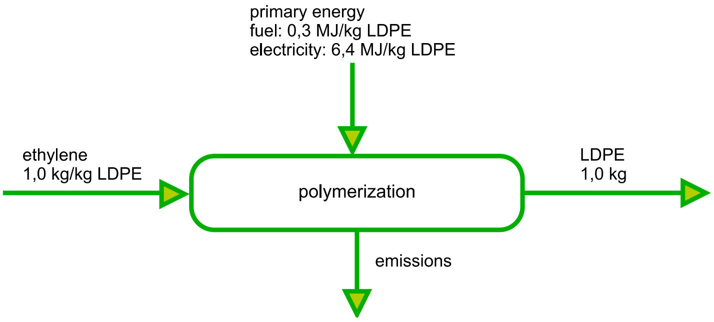
For the Process Description see section Polymerization in the Crude Oil Inventory.

Process Data

The process of polymerization was assessed using data from the Swedish PE producer Borealis (2008). The assumption was set, that there is no significant difference between Brazilian and Swedish producers.

The electricity consumed during polymerization was assessed using average and marginal electricity supply data, respectively – see electricity consumption. The environmental impact of external fuels consumed (parts of the process by-products are used for the internal energy supply, however they do not cover the full energy demand) was assessed according to emission data from SPINE LCI (2008). Whereby the fuels were treated as diesel under the assumption that diesel and fuel oil have the same environmental impact during their production.

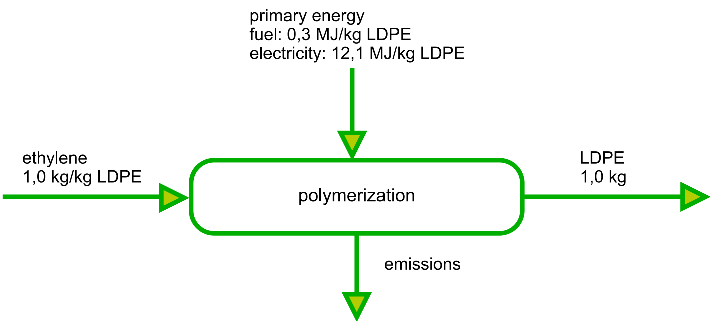
The data of the polymerization step differ between the sugarcane and crude oil route due to different electricity supply data used. However, the actual electricity consumption data are the same.



flows – attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
polymerization	246,3	0,7	2,1	0,3

Table 23: polymerization – environmental impact potentials; attributional approach



flows – consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
polymerization	857,5	0,5	1,4	0,2

Table 24: polymerization – environmental impact potentials; consequential approach

Incineration

Process Description see crude oil route

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
incineration	0,0	0,2	0,1	9,5E-03

Table 25: incineration – environmental impact potentials, attributional approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
incineration	0,0	0,9	0,2	4,1E-02

Table 26: incineration – environmental impact potentials; consequential approach

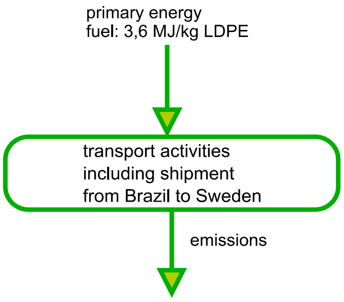
	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
crediting	-3497,8	-2,3	-4,9	-0,4

Table 27: crediting for avoided electricity production

Transport activities

The different processes described above included various transport activities.
Their environmental impact due to fuel consumption was assessed using emission data from SPINE LCI (2008) for the extraction of the fuels and from NTM (2009) for the combustion of the fuels during transport.
For the agricultural transport activities, consumption data according to Macedo (2004) were used.
The transport of the ethanol to the ethylene plant was assumed to be 350 km. The accordingly fuel consumption was estimated using the NTM database.

The ship transport from Brazil to Europe was assumed to be 10.500 km by means of cargo vessel (more than 8000 dtw) transport. The data for this transport were data from NTM (2009).



flows – attributional and consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
transport	315,2	1,7	7,4	0,9

Table 28: transport activities – environmental impact potentials; attributional approach & consequential

Sensitivity analysis data

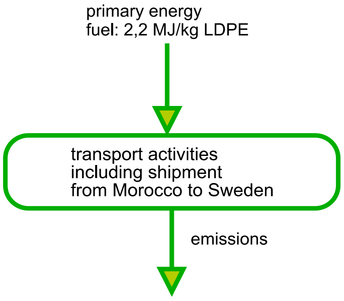
Sugarcane route

1. Short Transport distance for the sugarcane route

One scenario assessed in the course of the study was the supply of sugarcane based LDPE from Morocco.

