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On environmental LCA for selected transport fuels

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Table of Contents

Summary

This short report is part of the project ”Integrated assessment of vehicle fuels with sustainability LCA - social and environmental impacts in a life cycle perspective” financed by the Swedish Knowledge Centre for Renewable Transportation Fuels (f3) and the Swedish Energy Agency. The project aims at a Life Cycle Sustainability Assessment (LCSA) of a few selected transport fuels including biomass based and fossil based fuels. The selected transport fuels include (i) Petrol from crude oil originating from oilfields in Nigeria, (ii) Petrol from crude oil originating from oilfields in Russia, (iii) Ethanol based on sugar cane from Brazil and (iv) Ethanol based on corn produced in the USA. The purpose with this report is to present comparable life cycle inventory results for a selection of environmental aspects for the studied transport fuel chains. A brief review of a few existing life cycle assessments of the four selected transport fuel chains was performed. It was found that the reviewed studies did not provide results that are easily comparable. Thus, in order to obtain comparable life cycle assessments, judged crucial for the continued analysis in the project, adapted life cycle inventories from the Ecoinvent centre (Ecoinvent centre, 2014) were adopted and presented in this study. The result will be further analysed in the project.

Sammanfattning

Denna korta rapport ingår i projektet ”Integrerad utvärdering av fordonsbränslen med hållbarhets-LCA - sociala och miljömässiga konsekvenser i ett livscykelperspektiv” finansierat av Svenskt kunskapscentrum för förnybara drivmedel (f3) och Energimyndigheten. Projektets mål är att genomföra en så kallad Life Cycle Sustainability Assessment (LCSA) på några utvalda drivmedel med kunskap från olika livscykelmetoder. I en LCSA integreras miljömässiga, social och ekonomiska aspekter i samma analys. De utvalda drivmedlen är (i) bensin från råolja från oljefält i Nigeria, (ii) bensin från råolja från oljefält i Ryssland, (iii) brasiliansk sockerrörsetanol och (iv) amerikansk majsetanol. Syftet med denna rapport är att sammanställa jämförbara livscykelinventeringsresultat för ett urval av olika miljöaspekter för de studerade drivmedlen. En övergripande genomgång av ett par existerande livscykelanalyser av de fyra studerade drivmedlen visade att dessa studier inte innehöll jämförbara resultat. För att få fram jämförbara resultat, vilket bedöms centralt för den fortsatta analysen i projektet, utfördes anpassade livscykelinventeringar baserat på uppgifter från Ecoinvent centre vilka presenteras i denna studie. Dessa kommer att analyseras vidare i projektet.

1. Introduction

This short report is part of the project ”Integrated assessment of vehicle fuels with sustainability LCA - social and environmental impacts in a life cycle perspective” financed within the program ”Förnybara drivmedel och system” by the Swedish Knowledge Centre for Renewable Transportation Fuels (f3) and the Swedish Energy Agency. The project aims at a Life Cycle Sustainability Assessment (LCSA) of a few selected transport fuels including biomass based and fossil based fuels, based on different life cycle methods. An LCSA integrates environmental, social and economic aspects in one analysis. The following four transport fuel chains have been selected for the analysis:

- Petrol from crude oil originating from oilfields in Nigeria
- Petrol from crude oil originating from oilfields in Russia
- Ethanol based on sugar cane from Brazil (in particular the Sao Paulo region)
- Ethanol based on corn produced in the USA

The purpose with this report is to present comparable life cycle inventory (LCI) results for a selection of environmental aspects for the studied transport fuel chains. A brief review of a few existing life cycle assessments (LCA:s) of the four selected transport fuel chains are performed. The focus is on scientific LCA:s covering a range of environmental impacts from transport fuel chains i.e., not only greenhouse gas (GHG) emissions and energy use.

There are numerous studies analyzing the environmental performance of biofuels for transport and their fossil fuel based counterparts, applying LCA methodology. LCA is a method for systematic representation of environmental impacts that arise during the life cycle of a studied product. However, it was found that the reviewed studies did not provide easily comparable results, meaning that issues such as the allocation methodology as well as other assumptions made in the studies varied considerably. In addition, the transparency of the steps involved and input to the LCA analysis in the studies could in some cases have been improved.

