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Life cycle assessment parameters adaptation for Brazilian electricity production

Master's Thesis within the Industrial ecology programme

CARLA COELHO

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2008

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MASTER'S THESIS

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CARLA COELHO

SUPERVISOR(S):

Annette Koehler

Stefanie Hellweg

EXAMINER

Bengt Steen

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Energy and Environment
Division of Environmental System Analysis
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

Electricity is a major concern in the life cycle assessment (LCA) of most products since it is a required input for production of almost all goods. The largest life cycle inventory (LCI) databases contain, mainly, data for Europe and North America, while goods are produced in several other locations. Electricity generation in Brazil was chosen as a case study. Instead of making a totally new inventory this study started from an existing dataset for electricity mix, available on the database of ecoinvent (which has the composition of the mix according to Brazilian generation, i.e. the amount of electricity generation from each electricity source). The first step was to update the amount of each type of electricity contributing for the current mix, according to the latest available data. The impact assessment was carried out using three methods: EPS 2000, eco-indicator 99 and the single use method IPCC-GWP $_{100a}$. The results provided the base to identify which were the most contributing electricity types to certain categories. The impact assessment indicated the methane emissions from hydropower reservoirs, the bagasse electricity generation carcinogens impacts to be relevant parameters to be investigated further. As well the type of coal mining was altered to open cast mine in order to be more representative of the Brazilian coal mining reality. Difficulties were faced when attempting to select the most appropriate value for methane emissions in tropical reservoirs. In regards to the greenhouse gas emissions the greatest impact variation was a result of the usage of the worse and average cases, as well as alteration of characterization factors. Another factor highly relevant for the LCA impact of hydro power is the energy density, which had a significant variation from different hydropower plants in Brazil. For bagasse generation outdated data could have a significant impact in certain categories, although due to the small contribution to the Brazilian mix the difference impact becomes much less significant. The alteration of the type of mining did not result in a difference when compared to underground mining.

Key words:

Electricity, LCA, Brazil, adaptation

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Contents

Abbreviations

BR Brazil

CH Switzerland

CH_4 methane

CO_2 carbon dioxide

CO_2 eq carbon dioxide equivalent emissions

DALYs Disability Adjusted Life Years

ELU Environmental Load Units

EPS environmental priority strategy for product design

GLO refers to data representing the world

GWP Global warming potential

IPCC international panel of climate change

LCA life cycle assessment

LCI life cycle inventory

LCIA life cycle impact assessments

NEX Normalized Extinction of species

OECD Organization for economic co-operation and development

PAF potential of affected fraction of species

PDF Potential of Disappeared Fraction of plant species

RLA Latin America and Caribbean

SETAC society of environmental toxicology and chemistry

UCTE Union for the co-ordination of transmission of electricity

UNEP United Nations Environment Program

YOLL years of life lost

1 Introduction

Methods and tools which help to quantify and compare the environmental impacts of providing product to our societies are essential to the achivment of sustainable development (Rebitzer, Ekvall et al. 2004).

All activities, or processes, in a product's life result in environmental impacts due to consumption of resources emissions of substances into the natural environment etc (Rebitzer et al. 2004). In order to define the overall environmental profile of a product, energy data for all the phases of its life cycle is required i.e.: the acquisition of the raw material, manufacturing, use and disposal or recycling of a product (Dubreuil 2001). In the environmental assessment of most products life cycle, energy has been identified as a major consideration (Di, Nie et al. 2007).

Life cycle assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product (Rebitzer et al. 2004). LCA has rapidly grown into an invaluable tool to investigate the direct and indirect environmental implications of a product system and in the last decade, several advances have been made in the reliability and extensiveness of this tool (Raugei and Ulgiati 2009).

Little advancement appears to have been made so far within the respect of spatial and temporal differentiation of LCA (Raugei and Ulgiati 2009). The majority of the life cycle inventories databases (e.g. ecoinvent and spine), have datasets for electricity systems mainly in European or North American countries. When products are traded worldwide, it becomes fundamental to assess the impact of energy systems for other regions such as South America.

In order to perform the evaluation of the environmental aspects the Brazilian electricity mix was taken as a case study. The first tentative model for electric energy generation and distribution system in Brazil in terms of LCA was published for the reference year 2000 (Coltro, Garcia et al. 2003). The study considered the emissions of methane and carbon dioxide from hydropower reservoirs as biogenic and concluded that the Brazil has a clean electricity production mix.

In regards to life cycle databases, the ecoinvent has an electricity mix for Brazil, which is composed by the following processes (Frischknecht, Tuchschmid et al. 2007):

- hard coal, natural gas and industrial gas, using inputs from the European mix (UCTE[1]),
- diesel and nuclear sources were used as Switzerland mix (CH),
- hydropower and sugar cane bagasse used the process with Brazilian data (BR).

The entry for Brazilian hydropower and sugar cane bagasse based derived energy, have most of the inputs from technosfere are considered as European. The inventory inputs for sugar cane cultivation have their quantities based on literature (for Brazil) and most of the processes are European. The emissions of the hydropower reservoirs were considered as biogenic for methane and land transformation for carbon dioxide.

[1] Union for the co-ordination of transmission of electricity

2 Research objective

2.1 Purpose and goal of study

The goal of this study is to:

- identify which are the most relevant aspects related to the Brazilian electricity production environmental impacts, for which aspects adaptation would be required, and the uncertainties and difficulties to perform such adaptation,
- to evaluate how much adaptation of current inventories would be necessary in order to obtain sound data for LCA,
- and on a more general level, if is possible to obtain a recommendation for new datasets analyzing the weakness and strengths of different approaches when carrying out an inventory adaptation.

2.2 Hypothesis

Building inventories can be highly time and resource consuming. When there is a lack of an inventory of a processes, an alternative can be to use similar inventories (e.g. for other regions, or technologies), those may have some of its parameters of its inputs or outputs adapted to better represent the processes under study.

The principal hypothesis of this work is that an inventory adaptation approach may hide relevant parameters which can significantly affect the impact assessment once those parameters may not be indentified when analyzed for another region or technology.

3 Method

3.1 Brazilian electricity generation

The installed capacity of electricity generation in Brazil is based on large scale hydro power complemented with fossil based electricity (73% and 17% respectively). The remaining 10% encompasses small hydro power, nuclear, and biomass derived electricity. Solar and wind power currently play a minor role accounting for less than 0,5% of the countries installed capacity (ANEEL 2009).

The generation of electricity in Brazil reached 419 TWh in 2006, with the installed capacity experiencing a 5,9% growth with respect to 2005 (BEN 2008).

Brazilian electricity production relies strongly on hydro power. A major power shortage in 2001 lead to government policies supporting the increased use of small hydroelectric plants, natural gas, biomass and wind as electrical energy sources (Falleiros, Melo et al. 2008). The decrease of electricity consumption in 2001, driven by the hydropower shortage and the increase of other electricity sources can be observed in Figure 1. The graph shows that after 2001 the hydroelectricity continued to grow, while non-hydro sources remained generating the same amount of electricity to the mix.

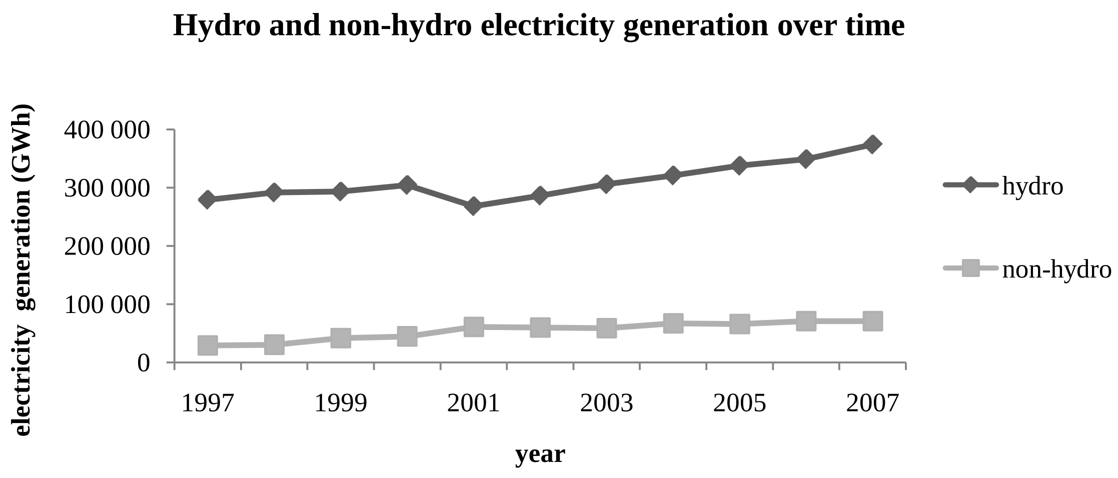

Figure 1 Historic of total Brazilian electricity production in GWh, based on BEN (2008), showing hydro and non-hydropower electricity generation across the years.

The drastic increase of non-hydro electricity sources in 2001, mainly driven by natural gas and nuclear power, can be observed in the Figure 2.

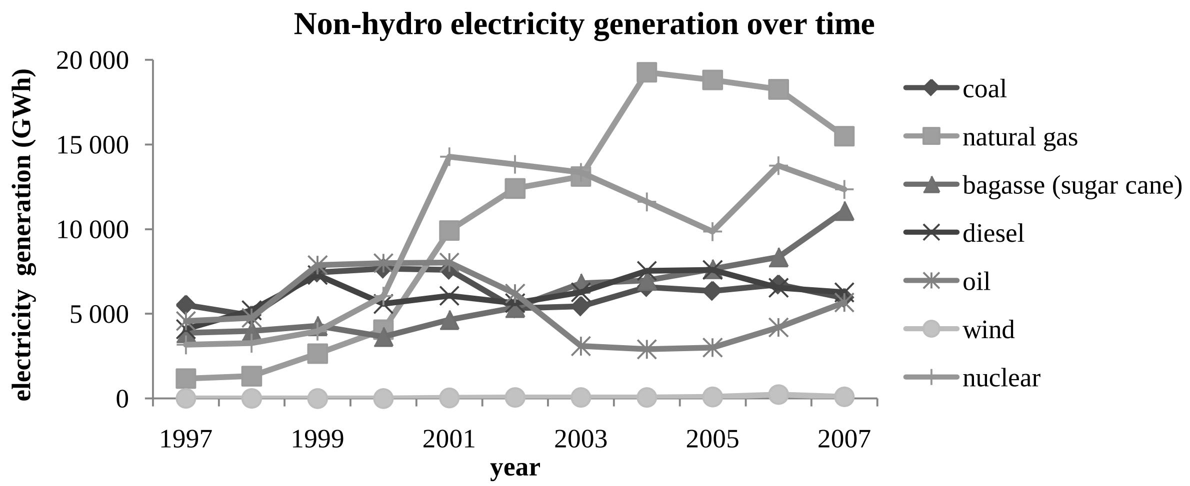

Figure 2 Non-hydro electricity sources historical series, BEN (2008).

3.2 Life cycle assessment

Life Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment (SETAC 1993).

LCA address the environmental aspects and potential environmental impacts (e.g. resource use and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment and disposal (i.e. cradle-to-grave) (SETAC 2009).

The international standard of LCA (ISO14040 2006) list topics for which life cycle assessment can assist in:

- identification of improvement opportunities of environmental performance of products,

- decision making support in industry, government or non-government organizations,
- selection of relevant indicators of environmental performance,
- and marketing (e.g. producing an environmental product declaration).

3.2.1 Impact assessment methods

The society of environmental toxicology and chemistry, SETAC (SETAC 1993) define impact, in the context of LCA, as the reasonable anticipation of an effect and state that the goal of an life cycle impact assessments (LCIA) is not to determine actual impact, but to link the inventory data to impact categories and to quantify the relative contribution to the impact category.

LCIA are likely to assign the consumption and loading data from the inventory to impact categories and then using characterization methods, quantify the magnitude of the contribution to the associated impact (SETAC 1993).

Environmental impacts can be expressed as a midpoint category indicator (e.g. global warming) or endpoint which is the ultimate environmental damage, impact assessments that use endpoint approach are also known as damage-oriented method (Jolliet, Muller-Wenk et al. 2004). The Figure 3 is a schematic representation of the general structure of LCIA differentiating the midpoint and endpoint categories.

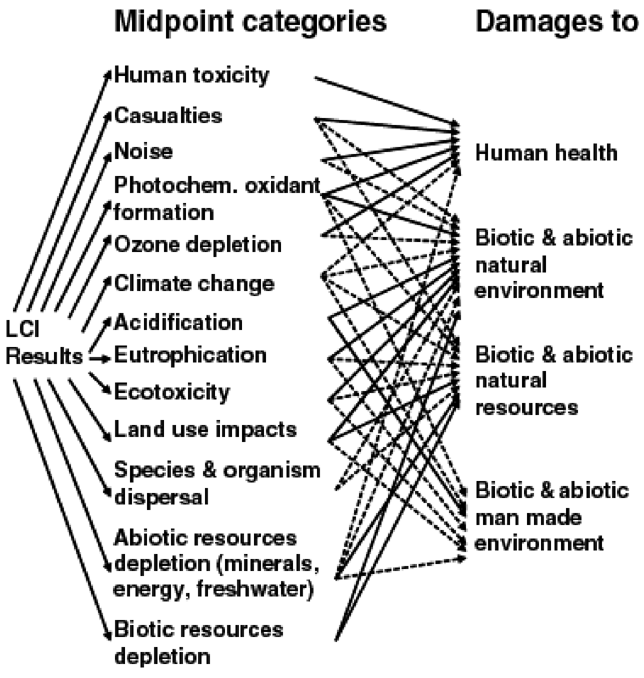

Figure 3 General structure of the LCIA framework, where solid arrows indicate that a quantitative model is available; dashed arrows indicate that only uncertain or qualitative relationships are known (Jolliet et al. 2004).