For this assessment, the shipped distance for the LDPE was assumed to be 3.400 km and the emissions released were assessed using data from NTM (2009).

All other processes were assessed according to the data used in the Brazilian cane route – see above.



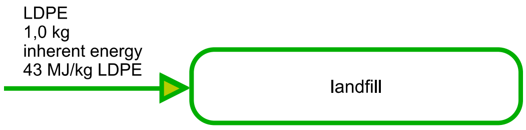
changed flows – attributional and consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
transport	186,1	0,7	3,0	0,4

Table 29: activities influenced by the change to African cane – environmental impact potentials

2. Waste disposal in the form of landfill storage

Another scenario assessed was the storage of the sugarcane based LDPE in a landfill after its use phase. The emissions resulting from this storage were accounted using data from the U.S. EPA (2009b), whereby the system was credited with the carbon stored in the LDPE, due to its renewable origin. All other processes were assessed according to the data used in the Brazilian cane route – see above.



changed flows – attributional and consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
landfill	-2440,0	0,0	0,0	0,0

Table 30: environmental impact potentials due to change in disposal scenario from incineration to landfill

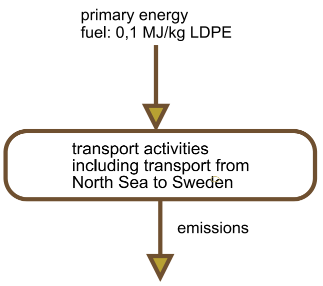
Oil route

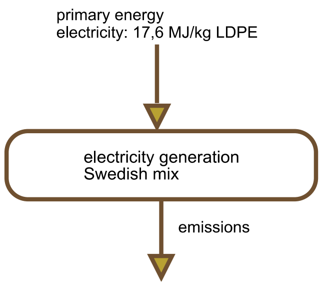
3. Short distance Transport and application of Swedish electricity supply

The oil route was assessed under different sensitivity scenarios. One scenario was the extraction of the crude oil in the North Sea and its subsequent processing to LDPE in Sweden. The transport distance applied for this scenario was 350 km and its environmental impact was assessed using data from NTM (2009).

The electricity supply was assessed using data for average and marginal Swedish electricity according to PE-International GmbH (2002a) for the average electricity respectively according to Markewitz et al. (2009) and PE International GmbH (2002d) for the marginal coal electricity.

All other processes were assessed according to the data used in the EU crude oil route – see above.





changed flows – attributional approach

	GWP 100 [g CO$_2$ eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO$_2$ eq/kg LDPE]	EP [g PO$_4$eq/kg LDPE]
refinery	202,4	3,4E-02	0,1	1,6E-02

	GWP 100 [g CO$_2$ eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO$_2$ eq/kg LDPE]	EP [g PO$_4$eq/kg LDPE]
steam cracking	722,5	0,1	0,4	0,1

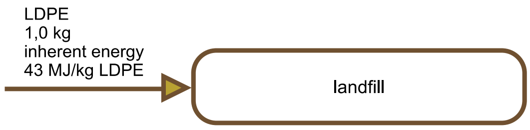
	GWP 100 [g CO$_2$ eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO$_2$ eq/kg LDPE]	EP [g PO$_4$eq/kg LDPE]
polymerization	228,0	0,2	0,3	2,5E-02

	GWP 100 [g CO$_2$ eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO$_2$ eq/kg LDPE]	EP [g PO$_4$eq/kg LDPE]
transport	10,6	0,1	0,4	3,9E-02

Table 31: activities influence by the change to short transport and Swedish electricity - environmental impact potentials; attributional approach

4. Waste disposal in the form of landfill storage

Another scenario assessed was the storage of the LDPE in a landfill after its use phase. The emissions resulting from this storage were accounted using data from the U.S. EPA (2009b). All other processes were assessed according to the data used in the Swedish crude oil route – see above.



changed flows – attributional and consequential approach

	GWP 100 [g CO_2 eq/kg LDPE]	POCP [g ethy eq/kg LDPE]x10	ACP [g SO_2 eq/kg LDPE]	EP [g PO_4eq/kg LDPE]
landfill	0,0	0,0	0,0	0,0

