Annex C2-1:
LCA/LCC study

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Project Report
26531

Life Cycle Assessment of ethanol production at St1

Etanolix plant

17-06-15

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CONTENTS

1

SUMMARY

A study was performed with the objective to assess the environmental impact of ethanol production from food residues at St1's Etanolix plant. To do this, a Life Cycle Assessment (LCA) with the functional unit 1 MJ ethanol at the gate of the production unit was made. The studied system is a gate-to-gate system, covering operations made at the Etanolix plant.

Data was collected through communication with Lars Olausson and Jonas Strandberg at St1 refinery. Two main scenarios were studied, the baseline scenario, based on data from Quarter 1, 2017 and the high utilization rate scenario, with estimated data on future operation conditions. Sensitivity analyses were made for different types of allocation and electricity.

The results show that for the baseline case, the global warming potential for production of 1 MJ ethanol is 45 g CO_2-equivalents. The largest contributor to global warming is treatment of waste in the municipal incineration plant. With the high utilization rate scenario, the total environmental impact for all studied impact categories is significantly lower per produced MJ ethanol, for global warming 15 - 28 g CO_2-equivalents, depending on the distances for sourcing of raw material. The largest difference is due to the lower amounts of waste that goes to incineration.

Some conclusions from the study are that if the aim is to minimize environmental impact from ethanol production, it is important to optimize the process in order to achieve a higher utilization rate. It is also important to minimize the amount of waste that goes to incineration since today, much food residues that could have been utilized as ethanol production feedstock goes to waste. A change to "green" electricity would lower the environmental impact further. From an environmental point of view, local sourcing of raw materials is favourable since transport of food residues has a significant environmental impact. It is also of importance to optimize the use of enzymes since enzyme production has relatively high environmental impact.

1. Introduction

The Etanolix plant, located at St1 Refinery in Gothenburg, Sweden, was set up with support from an EU project, Etanolix 2.0 - Demonstration of Innovative Method for converting Industrial Waste to Ethanol in oil refinery for LIFE+. One objective of the EU project was to produce ethanol from food waste in the context of an existing refinery and thereby achieve ethanol with low environmental impact from production. To verify this, a life cycle assessment (LCA) was made and this report contains a gate-to-gate LCA of ethanol production at St1's refinery.

1.1 Objectives

The objective of the study is to assess the environmental impact of ethanol production at St1's Etanolix plant.

1.2 General description of life cycle assessment

1.2.1 Principles of life cycle assessment

Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave, i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, to disposal or recycling, see Figure 1. Environmental impacts include emissions to air, water and soil as well as consumption of resources in the form of both energy and material, in the different stages of the life cycle.

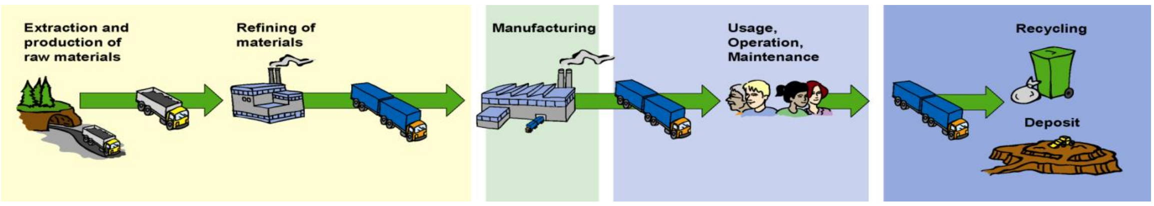

FIGURE 1. SCHEMATIC PICTURE OF A PRODUCT'S DIFFERENT LIFE CYCLE PHASES.

The purpose with performing an LCA is to get a fair and comparable evaluation of the environmental performance of a product (both services and goods can be assessed). The life cycle perspective is essential in order to avoid sub-optimization, i.e. that a certain process step or component is optimized, however the whole life cycle of the product does not reach its optimal environmental performance. Sub-optimization can occur when only parts of the life cycle are studied and the overall performance is not evaluated.

To facilitate the comparability of the results of a study, a clear definition of the functional unit used should be made. The functional unit describes the basis for the calculation, e.g. ”transporting one person one km‟, or “one year use of a vehicle”.

Another important LCA concept that facilitates comparability is system boundaries. The system boundary describes what has been included in the assessment and not. The study of a transport of one person one km can e.g. include or not include: the production of the vehicle, the tools used during production of the vehicle, the transports of goods and employees during the production of the vehicle, the production of the fuel, the combustion of the fuel, the infrastructure i.e. roads, gas stations etc., the waste management of the vehicle etc. depending on what is relevant for the specific study. It is important that the setting of the system boundaries follows the same principle when two products are compared with each other.

This life cycle assessment is performed in accordance with International Organisation for Standardization (ISO) 14040[1] and 14044[2] and the International Reference Life Cycle Data System (ILCD) Handbook[3].

1.2.2 Phases of an LCA

The ISO 14040 standard implies that the following steps shall be performed when performing an LCA:

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[1] International Organization for Standardization – ISO. Environmental management – life cycle assessment – principals and framework. International Standard ISO 14040, Geneva; 2006.

[2] International Organization for Standardization – ISO. Environmental management – life cycle assessment – requirements and guidelines. International Standard ISO 14044, Geneva; 2006.

[3] EC – European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010

- **Goal and scope definition**

The goal and scope definition is the first stage of an LCA, where the purpose of the study is described. Also the boundaries of the product system are defined according to factors such as time constraints, data available and depth of study required. At this point a ‘‘functional unit’’ is defined, which provide a reference to which the inputs and outputs of the analysis are related.

- **Inventory analysis**

Inventory analysis involves data collection related to the inputs and outputs of the system described in the ‘‘goal and scope definition’’. It inventories quantities of raw materials, waste flows and emissions attributed to the product’s life cycle.

- **Life cycle impact assessment**

Life cycle impact assessment involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts.

- **Interpretation**

Here results are interpreted, summarised and discussed, conclusions are drawn and recommendations made against the initial goals.

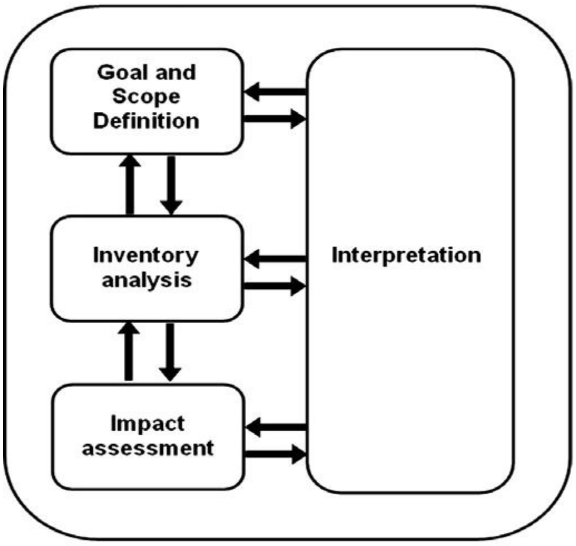

FIGURE 2 PHASES OF AN LCA.

Figure 2 shows that that there are interactions between interpretation and the other stages as the study is constantly measured against its initial goal and scope and refined during its duration.

2 Method

In this chapter, system boundaries, prerequisites and assumptions for the study are described.

2.1 Functional unit

The functional or declared unit is 1 MJ ethanol at the gate of the production unit.

2.2 System boundaries

The studied system is a gate-to-gate system, covering operations made at the Etanolix plant. That means that the feedstock material, food residues, is considered as discarded product which does not carry with it an environmental burden up to point of collection (as it is allocated to the production of the food). Distribution of the fuel to point of sale is not included in the system and neither is the environmental impact from the use or end-of-life phase of the fuel (emissions from combustions) as it the same for all ethanol products of the same quality.

The system boundary for the study is shown in Figure 3.

