ÉCOLE POLYTECHNIQUE
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Estimating Energy and Greenhouse gas balances of biofuels

Concepts and methodologies

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1. Introduction

The interest in developing biofuels has rapidly increased during the last decades followed by a strong controversy about their sustainability. Diverting a large amount of land from agriculture to fuels, impacting forests and grasslands, loss of biodiversity due to large monocropped fields are some threats that inhibit the momentum towards a significant substitution of fossil fuels by biofuels. From a methodological point of view, several estimations of the reduction of greenhouse gas (GHG) emissions from biofuels lead to a large variability of results even if they address the same biofuel pathway. It has been shown that the methods used and the assumptions on data inventories, system boundaries, allocation of resources and emissions may significantly impact the results. In different countries and regions in the world, sustainability standards are being developed in order to limit the promotion of biofuels to those that are environmentally sound, socially responsible and economically effective. Global warming is of a particular interest when assessing the sustainability of biofuels as one of the main drivers of their development is their potential to mitigate GHG emissions. Therefore global sustainability standards include GHG balances as a main point. In many cases, Carbon reporting is separate from the reporting on other sustainability criteria (e.g. UK and California initiatives), reflecting the importance given to that item. Furthermore, the general impression is that at policy level it is easier to quantify Carbon balances than local environmental and social impacts. However evaluating GHG balances of biofuels is not straightforward. This paper aims at investigating the main assumptions made in the literature when estimating the reduction of GHG emissions of biofuels in comparison with their fossil competitors. In section 2 the main items that structure the Life Cycle Analysis (LCA) of biofuels are commented and methodological choices are addressed from a constructive criticism point of view. Section 3 analyses selected papers and works on biofuels. Finally, the conclusion highlights the necessity of transparency and gives some recommendations for estimating the reduction of GHG emissions.

2. Methodological choices and their implications

2.1 Life Cycle Assessment (LCA) of biofuels

LCA is an internationally renowned methodology for evaluating the environmental performance of a product, process or pathway along its partial or whole life cycle. The ISO 14040-series provide the standard for LCA. In the case of biofuels, several LCAs have been performed with various frameworks, scopes, accuracy, transparency and consistency levels, making difficult to compare the results on a rational basis. In the next sections, the main items on which the choices may vary from one study to the other are commented i.e. system definition and boundaries, GHG that are considered, functional unit, reference system, allocation methods, time dynamics, use of default values, local specificities, uncertainty management.

2.2 System definition and boundaries

Choices on this item should depend on the goal and scope of the LCA. The goal may be process design, operation or policy oriented. The definition of the system should be more detailed in case of design or operation improvement while for policy purposes the flowchart of biofuel pathways is simplified. When policy is the LCA's framework, the system boundaries should be adapted to the purpose. For instance if the intent is the comparison of various pathways of the same biofuel say bioethanol, a Well-to-Tank (WtT) LCA is appropriate as the pathways do not impact the performance of the fuel combustion in the vehicle's engines. The situation changes dramatically if the LCA intends to compare selected biofuels with their fossil substitutes e.g. bioethanol blends vs. gasoline or in more general where different kinds of fuels and blends are compared. In these cases, the utilization stage plays a crucial role as the energy need in the vehicle's tank for a given service e.g. 100 veh. km depends on the combustion performances that in turn vary from one blend to the other. Ignoring this important factor even for simplicity will lead to implicit assumptions on the combustion performances and therefore may induce inconsistency. However several authors used WtT boundaries while comparing GHG emissions of biofuels and fossil fuels e.g. ADEME/DIREM (2002) and Elsayed (2003). In other studies the WtT is a step for a complete Well-to-Wheels (WtW) assessment e.g. GM/LBST (2002), LASEN (2002-2006), VIEWLS (2005), CONCAWE/EUCAR/JRC (2007), EMPA (2007). Other aspects concerning the system definition and boundaries are inclusion or not of the following elements in the system: co-products, waste treatment, land use.

2.3 Selection of Greenhouse gases

The major greenhouse gases include water vapor, carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydro-fluorocarbons, perfluorocarbons and chlorofluorocarbons. However, even if water vapor has the highest greenhouse effect, it results from natural processes. Only anthropogenic sources are concerned by GHG balances of fuels and the main gases taken into account in most of the studies are carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) according to IPCC These gases can be either biogenic or fossil originated. Other gases are sometimes considered e.g. in CSIRO (2001)

2.4 Time dynamics

The effect of GHGs is described by two factors, i.e. their atmospheric lifetime (AL) and their global warming potential (GWP). The latter factor is used to estimate the effect of each GHG over a given timescale after scaling the lifetime. CO_2 is taken as the reference GHG; therefore its GWP is taken as 1 over all time period. Methane has an AL of 9 to 15 years and a GWP of 62 over 20 years, 23 over 100 years and 7 over 500 years. Nitrous oxide has an AL of 120 years and a GWP of 275 over 20 years, 296 over 100 years and 156 over 500 years. Most of studies take 100 years as time reference following IPCC 100a.

2.5 Functional unit

When comparing biofuels with fossil fuels, it is of utmost importance to consider the same relevant service. As long as mobility is concerned, in case of motor fuels this service must be related to mechanical energy. However, most studies choose 1 MJ_{th} of fuel (in the Tank) as functional unit independently to the type of fuel. This choice is not relevant as the mechanical efficiency can vary from one fuel to the other. For example, several tests have shown that the consumption of E5 in liters is slightly less than gasoline consumption for the same service, i.e. 100 km. This means that 1 MJ_{th} of gasoline must be compared with less than 1 MJ_{th} of E5. For simplicity if one considers that the consumption in liters of gasoline equals this of E5, then, 1 liter of fuel (gasoline or ethanol) should be a good functional unit for comparing ethanol with gasoline when the blend is E5. Using (even for simplicity) 1 MJ_{th} of fuel as functional unit, when comparing gasoline to ethanol, means that one has made implicitly the choice that emissions of 1.5 liter of ethanol must be compared with those of 1 liter of gasoline! This choice would be relevant however if ethanol and fossil fuel were used to provide heat.