The link between life cycle inventories (LCI) results and midpoint and damage category was shown in Figure 3, but most cases the pathway may not be as simple. An example of the structure of such impact pathways is shown Figure 4, linking the emission of ozone depleting gases to a damage indicator (Jolliet et al. 2004).

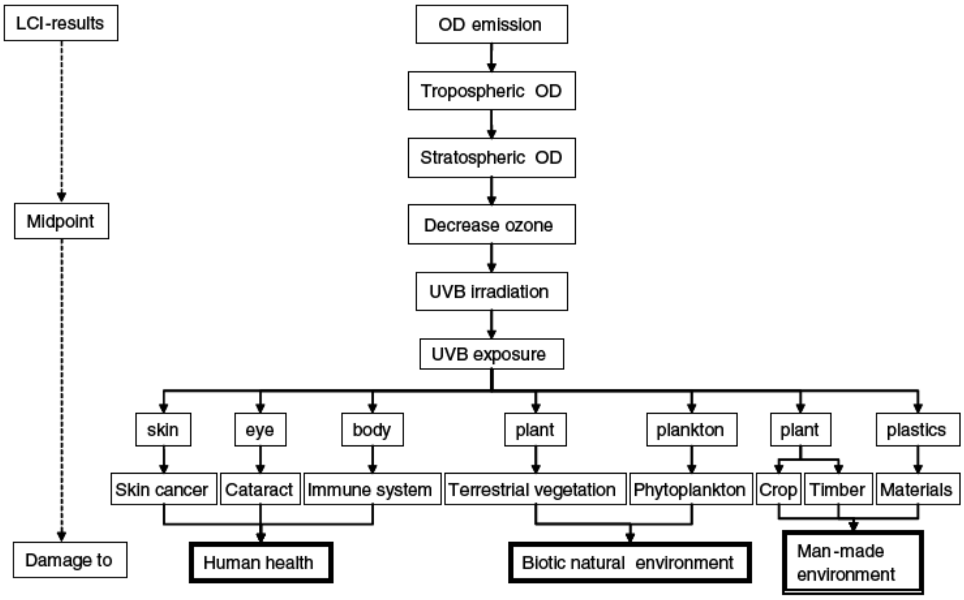

Figure 4 Example of a pathway structure linking ozone depleting emissions to impacts on human health, biotic natural environment and man-made. Source: Jolliet et al. (2004)

3.2.1.1 Global warming potential

The single use impact method for global warming, i.e. impact method which considers one single category of impact (global warming) was used in line with the values provided by the report of intergovernmental panel on climate change (IPCC) 2007 (Forster, V. Ramaswamy et al. 2007), the IPCC characterization factors:

- Do not include indirect formation of dinitrogen monoxide from nitrogen emissions.
- Do not account for radiative forcing due to emissions of NO_x, water, sulphate, etc. in the lower stratosphere and upper troposphere.
- Do not consider the range of indirect effects given by IPCC, such as the impact of the CO_2 occurs from the degradation of methane.
- Do not include CO_2 formation from CO emissions.
- Considers biogenic CO_2 uptake as negative impact.

Normalization and weighting are not a part of this method.

Global warming potential description according to SETAC (SETAC 2002)

The mechanism that causes the warming effect is called radiative forcing, the absorption of infrared radiation in the spectral region from about 10 to 15 µm. The enhanced radiative forcing and consequently enhanced global warming is seen as a primary effect from the increase of greenhouse gases in the atmosphere, named midpoint category in LCA context. While climate change covers secondary and tertiary effects and is considered an endpoint indicator. Climate change indicators do not have the same scientific confidence as the midpoint indicator.

One of the purposes of climate change models is to calculate the relative contribution of different gases at the basis of equal weight. Global warming potential (GWP) is normalized to 1 mass unit of CO_2. The average tropospheric life time of the greenhouse gases is greater than then tropospheric mixing time, because of that the location of emission is irrelevant, therefore climate change is a truly global impact category.

As long term scenarios defined today are most likely to better represent the present situation, SETAC considers a time horizon of 100 years to be appropriate. Due to the high uncertainty of the modeling, SETAC’s recommendation is to use midpoint approach on this impact category.

3.2.1.2 EPS 2000 (Steen 1999a) and (Steen 1999b)

One impact assessment method developed for designers and engineers is the environmental priority strategy for product design, or EPS. Anthropogenic activities can have endless consequences on the environment. In order to be able to handle such complex system the EPS method focus on general properties of the environment, i.e. impact categories and indicators, which are grouped into safeguards subjects. Weighing is based on williness to pay of OECD[2] inhabitants to recover the damage caused.

The EPS 2000 default method is an update of the 1996 version. The impact categories are identified from five safe guard subjects: human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values (previously known as aesthetic values).

- The Human Health indicators are:
    - Life expectancy, expressed in Years of life lost (person year),
    - Severe morbidity and suffering, in person year, including starvation,
    - Morbidity, in person year, like cold or flu,
    - Severe nuisance, in person year, normally causing a reaction to avoid the nuisance,
    - Nuisance, in person year, irritating, but not causing any direct action.

- The default impact categories of production capacity of ecosystems are:
    - Crop production capacity, in kg weight at harvest,
    - Wood production capacity, in kg dry weight,
    - Fish and meat production capacity, in kg full weight of animals,
    - Base cat-ion capacity, in H+ mole equivalents (used only when models including the other indicators are not available),
    - Production capacity of (irrigation) water, in kg which is acceptable for irrigation, with respect to persistent toxic substances
    - Production capacity of (drinking) water, in kg of water fulfilling WHO criteria on drinking water.

- Abiotic stock resource indicators is:
    - Depletion of elemental or mineral reserves and depletion of fossil reserves, in Environmental Load Units (ELU).

- Default impact category for biodiversity is:
    - Extinction of species, expressed in Normalized Extinction of species (NEX).

3.2.1.3 Eco-indicator 99 (Goedkoop 2000)

This method defines the environment as a set of biological, physical and chemical parameters influenced by man, which are the conditions to the functioning of man and nature. These conditions include:

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[2] Organization for economic co-operation and development

- Human Health (in DALYs - the Disability Adjusted Life Years), where the different disability caused by diseases are weighted. This include the following impact, per category:
    - Carcinogens, Respiration of organics, Respiration of inorganics, Climate change, Radiation, Ozone layer.
- Ecosystem quality (in PDF*m^2yr), where PDF is the Potential of Disappeared Fraction of plant species, this include the following impact, per category:
    - Acidification/Eutrophication (in PDF*m^2yr) and Ecotoxicity (in PAF*m^2yr- where PAF stands for potential of affected fraction of species in relation to a concentration of a toxic substance).
- Resources (in MJ surplus), where a damage of 1 means that the extraction of this resources in the future will require one additional MJ of energy to compensate lower concentration or for resource extraction. This include the following impact, per category:
    - Minerals and Fossil fuels.

The method considers that a small variation on the environment as damages. The method has developed three versions of the damage model, which are in short:

- Egalitarian (E): long term perspective even a minimum of scientific proof justifies inclusion,
- Individualist (I): short time perspective: only proven effects are included,
- Hierarchist (H): balances time perspective: consensus among scientist determines inclusion of effects.

The eco-indicator 99 method present different weighting perspectives: E (egalitarian), I (individualist), H (hierarchist), A (average).

The authors recommend the usage of hierarchist (H) damage perspective due to the development of consensus of impact methods and the balance of long and short term perspectives. Due to the small size of the sample of the weighting panel it is recommended to use the averaged weighting factor (A). A study using for example the hierarchist damage perspective and averaged weighting factor is referred as H/A. Hierarchist and average will be the approached used in this work.

3.3 Procedure for the selection of parameters and alteration

As a first step, the electricity mix was updated according to the most recent available report from the Brazilian government (BEN 2008) and a comparison of the two mixes was carried out. Then the impact assessments of both mixes were compared[3].

The second step was the analysis of the impact assessment aiming to identify which type of electricity most contributed to each impact category (midpoint). Electricity sources with high impact were further investigated in order to identify:

- which parameters were responsible for the significant impact, such as burning fuel at the coal electricity generation plant,

[3] Throughout the report the Brazilian mix used in ecoinvent "Electricity, production mix BR/BR U" will also be referred as 2004 mix, while the updated mix will be "Electricity, production mix BR/BR U- 2007" referred as 2007 mix.

- and if there were any technological differences that could alter this inputs or outputs. Technological differences could be e.g. the amount of concrete used to construct the hydropower dams.

When inventory alteration was possible, the altered process impact assessment was compared with the processes to verify if there were differences on the final impact of the relevant categories.

When applicable a comparison of the worse case, average and best case (of e.g. an emission) was performed. That means the results are considering the 95% confidence interval of the reported aspect, in this way the infrequent peaks would be ignored since 95% of all the observations values fall on that range.

A flowchart describing the steps followed on the study is presented in Figure 5.

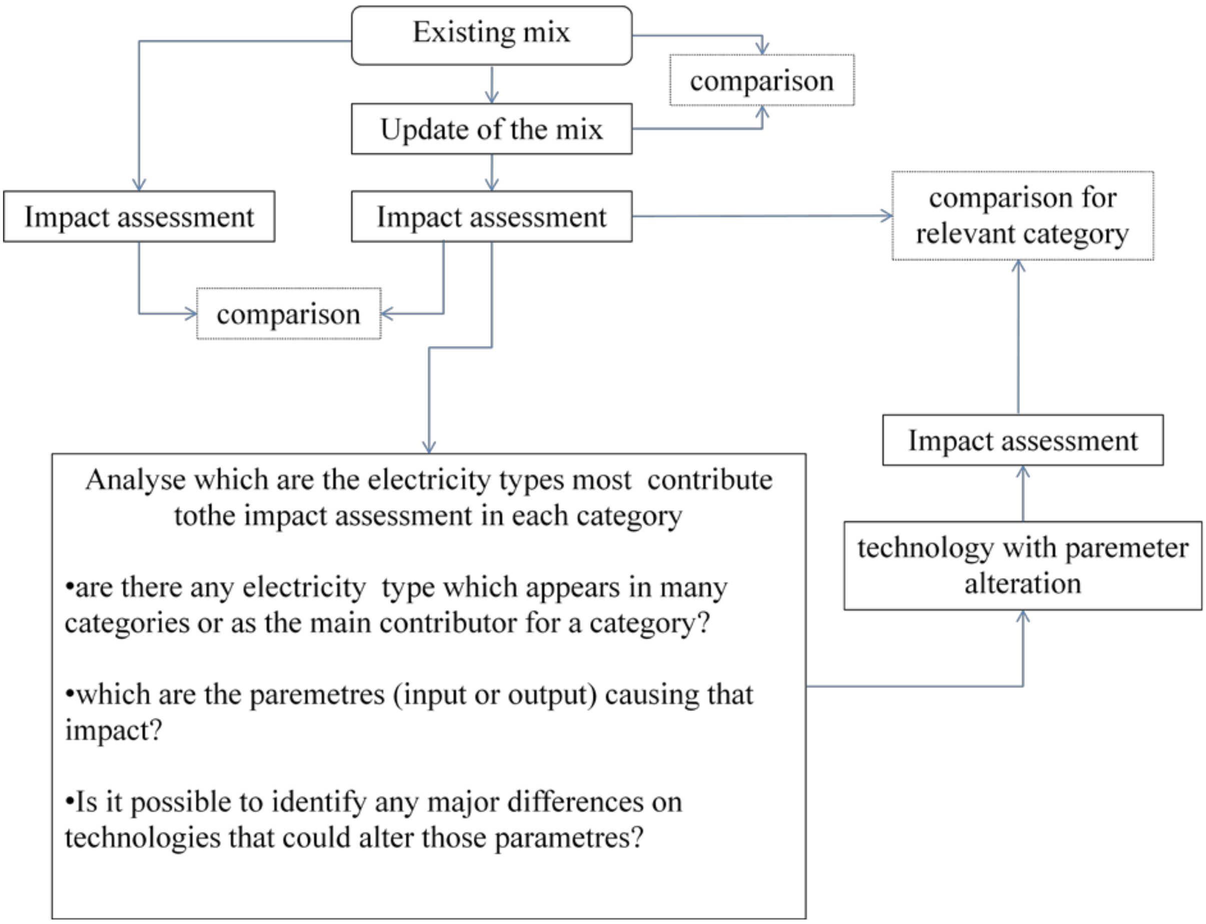

Figure 5 Flow chart of the steps of the study. Starting from the existing mix available in ecoinvent and follow up alterations and comparisons.