In order to obtain comparable life cycle assessments, judged crucial for the continued analysis in the project, adapted life cycle inventories (LCI:s) from the Ecoinvent centre (Ecoinvent centre, 2014) were adopted in this study. This was motivated by that the same methodology and system boundaries are applied for each of the included datasets. The Ecoinvent centre is a Competence Centre of the Swiss Federal Institute of Technology Zürich (ETH Zurich) in collaboration with four other Swiss institutions with the mission to establish and provide scientifically sound and transparent international LCA and life cycle management (LCM) data and services. The Ecoinvent database offers one of the most comprehensive international LCI databases including several thousands of LCI datasets in the areas of e.g., agriculture, energy supply, transport, biofuels and biomaterials, construction and packaging materials, as well as waste treatment (Ecoinvent centre, 2014).

2. Brief literature review of existing LCA:s of studied transport fuels

A brief review of some selected studies on LCA:s of the selected transport fuel chains focusing on environmental aspects is given below.

2.1. Petrol based on Nigerian or Russian crude oil

Jacobs Consultancy, 2012

Jacobs Consultancy (2012) was the only LCA of the petrol production in Europe based on only Nigerian or Russian crude oil found in this review. The main reason is most likely that crude oil for petrol production (as well as other petroleum products) in Europe originates from a number of countries and the petrol consists of a mixture of crude oil with different origin. Thus, most LCA:s of petrol production in Europe, model the crude oil extraction stage as a mix of the crude oils used in Europe, which make it impossible to define specific environmental impacts arising from gasoline production with only Nigerian or Russian oil. For instance, in 2010, the former USSR countries were responsible for 38% of the crude oil supplied to Europe; Norway 14%; Libya 9%; Saudi Arabia and Iran 5% each, UK, Iraq and Nigeria 4% each and other countries together 17% (Jacobs Consultancy, 2012). However, even though some data is provided for Nigerian and Russian crude oil in Jacobs Consultancy (2012) specific results are not disclosed publicly.

ADEME, 2010

The French Environment and Energy Management Agency (ADEME) performed in 2010 a LCA of the first generation biofuels used in France, including also results for petrol and diesel produced from crude oil. The LCA focuses on five environmental parameters. The functional unit chosen is "km traveled" i.e., the internal fuel combustion in the vehicle is taken into account. Results in "MJ of produced fuel" are also presented but only for GHG emissions and energy use. The extraction phase is based on Ecoinvent datasets (Ecoinvent centre, 2014), and the crude oil modelled is a mix of actual crude oil supplies to France. Refining data for energy use and CO_2 emissions is based on JEC (2007), where the allocation is incremental. The results are presented in Table 1.

Table 1. Energy use and GHG emissions for petrol (Ademe, 2010).

Category	Value	Unit
Non-renewable energy consumption[1)]	1.22	MJ/MJ fuel
GHG emissions (global warming)[2)]	0.0155	kg $CO_{2\ eq.}$/MJ fuel

[1)] Including the "MJ" contained in the fuel

[2)] "Refining", "raffinage" and "transport-distribution" phases (ADEME, 2010, table 78, p.122)

Eriksson and Ahlgren, 2013

Eriksson and Ahlgren (2013) present a literature review of LCA:s of petrol and diesel with different origin but with a European focus. The compiled results that focus on only energy use and GHG emissions (in CO_2-equivalents) were presented in both Well-to-Tank and Tank-to Wheel perspectives. In total, results from 9 studies were compiled, in a Well-to-Tank perspective varying from 0.04 to 0.3 MJ/MJ fuel for primary energy consumption and 6.7 to 27 g $CO_{2eq.}$/MJ fuel (with most results between 10-15 g $CO_{2eq.}$/MJ fuel) for GHG emissions.

2.2. Sugarcane based ethanol from Brazil

ADEME, 2010

As already mentioned ADEME performed in 2010 a LCA of the first generation biofuels used in France (Ademe, 2010). Ethanol based on Brazilian sugarcane as raw material is included and the LCA is based on Macedo et al. (2004). As in the case with petrol, results in “MJ of produced fuel” are only presented for GHG emissions and energy use (see Table 2).