Table 32: environmental impact potentials due to change in disposal scenario from incineration to landfill

7 Results

In this section, the results are presented, as potential environmental impact in the selected impact categories. First the results from the base scenarios are shown, i.e. sugarcane cultivation, fermentation and LDPE production in Brazil followed by transport to Europe and oil extraction in the Middle East, transport to Europe and subsequent production steps in Europe. For both alternatives, an end-of-life scenario was applied, consisting of incineration where the heat is recovered and used for electricity production. A comparison is then made of the results arrived for the oil route in this study with those presented by Plastics Europe. The section is ended by the results from the sensitivity analysis, which was done with respect to shorter transport distances, the oil route processes placed in a Swedish setting instead of an average European one, and a different en-of-life scenario, landfill deposition.

7.1 Results from base scenarios

The most important impact categories in this study are resource consumption and global warming. The driver for producing polyethylene from sugarcane is of course the expectation that since it is based on a renewable resource it will contribute less to carbon emissions, and also consume less non-renewable resources.

In Figure 10 the total primary energy consumption for the sugarcane route and the oil route are shown, for both the attributional approach and the consequential approach. As may be expected, the consumption of non-renewable energy is much lower for the sugarcane-based route, at the price of a higher consumption of renewable energy. Taken together, total energy use is higher for the cane-based route. Much of this is attributable to the ethanol production, which uses 40% of the total primary energy. It is also clear from the credited primary energy from avoided electricity production (brown bar, consequential approach) that a waste treatment process that makes use of the material, in this case energy in the material is important to the over-all results (in this case incineration followed by electricity generation).