2.6 Reference system

From the point of view of system analysis, as long as GHG emissions reduction is concerned, the biofuel pathway under study must be compared to a baseline (reference system). In most studies, the reference system is limited to a fossil fuel pathway (e.g. gasoline or diesel). However, this picture is not complete in different cases: for example when co-products from the biofuel's pathway replace existing products whose GHG balances are significantly different. To this end, a reference substituted product should be defined. The same applies for the case when production of feedstock for biofuels uses land that previously stores carbon or when the same feedstock is used for another purpose. In these situations, an "alternative land-use" and "alternative biomass-use", respectively, should be included in the baseline.

2.7 Allocation methods

Several allocation methods exist, i.e. allocation by mass (wet or dry), carbon content, energy content, volume, economic value, system expansion. Though the latter method is recommended by ISO 14040-series, its implementation can be difficult as the result depends significantly on the substitute that is chosen in the reference system. Furthermore, estimating the impact of this substitute may lead to another allocation problem. The issue of allocation is one of the weaknesses of biofuels LCA particularly in presence of co-products.

2.8 Land-use issues

Direct land use concerns for example the case where production of feedstock leads to the conversion of a carbon storage land. Missing to consider the previous storage of carbon will overestimate the performance of the biofuel. On the contrary, when feedstock is produced on degraded soil, they can contribute to store carbon. Direct land-use is taken in consideration in a few recent studies, e.g. CONCAWE-JRC_EUCAR (2007) and EMPA (2007). The recommendations of IPCC can be used for this purpose. Taking into account indirect land-use (land-use changes due to displaced activities or biomass use) is more complex as the indirect conversion of land is a global issue that is difficult to relate accurately to biofuels production; more research works are needed for improving the methodologies on this aspect.

2.9 Local specificity

Site, regional, country specific can show large difference from average data such as those provided by existing databases. Use of default values should be made with precaution and generalization should be avoided when the cost of supplementary information is affordable.

2.10 Uncertainty management

Uncertainty is managed using sensitivity analysis and scenarios. Few LCA tools such as SimaPro ® or ecoinvent® include sensitivity analysis and/or definition of the reliability level of the inputs. In other cases sensitivity analyses are made manually and make it possible to present the results in form of values range instead of precise values.

2.11 Carbon intensity of input data

The emission factors of the system inputs vary from one database to another. Each database contains a set of inputs for which a LCA has been done to calculate its carbon intensity, based on methodological choices. Consequently, for example, using carbon intensities of the GREET® model may lead to different results as those derived from using the ecoinvent® database.

3. Analysis of selected papers

In this section the methodological choices of the reviewed publications are presented, based on the items described in the previous section. A description of each item can be found in Annex 1.
The fact-sheets for the analysis of each publication are presented in Annex 2.

Item	Elements	CHOICE	ADEME-DIREM 2002	CONCAWE-JRC-EUCAR 2007	LBST-GM 2002	Macedo 2004	LASEN 2002-2006	EMPA 2007	CSIRO 2001	VIEWLS 2005	ANL/GM 2001	ELSAYED 2003	Count
Geography		EU		1	1			1		1			4
		USA						1		1	1		3
		Switzerland					1	1					2
		Brazil				1		1					2
		Other	1				1	1	1			1	5
Time horizon		Present				1	1	1		1		1	5
		Future Scenario	1	1	1	1			1	1	1		8
Objective	Scope	Policy	1	1	1	1	1	1	1	1	1	1	11
		Process design											0
		Operation											0
	Impact categories	Energy-GHG	1	1	1	1	1	1	1	1	1	1	11
		Economic		1			1	1		1			5
		Other						1	1		1		3
Fuels considered	Biofuel	Biodiesel	1	1	1		1	1	1	1		1	9
		Bioethanol	1	1	1	1	1	1	1	1	1	1	11
		ETBE	1	1	1		1	1		1			7
		Other	1	1	1				1	1	1	1	8
	Oil Feedstock	Rape	1	1	1		1	1	1	1		1	9
		Soy						1	1	1			4
		Sunflower	1	1						1			4
		Waste oil					1	1	1	1		1	6
		Other						1	1	1			4
	Alcohol Feedstock	Wheat	1	1			1	1	1			1	7
		Sugarcane		1		1	1	1		1			6
		Corn					1	1			1		4
		Lignocellulosic		1	1		1	1		1	1	1	8
		Straw		1				1	1	1			4
		Sugarbeet	1	1	1		1	1		1		1	8
		Waste wood		1	1			1	1	1			5
		Potatoes					1	1					3
		Molasses					1		1				5
		Other		1			1	1		1			4

Item	Elements	CHOICE	ADEME-DIREM	CONCAWE-JRC-EUCAR	LBST-GM	Macedo	LASEN	EMPA	CSIRO	VIEWLS	ANL/GM	ELSAYED	Count
			2002	2007	2002	2004	2002-2006	2007	2001	2005	2001	2003	
System definition and boundaries	Approach	WtT	1									1	2
		WtW		1	1	1	1	1	1	1	1		9
	Land-use	Included (simplified)		1				1				1	4
		Not included	1			1	1		1	1	1		6
	Blends	5		1		1	1	1					5
		10				1			1				2
		15						1	1		1		3
		100	1	1	1	1	1	1	1	1	1	1	11
		Other					1						1
	Background data	Only Primary Material/energy flows			1			1	n.a	1	1	1	5
		Including Capital goods and second order flows	1	1		1	1		n.a				4
	Use phase	Not included	1									1	2
		Simplified				1	1			1			4
		Detailed		1	1			1	1		1		5
Selection of GHG and time dynamics	GHG	CO2-CH4-N2O	1	1	1	1	1	1	1	1	1	1	11
		Others						1	1				2
	AL	20											0
		100	1	1	1	1	1	1	1	1	1	1	11
		500											0
	GWP	1-23-296 (IPCC 1996)	1	1		1	1						5
		1-21-310 (IPCC 2001)			1			1	1		1		4
		1-24.5-320										1	1
Functional unit		Kg											0
		Lt				1							1
		MJ	1									1	2
		Km (mile)		1	1		1	1		1	1		7
		ton feedstock				1							1
		ha											1
		ton.km							1				1
		passenger.km							1				1