Table 2. Energy use and GHG emissions for Brazilian ethanol (Ademe, 2010)

Category	Value	Unit
Non-renewable energy consumption	0.183	MJ/MJ fuel
GHG emissions (global warming)	0.0253[1)]	kg $CO_{2\ eq.}$/MJ fuel

[1)] “Cultivation”, “processing” and “transport-distribution” phases (ADEME, 2010, table 101, p.160)

2.3. Corn based ethanol from the USA

Kim and Dale, 2008

In Kim and Dale (2008) a LCA of ethanol derived from corn grain grown in the USA is performed in order to investigate the environmental performance of fuel ethanol used in a compact vehicle fueled with E10 (90% petrol and 10% ethanol). The functional unit is 1 kg of ethanol and the system boundary includes corn cultivation in the US, transportation of corn grain, dry milling process, transportation and distribution of ethanol as well as vehicle operation. The co-product distilled dried grains with solubles (DDGS) is handled by the system expansion approach, where DDGS is assumed to replace corn grain and soybean meal. The potential impact categories analyzed are non-renewable energy consumption, GHG emissions, acidification, eutrophication and photochemical smog formation. Table 3 summarizes the results for non-renewable energy use and GHG emissions.

Table 3. Energy use and GHG emissions of US corn based ethanol (Kim & Dale, 2008)

Category	Value	Unit
Non-renewable energy consumption	0.75[1)]	MJ/MJ[2)] fuel
GHG emissions (global warming)	0.0571[1)]	kg $CO_{2\ eq.}$/MJ fuel

[1)] Results do not include “distribution of ethanol” nor “vehicle operation”.
[2)] Original results “per kg fuel”. LHV ethanol: 26.8 MJ/kg.

3. Comparable LCI data for the selected transport fuel chains

The environmental impacts of the selected transport fuels chains from the Ecoinvent LCIs are assessed using the GaBi software (PE International, 2014). The results for the impact categories global warming, water consumption and non-renewable primary energy use are presented in Table 4. The result for more impact categories are presented in Appendix II. The datasets used in order to extract the results are described in the section below. All datasets used is listed in Appendix I.

Table 4. LCI results for selected impact categories for the studied transport fuel chains (Ecoinvent centre, 2014).

Fuel	Category	Value	Unit
Petrol – Nigerian oil	Global Warming[1)]	0.0289	kg $CO_{2\ eq.}$/MJ fuel[4)]
	Water Consumption[2)]	0.0344	kg water/MJ fuel
	Non-Renew. Prim. Energy Consump.[3)]	1.35	MJ/MJ fuel
Petrol – Russian oil	Global Warming	0.0252	kg $CO_{2\ eq.}$/MJ fuel
	Water Consumption	0.0727	kg water/MJ fuel
	Non-Renew. Prim. Energy Consump.	1.40	MJ/MJ fuel
Ethanol – Brazilian sugar cane	Global Warming	0.02	kg $CO_{2\ eq.}$/MJ fuel
	Water Consumption	0.668	kg water/MJ fuel
	Non-Renew. Prim. Energy Consump.	0.201	MJ/MJ fuel
Ethanol – US corn	Global Warming	0.0801	kg $CO_{2\ eq.}$/MJ fuel
	Water Consumption	0.806	kg water/MJ fuel
	Non-Renew. Prim. Energy Consump.	0.892	MJ/MJ fuel

[1)] IPCC global warming, excluding biogenic carbon
[2)] Total fresh water use (GaBi)
[3)] Primary energy from non-renewable resources (net calorific value) (GaBi)
[4)] Original results "per kg fuel" for both petrol and ethanol. LHV petrol: 42.5 MJ/kg. LHV ethanol: 26.8 MJ/kg.

3.1. Petrol based on Nigerian or Russian crude oil

Ecoinvent provides several life cycle inventories for oil derived products in Switzerland and Europe, basing all datasets on Jungbluth (2007a). The year considered is 2000 and the modelled chain includes oil field exploration, crude oil production, long distance transportation, oil refining and regional distribution. Moreover relevant production facilities and infrastructure, as well as transport services needed to supply energy and materials, and treatment processes needed for the production wastes are also considered (Dones et al., 2007).