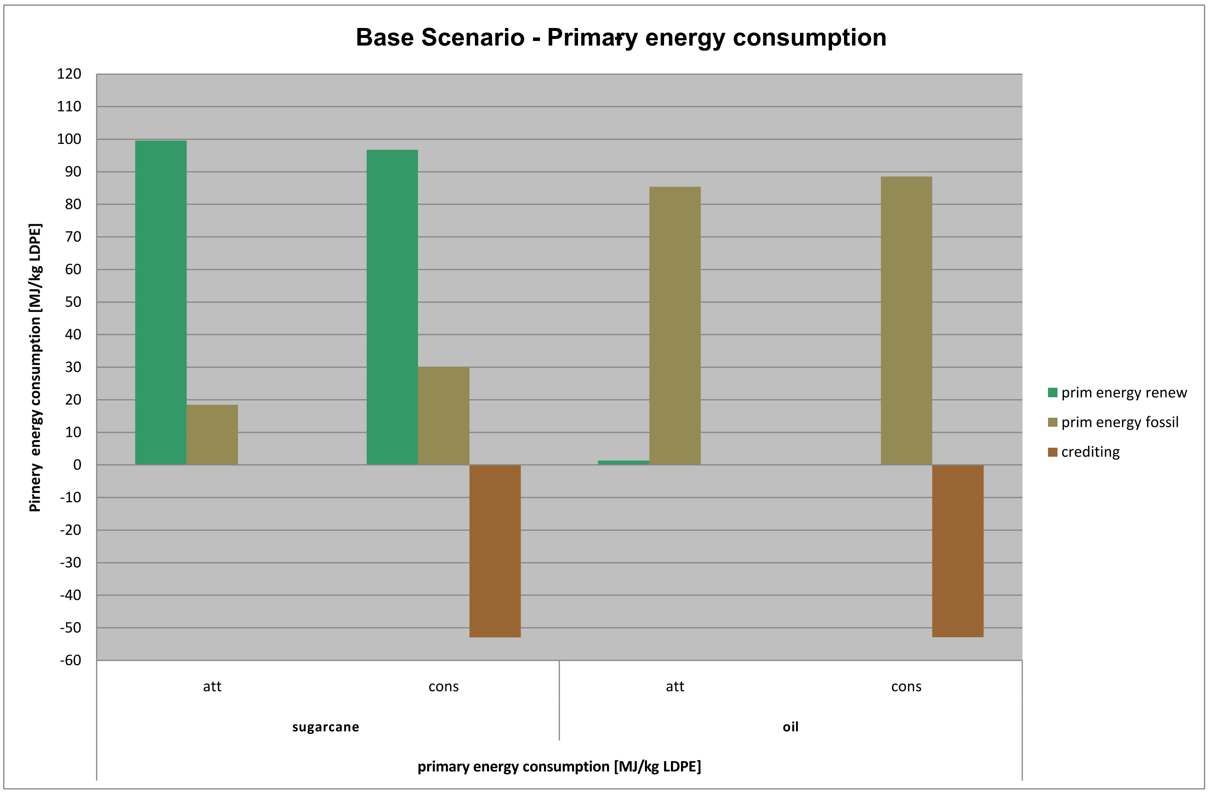


Figure 10: Primary energy use for the base scenarios, attributional and consequential approach. The label *prim energy fossil* includes nuclear energy

Turning to the global warming potential (Figure 11) the sugarcane route, as expected, has considerably lower GHG emissions than the oil route, as long as the impact from land use change is disregarded. Inclusion of the LUC emissions, however, more than doubles the GWP of the cane route and makes it come worse than the oil route (attributional approach) or only slightly better than the oil route (consequential approach). Both the methods and the data used for assessing effects of LUC are however too uncertain to underpin such ranking between the oil and cane route with regard to GWP. What may be concluded, however, is that LUC emissions can be significant, and cannot be ignored.

The bars in Figure 11 have been sub-divided into the different activities in the life cycle. Environmental impact from the generation of the electricity used in a particular activity is included in these shares.

Even if LUC emissions are not included, and even more so if they are, GHG emissions from the sugar cane route are dominated by the agricultural activities, resulting mainly from production and application of fertilizers and pesticides. When LUC is included approximately 80% of the GHG emissions of the sugar cane life cycle emanates from the agricultural operations (table 32). A comparison between the release of LUC emissions in the attributional, and consequential approach shows that they do not differ significantly.

When the sugarcane route is assessed under a consequential approach, also the polymerization step contributes to a significant share of the GWP. This is due to its use of electricity, which in the consequential study is supplied by natural gas (marginal Brazilian electricity production).

The oil route has no such clearly dominating activity as the sugar cane route. Steam cracking, polymerization and incineration all contribute significant shares of the total GWP. The difference in emissions from incineration between the attributional and consequential analysis depends on different allocation rules being applied.
Figure 11 also shows that the electricity production, which is avoided when waste polyethylene is incinerated, and electricity is produced from the released energy, significantly lowers the net GHG emissions. If effects of LUC are disregarded, the sugarcane route in the consequential assessment is even a net absorber of GHG.