3.4 System description

This session includes the description of the system of the Brazilian electricity mix. The electricity types or processes which will be evaluated for the alteration of the relevant parameters will be selected according to the impact assessment results of the electricity mix (in session 4.2 Impact assessment of the 2007 mix), the description of the other process and electricity types will be presented in the same session of its environmental assessment.

System description of the Brazilian electricity mix (Frischknecht et al. 2007):

Functional Unit

The electricity mix refers to the total amount of electricity generated by the different power sources in kWh during the year of 2004.

Boundaries

It includes the shares of domestic electricity production by technology at the busbar (the electrical conductor that makes a common connection between several circuits).
It does not include transformation, transport nor distribution losses
Electricity domestic net production shares are based on annual averages

Geography

Data is from public and self producers in Brazil.
Natural gas, industrial gas and nuclear power plants are modeled using UCTE averages.
Nuclear power plants are Swiss averages as well as diesel co-generation power.
Wind power is used as regional Europe.

Technology

No technology description is provided because the dataset just describes the power plant portfolio of the respective country using current (2004) average technology per energy carrier.

Time period

2004

4 Results

The following session will cover:

- the comparison of the mix being used in ecoinvent (referred as mix 2004) and the mix according to the latest information available (referred as mix 2007) and a comparison the impact assessment of these two mixes,
- the impact assessment of the updated mix and the electricity types which are identified to have a great contribution to most categories or a relevant contributor to a category.
- further investigation of the electricity types indentified in individual sessions covering:
    - bagasse on the impacts of the bagasse derived electricity
    - climate change impact of hydropower
- the alteration of parameters in the following electricity types:
    - hydropower
    - bagasse derived electricity
    - and coal power

4.1 Mix comparison

As previously described, the starting point of the work is the update of each electricity source accounting for the electricity generation for Brazil which was published by ecoinvent by Bauer, Bolliger et al. (2007b).

The Brazilian electricity mix in ecoinvent, consists of hard coal, natural gas and industrial gas inputs (European mix, UCTE), diesel and nuclear sources (Switzerland mix, CH) and hydropower and bagasse (Brazil mix, BR).

A comparison of the electricity mix used in ecoinvent and the updated mix is shown in Table 1.

Table 1 Comparison of the contribution of each type of electricity to the Brazilian electricity mix 2004 and 2007. The last column is the relative difference between the two, negative values represent that the electricity type has a smaller contribution in 2007 than in 2004.

Type of electricity (%)	2004	2007	Relative difference
	A	B	(B-A)/A
wind	0,02	0,13	7,31
industrial gas	1,20	1,01	-0,16
coal	1,56	1,53	-0,02
nuclear	2,46	2,78	0,13
diesel	2,89	3,00	0,04
bagasse	3,44	3,95	0,15
natural gas	4,67	3,49	-0,25
hydropower	83,76	84,13	0
	100	**100**	

4.1.1 Impact assessment

In order to access which aspects (inputs or outputs) most contribute for the environmental impacts of the electricity production, an environmental impact assessment of the Brazilian electricity mix was carried out. As a first step the LCIA was carried out for the existing Brazilian production mix available in ecoinvent. Figure 6 and Figure 7 presents the comparison of the environmental impacts of the Brazilian electricity grid for the mix 2004 and 2007, according to the eco-indicator 99 H/A and EPS 2000. Both impact assessments were normalized to the mix of 2004.

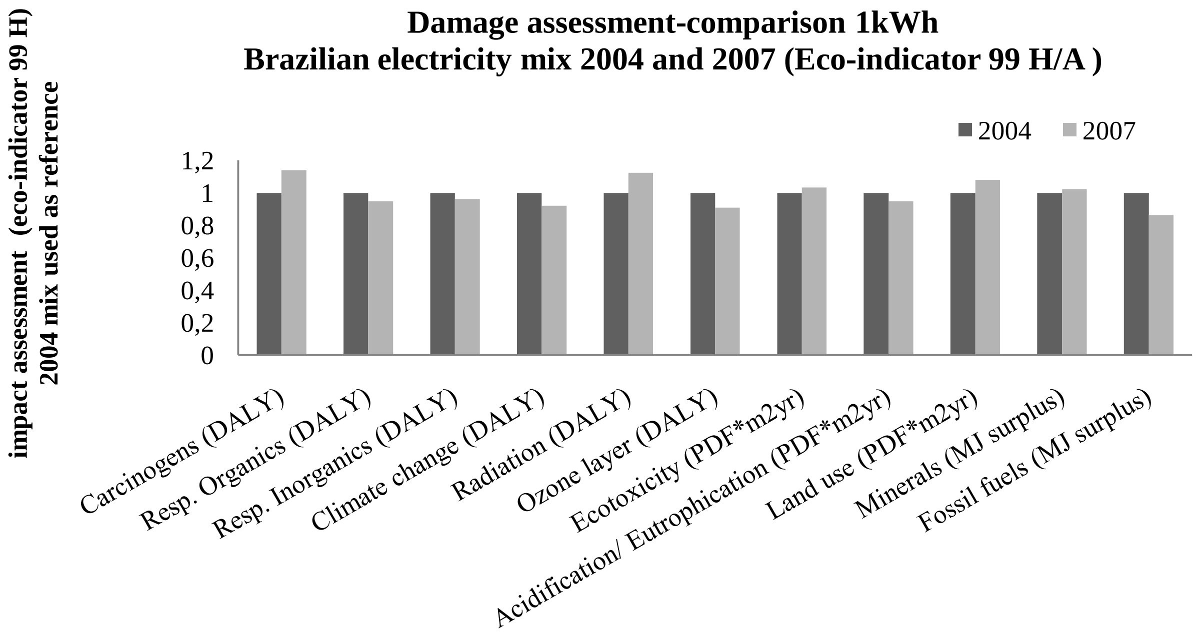

Figure 6 Comparison of the environmental impacts of the 1 kWh of the Brazilian electricity grid for the mix 2004 and 2007, according to the eco-indicator 99 H/A, where the impact of each category is normalized to the mix of 2004.

The environmental impact results show slight variations on the impact assessment results. A greater impact of the 2007 mix is observed on the categories: minerals, land use, ecotoxicity, radiation and carcinogens.

As well as in the eco-indicator 99 method, when analyzed using EPS 2000 method, the difference of the two mixes was less than 20% for all categories (Figure 7). On contrary to eco-indicator 99, none of the EPS 2000 categories presented increased impact, the only category which remained constant was severe nuisance, while all the remaining categories had a smaller environmental impact for the 2007 mix than for the 2004 mix.

The category nuisance referrers to the impact that causes harm or irritation without any direct action for the one being disturbed, while severe nuisance would normally cause a reaction to avoid the nuisance (Steen 1999a). The later category presents characterization factors for heavy metals, lead, metal and littering (Steen 1999b).

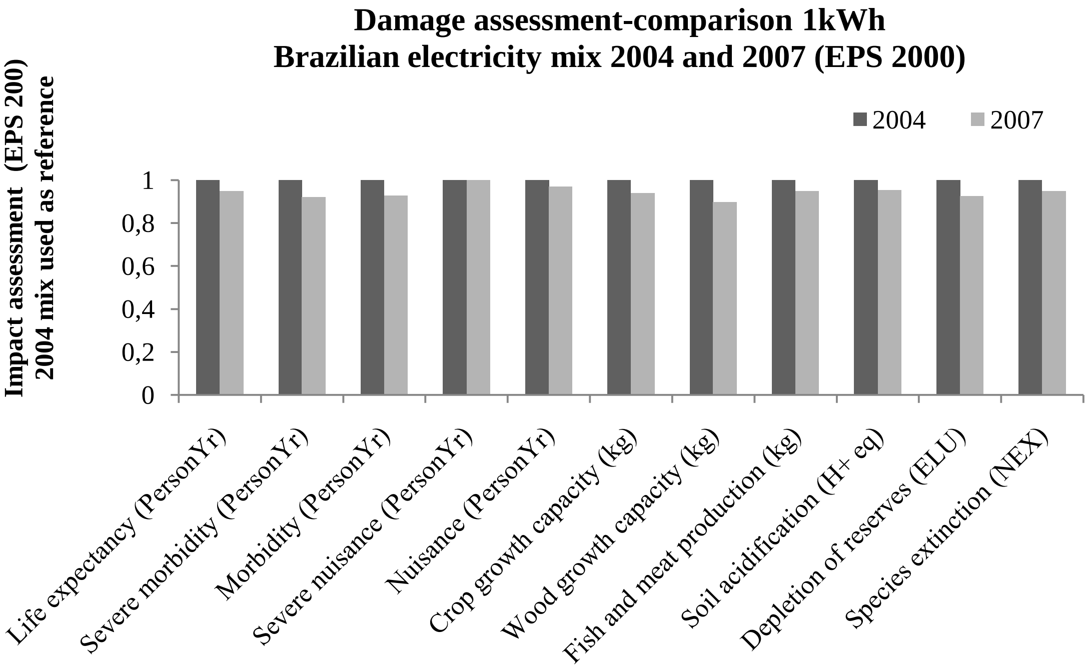

Figure 7 Comparison of the environmental impacts of 1 kWh of the Brazilian electricity grid for the mix 2004 and 2007, according to EPS 2000, where the impact of each category is normalized to the mix of 2004.

4.2 Impact assessment of the 2007 mix

In order to indentify the contribution of different electricity sources to the environmental impact categories the LCIA was carried out for the electricity mix used in ecoinvent (system description in session 3.4) altering the amount of each electricity type in the mix according to the year 2007 (as presented in Table 1). The LCIA was carried out for the selected methods: Eco indicator 99 H/A, EPS and Climate change (GWP 200a).

The goal of this session is to identify what are the electricity types which are relevant to the impact categories according to the three methods. Further analysis for the reasons for this contribution (e.g. which input of a certain electricity type is responsible for a high impact in a specific category) will be presented in the session 4.3 Identification of hot spots .

4.2.1 Eco indicator 99 H/A

The impact assessment per impact categories (eco-indicator 99 H/A) is presented in the Figure 9, it was possible to indentify that hydropower plays an important role in many categories, such as climate change, minerals, ecotoxicity and land use. Despite a low participation on the mix, diesel has a significant contribution to the categories fossil fuels, ozone layer and respiration of organics. Even thought generating less than 4% of the total Brazilian electricity, bagasse derived electricity has a massive contribution to carcinogens and land use.

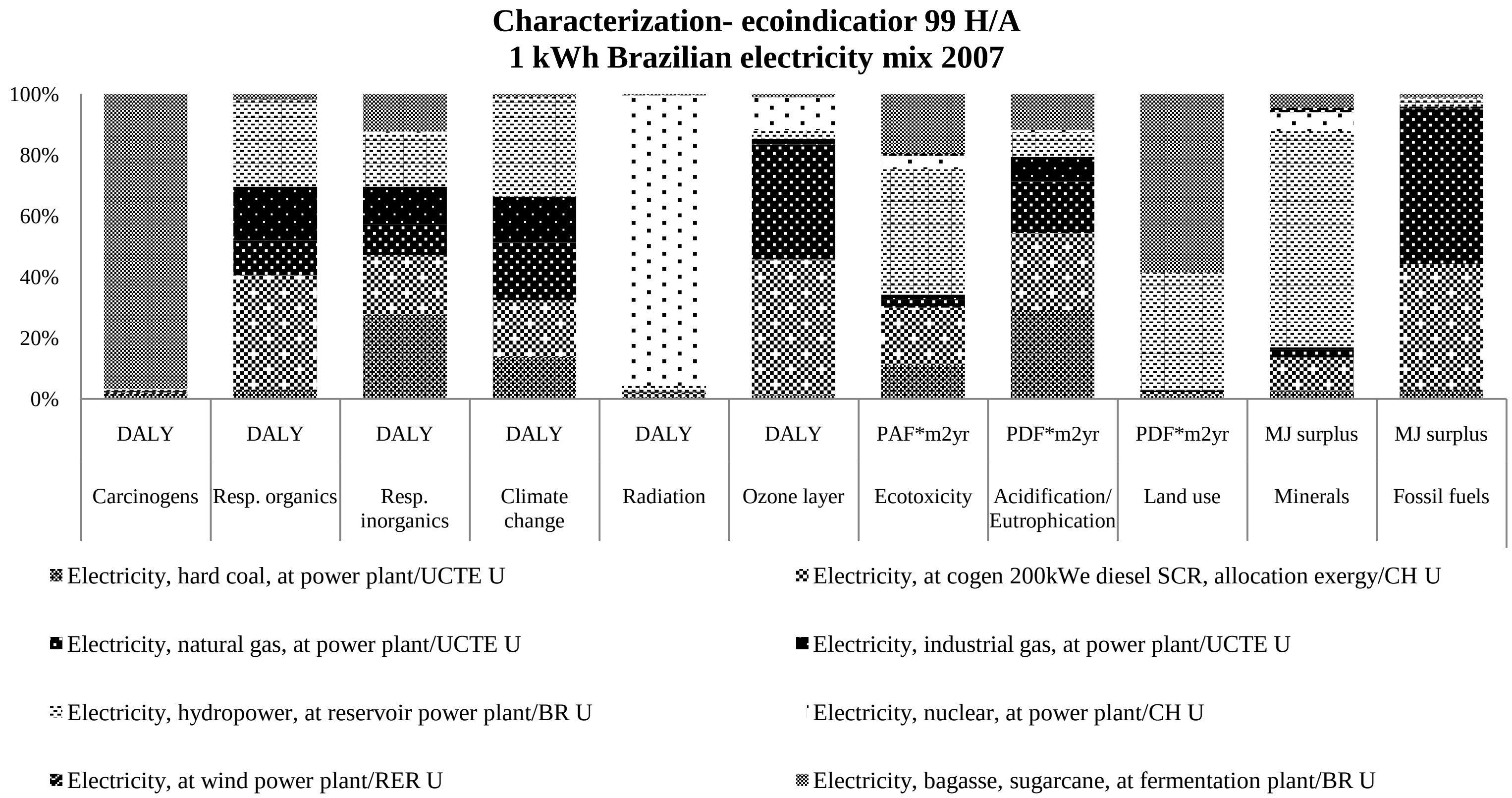

Figure 8 Impact assessment eco-indicator 99 H/A, of 1kWh of Brazilian electricity mix 2007. The bars represent the relative contribution of each type of electricity to each impact category.