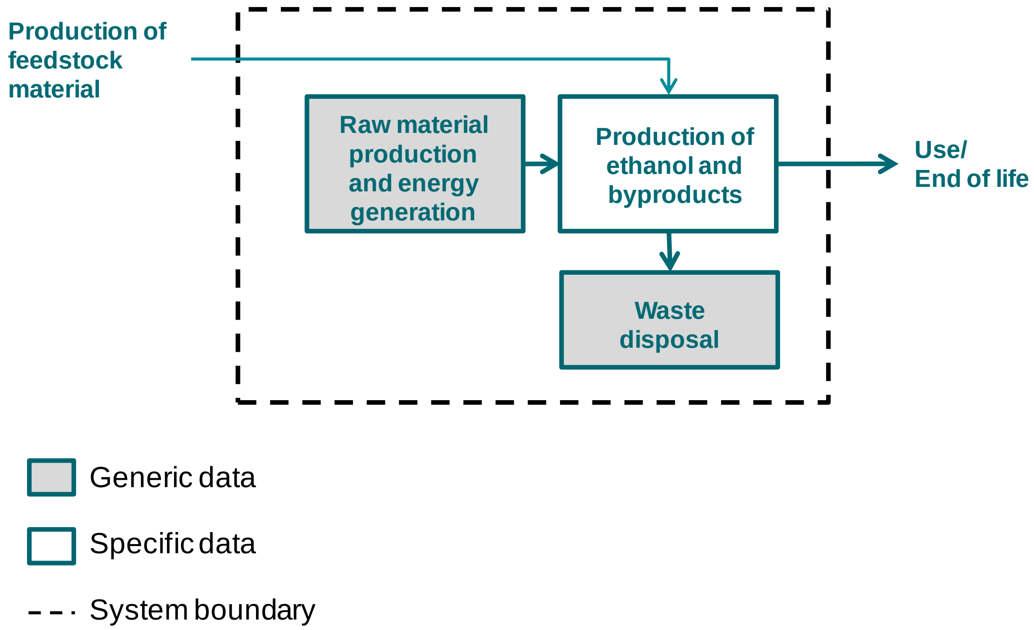

FIGURE 3 SYSTEM BOUNDARY OF THE STUDY

The system boundary for the life cycle assessment is based on the General Programme Instructions for the EPD® system (EPD®, 2013). Concerning the allocation of waste burdens and benefits, the EPD® system recommends the principle to separate the product systems at the point where the waste products have their lowest value. Furthermore, the product system that pays money at this "lowest-value-point" (either to get rid of the waste or to get the waste resource) should carry future environmental impacts. Hence, the system borders are a bit different for different materials and may even go through a plant, for example when household waste is burnt and the heat is utilized, see figure 4 below.

This type of systems boundary delimitation is often called the cut-off approach since there is a clear cut-off point between the product systems. It enables addition of consecutive product life cycles without double counting emissions and resources.

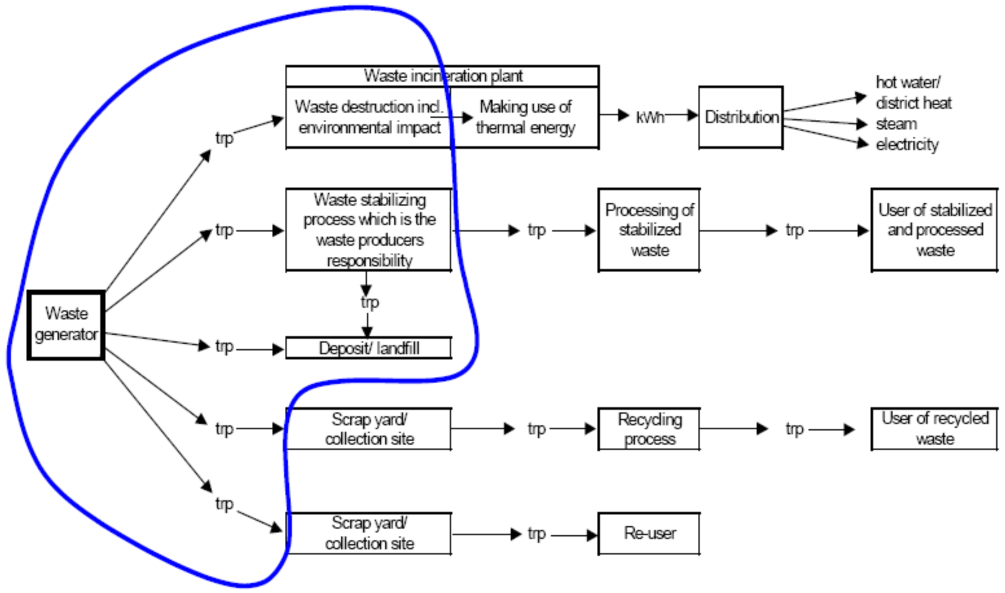

FIGURE 4 SYSTEM BOUNDARIES FOR DIFFERENT WASTES WHEN APPLYING THE PRINCIPLE TO SEPARATE THE PRODUCT SYSTEMS AT THE POINT WHERE THE WASTE PRODUCTS HAVE THEIR LOWEST VALUE (EPD®, 2008)

Regarding temporal system boundaries, both historical and contemporary and future emissions are included without temporal limitations in the generic data from the database Ecoinvent 3.1[4] which is normally used. The Ecoinvent database normally also includes emissions and resources for the necessary infrastructure, such as production equipment, roads, facilities etc.

The application of the principle of separating the product systems where the material has the lowest value, and the polluter pays principle means in practice that:

- Reuse of product. Transportation to any form of waste disposal facility shall be borne by the studied product. Any subsequent upgrading processes should be carried by the next product life cycle.
- Scrap metal, plastic waste and other waste that is recycled. Transport to the scrap yard should be borne by the studied

[4] Ruiz, M., Althaus, H., Bauer, C., Doka, G., Jungbluth, N., Nemecek, T., Stucki, M., Sutter, J., Tuchschmid, M., 2014. Documentation of changes implemented in ecoinvent version 3.1. Ecoinvent 1.

product. Subsequent recycling processes should be carried by the next product systems. This is applied on metal scrap in this study. Note that future avoided environmental burdens due to recycling is not credited to the studied product system. Instead the benefits of recycling is taken into account in the recycling content of used input materials, see Figure 4.

- Waste that is incinerated for energy recovery. Transport to the incinerator and emissions from combustion shall be borne by the studied product. If you have to pay to get rid of the waste, the recovered energy should be credited to the next product system (theoretically this next product system then gets virtually emission-free energy). In this study, this is the case for waste to incineration. If you get paid for the waste, the recovered energy should be credited to the studied product.
- Waste to be treated and/or put in disposal. The studied product accounts for all emissions since no other product systems have any use for the waste.

2.3 Environmental impact assessment

In this study, results are mainly presented as climate impact with the unit CO_2-equivalents. The CML-IA baseline method[5] in SimaPro was used. For more information regarding the impact categories, see Appendix 1.

2.4 Data collection and modeling

Data was collected through communication with Lars Olausson and Jonas Strandberg at St1 refinery. The studied system is the Etanolix plant, located at the St1 refinery, Gothenburg, Sweden. Data used for modeling is from quarter 1, 2017. At this time, the plant was operated at approximately 25-30% of its intended capacity. The plant is new with many obstacles in operation, making the utilization of the plant low. Some process parameters, for instance electricity use, is almost constant over time and not coupled to the produced volume while others are strongly related to the production volume. To estimate the environmental impact from future normal operation at the plant, a scenario was made with a high utilization rate. The process parameters

[5] Guinee, J.B. et al., 2001. *Handbook on Life Cycle Assessment, Operational guide to the ISO standards Volume 1, 2a, 2b and 3*.

for this scenario were estimated by Lars Olausson and Jonas Strandberg at St1.

2.4.1 Production

The main product from the process is ethanol fuel. There are two useful by-products, stillage that goes to biogas production and stillage that is used as animal feed. The energy content of the produced ethanol is 26,7 GJ/tonne and the density is 789 kg/m^3 which gives an energy content of 21 066 MJ/m^3. In Table 1, the useful products from the process are shown. The density of stillage and biogas feedstock is approximately 1000 kg/m^3.

TABLE 1 DESCRIPTION OF THE USEFUL PRODUCTS FROM ETANOLIX.

Product	Amount quarter 1, 2017 (m^3)	Amount high utilization (m^3)
Ethanol	270.3	1250
Biogas feedstock	2126	2500
Stillage	1722	10000

2.4.2 Raw materials

As raw material for the process, leftover bread from bakeries and other food residues are used. In the LCA model, the food residues are considered as discarded products or waste which do not carry with it an environmental burden up to point of collection (as it is allocated to the production of the food). The environmental impact associated with the raw material is only based on the transport from food industry to St1. Transport distances are logged thoroughly for the raw material collection, as shown in Table 2 for quarter 1, 2017.

TABLE 2 RAW MATERIALS AND TRANSPORT DISTANCES FOR QUARTER 1, 2017.

Amount quarter 1, 2017 (ton)	Transport distance (km)	Comment
11.9	480	
109.7	150	

124.16	20	
86.8	500	
220.45	200	
31.2	200	
135.68	500	
293.1	280	
12	100	
22.4	300	
303.8	11	
16.5	380	
Sum: 1367.69	91.6	Weighted mean distance for transports

For the high utilization scenario a total of 5000 tons has been estimated and a weighted mean distance of 91.6 km.

2.4.3 Energy use

To run the process, energy as heat and electricity is used. The heat used in Etanolix is excess heat from the St1 refinery that otherwise would be wasted and in the model it is not associated to any environmental impact. Since St1 has no specific contract for electricity, it has been modeled as average Swedish electricity [Electricity, medium voltage {SE}| market for | Alloc Rec, S]. In Table 3, the energy use for the process is shown and in Figure 5, the composition of the Swedish electricity mix is shown.