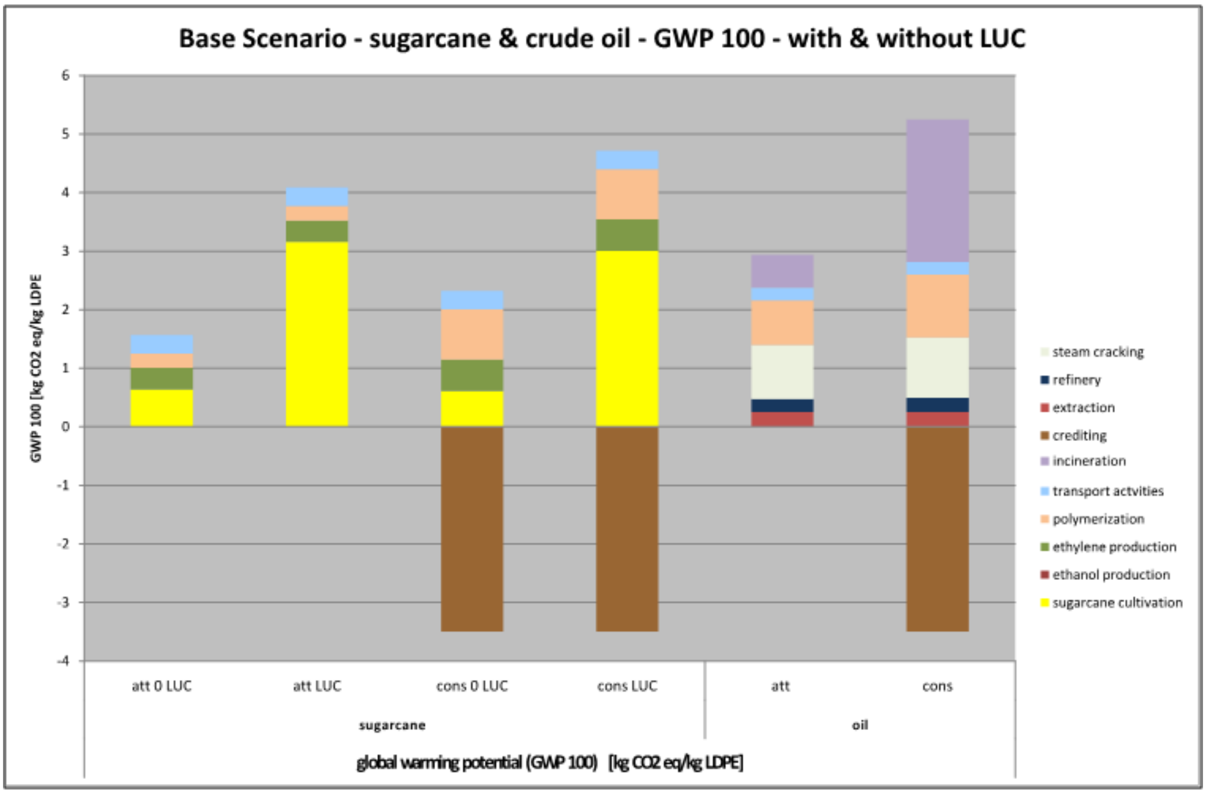


Figure 11: Global warming potential for the base scenarios, attributional and consequential approach. Sugar cane results shown with, and without, effects of land use change.

share of LUC emissions on GWP

	att LCA	cons LCA
share on GWP agri operations	0,80	0,83

Table 33: Share of agricultural operations

The remaining impact categories, acidification, eutrophication and photochemical ozone creation are shown in Figure 12, Figure 13, Figure 14, respectively. The most striking result is the high contribution to all three types of impact from transport activities. This is mainly due to the long sea transports, of crude oil from the Middle East to Europe, in the oil case and of polyethylene from Brazil to Europe, in the sugar cane case. Sea transport emits SO_2 (acidification), but also NO_x (acidification and eutrophication) and CO which gives rise to ozone creation. For ozone creation, also the incineration plays a role, as CO is emitted. Also the polymerization step is important for both routes, mainly due to its electricity consumption. The impact of the polymerization, however differs between the attributional and consequential approach due to different electricity supply and the resulting difference especially in SO_2 and emissions.

For the sugarcane route, the ethanol production step gives significant contributions to both acidification and eutrophication. This is due to its internal energy conversions, based on burning of bagasse, which gives rise to high emissions of NOx.
It should be noted that the results for eutrophication do not give the full picture, as it was not possible to quantify the emissions of eutrophying substances to water. However, there are

such emissions, from the agricultural operations, and the ethanol production, which takes place in aqueous media.