In general crude oil production is investigated in different regions and country-specific data is used whenever available. Furthermore the allocation between crude oil and natural gas under combined production is based on the lower heating values of both. Long distance transportation is based on national and international statistics on imports and exports, and tankers and pipelines are the considered means of transportation from each region producing crude oil to Europe. The refining process is assumed to take place in Europe and given that this activity delivers several intermediate products, allocation by mass is applied to each intermediate whenever possible, since no economic information about intermediate products is available and heating values are quite similar (Dones et al., 2007; Eriksson & Ahlgren, 2013). The regional distribution accounts for transport of the fuel to storage tanks as well as to customers (filling stations, households and companies). Emissions during this phase are modelled on product-specific basis (Dones et al., 2007).

In order to model the production of petrol based on only Nigerian or Russian crude oil it was necessary to perform a modification in one Ecoinvent dataset, chosen to represent the mentioned fuel. The dataset in question is named "RER: petrol, unleaded, at refinery", and it is a cradle-to-gate life cycle inventory of petrol refined in Europe. As explained before, crude oil used in Europe is a mix of oils extracted in several countries. Therefore, in this Ecoinvent dataset, crude oil input is comprised of different shares of oils extracted in different countries, according to statistics of the International Energy Agency (Jungbluth, 2007a). In order to represent the hypothetical situation where only Nigerian or Russian oil is used as input, the mentioned dataset was modified accordingly, and the only oil input assumed was instead Nigerian or Russian oil.

The dataset "RER: petrol, unleaded, at refinery", is a LCI of production of unleaded, high-sulfur content petrol, at the refinery, and it does not contain any emissions, energy and resource use related to none of the subsequent phases, such as decreasing of sulfur content in petrol, regional storage and transport to final consumer. This being said, the modified dataset "RER: petrol, unleaded, at refinery" having Nigerian or Russian oil as the only oil input, was linked to the dataset "RER: petrol, low-sulfur, at regional storage" which contains the emissions, energy and resource use of the aforementioned subsequent phases. The phases included in the LCA modelling are illustrated in Figure 1.

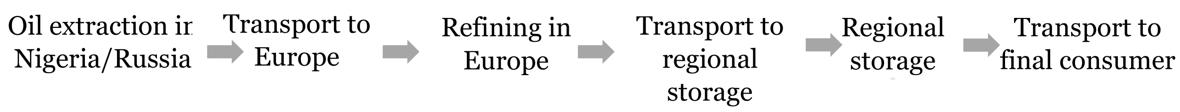

Figure 1. Life cycle phases included in petrol production and distribution.

3.2. Sugarcane based ethanol from Brazil

The Ecoinvent database has several life cycle inventories of biofuels for transport based on different sources and origin. Ethanol from sugar cane produced in Brazil is included specifically and therefore selected as proxy for this chain in this memo. The LCI in question was compiled from Jungbluth et al. (2007b) and the reference year is 2000. The dataset chosen to represent the process, "CH: ethanol, 99.7% in H2O, from biomass, production BR, at service station", comprise of the cultivation of sugar cane in Brazil, its transport to the mill, fermentation and dehydration processes, transport to Europe, regional storage and transport to service station (see Figure 2).

In all stages consumption of raw material, energy, infrastructure and land use as well as emissions to air and water are included. The cultivation is based on average values of studies conducted in different areas of Brazil (including the São Paulo state) and burning field emissions are taken into account. It is assumed that during ethanol production, bagasse is burned to produce electricity consumed during the process. A small share of surplus electricity is supposed to be sold to the grid. In order to tackle this multi-output situation, economic allocation between ethanol and electricity is applied. In order to reach Europe, ethanol is transported by pipeline and rail to the Brazilian coast where it is loaded to an oversea tanker. Once in Europe (Rotterdam), barge, truck and rail transports are considered before reaching final destination in a regional storage (Switzerland, in this case). No modifications are made to this dataset.

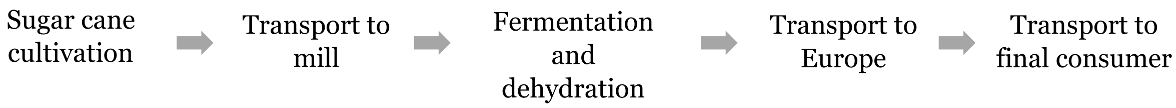

Figure 2. Life cycle phases included in Brazilian ethanol production and distribution

3.3. Corn based ethanol from the USA

The LCI data for corn based ethanol from the USA in the Ecoinvent database are also based on Jungbluth et al. (2007b). The dataset is comprised of the cultivation of corn in the USA, transport to the distillery, pretreatment, saccharification, fermentation, distillation, dehydration and stillage treatment processes, drying of co-products (DDGS), transport to Europe, regional storage and transport to service station (see Figure 3). Consumption of raw material, energy, infrastructure and land use as well as emissions to air and water is included in all stages.