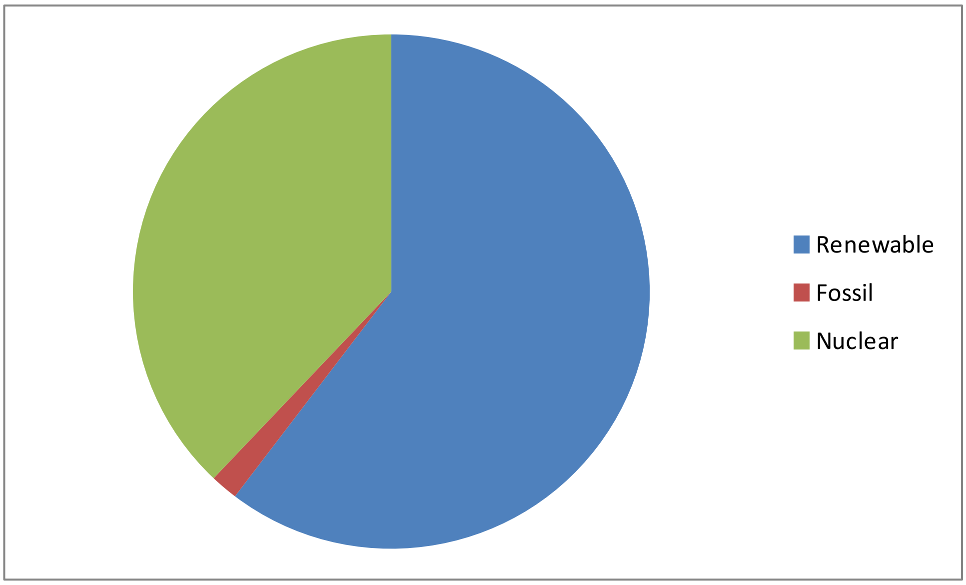

FIGURE 5 COMPOSITION OF THE SWEDISH ELECTRICITY MIX 2016[6] CATEGORIZED BY TYPE OF ENERGY SOURCE; RENEWABLES (HYDRO, WIND, SOLAR AND BIOFUELS), NUCLEAR AND FOSSIL.

TABLE 3 ENERGY USE FOR THE PROCESS.

Energy	**Amount quarter 1, 2017 (MWh)**	**Amount high utilization (MWh)**
Excess heat	1187.8	2800
Electricity	1584	2000

Excess heat is not considered to carry any environmental burden, as it is allocated to the first production process making use of the heat.

[6] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (Part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.

2.4.4 Chemicals

For production of ethanol, there is a need to add urea, sodium hydroxide, yeast, nitrogen gas, enzymes (Spirizyme and Viscamyl) and propylene glycol. The amount of chemicals for production of 270.3 m^3 ethanol during the time period January-March 2017 is shown in Table 4.

TABLE 4 CHEMICALS USED IN THE PROCESS.

Chemical	Amount quarter 1, 2017	Amount high utilization	Transport distance (km)	Comment
Urea	4.9 m^3	24 m^3	320 (truck)	
Sodium hydroxide	3.5 m^3	5.2 m^3	-	Average transports included in Ecoinvent market process
Yeast	2.95 m^3	6 m^3	28+230 (truck) 8 (ferry)	
Nitrogen gas	17,9 ton	36 ton	-	Average transports included in Ecoinvent market process
Spirizyme enzyme	1.935 m^3	9.9 m^3	40+230 (truck) 8 (ferry)	
Viscamyl enzyme	0.215 m^3	1.1 m^3	640+475 (truck) 22 (ferry)	
Propylene glycol	1 m^3	1 m^3	220 (truck)	

2.4.4.1 Urea

A solution with approximately 35% by weight urea is used in the process. The Ecoinvent process [Urea, as N {RER}| production | Alloc Rec, S] has been used in the modeling, where 1 kg Urea, as N corresponds to 2.17 kg urea. The density 1112 kg/m^3 has been used. Urea is produced in Norrköping and transported to St1 by truck.

2.4.4.2 Sodium hydroxide

A solution of 50% sodium hydroxide is used in the process. For this, the Ecoinvent process [Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Rec, S], representing global average has been used. The process includes transports (average distance) so no extra transports have been added. For calculations, a density of 1525 kg/m^3 has been used.

2.4.4.3 Yeast

Stabilized liquid yeast with a solids content of 19-26% is used in the process. It has been modeled as a mixture of 23% [Fodder yeast {CH}| ethanol production from whey | Alloc Rec, S] and 77% [Tap water {RER}| market group for | Alloc Def, S]. Yeast is produced in Denmark, and it has been assumed that it is transported 258 km by truck and 8 km by ferry.

2.4.4.4 Nitrogen gas

Nitrogen is stored in large tanks that serve the whole refinery. A small part is used for Etanolix. The gas is bought from AGA and produced in Sweden. It has been modeled with the process [Nitrogen, liquid {RER}| market for | Alloc Rec, S] representing European average. The process includes transports (average distance) so no extra transports have been added.

2.4.4.5 Enzymes

The enzymes Spirizyme and Viscamyl are used in the process. For both of them, the process [Enzyme, Glucoamylase, Novozyme Spirizyme/kg/RER] from the U.S. Life Cycle Inventory (LCI) Database (USLCI) has been used. For both enzymes, a density of 1150 kg/m^3 has been used. Spirizyme is produced in Denmark and it has been assumed that it is transported 270 km by truck and 8 km by ferry. Viscamyl is produced in the Netherlands and it has been assumed that it is transported 1115 km by truck and 22 km by ferry.

2.4.4.6 Propylene glycol

For production of propylene glycol, the Ecoinvent process [Propylene glycol, liquid {RER}| production | Alloc Rec, S] has been used. The density of propylene glycol is 1040 kg/m^3. Propylene glycol is produced in Sweden, and it has been assumed that the transport is 220 km by truck.

2.4.5 Water and waste water

Potable water used in all processes has been modeled with the Econinvent process [Tap water {RER}| market group for | Alloc Rec, S], representing European average tap water production. Wastewater has been modeled with the Econinvent process [Wastewater, unpolluted, from residence {CH}| treatment of, capacity 1.1E10 l/year | Alloc Rec, S].

2.4.6 Emissions

The only emissions monitored from the plant is VOC, see Table 5. All emitted carbon dioxide from fermentation is considered to be biogenic and thus not contributing to global warming in a long time perspective. Therefore, it has not been included in the model.

TABLE 5 EMISSIONS FROM ETANOLIX.

Emissions	Amount quarter 1, 2017 (kg)	Amount high utilization (kg)
VOC	250	400

2.4.7 Waste

The food residues generally come with some packaging attached which are sorted out in the process and become waste. Plastics, cardboard and other waste from production is sent to the municipal waste incineration plant in Sävenäs. The transport distance has been set to 14 km and the Ecoinvent process used for incineration is [Municipal solid waste {SE}| treatment of, incineration | Alloc Rec, S]. During quarter 1, 2017, this waste fraction also included a large share of food residues aimed for fermentation and some water. When the process is functioning better, there will be much less of these residues in the waste fraction. Therefore, the waste amount for the high utilization scenario is only a few kg larger than for quarter 1, 2017. Another waste from the process is sludge. The sludge is, via a waste company, transported to a farmer where it is utilized as nutrient. The sludge has a density of 1400 kg/m^3. The transport distance has been assumed to be 50 km. Since the sludge is assumed to be a valuable resource for the farmer (possibly substituting fertilizers), no further environmental impact has been allocated to this waste stream. There is also a small amount of metal scrap from production. This scrap is assumed to be transported to a sorting facility 15 km away.

TABLE 6 WASTE FROM ETANOLIX.

Waste	Amount quarter 1, 2017	Amount high utilization
Waste for incineration	188,26 ton	200 ton
Waste sludge	14,5 m^3	20 m^3
Metal scrap	30 kg	30 kg

2.4.8 Transports

The following Ecoinvent transport processes have been used consequently in the modeling:

- [Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Rec, S] – used for all truck transports
- [Transport, freight, inland waterways, barge {GLO}| market for | Alloc Rec, S] – used for ferry transports.

3 Results and discussion

In the following sections, results from the calculations as well as different scenarios and sensitivity analysis are shown. Detailed results for the baseline scenario and the high utilization rate scenario can be found in Appendix 2.

3.1 Baseline scenario

In the baseline scenario, all environmental impact from ethanol production is assigned to the ethanol product. By-products stillage and biogas feedstock is not allocated any environmental impact. The results show that the global warming potential for production of 1 MJ ethanol is 0.045 kg CO_2-equivalents. As shown in figure 6, the largest contributor to global warming is treatment of waste in the municipal incineration plant. According to the cut-off approach used in the study, transport to the incinerator and emissions from combustion are allocated to the ethanol production while generation of heat from incineration belong to the next product system and benefits from using this for e.g. district heating is not included in the study. Also electricity use at the Etanolix plant and transport of food residues to the plant are large contributors to the global warming potential.