Item	Elements	CHOICE	ADEME-DIREM 2002	CONCAWE-JRC-EUCAR 2007	LBST-GM 2002	Macedo 2004	LASEN 2002-2006	EMPA 2007	CSIRO 2001	VIEWLS 2005	ANL/GM 2001	ELSAYED 2003	Count
Reference system		Fossil	1	1	1	1	1	1	1	1	1	1	10
		Substituted co-product	1	1	1	1	1	1		1	1	1	10
		Alternative land-use	1					1		1			3
Allocation methods		System expansion	1	1	1	1			1	1	1	1	9
		Mass	1										1
		Energy							1				1
		Economic					1	1	1		1	1	5
Local specificity and default values	Agricultural inputs	Specific region											0
		National values	1			1	1	1	1		1	1	7
		International average		1	1					1			4
	Industrial inputs	Specific company	1		1		1						3
		Specific process			1		1	1	1		1		5
		National data				1	1	1	1		1	1	6
		International data		1						1			3
	Use phase inputs	Specific Fleet Vehicle		1	1		1	1	1		1		6
		Emissions measurement			1			1	1		1		4
	Fossil reference specificity	Yes	1	1	1		1	1	1		1		7
		No				1							1
Uncertainty management	Sensitivity analysis	Yes	1	1	1		1	1	1	1	1	1	9
		No				1							2
	Type	Scenarios	1	1			1			1			4
		Input data	1	1	1		1	1	1		1	1	8
	Uncertainty of inputs	Max-min values	1	1	1		1		1			1	6
		Distribution			1						1		2
		Other						1					1
Carbon intensity of inputs		ecoinvent	1				1	1					3
		GREET	1		1				1		1		4
		CONCAWE		1						1			3
		Mix sources	1	1	1	1			1	1	1	1	9

4. Conclusion

In face of missing data and time stress, many studies use pragmatic approaches to evaluate energy and GHG balances of biofuels. Thus several studies are not transparent enough. As policymakers will decide using these results it is important to establish the rationale of the evaluation methods. Some items need further research works, e.g. rationale of allocation methods, indirect land use. Others are till now subject to low transparency and consistency requirements.

4.1 Recommendations

Especially concerning the boundaries of the system, we recommend to use a WtW approach. No mind if the implementation of the WtW should be simplified, utilization stage must be taken into account as long as comparison of fuels with different mechanical efficiency is concerned. The functional unit must be appropriate, reflecting the fact that these fuels must be compared for the same service. Finally, for transparency purpose, the reference system must be explicitly defined.

4.2 Further research works

The LASEN is developing a platform of assessment method in order to compare the effects of various assumption and evaluation choices on the results. This work will allow us to make further recommendations on the allocation methods and considerations related to land use change.

5. References

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ANNEX 1. Items description

Item	Description
Geography	Geographical coverage of the study
Time horizon	Time horizon considered for the study
Objective	Scope and environmental impact categories considered in the study
Fuels considered	Type of biofuels and related feedstock included in the study
System definition and boundaries	Definition of the biofuel pathway to be studied and its boundaries, considering assumption made for the agricultural, industrial and use phase, and the inclusion or not of waste streams and land-use change emissions.
The selection of GHG	Types of GHG, atmospheric lifetime (AL) and global warming potential (GWP) considered in the study
Functional unit	Type of functional units of the study
Reference system	Characterization of the fossil, co-product and alternative land-use reference system
Allocation methods	Choice of allocation method and its assumptions
Local specificity and default values	Description of local data, models used and default values assumed
Uncertainty management	Definition of the sensitivity analysis of input data and the scenarios considered
Carbon intensity of inputs	Source of emission factors