Data for cultivation is based on statistics and are representative for 91% of the area cultivated with corn in the USA. Drying of grains is taken into account. The ethanol production process is based on dry-milling technology and the dehydration process is assumed performed by means of molecular sieves. Economic allocation is used between ethanol and DDGS. In order to reach Europe, ethanol is transported within the USA from the mid-west, by rail and road, to the east coast where it is loaded to an oversea tanker. Once in Europe (Rotterdam), barge, truck and rail transports are considered before reaching final destination in a regional storage (Switzerland, in this case). No modifications are made to this dataset.

Figure 3. Life cycle phases included in US corn ethanol production and distribution

4. Discussion

Differences between LCA results can arise from factors such as differences in the natural and techno-economic system modelled (e.g., origin of oil/feedstock, refining/milling technology, oil/fuel/by-products price and supply and demand) and methodological factors (e.g., data quality, by-products allocation, and system boundaries).

From Table 5, where the results are converted to "per MJ of fuel" using the net calorific value for petrol of 42.5 MJ/kg (Jungbluth et al., 2007a) it is indicated that the Ecoinvent results for petrol are somewhat higher than the corresponding results obtained by ADEME (2010) and the interval compiled in Eriksson & Ahlgren (2013). But the result could still be considered as in line with other studies.

Table 5. Comparison of results in the case of petrol based on Nigerian and Russian crude oil. References specified in the Table.

Fuel	Category	Value	Unit
Petrol – Nigerian oil (Ecoinvent centre, 2014)	Global Warming	29	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	1.35	MJ/MJ fuel
Petrol – Russian oil (Ecoinvent centre, 2014)	Global Warming	25.2	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	1.40	MJ/MJ fuel
Petrol (ADEME, 2010)	Global Warming	15.5	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	1.22	MJ/MJ fuel
Petrol (Eriksson & Ahlgren, 2013)	Global Warming	6.7 - 27	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	1.04 – 1.3	MJ/MJ fuel

For sugarcane based Brazilian ethanol the Ecoinvent data based results are in line with the result from the study by ADEME (2010) for both global warming and non-renewable energy consumption (see Table 6). On the other hand, the global warming result for US corn based ethanol in the Ecoinvent case is higher than the corresponding result in Kim and Dale (2008). Ecoinvent uses an economic allocation approach to deal with the co-product DDGS, while Kim and Dale (2008) applies the system expansion approach. The results are converted to "per MJ of fuel" using the net calorific value for ethanol of 26.8 MJ/kg (Jungbluth et al., 2007b).

Table 6. Comparison of results in the case of ethanol based on Brazilian sugarcane and US corn. References specified in the Table.

Fuel	Category	Value	Unit
Ethanol – Brazilian sugarcane (Ecoinvent)	Global Warming	20	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	0.21	MJ/MJ fuel
Ethanol – Brazilian sugarcane (ADEME, 2010)	Global Warming	25.3	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	0.18	MJ/MJ fuel
Ethanol – US corn (Ecoinvent)	Global Warming	81	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	0.89	MJ/MJ fuel
Ethanol – US corn (Kim & Dale, 2008)	Global Warming	57.1	g $CO_{2\ eq.}$/MJ fuel
	Non-Renew. Prim. Energy Consump.	0.75	MJ/MJ fuel

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Appendix I – Datasets

Table A1. Datasets from the Ecoinvent Database (Ecoinvent centre, 2014) used in the GaBi modelling of the selected transport fuels.