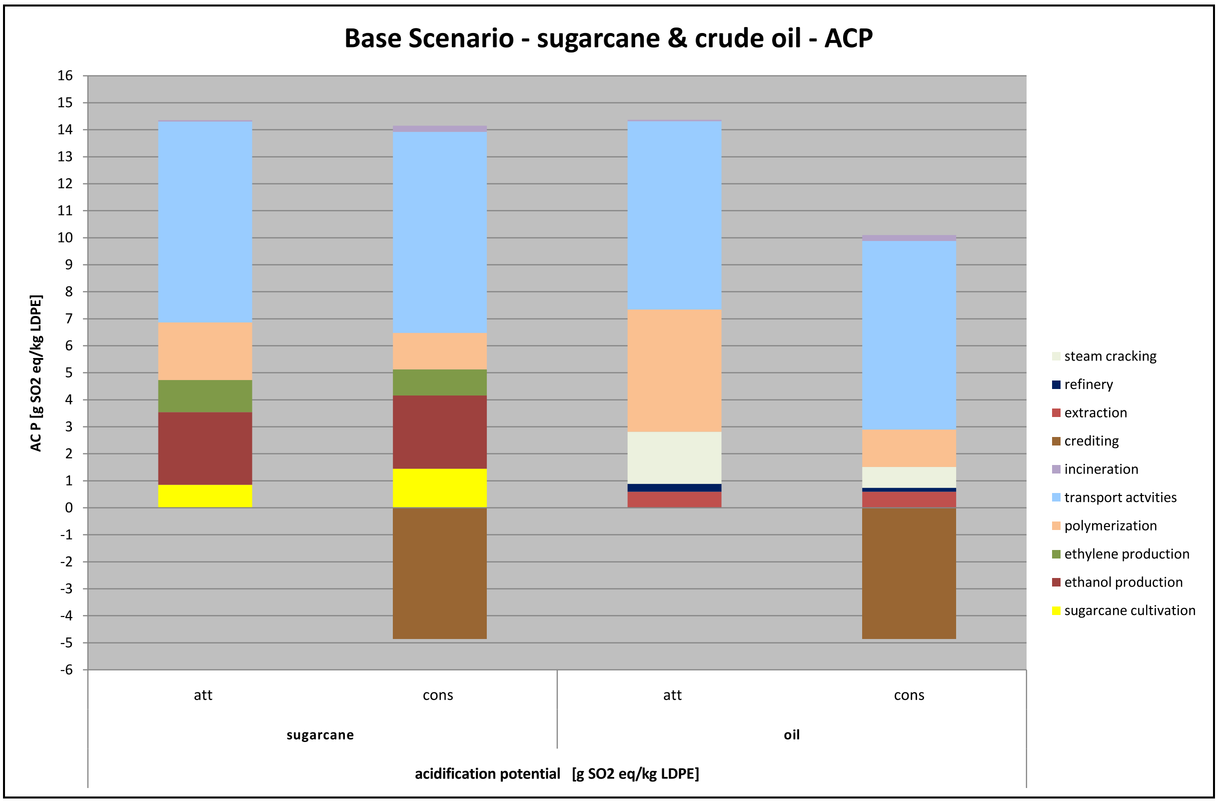


Figure 12: Acidification potential for the base scenarios, attributional and consequential approach.

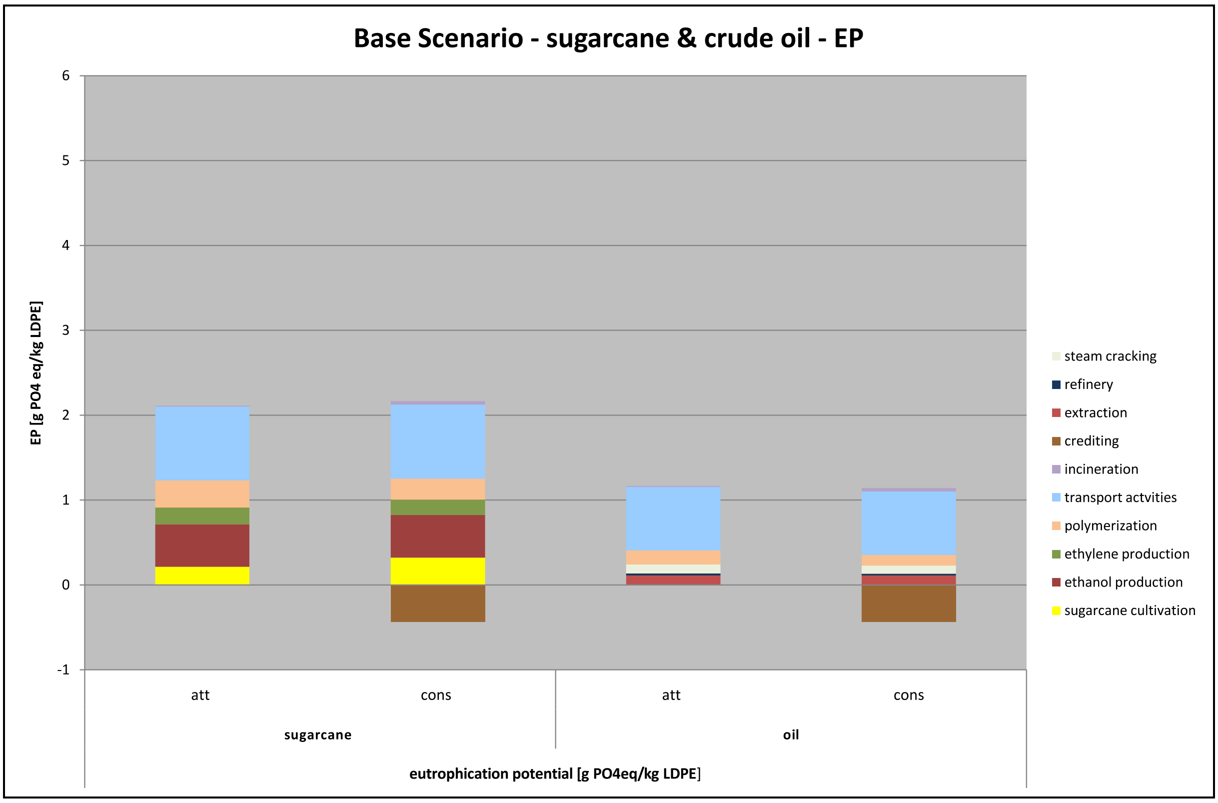


Figure 13: Eutrophication potential for the base scenarios, attributional and consequential approach