ANNEX 2. Fact-sheets of selected papers

Item	ADEME-DIREM-PWC (2002)
Geography	France
Time horizon	Data from 1995-2000, Fossil fuel specifications for 2005 The reference scenario is referred to as 2005 scenario A prospective scenario is considered in order to evaluate the possible effect of technological improvements on the results (2009 scenario)
Objective	Propose updated CO2 and energy balances adapted to the French situation, with the objective of having reliable elements of comparison Provide all the parties with reliable and robust information on transportation fuels, which can then be integrated to decision-making processes Limited to energy and global warming aspects Economic aspects not considered
Fuels considered	Bioethanol (wheat, sugarbeet) Biodiesel (rapeseed, sunflower) ETBE, MTBE
System definition and boundaries	WtT (Weel to Tank): the utilization phase is not included. The downstream boundary is set at regional storage. An estimate of combustion emissions (in case of a complete combustion) is however indicated (to somehow include some utilization phase) Land-use change is not considered: In the reference scenario, carbon storage in soil is not taken into account. The study however considers two scenarios including carbon capture in soil (different levels) Waste streams not applicable
Selection of GHG and time dynamics	GHG are limited to CO2 (GWP 1), CH4 (GWP 23) and N2O (GWP 296), which corresponds to IPCC 100a (other GHG are not considered) Biogenic CO2 is considered to have a 0 GWP Biogenic CH4 on the contrary has the same GWP as fossil CH4 No CO2 credit is attributed to biomass. Accordingly, CO2 emissions relating to biogenic carbon are counted as zero.
Functional unit	1 MJ of fuel, 1 kg of fuel
Reference system	Land use change is not included The reference system is limited to gasoline and/or diesel
Allocation methods	System expansion (substitution) is applied to all by-products substituting fertilizers (i.e. leaves, straw, stillage in the beet-to-ethanol process) Allocation by mass in all other cases (pulps of sugar-beet, sugar, DDGS, press cake, gasoline and diesel)
Local specificity and default values	The study is limited to the situation in one country: France N2O emissions are taken into account according to a simplified method, based of 1996 IPCC Guidelines Data relating to fossil fuel production are derived in association with the IFP (Institut Français du Pétrole), TotalFinaElf, etc. Data relating to the production of biofuels is based on industrial data, established in association with many actors in the French biofuels sector
Uncertainty management and sensitivity analysis	Sensitivity analysis is considered in the form scenarios Sensitivity analyses are performed regarding the following aspects: - carbon storage in soil - N2O field emission factors - technological progress (2009 scenario)
Carbon intensity of inputs	Various sources are used concerning carbon intensities, including the GREET model (US), IEA data, former ecoinvent database

Item	CONCAWE-JRC-EUCAR (2007)
Geography	Europe
Time horizon	2010-2020 Based upon scenarios of fuel consumption evolution, biofuels introduction, effect on the blendstocks for biofuels incorporation, etc. Two scenarios are evaluated: 2002 and 2010+
Objective	Establish a consensual WtW energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond Consider the viability of each fuel pathway and estimate the associated macro-economic costs The study is limited to two environmental impacts, i.e. primary energy use and GHG emissions. Simplifications usually apply to the two criteria. Other impact categories are only treated qualitatively Economic values are estimated for 2010, according to the recent trends of prices evolutions and projections of experts. Economic values are used as an indication of the products most likely replaced by biofuels by-products.
Fuels considered	Bioethanol (sugarbeet, wheat, wheat straw, sugarcane, wood waste, farmed wood) Biodiesel (rapeseed sunflower) DME (wood waste, farmed wood, black liquor) FT diesel (wood waste, farmed wood, black liquor) Biomethanol (wood waste, farmed wood, black liquor) Bio-ETBE Bio-MTBE
System definition and boundaries	WtW (Well to Wheel) approach, divided in 2 stages: WtT (Well to Tank) and TtW (Tank to Wheel) The WtT chain is divided into 5 stages:Production and conditioning at source, Transformation at source, Transportation to market, Processing in EU, Conditioning and distribution The TtW (use phase) chain assums: E5 and B5 blend Typical European compact size 5-seater sedan (e.g. VW Golf) NEDC driving cycle CH4 emissions are considered to be 20% of HC limits N2O emissions are considered to be 2% of NOx limits The equivalence between fossil fuels and biofuels is based on the energy content (e.g. same energy consumption between E5 and gasoline) Simplified accounting of land use change (Carbon release due to land use change is considered according to IPCC 1996/2) Waste stream: When considering waste to biofuels, the system includes only the collection of wastes from the production site
Selection of GHG	GHG are limited to CO2 (GWP 1), CH4 (GWP 23) and N2O (GWP 296), which corresponds to IPCC 100a (other GHG are not considered)
Functional unit	WtT: 1 MJ of final fuel / WtW: 1 km

Reference system	According to the so-called **"incremental approach"**, the reference scenario must include either an existing process to generate the same quantities of by-product as the alternative-fuel scenario, or another product which the by-product would realistically replace **Energy crops are considered to be mostly grown on set-aside land.** The reference crop, therefore, is the alternative use of land under set-aside (i.e. land left fallow or sown with some green cover crop). **Grass grown on set-aside land is taken as the reference crop (but with no farming inputs as this reference crop has to represent all types of set-aside use, including fallow).** The indirect effect of exporting less cereals (thereby developing foreign agriculture and possibly deforestation) is not taken into account Average European values for fossil fuel chains (average of CONCAWE member companies estimates) No consideration of how allocation should be dealt with regarding oil refineries
Allocation methods	**Allocation by system expansion (substitution):** - all energy and emissions generated by the process are allocated to the main or desired product of that process - the by-product generates an energy and emission credit equal to the energy and emissions saved by not producing the material that the by-product is most likely to displace The material which the by-product is most likely to replace is going to depend mostly on economics (rather than on energy or GHG emissions) In the case of surplus electricity generation (CHP schemes in biofuels production), the reference electricity generation scheme is not the usual mix. The credit, in fact, is based on the same fuel (i.e. gas, straw, biogas, etc.) producing electricity only in a stand alone power plant.
Local specificity and default values	**Country specificity is considered at the input level**, and to some extent at the carbon intensity level (depending on references) Average agricultural yields according to DG AGRI 2005 (projections for 2012) Farming inputs (fertilizers, diesel use, direct field emissions, baling, collection, harvest, etc.) according to FfE 1998, ETSU 1996, Kaltschmitt 2001, GEMIS 2002 Direct N2O emissions were evaluated using the database-calculation-model of JRC-Ispra, based on the DNDC model (UNH 2003) coupled with statistical EU agricultural data (Eurostat 2003) Indirect N2O emissions from leached nitrogen were calculated from IPCC N2O emission factors Fuel consumption and GHG exhaust emissions were obtained with the ADVISOR model from NREL adapted to European conditions
Uncertainty management	Sensitivity analysis is carried out in the form of **scenarios** (typically various uses of by-products, etc.) Definition of **min and max value** on some parameters/values
Carbon intensity of inputs	Average European values for fossil fuel chains (average of CONCAWE member companies estimates) Some carbon intensities are derived in the study, while others are taken from other references and studies (lack of coherence)