For photochemical oxidation, the largest environmental impact comes from electricity use, but also transport of food residues and production is important. For both acidification and eutrophication, electricity use is the largest contributor to environmental impact. Also enzyme production, transport of food residues and waste incineration are important for acidification and eutrophication. The detailed results for all calculated environmental categories can be found in Appendix 2.

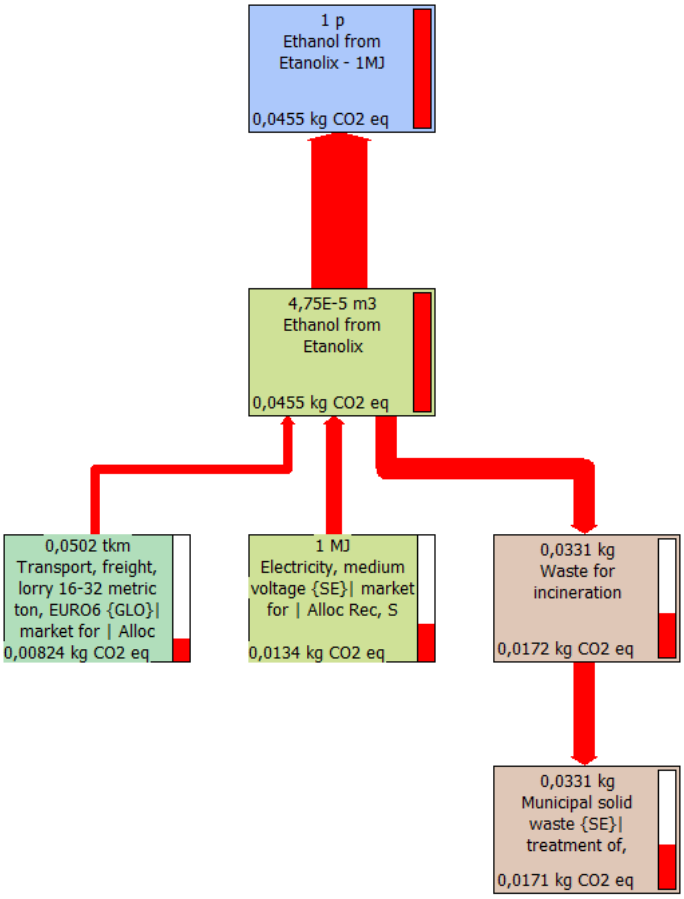

FIGURE 6 GLOBAL WARMING POTENTIAL FOR PRODUCTION OF 1 MJ ETHANOL AT ETANOLIX. PROCESSES THAT CONTRIBUTE MORE THAN 5% TO THE TOTAL RESULT ARE INCLUDED IN THE FIGURE.

3.2 High utilization rate scenario

With the high utilization rate scenario, the total environmental impact for all studied impact categories is significantly lower per produced MJ ethanol. The largest difference is due to the lower amounts of waste that goes to incineration. Also environmental impact from transports of food residues to the Etanolix plant is significantly reduced in the high utilization rate scenario. The relative environmental impact of enzymes increases with a higher utilization rate.

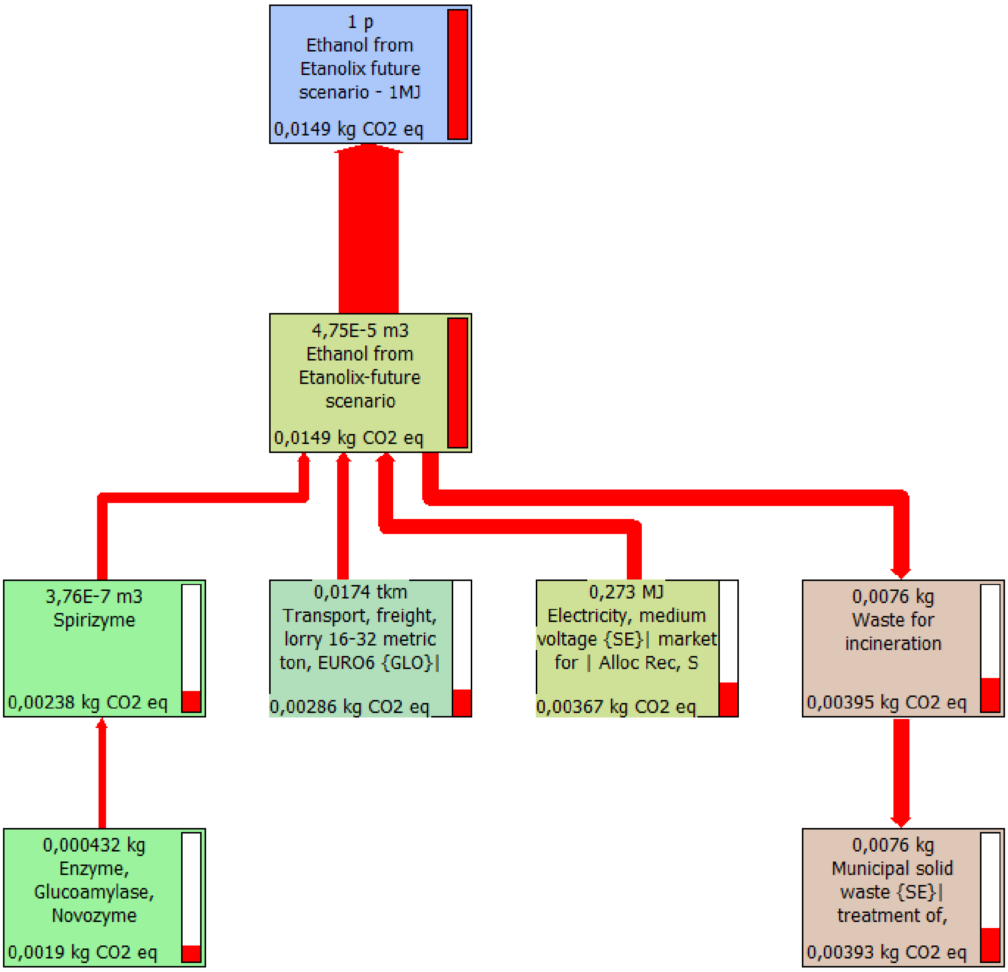

FIGURE 7 GLOBAL WARMING POTENTIAL FOR PRODUCTION OF 1 MJ ETHANOL AT ETANOLIX FOR THE HIGH UTILIZATION RATE SCENARIO. PROCESSES THAT CONTRIBUTE MORE THAN 5% TO THE TOTAL RESULT ARE INCLUDED IN THE FIGURE.

3.3 Sensitivity analysis

Sensitivity analyses were made in order to check how changes in actual conditions and assumptions affect the environmental impact from ethanol production. Besides the two main scenarios, quarter 1 2017 and high utilization rate scenarios, the following scenarios, based on the high utilization rate scenario, were made:

- **Long transport scenario** – in this scenario, a transport distance of 500 km is assumed for all food residues. The weighted mean distance for transportation of food residues was 91.6 km which is unlikely to be realistic when the production is scaled up.
- **Green electricity scenario** – in this scenario, electricity at St1 is assumed to be representing electricity only from renewable energy sources on the Swedish market.
- **Residual electricity scenario** – in this scenario, electricity at St1 is assumed to be representing the average electricity on the Swedish market after sale of electricity from renewable resources.

Many industrial processes (including Etanolix) produce not just the intended product, but also co-products and by-products. Normally, the material flows of inputs, waste, emissions and energy flows are not used and generated isolated from one another but commonly to optimize the resource use towards the output. In those cases environmental impact needs to be allocated between the different products so each product carry their share of the environmental impact. In many cases is the production though driven by one main products and the environmental load therefore allocated solely to that (this is often represented in the economic value of the different outputs and results in that the process is optimized to maximize a certain output).

When using allocation the following principles are recommended by the EPD system:

- If the difference in economical revenue from the co-products is low, allocation shall be based on physical properties.
- Material flows carrying specific inherent properties, e.g. energy content, elementary composition (e.g. biogenic carbon content), shall always be allocated reflecting the physical flows, irrespective of the allocation chosen for the process.
- In all other cases allocation shall be based on economic values.