Fuel	Dataset in Ecoinvent	Description
Petrol, Nigerian/Russian oil	RER: petrol, unleaded, at refinery	Description of all flows of materials and energy due to the throughput of 1kg crude oil in the refinery. The multi output-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated to the different products.
	RER: petrol, low-sulphur, at refinery	Estimation for the conversion of refinery production to low-sulphur petrol with a sulphur content < 50ppm (Today 150ppm). An additional energy use of 6% has been estimated. Data for additional emissions and additional infrastructure were not available.
	RER: petrol, low-sulphur, at regional storage	Inventory for the distribution of petroleum product to the final consumer (household, car, power plant, etc.) including all necessary transports.
Ethanol, sugar cane, Brazil	CH: ethanol, 99.7% in H2O, from biomass, production BR, at service station	The inventory for "ethanol, 99.7% in H2O, from biomass, production BR, at CH" is modelled with data of the regional distribution of petrol in Switzerland. The transports are modelled with the distance Brazil - Rotterdam for the transoceanic transport, the distance Rotterdam - Basel for the transport from the Netherlands to Switzerland, and standard distances for transports in Switzerland.
Ethanol, corn, US	CH: ethanol, 99.7% in H2O, from biomass, production US, at service station	Inventory refers to the distribution of 1 kg of anhydrous ethanol 99.7% in Switzerland. Ethanol is imported from US and produced from corn grains. Distribution to the final consumer (service station) including all necessary transports.

Appendix II – Results

Table A2 presents the impact assessment results for the 12 impact categories comprised in the CML method (Guinée et al., 2001) for the modified Ecoinvent dataset "RER: petrol, low-sulphur, at regional storage", with Nigerian crude oil being the only oil input in the dataset. The results refer to 1 kg of low-sulfur petrol, at regional storage.

Table A2. Results for petrol based on Nigerian crude oil, per kg of low-sulfur petrol, at regional storage (CML impact assessment method)

Category	Value	Unit
Abiotic Depletion (AD elements)	3.35E-07	kg Sb-Equiv.
Abiotic Depletion (AD fossil)	56.8	MJ
Acidification	6.10E-03	kg SO2-Equiv.
Eutrophication	1.23E-03	kg Phosphate-Equiv.
Freshwater Aquatic Ecotoxicity	0.0753	kg DCB-Equiv.
Global Warming (GWP 100 years)	1.23	kg CO2-Equiv.
Global Warming, excl. biogenic carbon (GWP 100 years)	1.23	kg CO2-Equiv.
Human Toxicity	0.276	kg DCB-Equiv.
Marine Aquatic Ecotoxicity	224	kg DCB-Equiv.
Ozone Layer Depletion (steady state)	7.34E-07	kg R11-Equiv.
Photochem. Ozone Creation	2.83E-03	kg Ethene-Equiv.
Terrestric Ecotoxicity	3.63E-03	kg DCB-Equiv.

Table A3 presents the impact assessment results for the 12 impact categories recommended by the International Reference Life Cycle Data System (ILCD) (European Commission, 2011), for the modified Ecoinvent dataset "RER: petrol, low-sulphur, at regional storage", with Nigerian crude oil being the only oil input in the dataset. The results refer to 1 kg of low-sulfur petrol, at regional storage.

Table A3. Results for petrol based on Nigerian crude oil, per kg of low-sulfur petrol, at regional storage (ILCD recommended impact categories)

Category	Value	Unit
Acidification, accumulated exceedance	7.25E-03	Mole of H+ eq.
Ecotoxicity for aquatic fresh water, USEtox	1.10	CTUe
Freshwater eutrophication, EUTREND model, ReCiPe	8.13E-05	kg P eq
Human toxicity cancer effects, USEtox	1.77E-08	CTUh
Human toxicity non-canc. effects, USEtox	9.59E-08	CTUh
Ionising radiation, human health effect model, ReCiPe	38.1	kg U235 eq
IPCC global warming, excl biogenic carbon	1.23	kg CO2-Equiv.
IPCC global warming, incl biogenic carbon	1.23	kg CO2-Equiv.
Marine eutrophication, EUTREND model, ReCiPe	3.84E-05	kg N-Equiv.
Ozone depletion, WMO model, ReCiPe	7.34E-07	kg CFC-11 eq
Particulate matter/Respiratory inorganics, RiskPoll	4.02E-04	kg PM2,5-Equiv.
Photoch. ozone form., LOTOS-EUROS model, ReCiPe	9.63E-03	kg NMVOC

Table A4 presents the impact assessment results for the 12 impact categories comprised in the CML method (Guinée et al., 2001) for the modified Ecoinvent dataset "RER: petrol, low-sulphur, at regional storage", with Russian crude oil being the only oil input in the dataset. The results refer to 1 kg of low-sulfur petrol, at regional storage.