Item	LBST-GM (2002)
Geography	Europe
Time horizon	EU 2010
Objective	Identify future fuels and corresponding powertrains for passenger cars, which may have the technical and environmental potential to complement, and eventually substitute gasoline and diesel Provide advice and assistance to decision-makers The study is limited to two environmental impacts, however, it also evaluates energy aspects: energy use includes renewables and non renewables, as well as fuel energy content (or energy content of the crop in case of biomass pathways) Economic aspects are not considered
Fuels considered	Bioethanol (wood, wood waste, sugarbeet) as neat fuel for FCs Biodiesel (rapeseed) as blending agent Biomethanol, FT-diesel as neat fuels, ETBE and MTBE as blending agents
System definition and boundaries	WtT, TtW and WtW Land use change is not taken into account Energy requirements for the construction or manufacturing of components, plants and subsystems are excluded A carbon credit is applied at the crop growth phase No details for waste stream when considering feedstocks for biofuels production The use phase assumes: Reference vehicle: OPEL Zaphira 1,8 projected to 2010 (i.e. advanced powertrain and anticipated vehicle performances) NEDC driving cycle (incl urban and extra-urban cycle) Blends: RME is added to diesel at 5% and ETBE to gasoline at 10% Bioethanol is considered as a neat fuel for powering fuel cells, not as a motor fuel
Selection of GHG and time dynamics	GHG are limited to CO2 (GWP 1), CH4 (GWP 21) and N2O (GWP 310), which corresponds to outdated IPCC GWPs 100a (other GHG are not considered) Biogenic CO2 is considered the same as fossil CO2 in the sense that it has a -1 GWP when absorbed and a +1 GWP when emitted
Functional unit	WtT: 1 MJ of final fuel / WtW: 1 km
Reference system	Alternative land use is taken into account as set-aside land with/without N-fixing crops cover Little detail is given concerning the allocation method applied to fossil fuel refineries. Apparently, allocation according to the energy content of finished products
Allocation methods	Allocation by system expansion (substitution)
Local specificities and default values	No detail about regional specificities N2O field emissions are calculated according to IPCC Guidelines of 1996 and include direct as well as indirect emissions (similar to ecoinvent) Data for the use phase is produced by GM internal model (internally developed simulation model) CH4 and N2O exhaust emissions are the result of GM experience and estimations regarding advanced post-treatment
Uncertainty management	Sensitivity to key parameters are taken into account in the form of variation intervals (LB and UB limits) Best estimates and confidence intervals (lower bound and upper bound) for each subsystem The effects of the use of by-products and field N2O emissions are addressed in the form of scenarios Probability distributions are associated to each of the key inputs
Carbon intensity of inputs	Very little detail is provided regarding how carbon intensities are derived. These are most likely taken from various literature references, similar studies and databases

Item	Macedo (2004)
Geography	Brazil
Time horizon	Time of the study (2000-2004) Two scenarios are considered: - average values (present situation, 2000-2004) - state-of-the-art (best technology and best practice)
Objective	Understand the renewable energy value and energy efficiency of the fuel-bioethanol industrial sector Establish the life cycle analysis of GHG emissions relating to the production and use of fuel-bioethanol, in Brazilian conditions Only "primary" energy use and GHG emissions are considered in this study Economics are not taken into account
Fuels considered	Bioethanol (sugarcane)
System boundaries	WtW (both production and utilization phases are included) The system includes sugarcane production, ethanol manufacturing and the final use of fuel ethanol GHG emissions are divided into 4 groups: - uptake and release of atmospheric carbon (considered to be neutral) - emissions of fossil carbon in the manufacturing/supply of all inputs - non-CO2 GHG direct emissions along the life-cycle - GHG emissions relating to the reference scenario (no ethanol) Land use change is not included, although the document mentions that growing sugarcane leads to a net carbon uptake Alternative land use is not considered Data regarding the utilization phase is very limited and hardly documented Equivalence factors between gasoline, E25 and E100 (hydrated) are based on equivalent performance; typical figures are used, based on the performance of new vehicles: - 1 litre of hydrated ethanol equals 0.7 litres of gasoline - 1 litre of anhydrous ethanol (used as E25) equals 1 litre of gasoline Data does not refer to a specific vehicle type, but rather to average values hydrated ethanol used in dedicated ethanol engines typical ethanol/gasoline blend under Brazilian conditions (25% v/v ethanol)
Selection of GHG and time dynamics	GHG are limited to CO2 (GWP 1), CH4 (GWP 23) and N2O (GWP 296), which corresponds to IPCC 100a (other GHG are not considered) Carbon flows associated with the uptake of atmospheric carbon by photosynthesis and its gradual release by oxidation are considered to be neutral (i.e. the GWP of biogenic CO2 is considered to be 0) Emissions of biogenic CH4 are considered in the same way as fossil CH4 but are ignored in the study
Functional unit	1 litre of ethanol and 1 ton of sugarcane
Reference system	The reference includes the production and use of gasoline for transport, plus the heat and power production substituted by the excess bagasse and electricity
Allocation methods	Allocation is based on system expansion (substitution) - ethanol replaces gasoline as a vehicle fuel - excess bagasse replaces diesel oil in heat production applications Substitution is based on equivalent services