These principles have been considered when constructing the following allocation scenarios:

- **Volume allocation scenario** – in this scenario, environmental impact is distributed between ethanol, biogas feedstock and stillage according to volumetric proportions. This means that 6.6% of the environmental impact from ethanol production is allocated to ethanol while 51.6% is allocated to biogas feedstock and 41.8% is allocated to stillage.
- **Energy allocation scenario** – a scenario where the environmental impact is distributed between the outputs based on assumptions on energy content. In this scenario 72.2% of the environmental impact from ethanol production is allocated to ethanol while 5.6% is allocated to biogas feedstock and 22.2% is allocated to stillage. The scenario was based on the following assumptions:
  - The potential for biogas production from biogas feedstock and stillage is 276.1 Nm^3/tonne dry matter
  - The energy content of 1 Nm^3 biogas is 37.5 MJ
  - The average amount of dry matters in the biogas feedstock and stillage is 7.83%
  - The density of biomass feedstock and stillage is 1000 kg/m^3.

Product	**Amount high utilization (m^3)**	**Energy content (MJ)**
Ethanol	1250	26332.9
Biogas feedstock	2500	2026.7
Stillage	10000	8107.0

The results from the sensitivity analyses (see Table 7 and 8 and Figure 8) show that to run the process with a high utilization rate is of large importance, the environmental impact from operation at a high utilization rate is approximately 40% of the environmental impact in the baseline scenario. Longer transportation distances for the biomass feedstock would increase environmental impact. Today, much of the food residues have short transport distance but in a future scenario with high utilization rate, the demand for food residues will be larger, thus making it probable that the average transport distance for the food residues will increase. The choice of electricity is of large importance for the environmental performance of the process, with Swedish residual electricity, the environmental impact is more than doubled compared to when Swedish average electricity is used. The environmental impact for the process when using Swedish green electricity is lower than when Swedish average electricity mix is used. If there is an aim to reduce the environmental impact from ethanol production, a change towards green electricity is recommended. In the directive EN 2009/30/EC on fuels it is specified (Annex IV, section C, paragraph 11) that electricity used for processing shall be assumed to be equal to the average emission intensity for production and distribution in the defined region if the plant is connected to the grid. But it does not define region to be within national boarders specifically. The electricity mix undergoes fast changes so the emission factor for reporting should be updated yearly at least. The national statistics from SCB and or Naturvårdsverket for emission factors for energy generation are a preferable source. The scenarios green electricity and residual electricity can also be used to see how these changes influence the product GWP potential and how important it is to support increased use of renewable energy generation. The Swedish residual electricity has an emission intensity of the same order of magnitude as the average in Europe as a region.

The choice of allocation has a large impact on the final result. The scenario in which environmental impact from ethanol production is allocated between all useful products based on product volume shows a significantly lower environmental impact per MJ produced ethanol. Since product volume is affected by e.g. the water content in the products this allocation method is not recommended since it in practice rewards ethanol that has water-rich by-products and does not represent the distribution of value between the production outputs. A better way to allocate environmental impact between by-products is through energy allocation, based on energy content in the products. The actual energy content in the stillage and biogas feedstock has not been measured, but an assumption based on theoretical values and calculations has been made. With this type of allocation, the environmental impact from ethanol production is lower than in most other scenarios. This is considered to be a more reasonable allocation method as the energy better represents the value of the useful products.

TABLE 7 ENVIRONMENTAL IMPACT FOR 1 MJ ETHANOL FOR THE SCENARIOS MADE IN THE SENSITIVITY ANALYSIS.

Environmental impact	Unit	Baseline scenario	High utilization rate scenario	Long transport scenario	Green electricity scenario	Residual electricity scenario	Volume allocation scenario	Energy allocation scenario
Global warming potential	kg CO_2-eq	0.046	0.015	0.028	0.013	0.035	0.0014	0.011
Photochemical oxidation	kg C_2H_4-eq	7.02E-06	2.9E-06	4.9E-06	2.5E-06	5.5E-06	2.7E-07	2.11E-06
Acidification	kg SO_2-eq	0.00011	4.2E-05	7.4E-05	4.3E-05	0.00011	3.8E-06	3.04E-05
Eutrophication	kg PO_4^{3-}-eq	6.08E-05	2.77E-05	3.4E-05	2.7E-05	6.3E-05	2.5E-06	2.00E-05

TABLE 8 ENVIRONMENTAL IMPACT FOR 1 TONNE ETHANOL FOR THE SCENARIOS MADE IN THE SENSITIVITY ANALYSIS.

Environmental impact	Unit	Baseline scenario	High utilization rate scenario	Long transport scenario	Green electricity scenario	Residual electricity scenario	Volume allocation scenario	Energy allocation scenario
Global warming potential	kg CO_2-eq	1216	399	739	335	932	36	288
Photochemical oxidation	kg C_2H_4-eq	0.187	0.078	0.132	0.066	0.146	0.0071	0.056
Acidification	kg SO_2-eq	3.032	1.13	1.97	1.14	2.91	0.102	0.81
Eutrophication	kg PO_4^{3-}-eq	1.62	0.74	0.92	0.73	1.68	0.067	0.53

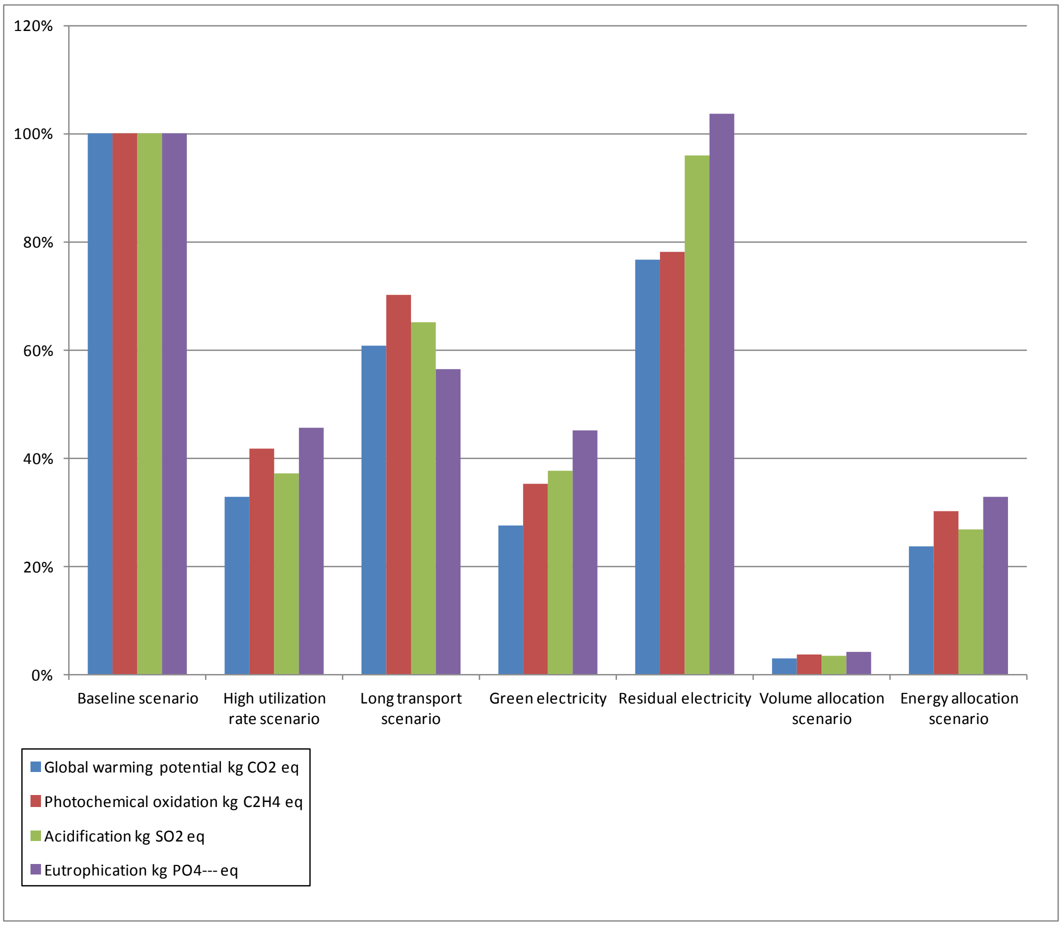

FIGURE 8 RELATIVE RESULTS FROM THE SENSITIVITY ANALYSIS.

3.4 Comparison with other available datasets on ethanol fuels

To evaluate if ethanol from Etanolix is competitive from an environmental point of view with other bio-based ethanol, a rough comparison with database data was made. The directive EN 2009/30/EC specifies thoroughly how greenhouse gas emissions from fuels should be calculated and both the results in this study and the datasets refer to only parts of the life cycle. Please note that the datasets have not been analyzed with regard to the specific system boundaries and may vary on those aspects! Figure 9 below shows a very rough comparison between two of the Etanolix scenarios *baseline* and the *high utilization rate* and datasets available in the EcoInvent database for ethanol produced from e.g. rye, maize, sugar cane, sugarbeet and wood. The results indicate that for the high utilization rate scenario, ethanol from Etanolix has good potential to have relatively low environmental impact.