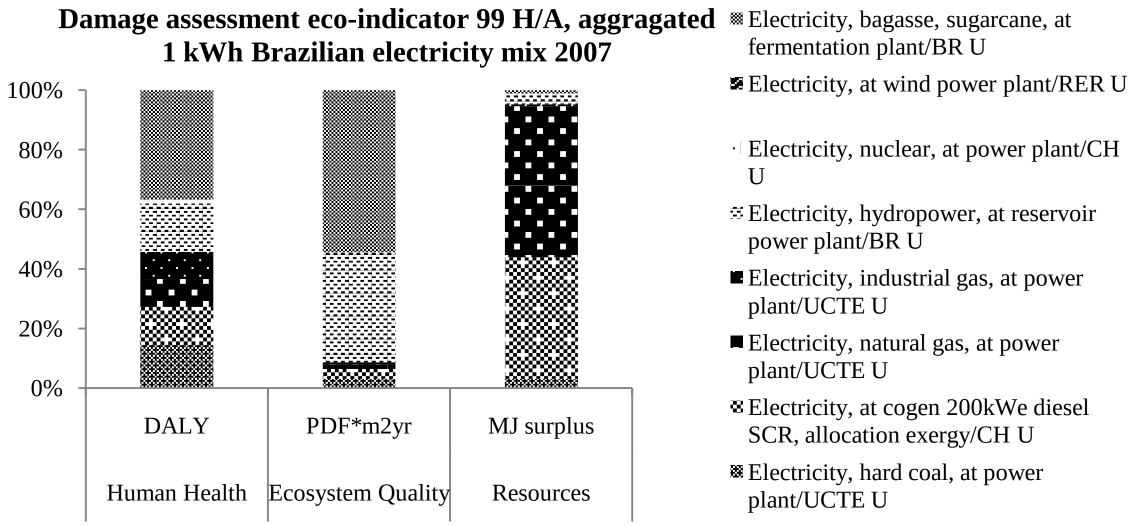

Figure 9 Aggregated damage assessment of 1kWh of 'Electricity, production mix BR/BR U -2007', eco-indicator 99 H/A. The bars represent the relative contribution of each type of electricity to each impact category.

The damage assessment of the eco-indicator 99 H/A, aggregated to the three damage categories (human health, ecosystem quality, resources) is presented in Figure 8. The diesel co-generation and natural gas accounted for about 90% of the impact to resources category. Hydropower and bagasse together accounted for approximately 60% of human health. The ecosystem quality had 90% of its impact from hydro power and bagasse derived electricity.

Bagasse derived electricity contribution to human health is due to its overwhelming impact for the carcinogens category. While its impact to ecosystem quality is due to its contribution to land use (accounting for nearly 50% of this category impact as seen on Figure 8) as well as ecotoxicity and acidification/eutrophication impact categories.

4.2.2 EPS 2000

The EPS 2000 impact assessment for the Brazilian mix 2007 is present in Figure 10. The environmental impacts to most categories can be considered evenly distributed throughout the electricity sources. Hydroelectricity has a fair contribution in many categories, while hard coal appears as the greatest contributor to nuisance and soil acidification. Natural gas and diesel are also relevant for environmental impacts in all categories.

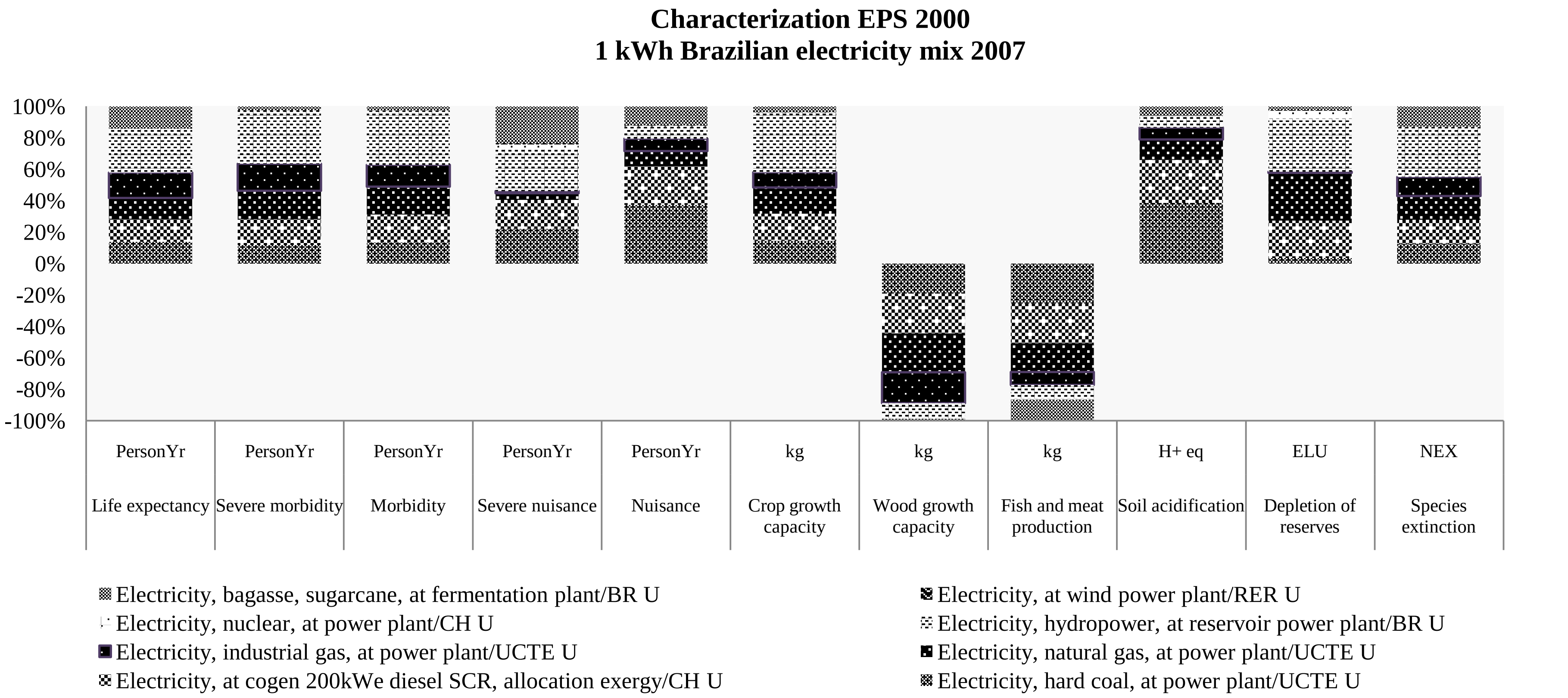

Figure 10 Impact assessment EPS 2000, of 1kWh of Brazilian electricity mix 2007. The bars represent the relative contribution of each type of electricity to each impact category.

The coal impact for nuisance and soil acidification is mainly originated from the coal burning at the difference plants composing the UCTE mix.

When aggregated into the four damage categories (human health, ecosystem production capacity, abiotic stock resource and biodiversity) the impacts are again fairly distributed among the different electricity sources (Figure 11).

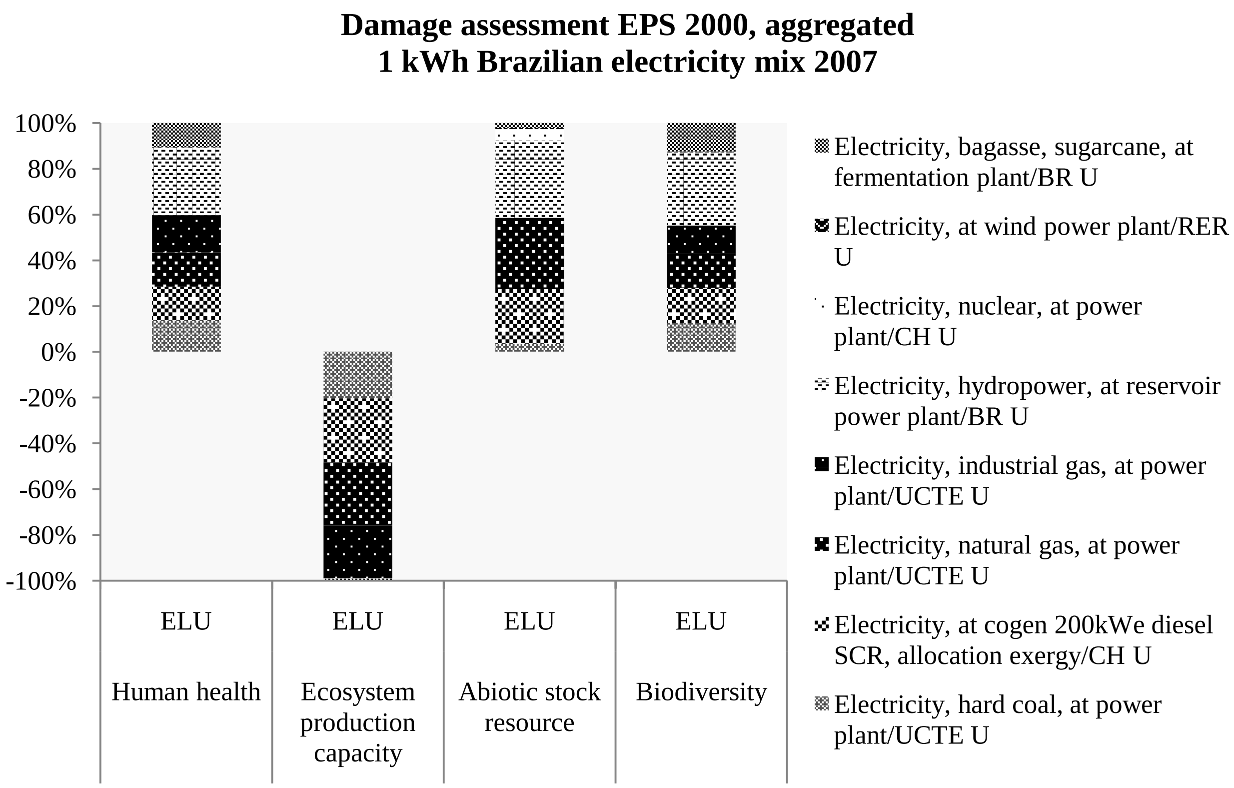

Figure 11 Aggregated damage assessment of 1kWh of 'Electricity, production mix BR/BR U 2007', EPS 2000. The bars represent the relative contribution of each type of electricity to each impact category.

4.2.3 Climate change

Figure 12 presents the climate change assessment of the Brazilian electricity mix 2007, using the global warming potential for 100 years according to the values provided on the IPCC report 2007 (Forster et al. 2007). Note that the nuclear, bagasse and wind derived power has been excluded from the graph once the contribution of these electricity sources were negligible.

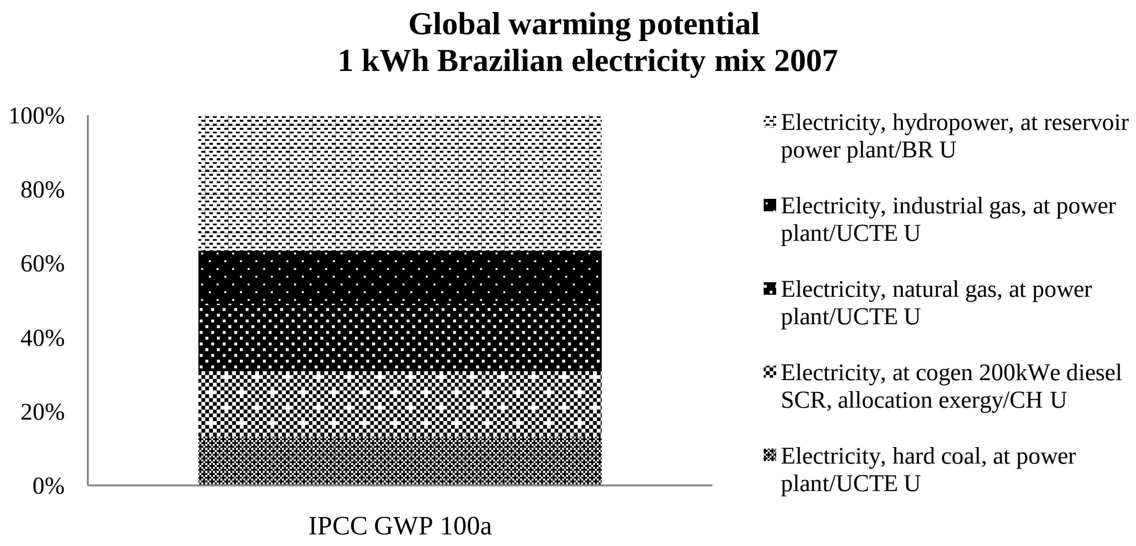

Figure 12 Impact assessment of 1kWh of 'Electricity, production mix BR/BR U -2007', IPCC (2007) GWP 100a.