Local specificity and default values	The study refers to a single country Depending on the scenario considered, average values or best practice values are employed in the inventory Emissions from sugarcane trash burning in the field are based on IPCC recommendations regarding agricultural residues CH4 emissions relating to burning bagasse in boilers are ignored CH4 emissions relating to fuel-ethanol and gasoline combustion in vehicle engines are ignored N2O field emissions are taken as a percentage (1.5%) of the nitrogen applied as fertilizer, based on a reference relating to the culture of miscanthus (Lewandowski 1995) Data relating to the production of biofuels is based on average (scenario 1) and state-of-the-art (scenario 2) industrial data, established in collaboration with ethanol producers
Uncertainty management	Sensitivity analysis is not included The two scenarios provide limited information on the effect of technological choices in the production of bioethanol
Carbon intensity of inputs	Carbon and energy intensities are obtained from various literature sources, most of which are not specific to Brazil but rather international values

Item	LASEN 2002-2006 (various studies)
Geography	Switzerland, China
Time horizon	Time of the study (2000-2006) Results refer to the year(s) of operational and economic data
Objective	Compare the environmental impacts associated to the production and utilization of fossil fuels and biofuels, on the basis of coherent and rigorous data Evaluate the sensitivity of the results with respect to the most significant parameters, in order to establish some confidence intervals Economic data are the core of the allocation approach and must be as reliable as possible Market prices of finished products and detailed production costs are obtained from actual industrial actors The shadow-price of intermediate co-products is equal to the market price of the finished products minus the cost of finishing operations (e.g. the price of raw stillage water equals the price of DDGS minus the cost of stillage treatment, concentration and drying) Sensitivity analysis with respect to the market prices is included in order to take into account the possible evolution of market prices Additional environmental criteria are included, namely eutrophication and acidification
Fuels considered	Bioethanol (corn, sugarcane, sugarcane molasses, cassava, sorghum, wood, potatoes, wheat, sugarbeet, cheese whey, waste paper, grass) Biodiesel (rapeseed, waste vegetable oil) ETBE
System boundaries	WtT and WtW Land use change is not included Alternative land use is not considered Data regarding the utilization phase are based on actual vehicle emission testing (EMPA) as well as literature data (extensive survey) Type of blends: E5, B5, B30 blends and B100 Waste streams are considered to have no impact relating to upstream activities The system boundary is set at the point of production and waste collection is included in the system
Selection of GHG and time dynamics	GHG are limited to CO_2 (GWP 1), CH_4 (GWP 23) and N_2O (GWP 296), which corresponds to IPCC 100a. Other GHG are not considered.
Functional unit	1 litre of fuel in the WtT approach 1 km in the WtW approach
Reference system	The reference system is limited to gasoline and/or diesel
Allocation methods	Allocation is based on the respective economic values (shadow-price) of the products at the point of separation (e.g. stillage and hydrated ethanol exiting the distillation stage)
Local specificity and default values	Where regional specificity is considered to be significant (heat production, electricity supply, modes and distances of transport, agricultural practice, etc.), data are obtained from industrial actors (biofuels producers, farmers, transporters) N_2O field emissions are taken into account according to the method described and used in ecoinvent (based on the IULIA model, itself adapted from the IPCC method), calculated on the basis of the available nitrogen Data relating to fossil fuel and inputs to the production process described are taken from the ecoinvent database and adapted to region-specific conditions (electricity mix, fuels employed, etc.) Data relating to the production of biofuels is based on industrial data, established in association with many actors in the Swiss biofuels sector

Uncertainty management	Sensitivity analyses are based on the most significant parameters, according to the impact criteria considered Significant parameters include: - market prices of biofuels and by-products - performance at the utilization phase (fuel economy, CO_2 emissions) - distances and modes of transport - feedstock composition, conversion efficiency (yield)
Carbon intensity of inputs	Mainly ecoinvent database, with adaptations regarding regional and/or site specificities

Item	EMPA (2007)
Geography	Switzerland, Brazil, United States, European Union, China, Malaysia
Time horizon	Time of the study (2000-2006) Results refer to the year(s) of operational and economic data
Objective	Provide decision-makers at the political level with quantitative data regarding the environmental performance of the various bioenergy pathways in the field of transportation as well as heat and power applications Identify the most efficient (in terms of fossil energy substitution, GHG emissions reduction, global environmental impact) conversion routes for a given feedstock Economic data are the core of the allocation approach and must be as reliable as possible Market prices of finished products are obtained from the literature and/or actual industrial actors Additional environmental criteria are included Global environmental impact evaluation according to EcoIndicator 99 and UBP06 (BAFU)
Fuels considered	Bioethanol (wheat, sugarbeet, corn, sugarcane, sorghum, cheese whey, potatoes, wood, straw, grass) Biodiesel (rapeseed, soybeans, palm fruit, waste vegetable oil) ETBE
System boundaries	WtT as a step for WTW, WtW Land use change is included and based on IPCC recommendations Alternative land use is not considered Inputs include infrastructure, equipment and machinery Waste streams are considered to have no impact relating to upstream activities The system boundary is set at the point of production and waste collection is included in the system Data regarding the utilization phase are established as follows: - Specific fuel consumption is based on literature data, vehicle emissions testing - CO2 emissions are calculated according to the specific fuel consumption and carbon balance The utilization phase refers to either passenger car (average vehicle type in EU/CH) or heavy-duty trucks (typically 28t) Type of blends: E5, E85, B5, B100. E5 and B5 are considered in passenger cars, B100 is considered in lorries
Selection of GHG and time dynamics	The full range of GHG based on IPCC 100a is included
Functional unit	1 MJ of fuel in the WtT approach 1 km in the WtW approach
Reference system	The reference system is limited to gasoline and/or diesel
Allocation methods	Allocation is based mostly on the respective economic values of co-products In some cases (mainly CHP application), other allocation approaches are considered (energy, exergy)