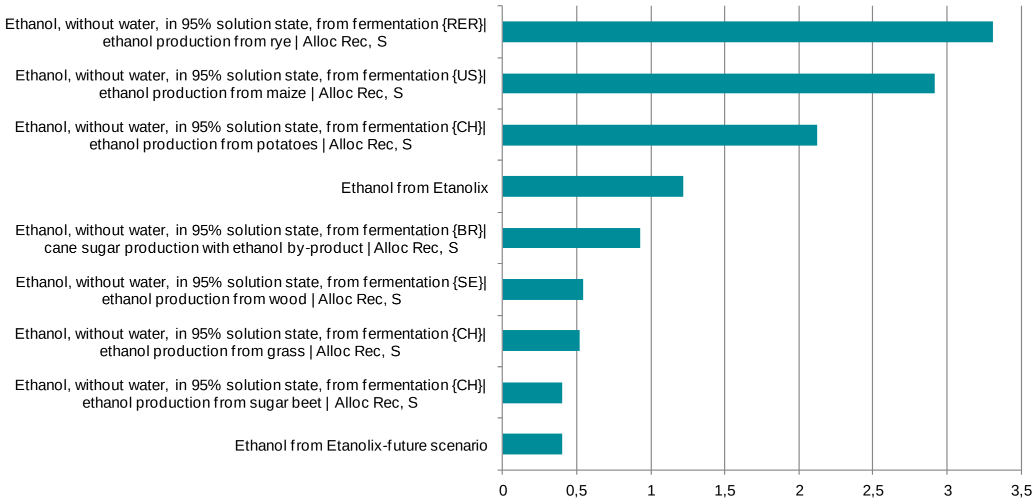

FIGURE 9 COMPARISON OF GLOBAL WARMING POTENTIAL FOR PRODUCTION OF 1 KG ETHANOL FOR DIFFERENT TYPES OF BIO-BASED ETHANOL. NOTE THAT ONLY DATA FOR ETANOLIX IS SPECIFIC. THE OTHER DATA-SETS ARE GENERIC FROM THE ECOINVENT DATABASE AND ASSUMPTIONS AND SYSTEM BOUNDARIES PROBABLY VARY SO THIS COMPARISON IS JUST AN INDICATION AND SHOULD NOT BE USED IN EXTERNAL COMMUNICATION.

Please remember that the results are only for part of the fuel life cycle and there are assumptions in the calculation that are uncertain and can both influence the results presented here as well as parameters that can influence the greenhouse house gas emissions in later life cycle stages. Referring to the methodology laid out in EN 2009/30/EC, Section C in appendix IV, the results in this study refer to emissions from processing only (e_p).

4 Conclusions

Some conclusions from the study are:

- To minimize the environmental impact from ethanol production, it is important to optimize the process in order to achieve a higher utilization rate. It is also important to minimize waste to incineration since today, much food residues that could have been utilized as ethanol production feedstock goes to waste.

- The choice of electricity has a large impact on the environmental impact. If the aim is to minimize environmental impact, a change to green electricity would be preferable.
- From an environmental point of view, local sourcing of raw materials is favourable.
- Enzyme production has large environmental impact. Therefore it is important to optimize the use of enzymes.

APPENDIX 1 - ENVIRONMENTAL IMPACT CATEGORIES

Climate impact

Global warming, or climate impact, is measured as kilogram CO_2-equvivalents. Global warming is the gradual increase, over time, of the average temperature of earth's atmosphere and oceans sufficient to induce changes on the earth's climate. This increase on earth's temperature is related to the increase of the emission of gases, such as, CO_2, methane, water vapour, nitrous oxide and CFCs, among others, from anthropogenic (man-made) sources, mainly from the burn of fossil fuels. Europe´s emissions in 2005 corresponded to 11200 kg CO_2 equivalents per person[7]. Burning 1000 litres of petrol in a car generates approximately 2500 kg CO_2-eq as a comparison. To avoid unwanted global warming effects requires global yearly emissions to be reduced by between 50 to 85% by 2050 on current levels, according to the Intergovernmental Panel on Climate Change[8]. This would translate to approximately 1000 kg CO_2-eq per capita world average.

Acidification

The most important man-made emissions of acidifying gases are sulphur dioxide (SO_2) and nitrous oxide (NO_X) from combustion processes. Thus, acidification is measured in equivalents of sulphur dioxide SO_2. Acidification, or acid rain, is best known for the damage caused to forests and lakes. Less well known are the many ways acid rain damages freshwater and coastal ecosystems, soils and even ancient historical monuments, or the heavy metals these acids help release into groundwater. Europe's emissions in 2005 corresponded to 57 kg SO_2 equivalents per person[9].

[7] European Environment Agency, 2005. The European Environment, State and Outlook 2005. Copenhagen.

[8] IPCC, 2014. Climate Change 2014: Synthesis report. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for policymakers. Geneva, Switzerland.

[9] European Environment Agency, 2005. The European Environment, State and Outlook 2005. Copenhagen.

Eutrophication

Eutrophication is measured as equivalents of PO_4. Nutrients like phosphor or nitrogen released in a lake leads to an increased production of planktonic algae. The algae sink to the bottom and are broken down with consumption of oxygen in the bottom layers, causing a dead environment at the bottom. The most significant sources of nutrient enrichment are the agricultural use of fertilizers, the emissions of oxides of nitrogen from energy production and wastewater from households and industry. In 1995 the Baltic Sea received 761 000 t nitrogen and 38 000 t phosphorus from land[10]. The anthropogenic part of the nitrogen was assumed to be 79%, for phosphorus no assumption could be made.

Photochemical smog potential

Potential photochemical ozone creation, or summer smog, is measured in kg ethene equivalents (C_2H_4).

Increased levels of ozone at ground level, arise through the reaction of volatile organic compounds, for example ethene and solvents, with oxygen compounds or oxides of nitrogen in air and under the influence of sunlight, so called photochemical oxidation. The effects on human health are amongst others irritation of eyes and mucous membranes as well as impaired respiratory function. Ground level ozone also has severe effects on vegetation, resulting in agricultural production losses.

Europe´s emissions in 2005 corresponded to 12 kg ethene equivalents per person[11]. Burning 1000 litres of petrol in a modern car generates around 1 kg ethene equivalents as a comparison.

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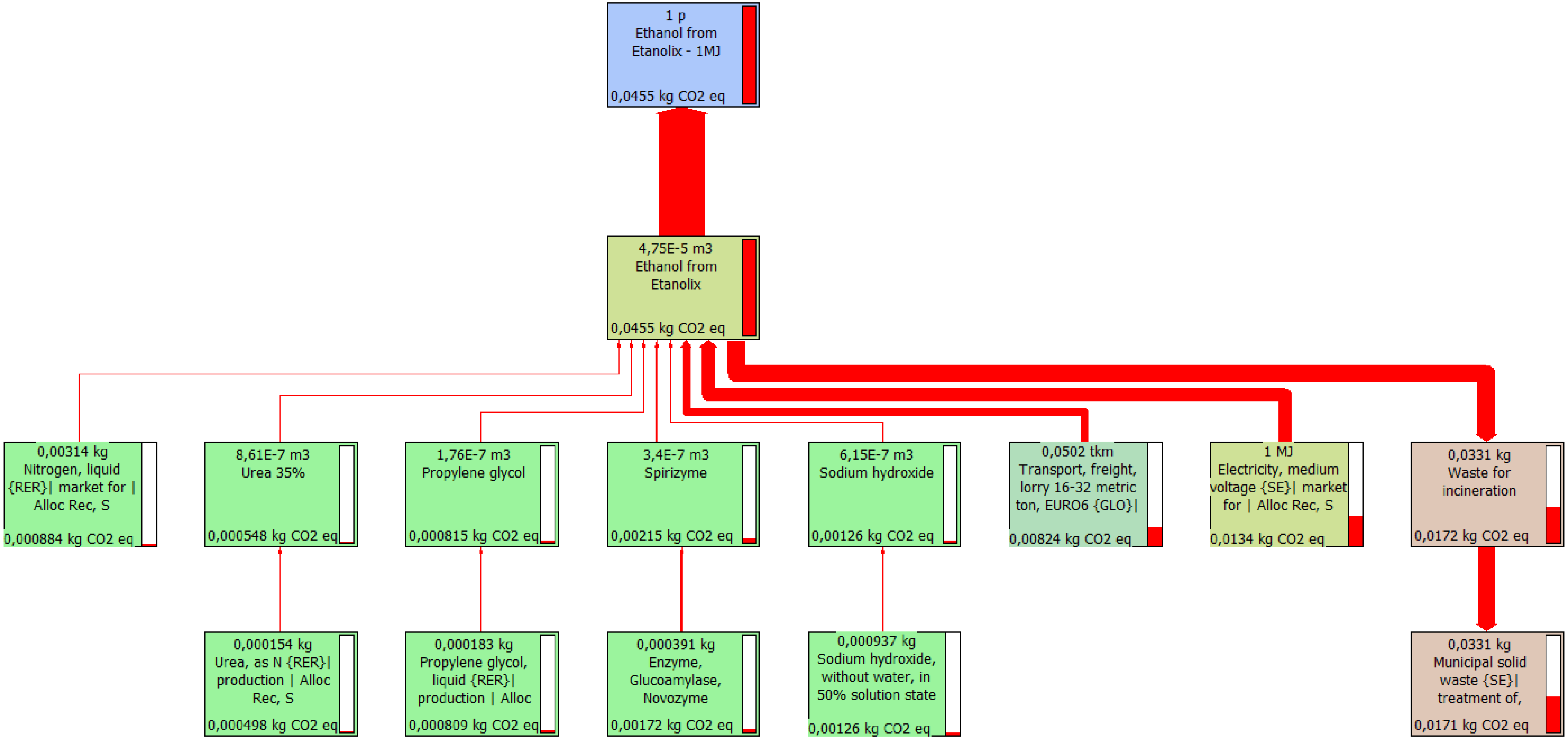
[10] European Environment Agency, 2010. The European Environment, State and Outlook 2010: synthesis. Copenhagen.