4.3 Identification of hot spots

The following sessions will further investigate the aspects leading to these environmental impacts and the factor leading to the impacts.

The impact assessment of eco-indicator 99 (Figure 9), showed a notable share of contribution of nuclear to radiation category and bagasse to carcinogens category. The main contributor to radiation category is nuclear power can be easily understandable, while the factor contributing to the bagasse derived energy high impact to carcinogens is not as straight forward and will be investigated.

All the impact assessment methods showed hydropower contributing to most of impact categories, as well as climate change.

4.3.1 Bagasse power generation

The sugarcane production can be considered one of the most important economical activities in Brazil and nowadays almost all sugar cane derived ethanol and sugar factories in Brazil are self-sufficient in electrical energy (Ensinas, Nebra et al. 2007). The authors affirm that in the last few years electricity has also become a product once sugarcane bagasse can be used as fuel in cogeneration systems.

The description of the system in the ecoinvent (Jungbluth 2007a):

Included processes

Fermentation of sugar cane including materials, energy uses, infrastructure, and emissions.

Functional unit

1 kWh of electricity derived from sugar cane bagasse.

Included process

Fermentation of sugar cane including materials, energy uses, infrastructure, and emissions.

Allocation

The multi-output process "sugar cane, to fermentation" delivers the co-products Ethanol, 95% in H_20, from sugar cane" and "electricity, bagasse, at fermentation plant". The allocation is based on economic criteria.

Geography

The inventory is modeled for Brazil.

Technology

Production of ethanol from sugar cane with extraction, fermentation and distillation of ethanol.

Time period

The date of the publications ranged from 1988 and 2004.

4.3.1.1 Carcinogens

The risk that a substance may cause cancer at different doses is estimated by models (p.131), the years of life lost (YOLL) indicators requires quantitative information on the actual increase of cancers as a result from a increase of exposure to a given substance and on the expected loss of life expectancy per case of fatal cancer (p. 137) (SETAC 2002).

The bagasse-derived electricity is the main contributor to the carcinogens category, such high impact due to arsenic from sugar cane at the farm. The process most contributing to this impact is the fertilization, because the phosphate (P_2O_5) contains arsenic.

Another important point to note is that the pesticides data is likely to be out of date since it is based on a report published in 1988 (Jungbluth 2007a). One example is the usage of the pesticide aldrin[4] which is an input in the data set for ‘sugar cane at farm BR’, this substance has been prohibited in 1985 (ANVISA 1985).

The input aldrin, do not present a characterization factor in the eco-indicator 99 (H and I approach). The EPS 2000, however, does have a characterization factors for aldrin (for the categories: life expectancy, severe morbidity, morbidity and species extinction. Taking into consideration that aldrin has been banned and assuming zero input of aldrin, an analysis excluding this input is later presented in session 4.4.4.1.2.

4.3.1.2 Future changes in the cane harvest

The sugar cane harvesting process has been changing on the past years, it has had a gradually increase in the mechanized harvest. This increase in mechanized harvest is a consequence of the regulation been implemented on the state of São Paulo (the most significant sugar-cane production region) which aim to eliminate the burn of the cane by 2020, since manual harvest is not possible when the cane is not burned (in Portuguese *cana-crua).* This has been a slow change process but may have significant implications on life cycle assessments in the long run.

It is expected that mechanized harvest will increase the fuel consumption for tractors, and will eliminate particulate emissions once the practice of burning of the leaves will is left aside. Besides that, the leaves when left on the field will also alter the physical and the chemical characteristics of the

[4] Aldrin CAS 309-00-2

soil influencing the spring and growth of the harmful herbs which are common to occur in the plantation and the interaction of the herbicides (Novo 2005). There is a potential for the utilization of the straws for electricity generation (Filho 2006). Current ongoing project, financed by the ministry of science and technology are researching possibilities for co-generation of the leaves (Braunbeck 2007).

4.3.2 Hydro power and climate change

Description of the process 'Electricity, hydropower, at reservoir power plant/BR' (Bauer, Bolliger et al. 2007a)
Functional Unit

1 kWh of electricity generated from the power plant.

Included processes

Process is an average of the dams in operation of Brazilian dams.
It includes the area occupied; lubricant oil; volume of the reservoir; mass of water passing through the turbines.
Lifetime is assumed to be 150 years for the structural part and 80 years for the turbines.
Greenhouse gas emissions are calculated on the basis of a sample of 9 Brazilian reservoirs in the latest study on this matter (123TWh which is approximately 34% of total hydropower generation).

Geography

Data were extrapolated from the average Swiss reservoir hydropower plant

Technology

The module describes average installed technology.

The climate change impact from hydroelectricity in Brazil is mainly due to the direct emissions of the reservoir, the second greatest impact is accounted from cement production.

The result of the impact assessment emissions from reservoirs for eco-indicator 99 (H) in DALYs and for the IPPC GWP 100a (in CO_2 equivalents) were found to be 18 and 21 times, respectively, the impact for the emissions of those from cement production. The comparison of two impact methods is presented in Table 2. In both methods the emissions from reservoirs were responsible from 90% of the impacts.

Table 2 impact contribution of 1kWh from hydroelectric of Brazilian power (ecoinvent processes: 'Electricity, hydropower, at reservoir power plant/BR U').

Process	Eco-indicator 99 (H) V2.05 / Europe EI 99 H/A	IPCC 2007 GWP 100a V1.00
	DALY	g CO_2 eq
Total of all processes	9,59E-09	53,65
Electricity, hydropower, at reservoir power plant/BR U	8,67E-09	49,25
Clinker, at plant/CH U	4,80E-10	22,84

4.3.2.1 Cement for the construction of dams

The impact assessments (Eco-indicator 99 H/A and GWP 100a) of hydroelectricity showed that the overwhelming impact to global warming and consequently to climate change is attributed to the reservoirs emissions. Investigation of the accuracy of the values of clinker input and production could be relevant if the Brazilian dams were constructed with a significant difference on the amount to concrete. On this study priority is given to the investigation of the emissions from hydropower.

4.3.2.2 Emissions from reservoirs

Airborne emission such as carbon dioxide and methane may be classified according to its origin, e.g. carbon dioxide fossil, biogenic or from land transformation. According to Jungbluth (2007b) it is important to make the differentiation between biogenic and fossil carbon compounds since biogenic CO_2 does not contribute to the problem of climate change as it is renewable and the same amount of carbon which is stored in the plants has been up taken by the plants during growing

Despite the concept of biogenic and fossil carbon emissions may seem widely accepted; the impact assessment indexes may not be up to date. The comparison of the indexes for the climate change of the Eco-indicator 99 H, IPCC 100a and a third method, impact 2002+ is presented in Table 3.

Table 3 characterization indexes for different impact assessment methods (climate change category).

method	impact category	substance	type	value	unit
Eco-indicator H/A	climate change	methane	fossil	2,1 x10^{-7}	DALY/kg
			biogenic	2,1 x10^{-7}	DALY/kg
		carbon dioxide	fossil	4,4 x10^{-6}	DALY/kg
			biogenic	4,4 x10^{-6}	DALY/kg
IPCC 2007 100a	global warming	methane	fossil	25	kg CO_2 eq/kg
			biogenic	25	kg CO_2 eq/kg
		carbon dioxide	fossil	1	kg CO_2 eq/kg
			biogenic	1	kg CO_2 eq/kg
impact 2002+	climate change	methane	fossil	10,35	kg CO_2 eq/kg
			biogenic	7,5	kg CO_2 eq/kg
		carbon dioxide	fossil	1	kg CO_2 eq/kg
			biogenic	0	kg CO_2 eq/kg

The carbon dioxide emissions from the reservoirs in the ecoinvent are accounted as 'carbon dioxide, land transformation'. From the methods selected (Eco-indicator 99, ESP 2000 and IPCC 2007) the entry 'carbon dioxide, land transformation' does not have a characterization factor. Therefore according to those methods the contribution of the reservoir emissions to climate change is only attributed to its emissions of methane.

In the newest version of the impact 2002+ the updated values for CO_2 from 'land transformation' are assumed to come from deforestation or of net reduction in the carbon content of agricultural soils because of oxidation and therefore not replaced by an equivalent amount of carbon in forest or soil over the same land and is therefore taken as a *fossil* emissions (Humbert et al. 2009).

The Brazilian electricity mix life cycle inventory published by Coltro et al. (2003) used emissions from reservoirs which were a result of a study carried out by the Federal University of Rio de Janeiro in co-operation with the Brazilian electricity company Eletrobras, published by MCT/COPPE (2002). The Brazilian hydropower reservoir emissions ecoinvent inventory also uses the data from MCT/COPPE, which was later published in English (dos Santos, Rosa et al. 2006).

In the ecoinvent report (Bauer et al. 2007b) it is stated that the Brazilian electricity mix are not meant to be used for comparison with other datasets, in page 101 table 12.6 of the report :

> "*Greenhouse gas emissions are calculated on the basis of a sample of 9 reservoirs in the latest study on this matter. There are great uncertainties on the origin of the CH_4 and CO_2 emissions. A part of them are assumed to originate from living biomass and from sewage discharged in the reservoirs and not only from biomass flooded. (…) Data of greenhouse gas emissions from hydropower in Brazil are controversial. Uncertainty may be underestimated. A deeper analysis and updates is necessary on the sensitive issue of greenhouse gas emission. This dataset is not designed for comparisons with other countries and serves only as a background data for the electricity mix.*"

The following sub-sessions aim to examine the factors which influence the emissions of the greenhouse gases focusing on methane, looking into: the Emissions processes, the Seasonal variations and concentration decay over time, Other influencing factors, a closer look in to The Brazilian reservoir emission, as well as The Brazilian methane emission.

4.3.2.2.1 Emissions processes

Studies on the emissions are indeed still lacking, not only for the Brazilian but also for other tropical reservoirs. A very extensive study has been carried out on the Petit Saut reservoir in French Guiana, which published measured values for emissions of methane for 20 years starting from the year of impoundment (Abril, Guerin et al. 2005).

Co-workers form the French Guiana reservoir (Delmas, Richard et al. 2005) identified that greenhouse gas emission from the Petit Saut reservoir result from three distinct processes:

- bubbling in shallow zones (for further explanation see session 4.3.2.2.1.1)
- diffusion at the water body surface,
- degassing of turbined water by the aerating weir (see session 4.3.2.2.1.2)

A scheme of the key factors influencing greenhouse gas emissions in reservoirs is presented in Figure 13, describing the influencing factor on reservoirs greenhouse gas emissions. Note that the figure (McCulle 2006) does not include the emissions of CH_4 by diffusion which was considered by researchers of Petit Saut, (Delmas et al. 2005) as one of the four pathways.

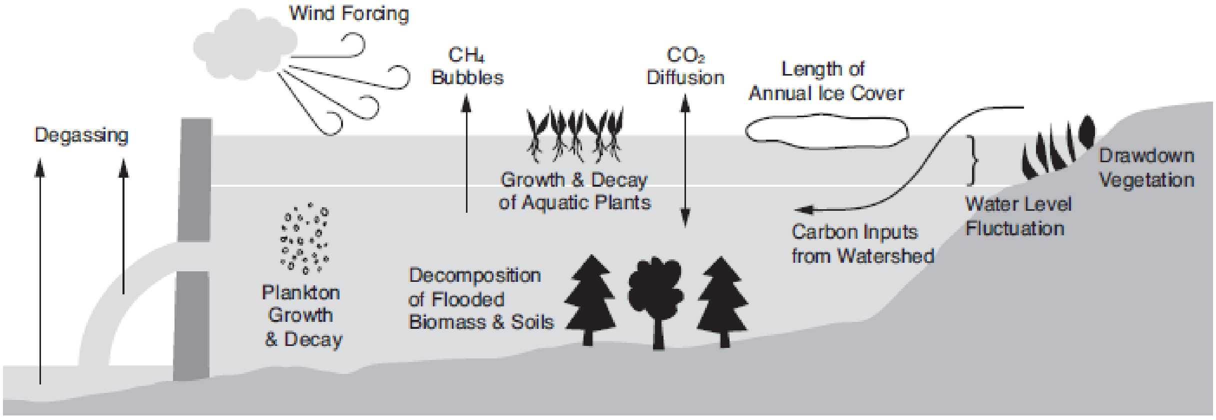

Figure 13 key factors ruling the emissions process (McCulle, 2006).

4.3.2.2.1.1 Bubbling

Rapid production of CH_4 can result in ebullition of CH_4 rich bubbles from gas saturated sediments (Kipphut and Martens 1982). The process when the bubbles are released is called bubbling.