Local specificity and default values	Electricity is specific to the country where biofuels are produced Biofuels production pathways (including choice of feedstocks, farming, biomass conversion technologies, wastewater treatment and energy supply) are to a certain extent specific to the country N2O field emissions are taken into account according to the method described and used in ecoinvent (based on the IULIA model, itself adapted from the IPCC method), calculated on the basis of the available nitrogen Data relating to fossil fuel and inputs to the production process described are taken from the ecoinvent as such Data relating to the production of biofuels is the result of extensive surveys, based on both industrial and literature data
Uncertainty management	Sensitivity analysis is limited The effect of the type of farming (IP, extensive, BIO) is evaluated A simplified procedure was developed in order to quantify the uncertainty from qualitative estimations (so-called Pedigree Matirx, ecoinvent)
Carbon intensity of inputs	Exclusively ecoinvent

Item	CSIRO (2001)
Geography	Australia
Time horizon	2001-2006
Objective	Compare transport fuels emissions (GHG and air pollutants) for heavy vehicles (trucks and buses).
Fuels considered	Biodiesel B100 (soybeans, rapeseed, tallow and recycled waste cooking oil Bioethanol (wheat, straw, wood residues, molassess) Rapeseed, Diesohol (E15D), Petrohol (E10P)
System boundaries	WtW approach, divided in 2 stages: WtT and TtW Land-use change and alternative land-use are not considered. Emphasis is put on tailpipe emissions Excluded emissions: 1) Capital equipment and infrastructure, 2) Cooking oil production and use, 3) Wheat production in starch chain Combustion. Emissions are presented for pre-c (upstream) and combustion (downstream). All the emissions for biofuels are allocated to the pre-c process (p169) For biodiesel from cooking oil and tallow, only the recycling process is allocated to the biodiesel (credits for avoided treatment process). Type of blends: B100, E15, E10
Selection of GHG and time dynamics	CO_2 (1), CH_4 (24), N_2O (310), CFC-11 (3800), CF_4 (6500), C_2F_6 (9200), SF_6 (23900), which corresponds to IPCC 100a
Functional unit	1 ton.km (truck) 1 passenger.km (bus)
Reference system	Low Sulfur Diesel (LSD) Premium Unleaded Petrol The reference vehicles are a conventional diesel engine, standard 59 seat bus and a 45 tonne articulated truck. Direct and fugitive emissions are considered. Oil and gas are assumed to be produced together and emissions and extraction energy are allocated between them based on the energy content of each fuel. Similarly, refinery products are treated as co-products with the energy consumption, and consequent emissions being allocated to the output products (diesel, petrol, LPG), based on the energy content of each fuel.
Allocation methods	Main product feedstock: Economic allocation Co-product feedstock: System boundaries expansion Ref. system: Energy content
Local specificity and default values	Biofuels and reference system specifics for the Australian context Taken from national studies (Beer et al.). When no Australian data was available EU or USA values were used. The reference fossil fuels are described in detail and are specific for the Australian context. Transportation of crude oil imported into Australia are taken into account. Assumptions for oil imports are taken from the National Greenhouse Gas Inventory, with 58% of crude taken to be transported 10,000 km predominantly from Malaysia and the Middle East.
Uncertainty management	Model of driving conditions (p393) to evaluate the impact on emissions Uncertainty values for combustion values from tucks and buses, base on standard deviation. (Appendix 3)
Carbon intensity of inputs	Data from multiple sources, including Simapro databases, the GREET model (US), Australian and international sources.

Item	VIEWLS (2005)
Geography	EU, USA
Time horizon	2005-2010 and >2010
Objective	Evaluate economical and environmental performance of biofuels. The study is based on a compilation of previous studies. Economic performance assessment included: Fuel cost at the filling station (€/GJ), total driving costs per kilometre (€/Km), mitigation cost per avoided ton of CO_2 and CO_2-equivalent (€/t of CO_2 avoided)-base on the difference of transportation costs and emissions between biofuels and fossil fuels. Costs are allocated by subtracting by-product costs from the process cost. The unit price is the economic shadow price. Two scenarios for fossil fuel prices are given (til 2010 and after 2010).
Fuels considered	Biodiesel (oil seeds, organic wastes) Bioethanol (lignocellulosic crops , sugar crops, starch crops, ligno-cellulosic residues) ETBE (ethanol) Biomethanol (lignocellulosic crops, lignocellulosic residues) MTBE (methanol) Pure vegetable oil (oil seeds) Fischer-tropsch diesel (lignocellulosic crops, lignocellulosic residues) Biodimethylether-DME (lignocellulosic crops, lignocellulosic residues) Biogas (animal manure and organic wastes) Synthetic natural gas (lignocellulosic crops, lignocellulosic residues) Biohydrogen (liquid and gaseous) (lignocellulosic crops, lignocellulosic residues)
System boundaries	WtW approach Alternative land-use and biomass use are considered. Construction, operation and disposal of the car/facilities, use of by-products and land use change are considered When using wastes as inputs, the price is zero to calculate the economic performance.
Selection of GHG	GHG are limited to CO2 (GWP 1), CH4 (GWP 23) and N2O (GWP 296), which corresponds to IPCC 100a (other GHG are not considered)
Functional unit	1 km
Reference system	Fossil fuel reference (diesel, gasoline, mix diesel/gasoline use in EU25) Reference car: Passenger car Vehicle technologies: Internal combustion engine (2005-2010 and >2010), Fuel cell with electric engine (>2010) (For biohydrogen and biomethanol) The system boundaries of the reference fossil system include also the avoided reference use of the biomass and the agricultural land (for comparison). An alternative use of the fossil system is considers (remain in the ground, so no emissions) p 22. Alternative use of the agricultural land (for short rotation lignocellulosic the reference land-use is set-aside land) Alternative use of the biomass (for forest residues the references use is natural decay)
Allocation methods	System boundaries (Substitution)
Local specificity and default values	No regional specificities Based on EU and USA studies, Based on studies review (73 studies)
Uncertainty management	Data quality: based on time related coverage (after 1995), geographical coverage (EU and USA), technology coverage (current and future)
Carbon intensity of inputs	Mainly from CONCAWE (2004) but also from other sources