[11] European Environment Agency, 2005. The European environment — State and outlook 2005.

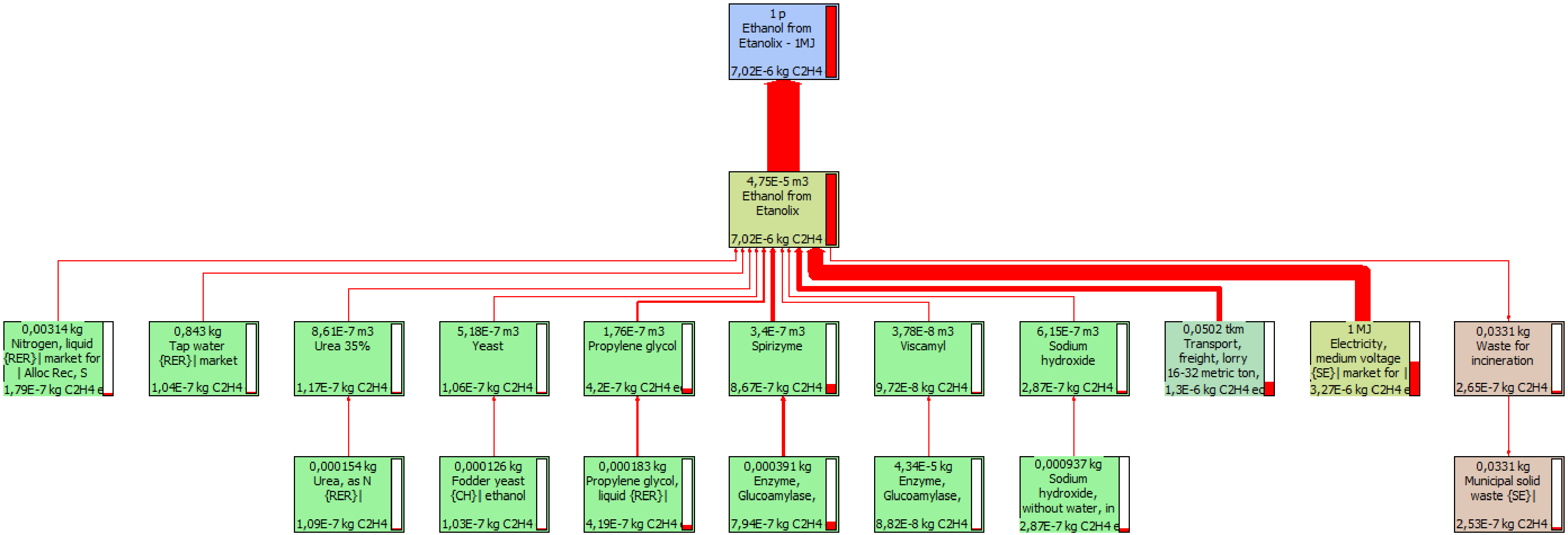
Copenhagen

APPENDIX 2 – RESULTS

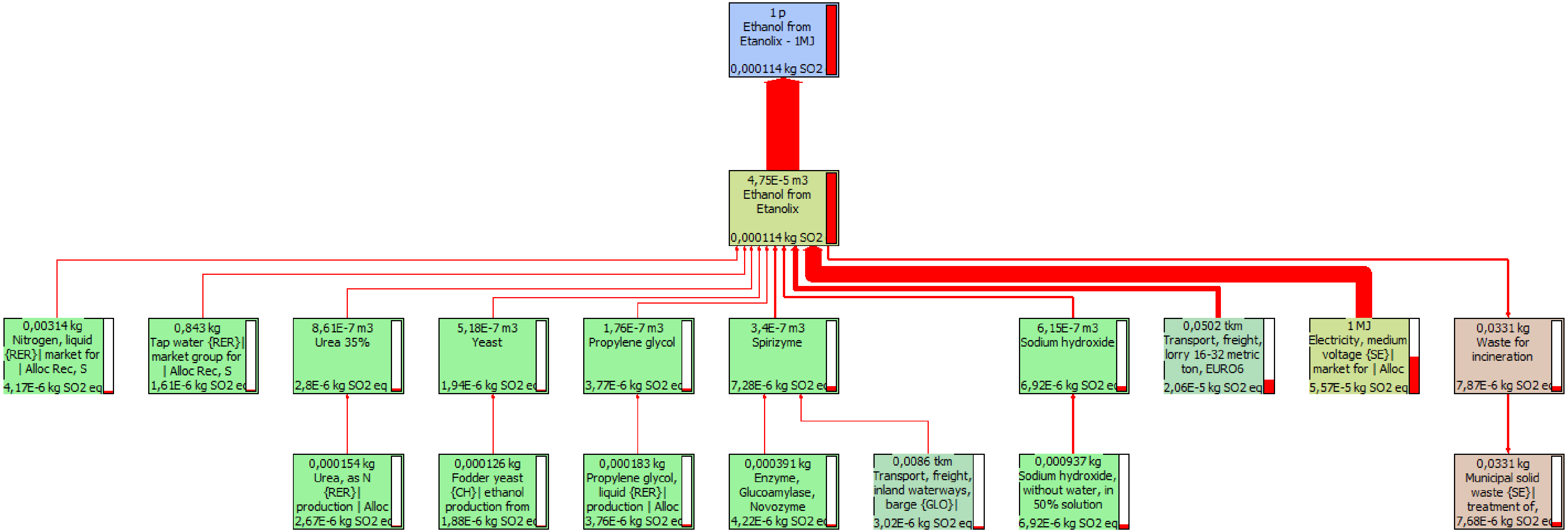
Baseline scenario, Global warming potential



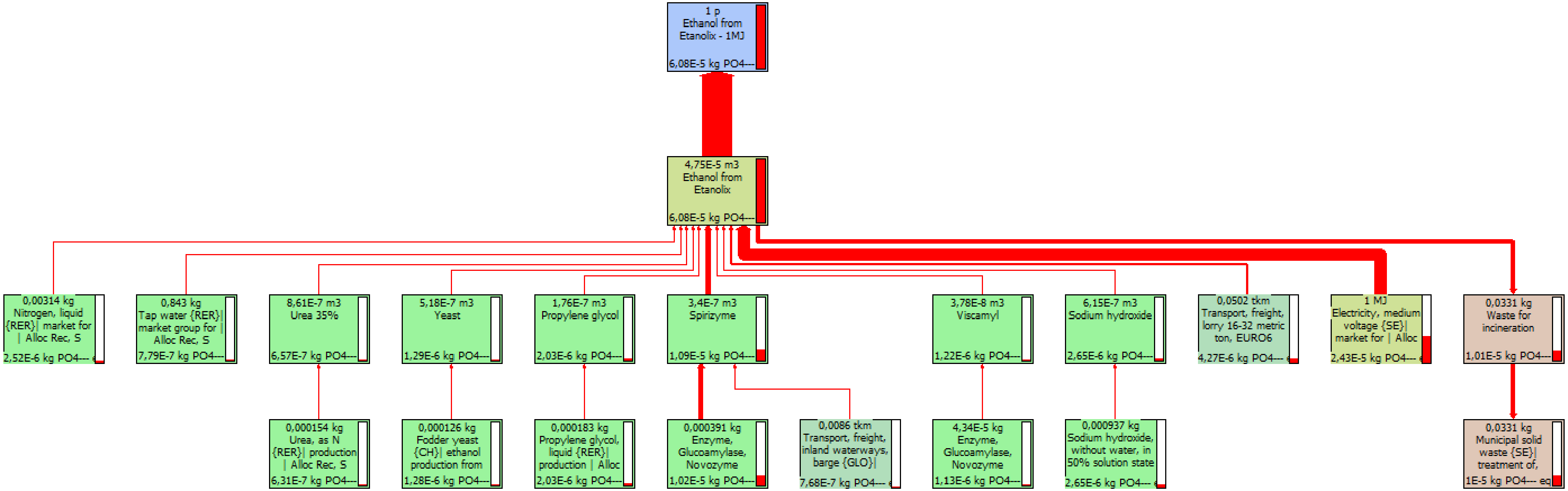
Baseline scenario, Photochemical smog potential