Dispite the lack of information on the behaviour of methane emissions due to bubbling Galy-Lacaux, Delmas et al. (1999) considerd that emissions due to bubbling persist over time and are not expected to increase, this argument is supportted on the observations of Gatun Lake in Panama published by of Keller and Stallard (1994).

Gatun Lake, a reservoir impounded in 1910, presented very high emissions rates compared to Amazonia floodplain (Keller and Stallard 1994). Assuming that methane is continually produced in the sediments, Keller and Stallard, expect that bubbles will form and eventually escape the sediments as a result of their own buoyancy. According to the authors, although wind may initiate bubble emission on a given day, for longer time periods emission must be supported by methane production in the sediments, in there study bubbling did not correlate with average daily wind speed.

Keller and Stallard (1994) belived that shallow water sediments may produce more methane because of higher temperatures and greater availability of organic substrates, and based on Yamamoto, Alcauskas et al. (1976), the authors concluded that a difference in temperature of $2^{o}C$ between the deep and shallow sites (27^{o} to $25^{o}C$) would enhance methane solubility by about 4% in sediments at deeper (colder) sites, thereby diminishing the gaseous methane pool available for bubble formation

4.3.2.2.1.2 Degassing

Degassing is the term used to refer to the emissions of gases which occur when water is discharged under pressure at hydropower dams. The emission by deagassing were accounted as the main source of methane in Petit Saut due to the aerating weir installed 15 months after reservoir filling (Galy-Lacaux, Delmas et al. 1997) built to guarantee a minimun of dissoveld oxigem downstream the river. A fundamental remark was made by Delmas et al (2004), highlinting that aerating weir is not present in other dams from South America, being a particular technology of Petit Saut.

The study presented by Galy-Lacaux et al (1999) shows a high contribution of the diffusion process deacreasing on the first four years after impondment and model as it would tend to zero.

Galy-Lacaux et al (1999), modelled the long term variations in total emissions flux, presenting the high contribution of degassing of methane (Figure 14 to the left). The estimation of emission trend and influence of the installation of the aerating weir, after 15 months (450 days), on the methane release can be observe on Figure 14 (on the right).

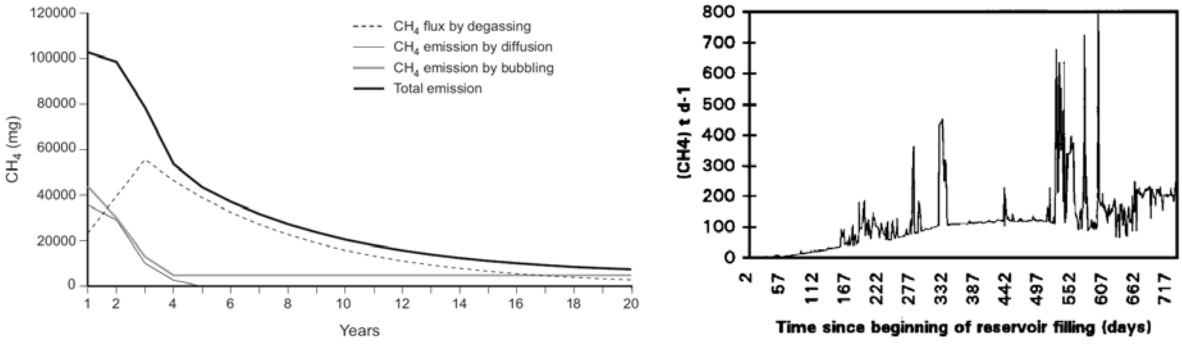

Figure 14 Left: estimated methane emission trends, over a 20-year period, from the Petit Saut reservoir (Galy-Lacaux, 1999); Right: variations in daily amounts of methane exported from the dam since reservoir filling (Galy-Lacaux et al 1997).

4.3.2.2.2 Seasonal variations and concentration decay over time

The study published by Galy-Lacaux et al. (1999), shows a high seasonal variation on the methane concentration on the reservoir over a 20 years period on Petit Saut.

The variations are attributed to the water flow variations throughout the reservoir (Galy-Lacaux et al. 1999):

The authors considered a simple schematic representation of the reservoir the balance of sources and sinks representing the temporal variation of the dissolved methane mass in the reservoir neglecting the precipitation and the evaporation; leading to equation 1.

$$\frac{dC}{dt} = \frac{P-F-L}{V} - \frac{q_{in}.C}{V} \quad \text{(eq. 1)}$$

Where C is methane concentration in the reservoir; V is the volume of reservoir, P represents in situ production (positive emission flux at the bottom) per unit time basis, F represents the net vertical water exchange and L represents the in situ loss by oxidation of methane. The terms q_{in}, is the inlet flows. It was assumed that vertical methane fluxes (P-F-L) throughout the reservoir do not vary dramatically over the time. Therefore, according to this model the temporal variations of methane concentration are primarily determined by the reservoir in flow q_{in}, variations of the Sinnamary River (of the Petit Saut reservoir) inflow are correlated with the alternation of rainy and dry seasons.

Galy-Lacaux (1997) observed that the methane concentrations measured significant decreased after the first years after impoundment. The authors used values of methane concentration from a different reservoir, older, with comparable landscape and vegetation type in order to extrapolate the values for a longer time period (Figure 15). On that figure the seasonal variation of the experimental values can be clearly observed as well as a reduction on the maximum values of methane concentration.

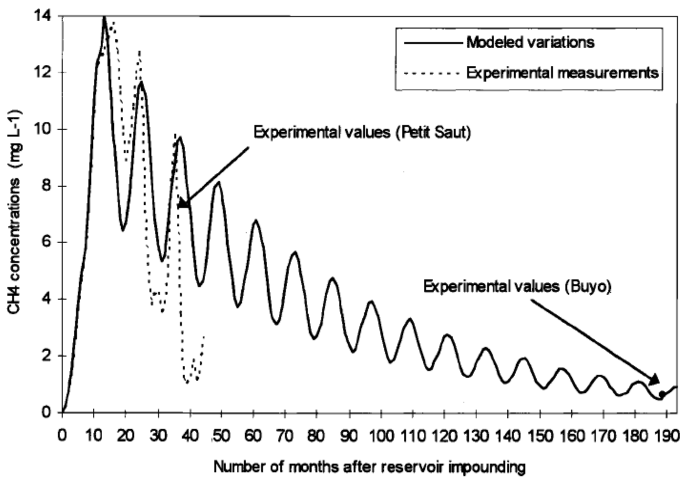

Figure 15 Variations of dissolved CH4 concentration in Petit Saut reservoir over a 20-year period, Galy-Lacaux et al 1997.

4.3.2.2.3 Other influencing factors

A study in marine sediments concluded that methane production does not begin until dissolved sulfate concentrations approaches zero (Martens and Berner 1974). While a research in wetlands of Belize, found that concentration of methane decreases with an increasing sulfate concentration, (Rejmankova and Post 1996). The studies of tropical reservoirs investigated on this study do not point sulfate as influencing factor, i.e. the authors do not mention low concentration of sulfate as a justification of high generation of methane in tropical reservoirs.

4.3.2.2.4 The Brazilian reservoir emission

The goal of the study of MCT/COPPE was to establish a method to account the greenhouse gases emissions from different Brazilian reservoirs of hydropower dams (MCT/COPPE 2002). The emissions were measured to determine the emissions of methane (CH_4) and carbon dioxide (CO_2) Two types of measurement were performed to cover emissions by bubbles (also known as ebbullitive flux or bubbling) and diffusive gas exchanges at the water–air interface[5].

The measurements taken in two-field surveys (1998 and 1999) consisted of collecting gas flow data. The reservoirs selected had different geographic location (from 2°S to 25°S), Figure 16, and covered different biomes. The year of impoundment of the reservoirs varied from 1961 and 1997 (Três Marias and Miranda, respectively).

[5] Note that as stated by dos Santos et al, 2006, (pg 482), the study does not calculate natural emissions from soils and water before the impoundment.

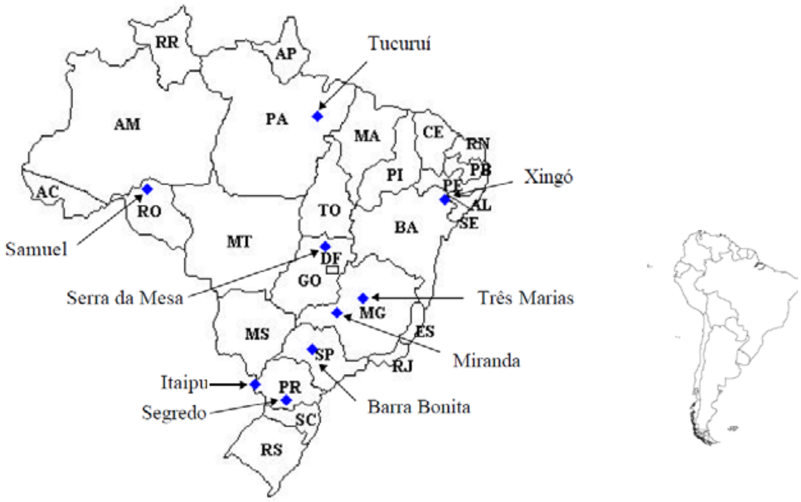

Figure 16 location of the hydro power reservoirs (MCT/COPPE 2002).

As the experimental observations took place at different points (including different depths) of each reservoir, in order to have an average for the entire reservoir, the data had to be extrapolated. Bubbled emissions were found to be depth dependent and as they do not occur at greater depths, a weighted average was created for the entire reservoir, taking into consideration the area which emitted the bubbles. For diffusive emissions, which were found to be independent of depth, the simple mean of the measured values were used.

4.3.2.2.4.1 The Brazilian methane emission

Methane emissions from reservoirs are a high controversial topic in Brazil, with discussion around the emissions and its accounting methods for almost 15 years (Cullenward and Victor 2006).

The emissions of the reservoirs are presented in Figure 17. No significant correlation was possible to be drawn when analyzing the emissions per area across the ages of the reservoirs as it is predicted for Petit Saut (Figure 15).

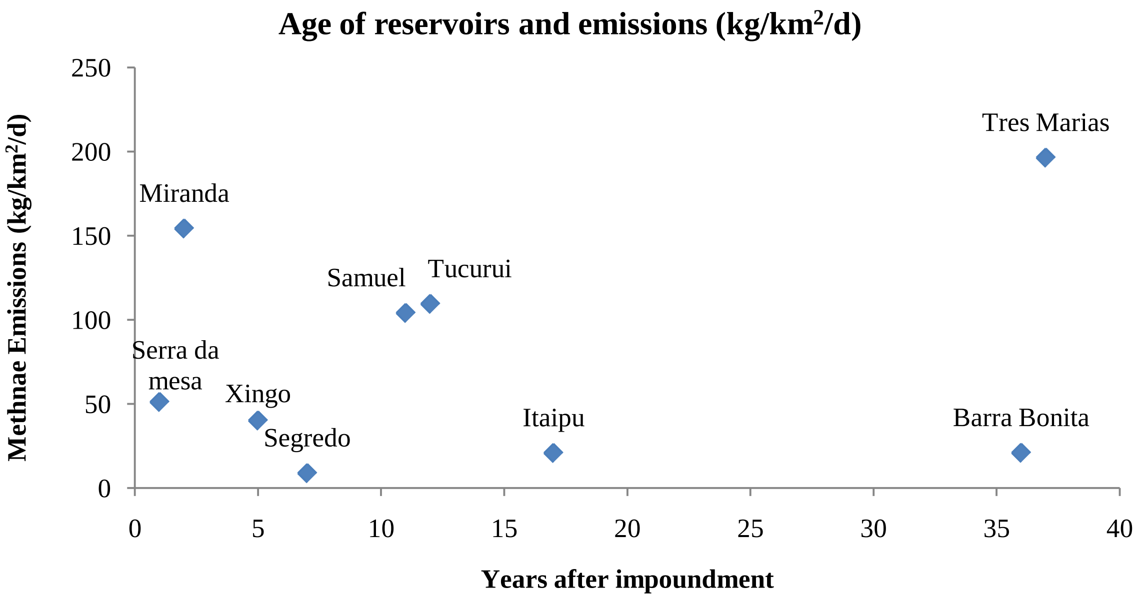

Figure 17 methane emissions in kg/km^2/d on the vertical axis and age of reservoirs on the horizontal axis for each of the reservoir

4.3.2.2.4.1.1 Bubbling and diffusion

From the Brazilian reservoirs studied by MCT/COPPE 2002, the reservoir Três Marias 37 years after the impoundment was the only reservoir that had methane emissions originated mainly from bubbling process in the two campaigns. The data (averaged as described in previously in session 4.3.2.2.4) for first and second surveys (taken mainly in 1998 and 1999 respectively) is presented in Figure 18.

The contribution of the methane emissions through the diffusion processes for the Três Marias reservoir was 16% and 12% on the first and second campaign respectively. For the remaining reservoirs studied diffusion contribution was greater than 60% from the average of the two surveys.