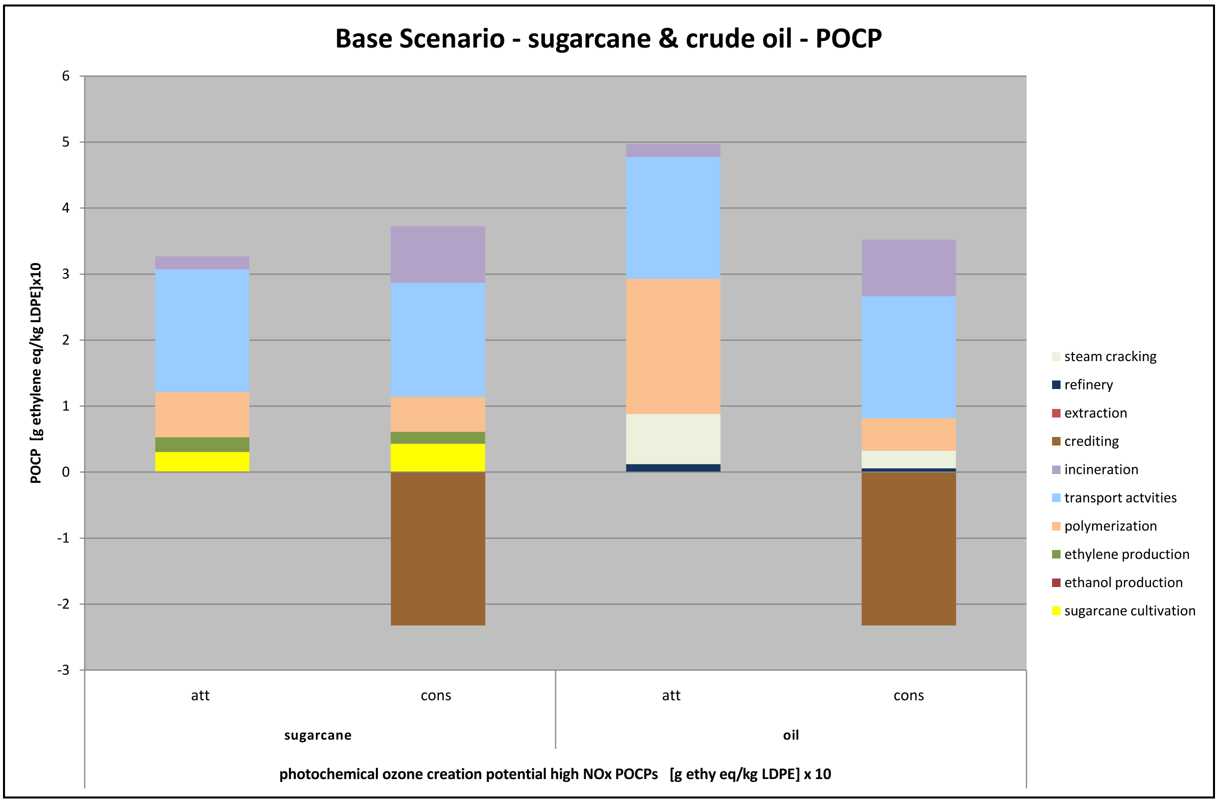


Figure 14: Photochemical ozone creation potential for the base scenarios, attributional and consequential approach

Comparison of results for the oil route with data from Plastic Europe

It is interesting to see how the results of this study compares to those of other studies. The most authoritative LCA data in the plastics sector are those from Plastics Europe. Figure 15 shows a comparison of the attributional base case LCA of oil based LDPE in this study with data from Plastic Europe (PlasticsEurope, 2008). Only the emissions taken into account in this study are shown (Plastic Europe data cover a broader set of emissions). The end-of-life treatment is excluded, to enable comparison between as equivalent systems models as possible.