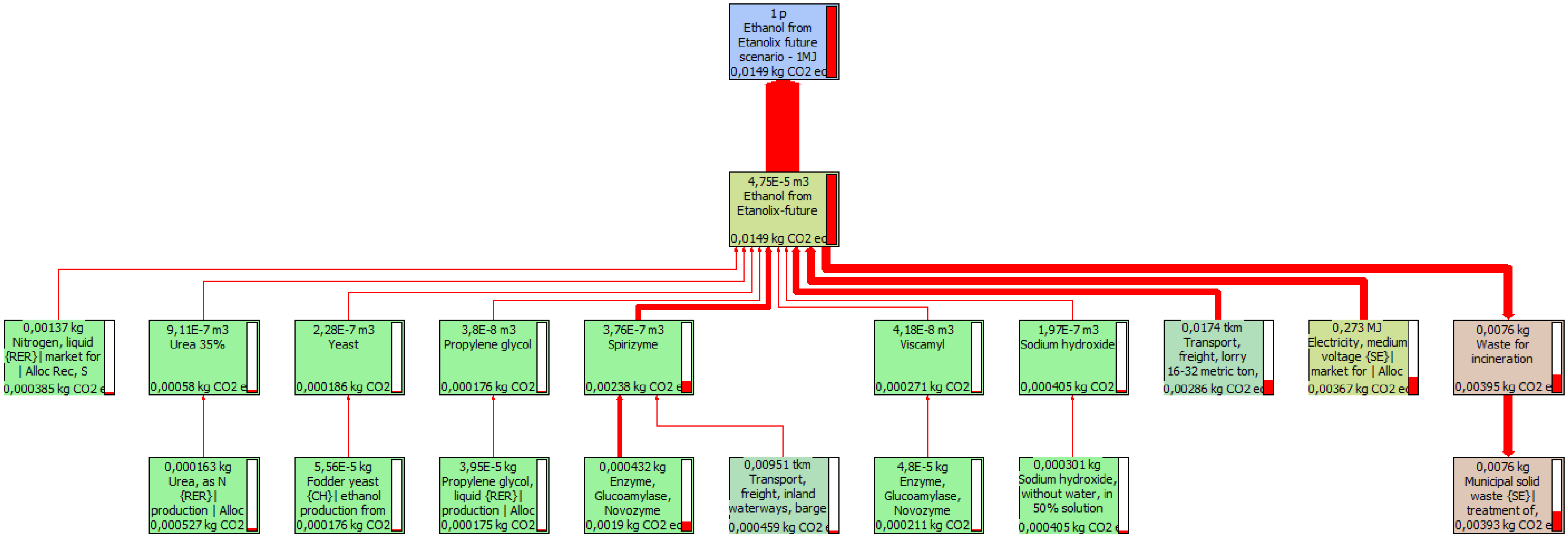
Baseline scenario, Acidification



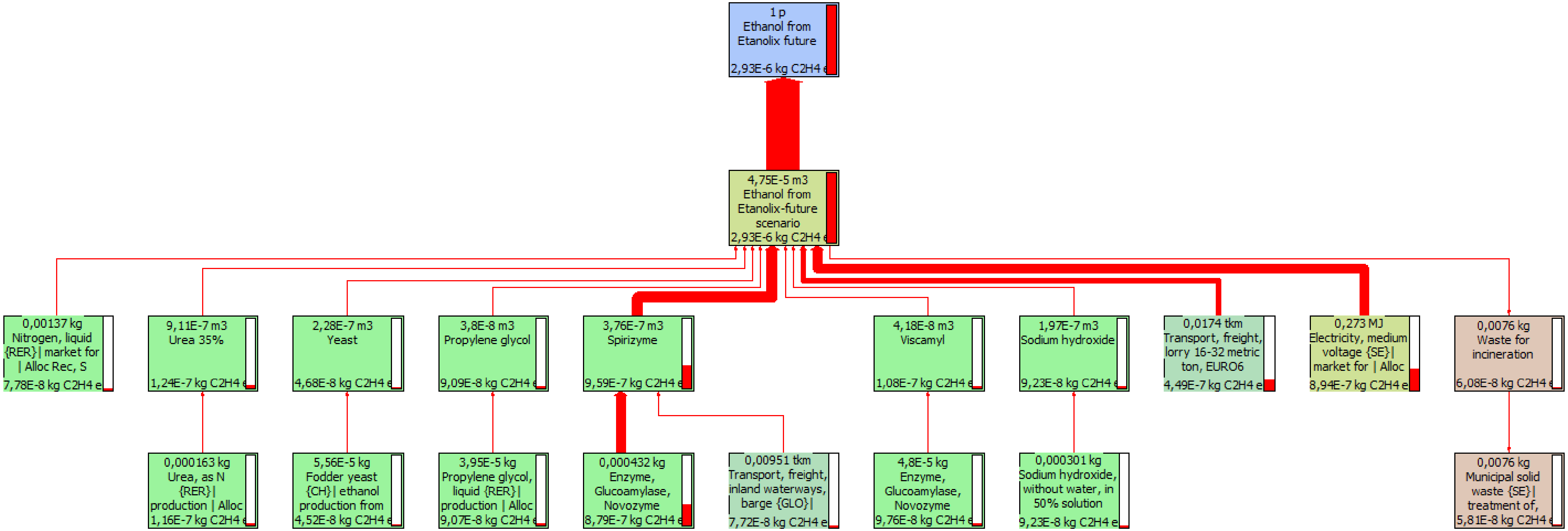
Baseline scenario, Eutrophication



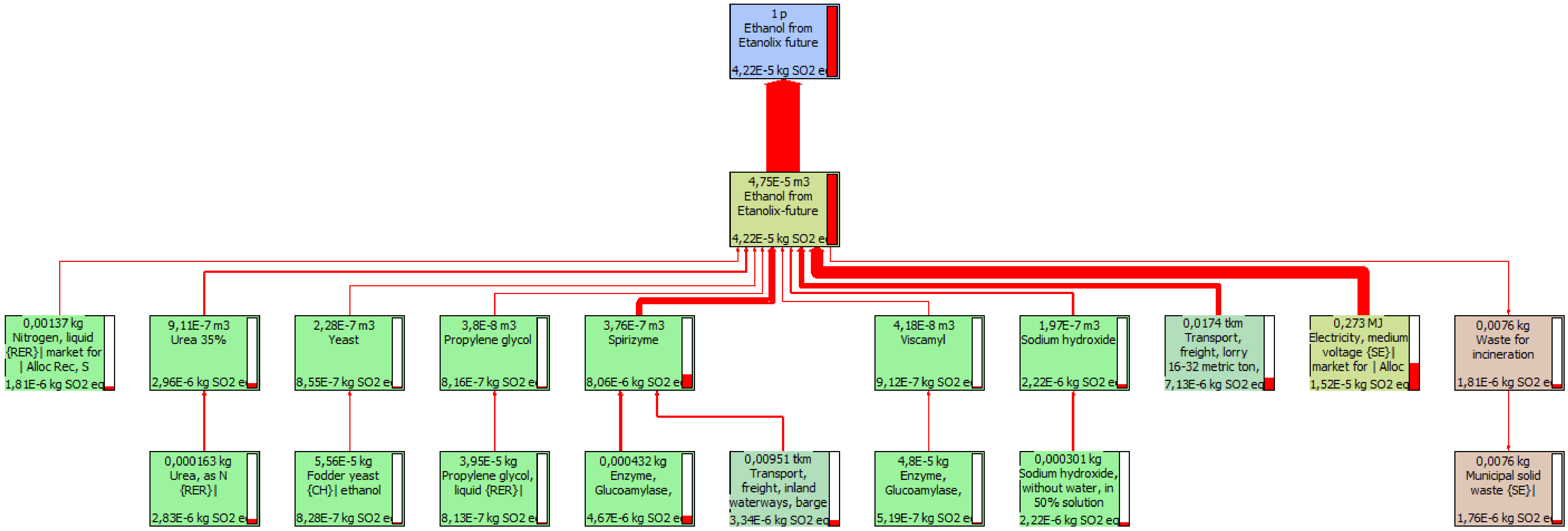
High utilization rate scenario, Global warming potential



High utilization rate scenario, Photochemical smog potential



High utilization rate scenario, Acidification



High utilization rate scenario, Eutrophication