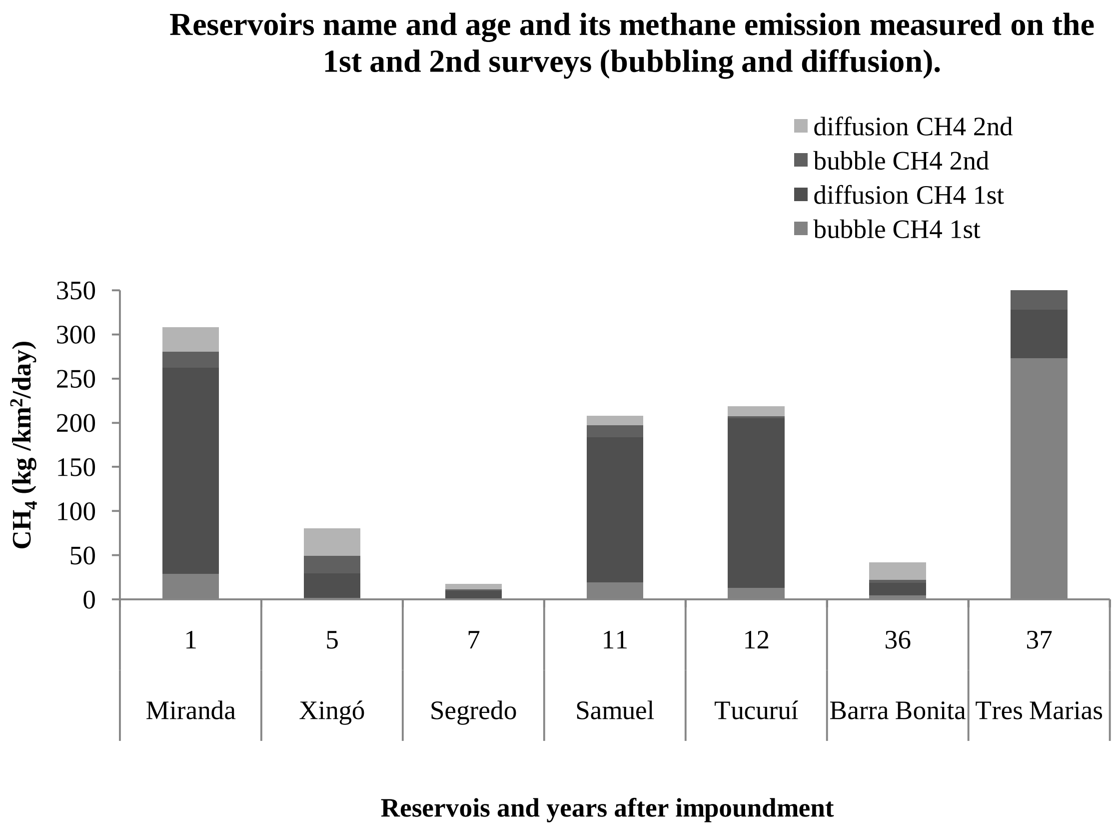

Figure 18 methane emissions of bubbling and diffusion on the first and second surveys of 7 reservoirs in kg/km²/day, based on the data of MCT/COPPE (2002) , on the horizontal axis the name and age of reservoir.

The study from MCT/COPPE concluded that emissions from bubbles had a relation with the age of reservoir except from one reservoir (namely Três Marias), while for diffusion emissions some older reservoirs presented higher emissions than recently impounded ones.

As well as the reservoir of Gatun Lake in Panamá (presented in session 4.3.2.2.1.1 - Bubbling) the Três Marias called attention for its high methane emission despite its age. The methane emission due to bubbling from both reservoirs accounted for most of emissions. This last observation is aligned with the predictions made for Petit Saut, which expected the bubbling process is to play a major role in older reservoirs. Despite there were very limited measurements, most of the Brazilian reservoirs had on the later measurements a higher contribution from bubbling.

4.3.2.2.4.1.2 Degassing

Philip Fearnside researches the Amazonian environment and supports the argument that a quick drop in the pressure which occurs in the spillways lead to a great emission (Fearnise 2004). In his work, in page 29, Fearnside (2004) assumes that 60% of the methane will be released and justify this values an estimation since the reservoirs lack the aerating device from Petit Saut (which makes degassing contribute to more than 80% of the methane emissions of the French Guiana reservoir).

Despite is now accepted that degassing at the dam can also be a GHG emission source, McCulle (2006) whom wrote about the overall discussion on the subject, remarks that the actual scale of degassing emissions is hotly contested.

4.3.2.2.4.1.3 Time gap of campaigns measurements
As the study from Galy-Lacaux et al. (1999) pointed that the emissions may vary depending on the season (previously discussed in session 4.3.2.2.2) one factor which called the attention on the research of MCT/COPPE (2002) was data collection periodicity.

The starting point was to verify if the measurements were taken in alternate season (e.g. rain and dry season). The two campaigns measurements of Três Marias, Tucuruí and Samuel (37, 14 and 3 years of impoundment respectively) were taken in with a gap of one year, i.e. the measurements were taken in the same season one year later. Those 3 reservoirs presented very high emissions of methane in $kg/km^2/d$.

According to Fearnside (1997) there is a natural phenomena which occurs in the western part of Brazilian Amazonia, which are the cold spells (*friagens*) which cause breakage of the thermocline and complete mixing of the water column, bringing anoxic CH_4 rich water to the surface where a pulse of emissions can occur. This does not affect the location of Tucuruí in eastern Amazonia (Fearnside 1997), but is relevant for the Samuel dam in western Amazonia and the effect is not likely to be captured in short measurement surveys (Fearnise 2004)

4.3.2.2.4.1.4 Depth variations of reservoir
One of the possible justifications for the high emissions from the Três Marias reservoir can be the level of the lake; this causes a periodic flooding and exposition of large area of soil leading high subsequent emissions of methane. The report from MCT/COPPE (2002), on page 71, also attributed high emissions of the Três Marias and Samuel reservoir to the quick variation on the level of the reservoirs.

4.3.2.2.4.2 N_20 emissions
Despite nitrous oxide (N_2O) is a powerful greenhouse gas, being almost 300 times more potent than CO_2, formed by the bacterial breakdown of nitrogen, there have been only a handful of measurements quantifying nitrous oxide fluxes from reservoirs (International-Rivers 2008). Emissions might significant for at least some tropical reservoirs (Guérin, Abril et al. 2008). More studies are imperative to better quantify its emissions (International-Rivers 2008).

4.3.3 Other indentified impacts (Fearnside 2004)
Another impacts indentified by Fearnside (2004) of hydroelectric dams in the Amazon is release of mercury (Hg) of soil in its toxic form (methyl mercury). While the gold mining is not a problem the water basin where Samuel reservoir is located, the land occupied by reservoir was found to contain higher level of mercury than the accepted. The ancient soils of Amazonia are gradually accumulating mercury deposition in the rain and particles from volcanic eruptions and other sources. Anoxic conditions at the bottom of the reservoir favors the reaction in which mercury is brought to its toxic form.

4.4 Parameters alteration
The following sections aim to investigate based on the research findings what are the implication of the alterations of parameters to life cycle inventory and consequently to the final result of the life cycle assessment.

4.4.1 Hydro power parameters alteration
The aspects indentified to be possibly different from the existing inventories in ecoinvent were the increased installed capacity, the CO_2 type and a comparison of the worse, best and average case for methane emissions from the reservoirs.

4.4.1.1 The increased installed capacity

Information on hydropower plants is mostly presented in installed capacity (in MW). As commonly the functional unit for electricity is kWh, it is necessary to establish the usage factor to relate installed capacity and electricity generation. As explained in footnote[7] (page 31), dos Santos et.al (2006) assumed 60% of usage factor. This value is very similar to the factor obtained by the ecoinvent report, which calculated a very similar value taking the installed capacity and the total generation of the country in year 2005.

Installed capacity and electricity generation is not constant over time; a straight forward example is the hydropower plant Itaipú (Figure 19). This occurs due to turbines been added along the years, enhancing the installed capacity.

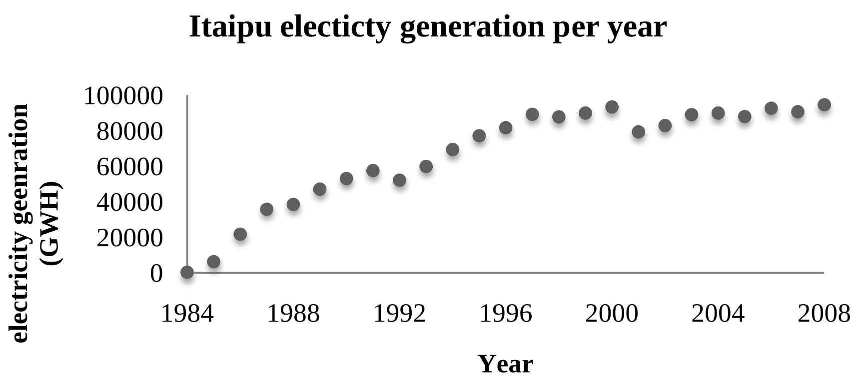

Figure 19 Electricity generation by the hydropower plant Itaipú over time (ITAIPU 2009).

When developing a LCA, in general, the functional unit of electricity is kWh (or equivalent), therefore the amount of electricity generated (and of installed capacity) will influence the inventory once emissions will be divided by total electricity generated on the same time frame.

From the nine hydro power plants investigated (dos Santos et al. 2006) and currently used by ecoinvent, two had its installed capacity significantly expanded. With the accomplishment of its second phase, the installed capacity of Tucuruí was increased from 4000MW to 8370 MW, Miranda expanded to 408MW, and Itaipú from 12600MW to 14000 MW.

The Figure 20, based on the emissions data from dos Santos et al.(2006) and using the updated valued for installed capacity, presents the values of area, electricity generation, methane and carbon dioxide emissions (referred as emissions index[6]). The figure is an attempt to identify possible correlations between characteristics of the reservoir (e.g. area, energy density) to emissions of methane or carbon dioxide.

[6] Emissions indexes were calculated based on: spatial extrapolation (since the measurements were taken on certain points of the reservoir) and temporal extrapolation (fluxes were measured in two surveys).

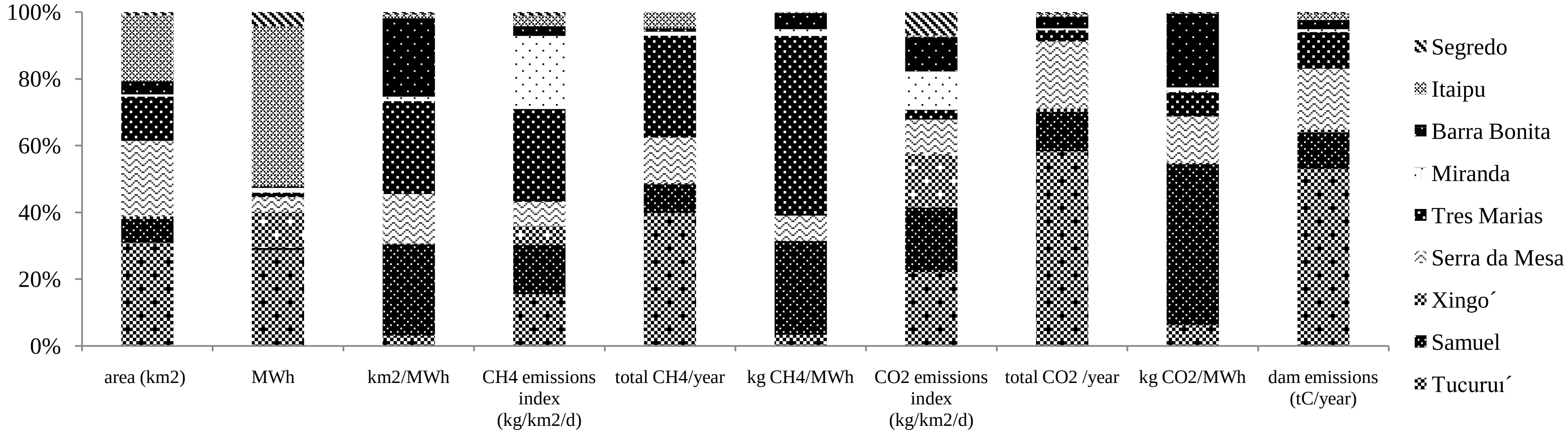

Figure 20 Characteristics and emissions of the dams adapted from dos Santos et al. (2006), showing the contribution of each dam.

The values for reservoirs characteristics (area, electricity generation[7], energy density and emissions[8]), which were used to make the Figure 20 were adapted from Santos et al. (2006) and are presented in Table 4. Remark that the emissions published by the authors were calculated from an extrapolation of the measurements taken at certain points of the reservoirs and were presented in emission per unit of area (as explained in session 4.3.2.2.4).

Table 4 reservoirs characteristics and methane emissions, adapted from dos Santos (2006), where emission index is the methane emissions per area per day.