The comparison shows a somewhat higher primary energy consumption for the oil route of this project. However, with 87 MJ/kg LDPE it lies in the range (64 – 93 MJ/kg LDPE) stated in the Plastic Europe report, which uses an energy consumption of 78 MJ/kg LDPE as calculation basis for all potential environmental impacts. The higher primary energy consumption is also reflected in the higher acidification and eutrophication potential in our results. Only for the creation of photochemical ozone, the potential impact stated by Plastic Europe is higher. The cause is the higher amount of CO and CH_4 emissions reported by Plastics Europe.

The higher amount of CH_4 emissions is also the reason for the similar global warming potential of the two datasets, since the Plastic Europe reports only half of the amount of CO_2 found in this project. This is due to natural gas being, next to crude oil, the feed-stock in Plastic Europe dataset.
In summary, despite variation in some of the impact categories, which are mainly caused by the difference in energy consumption, the results of our study are in the range of comparable production scenarios.

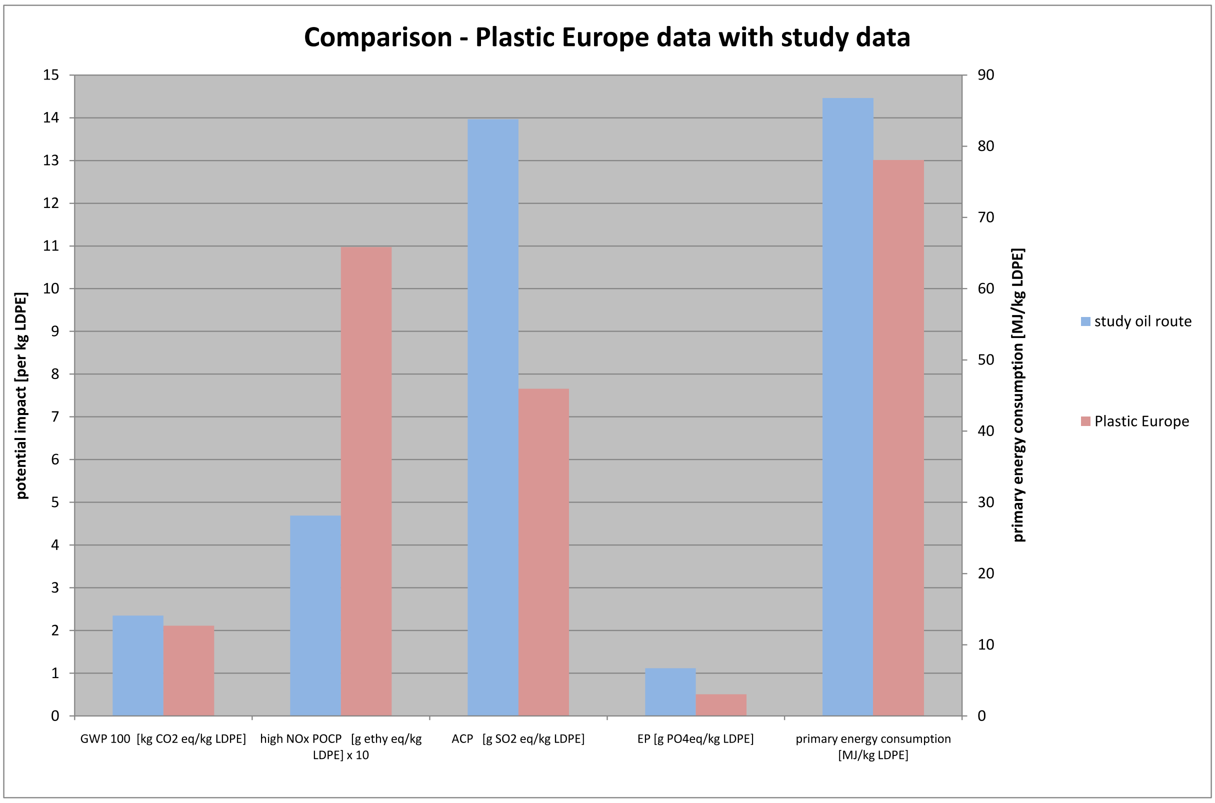


Figure 15: Comparison of the attributional base case oil route with data from Plastics Europe. End-of-life processes excluded