Table A4. Results for petrol based on Russian crude oil, per kg of low-sulfur petrol, at regional storage (CML impact assessment method)

Category	Value	Unit
Abiotic Depletion (ADP elements)	1.14E-06	kg Sb-Equiv.
Abiotic Depletion (ADP fossil)	57.7	MJ
Acidification	0.0196	kg SO2-Equiv.
Eutrophication	7.78E-03	kg Phosphate-Equiv.
Freshwater Aquatic Ecotoxicity	0.237	kg DCB-Equiv.
Global Warming (GWP 100 years)	1.07	kg CO2-Equiv.
Global Warming, excl. biogenic carbon (GWP 100 years)	1.07	kg CO2-Equiv.
Human Toxicity	0.611	kg DCB-Equiv.
Marine Aquatic Ecotoxicity	655	kg DCB-Equiv.
Ozone Layer Depletion (steady state)	7.58E-07	kg R11-Equiv.
Photochem. Ozone Creation	1.87E-03	kg Ethene-Equiv.
Terrestric Ecotoxicity	0.0107	kg DCB-Equiv.

Table A5 presents the impact assessment results for the 12 impact categories recommended by the ILCD (European Commission, 2011), for the modified Ecoinvent dataset "RER: petrol, low-sulphur, at regional storage", with Russian crude oil being the only oil input in the dataset. The results refer to 1 kg of low-sulfur petrol, at regional storage.

Table A5. Results for petrol based on Russian crude oil, per kg of low-sulfur petrol, at regional storage (ILCD recommended impact categories)

Category	Value	Unit
Acidification, accumulated exceedance	0.0221	Mole of H+ eq.
Ecotoxicity for aquatic fresh water, USEtox	3.35	CTUe
Freshwater eutrophication, EUTREND model, ReCiPe	2.76E-04	kg P eq
Human toxicity cancer effects, USEtox	7.71E-08	CTUh
Human toxicity non-canc. effects, USEtox	2.76E-07	CTUh
Ionising radiation, human health effect model, ReCiPe	127	kg U235 eq
IPCC global warming, excl biogenic carbon	1.07	kg CO2-Equiv.
IPCC global warming, incl biogenic carbon	1.07	kg CO2-Equiv.
Marine eutrophication, EUTREND model, ReCiPe	9.27E-05	kg N-Equiv.
Ozone depletion, WMO model, ReCiPe	7.58E-07	kg CFC-11 eq
Particulate matter/Respiratory inorganics, RiskPoll	1.29E-03	kg PM2,5-Equiv.
Photoch. ozone form., LOTOS-EUROS model, ReCiPe	7.06E-03	kg NMVOC

Table A6 presents the impact assessment results for the 12 impact categories comprised in the CML method (Guinée et al., 2001) for the Ecoinvent dataset "CH: ethanol, 99.7% in H2O, from biomass, production BR, at service station". The results refer to 1 kg of ethanol.

Table A6. Results for ethanol based on Brazilian sugarcane per kg ethanol (CML impact assessment method)

Category	Value	Unit
Abiotic Depletion (ADP elements)	2.45E-06	kg Sb-Equiv.
Abiotic Depletion (ADP fossil)	4.94	MJ
Acidification	7.11E-03	kg SO2-Equiv.
Eutrophication	2.53E-03	kg Phosphate-Equiv.
Freshwater Aquatic Ecotoxicity	0.36	kg DCB-Equiv.
Global Warming (GWP 100 years)	-2.03	kg CO2-Equiv.
Global Warming, excl. biogenic carbon (GWP 100 years)	0.537	kg CO2-Equiv.
Human Toxicity	4.14	kg DCB-Equiv.
Marine Aquatic Ecotoxicity	250	kg DCB-Equiv.
Ozone Layer Depletion (steady state)	5.89E-08	kg R11-Equiv.
Photochem. Ozone Creation	0.0123	kg Ethene-Equiv.
Terrestric Ecotoxicity	0.165	kg DCB-Equiv.