Item	ANL/GM (2001)
Geography	USA
Time horizon	2005 - 2010
Objective	Evaluate the impact of the introduction of advanced fuel/propulsion systems from a societal perspective. Limited to GHG emissions calculations.
Fuels considered	Ethanol (corn, woody biomass, herbaceous biomass) Low-sulfur gasoline (CG, FRFG2, CARFG2, CARFG3)-varies in S content and are MTBE and EtOH blends Low-sulfur diesel (current and future based on S content) Crude oil-based naphtha (for FCV) CNG Methanol Fischer-Tropsch diesel Fischer-Tropsch naphtha-gaseous hydrogen (G.H2) produced at central plant or refuelling station Liquid/compressed hydrogen produced in central plant (CCPP, hydroelectric and nuclear) or refuelling station
System boundaries	WtW (Wel to Wheel). Use phase is specifically studied. Land-use change is not considered. Alternative land-use is not considered. GHGs other than CO2 were considered negligible in the utilization phase. The carbon credit of using co-products for electricity generation in the process is considered (use of biomass lignin in bioethanol production from lignocellulosic sources) Type of blends: E100, E85, M100
Selection of GHG and time dynamics	GHG are limited to CO2 (GWP 1), CH4 (GWP 21) and N2O (GWP 310), which corresponds to IPCC 100a (other GHG are not considered) In use phase only CO2 is considered.
Functional unit	1 mile
Reference system	Fuels are compared between them without a specific reference system. Fuel/propulsion system configurations are compared to a conventional vehicle with spark ignition gasoline engine. Fleet: Chevrolet Silverado full-size pick-up (light truck) Vehicle technologies: Hybrid electric vehicles (HEV), Fuel cell vehicles (FCV) The energy use of the fossil fuels was estimated without considering the intrinsic energy content of the fuel. So, bioethanol are presented as the most energy consuming fuel.
Allocation methods	System boundaries (substitution) Market value
Local specificity and default values	Biofuels and reference system specifics for the USA context. An European specific counterpart was also developed by LBST (2002). Natural gas-based fuels are produced from different feedstock sources (USA, Non-USA, Non-USA flared gas). Crude oil production and importation in US in considered. Electricity mix: USA, California, Northeast USA. Based on the GREET model. The default energy efficiencies of U.S. petroleum refineries in the GREET model are based on studies for U.S. average refineries, which reflect the average quality of the crude that U.S. refineries process. The GM HPSP simulation model was used to analyze different architecture -fuel configurations. Urban and highway duty cycles are assessed.

Uncertainty management	Probability distribution (normal and triangular) for key parameters was used to estimate uncertainties statistically. 20, 50, 80 percentile fuel use estimates are given. Uncertainty was assessed separately for WTT and TTW and the integrated as continuous distribution functions (Weibull) for each fuel/vehicle pathway. The joint probability distribution was simulated using the Monte Carlo method. (See Vol 3, pp 37).The approach of probability distribution functions is useful to determine the uncertainty in this type of studies, more that the point approach. The study not only analyzes fuels but also their combination with different use phase technologies.
Carbon intensity of inputs	Based on GREET model (US) and Vehicle simulation model of General Motors

Item	ELSAYED (2003)
Geography	UK
Time horizon	The year to which the original study refers determine the relevant year of the results (1995, 1996, 2000, 2001, 2002). Different for each biofuel.
Objective	Produce a set of baselines energy and carbon balance for a range of electricity, heat and transport fuel production systems based on biomass feedstock under a consistent, coherent approach that allows comparison in the UK context.
Fuels considered	Biodiesel (oilseed rape, recycled vegetable oil)¨ Ethanol (lignocellulosic, sugar beet, wheat) Rapeseed oil from oilseed rape Heat and electricity production from wheat straw and wood chips (pyrolisis, gasification and combustion)
System boundaries	WtT approach. Use phase not included, as no agreed consensus over vehicle performance data exists. Land-use change is not considered. Alternative land-use is considered but not methodologically addressed. Specific assumption were made for each biofuel regarding manufacture and maintenance of facilities, upstream considered emissions (CH4 and N2O) and start-up fuel of power plants. No GHG emissions are allocated to the upstream process of the waste. Collection and transport is not considered as assumed to be the same of disposal
Selection of GHG and time dynamics	CO2 (1), CH4 (24.5) and N20 (320) are considered. The GWPs used are assumed to be for 100 years, but they are own calculation and do not correspond to the IPCC values.
Functional unit	1 tonne of biofuel, MJ (based on the net caloric value of the biofuel)
Reference system	The system is not described. Only reference values are given for: Ultra-low sulphur diesel from crude oil and Unleaded petrol from crude oil CH4 and N20 emissions are not considered for the reference systems Alternative land use references systems are mentions for each biofuel (fallow set-aside, original wildness state, no management of the forest, no reference, straw ploughing).
Allocation methods	Different allocation methods were applied for each biofuel: Market price for biodiesel, bioethanol from wheat and rapeseed oil Substitution for bioethanol from wheat straw and heat and electricity generation from wood chips. Relative prices for wood chips from forest residues and woodland management Effective price for bioethanol from sugar beet
Local specificity and default values	Biofuels and reference system specifics for the UK context. The electricity mix is the average for the UK and fossil fuels is from UK refinery and crude oil from North Sea. Default values are taken from literature studies worldwide (mostly EU and USA) and adapted to the UK conditions.
Uncertainty management	Data certification by advisory board. A specific range is given of each input value base on a standard propagation error of routine.
Carbon intensity of inputs	Own calculations based on data, essentially from Kaltschmitt and Reinhardt (1997) and Matthews and Mortimer (2000).

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