Table A7 presents the impact assessment results for the 12 impact categories recommended by the ILCD (European Commission, 2011), for the Ecoinvent dataset "CH: ethanol, 99.7% in H2O, from biomass, production BR, at service station". The results refer to 1 kg of ethanol.

Table A7. Results for ethanol based on Brazilian sugarcane per kg ethanol (ILCD recommended impact categories)

Category	Value	Unit
Acidification, accumulated exceedance	0.0104	Mole of H+ eq.
Ecotoxicity for aquatic fresh water, USEtox	6.65	CTUe
Freshwater eutrophication, EUTREND model, ReCiPe	1.87E-04	kg P eq
Human toxicity cancer effects, USEtox	5.63E-08	CTUh
Human toxicity non-canc. effects, USEtox	1.87E-06	CTUh
Ionising radiation, human health effect model, ReCiPe	42.1	kg U235 eq
IPCC global warming, excl biogenic carbon	0.537	kg CO2-Equiv.
IPCC global warming, incl biogenic carbon	-2.03	kg CO2-Equiv.
Marine eutrophication, EUTREND model, ReCiPe	2.58E-04	kg N-Equiv.
Ozone depletion, WMO model, ReCiPe	5.94E-08	kg CFC-11 eq
Particulate matter/Respiratory inorganics, RiskPoll	1.73E-03	kg PM2,5-Equiv.
Photoch. ozone form., LOTOS-EUROS model, ReCiPe	0.0253	kg NMVOC

Table A8 presents the impact assessment results for the 12 impact categories comprised in the CML method (Guinée et al., 2001) for the Ecoinvent dataset "CH: ethanol, 99.7% in H2O, from biomass, production US, at service station". The results refer to 1 kg of ethanol.

Table A8. Results for US corn based ethanol per kg ethanol (CML impact assessment method)

Category	Value	Unit
Abiotic Depletion (ADP elements)	3.84E-06	kg Sb-Equiv.
Abiotic Depletion (ADP fossil)	21.3	MJ
Acidification	0.0139	kg SO2-Equiv.
Eutrophication	0.0148	kg Phosphate-Equiv.
Freshwater Aquatic Ecotoxicity	0.642	kg DCB-Equiv.
Global Warming (GWP 100 years)	0.248	kg CO2-Equiv.
Global Warming, excl. biogenic carbon (GWP 100 years)	2.17	kg CO2-Equiv.
Human Toxicity	0.673	kg DCB-Equiv.
Marine Aquatic Ecotoxicity	724	kg DCB-Equiv.
Ozone Layer Depletion (steady state)	2.02E-07	kg R11-Equiv.
Photochem. Ozone Creation	9.68E-04	kg Ethene-Equiv.
Terrestric Ecotoxicity	0.0259	kg DCB-Equiv.

Table A9 presents the impact assessment results for the 12 impact categories recommended by the ILCD (European Commission, 2011), for the Ecoinvent dataset "CH: ethanol, 99.7% in H2O, from biomass, production US, at service station". The results refer to 1 kg of ethanol.

Table A9. Results for US corn based ethanol per kg ethanol (ILCD recommended impact categories)

Category	Value	Unit
Acidification, accumulated exceedance	0.0212	Mole of H+ eq.
Ecotoxicity for aquatic fresh water, USEtox	12.5	CTUe
Freshwater eutrophication, EUTREND model, ReCiPe	6.04E-04	kg P eq
Human toxicity cancer effects, USEtox	7.05E-08	CTUh
Human toxicity non-canc. effects, USEtox	-3.30E-07	CTUh
Ionising radiation, human health effect model, ReCiPe	167	kg U235 eq
IPCC global warming, excl biogenic carbon	2.17	kg CO2-Equiv.
IPCC global warming, incl biogenic carbon	0.248	kg CO2-Equiv.
Marine eutrophication, EUTREND model, ReCiPe	0.0202	kg N-Equiv.
Ozone depletion, WMO model, ReCiPe	2.02E-07	kg CFC-11 eq
Particulate matter/Respiratory inorganics, RiskPoll	8.97E-04	kg PM2,5-Equiv.
Photoch. ozone form., LOTOS-EUROS model, ReCiPe	7.33E-03	kg NMVOC

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