Hydropower plant name	area (km^2)	Annual electricity generation (MWh)	Area requirement (km^2/MWh)	CH_4 emissions index (kg/km^2/d)	Annual emissions CH_4 kg/year	Emission per unit of electricity (CH_4 kg /MWh)
Tucuruı´	2430	4,40E+07	5,52E-05	109,4	9,70E+07	2,21
Samuel	559	1,10E+06	4,92E-04	104	2,12E+07	18,69
Xingo´	60	1,70E+07	3,60E-06	40,1	8,78E+05	0,05
Serra da Mesa	1784	6,70E+06	2,66E-04	51,1	3,33E+07	4,97
Três Marias	1040	2,10E+06	5,00E-04	196,3	7,45E+07	35,8
Miranda	51	2,10E+06	2,36E-05	154,2	2,85E+06	1,33
Barra Bonita	312	7,40E+05	4,22E-04	20,9	2,38E+06	3,22
Itaipu	1549	7,40E+07	2,11E-05	20,8	1,18E+07	0,16

It is possible to identify that the reservoirs Miranda, Segredo, Itaipú and Xingó have a greater energy generation per km^2, while the reservoirs with high area per electricity unit (Barra Bonita, Três Marias, Serra da Mesa and Samuel) are the ones that most account for emissions of either CO_2 or CH_4 per electricity unit. Also it is possible to identify that reservoirs with large impounded area (exception of Itaipú) also present a great emissions of carbon per year.

The weighted average of the emissions of the hydropower plants used by ecoinvent (2004 data) and the emissions calculated using the current installed capacity (updated) is shown in Table 5.

Table 5 comparison of emissions of carbon dioxide and methane emissions from reservoirs per electricity unit for the current installed capacity (2007) and used in ecoinvent 2004.

Dataset	kg CO_2/kWh	kg CH_4/kWh
Ecoinvent data with installed capacity updated	0,084	0,00158
Ecoinvent, 2004 original data	0,104	0,00197

[7] The electricity generation was calculated assuming a usage factor of 60% during a period of one year: $\text{electricity generation (MWh)} = \text{installed capacity(MW)} \times 0{,}6 \times 8760\text{(h)}$

[8] Emissions per electricity unit where calculated by: $\frac{\text{kg}(CH_4)}{\text{MWh}} = \frac{\text{emissions index}\left(\frac{\text{kg}}{\text{km}^2.\ \text{d}}\right).\text{area}(\text{km}^2).365\ \text{days}}{\text{electricity generation (MWh)}}$

For the LCIA, eco-indicator 99 H/A, is presented on Figure 22. It presents the impact of climate change and respiration of organics, for Brazilian hydro power generation of the two data sets, currently used by ecoinvent, with methane and carbon dioxide altered according to the values presented on Table 5. This new hydropower will be called ‘production mix BR - UPDATED’.

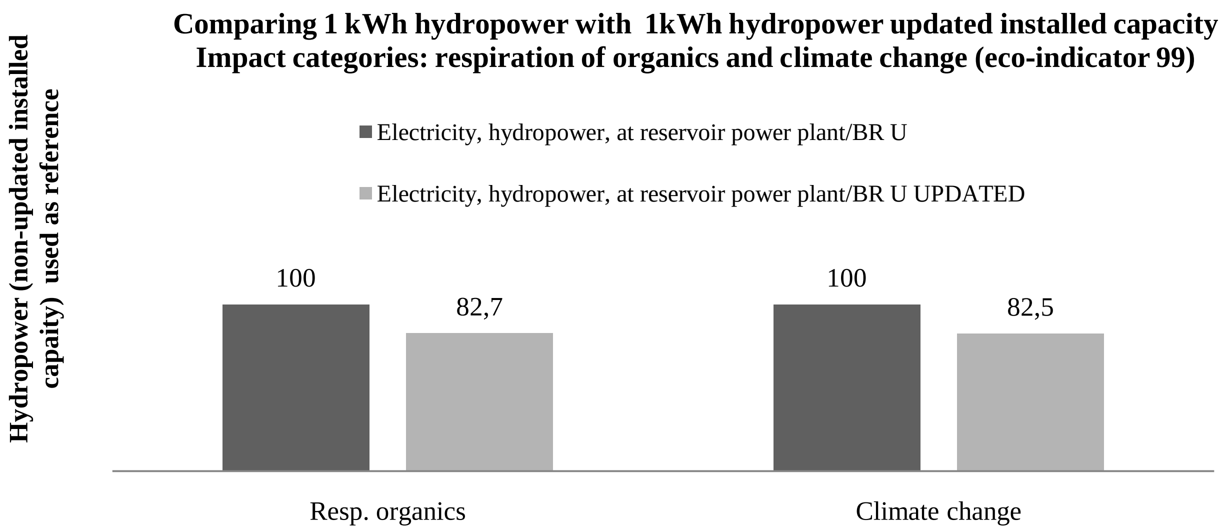

Figure 21 Comparison of the updated values of installed capacity of 1kWh of the Brazilian hydropower impact to the categories of resp. organics and climate change. Graph normalized to the hydropower, at reservoir power plant /BR U

The comparison of the mix 2007 and the mix using the hydropower with the altered values of methane and carbon dioxide is presented in Figure 22.

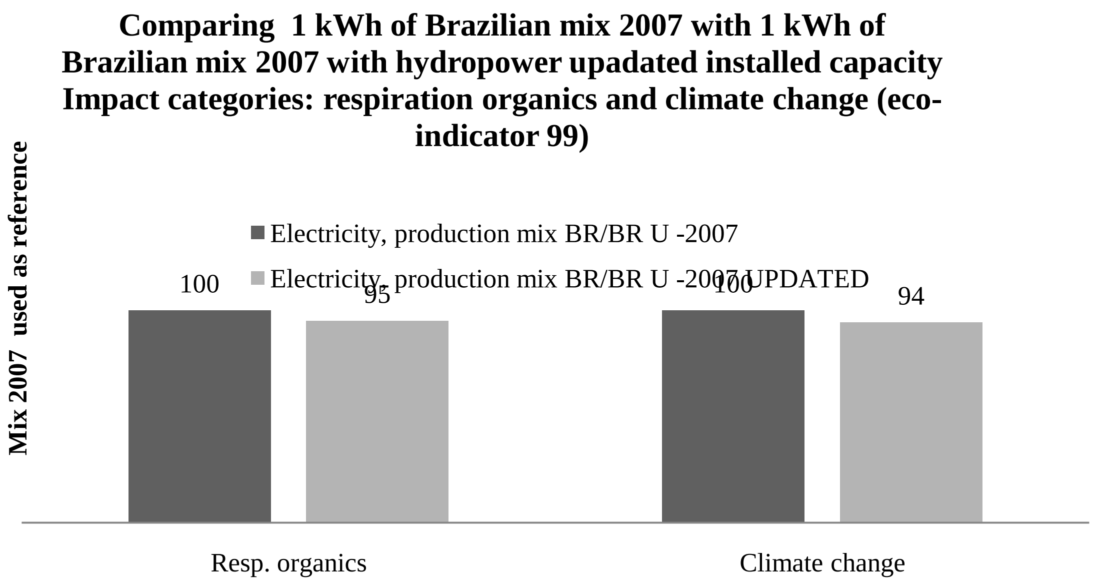

Figure 22 two categories of the impact assessment of 1kWh of the electricity mix, eco-indicator 99 H/A, which presented differences when modifying the CO_2 and CH_4 emissions from reservoirs the values according with the increased installed capacity. Graph uses electricity 2007 as reference.

4.4.2 Changing the CO_2 type

To verify the differences in the final assessment if CO_2 was considered biogenic, the updated dataset changed from ‘carbon dioxide, land transformation’ to ‘carbon dioxide, biogenic’ (Figure 23).

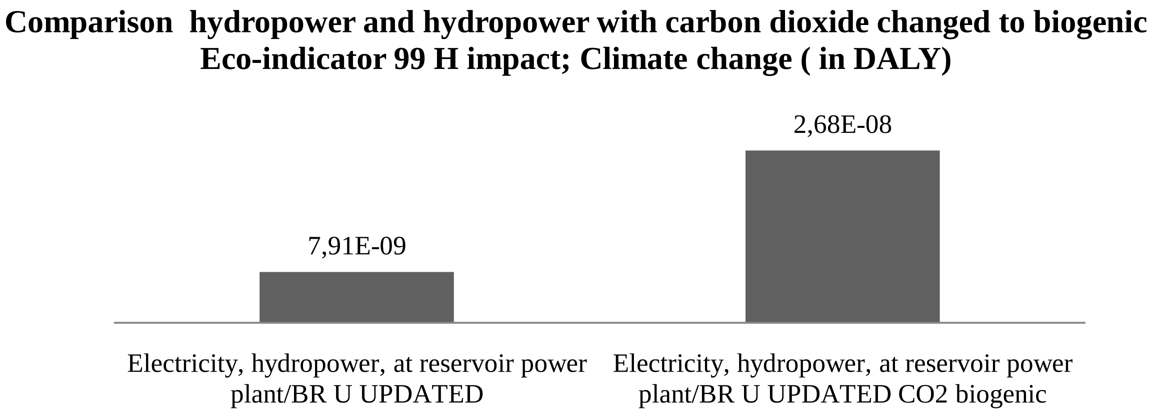

Figure 23 Impact of climate change of 1kWh of electricity generation from hydropower reservoirs if CO_2 is altered to CO_2 biogenic (method eco-indicator 99H) .

4.4.3 Best, average and worse case of methane emissions from reservoirs

To verify the implications of using worse case, best case or a weighted average for the methane emission, the emissions (per unit of electricity produced[9]) calculated from the data of 9 reservoirs published by MCT/COPPE (2001) were arranged into 95% confidence interval and compared according to the impact on climate change of lower limit, upper limit and average (Figure 24).

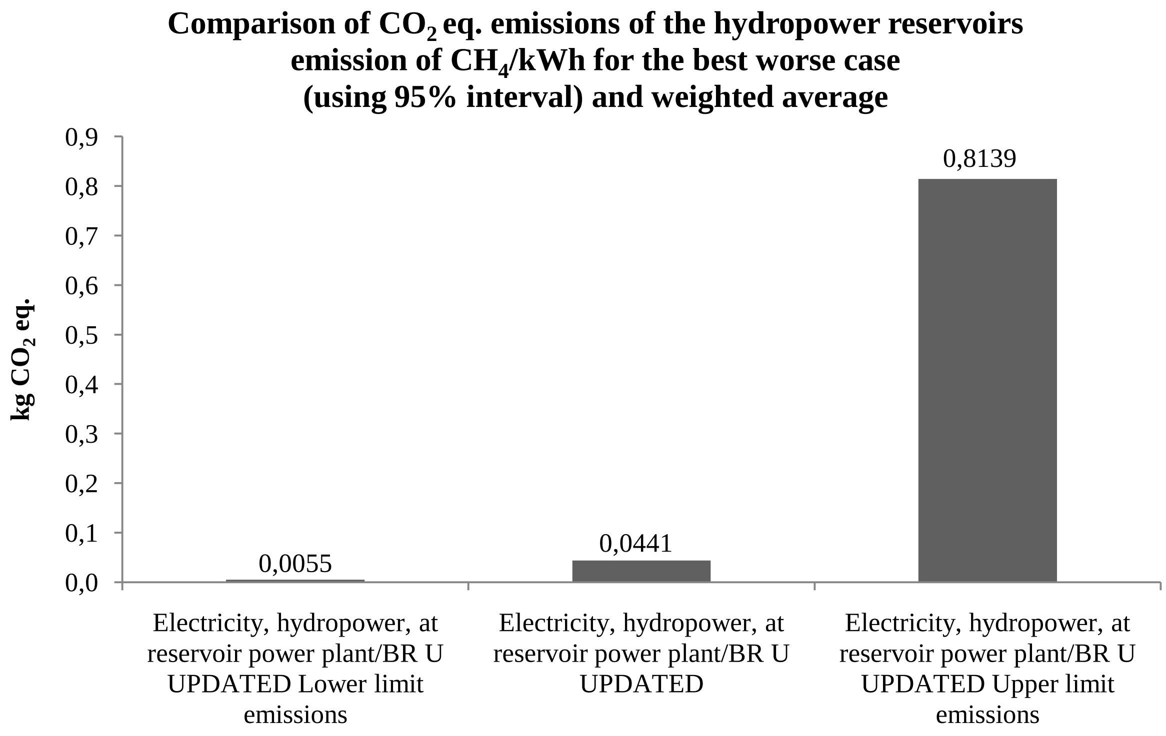

Figure 24 comparison of the climate change impact of the best case, weighted average and worse case of the 1kWh generation of electricty from hydropower.

[9] Calculated by: $\text{emission per electricty unit} = \frac{\text{emission index}\left(\frac{kg}{km2*d}\right)*\text{area of reservoir(km2)}*\text{days}}{\text{electricity produced}}$

From this result is possible to identify that the reservoirs with high emissions per unit of electricity produced also have generate few electricity (explaining the fact that weighted average emissions being low).

4.4.4 Sugar cane derived electricity

The following sessions will investigate the bagasse derived electricity environmental impacts; looking at the fertilizers impacts and alteration of the current inventory eliminating the pesticide aldrin.

4.4.4.1 Sugar cane production impacts

The analysis of the bagasse derived electricity pointed that the only processes which contributes to the impact category 'carcinogens' (eco-indicator 99 H/A) is diammoniun phosphate (as P_2O_5).

4.4.4.1.1 Phosphorous fertilizer

System description of diammoniun phosphate, summarized from (Nemecek and Kägi 2007)

Functional unit

1kg of diammoniun phosphate as P_2O_5.

Included processes

The unit process inventory takes into account the production of single superphosphate from sulphuric acid and rock phosphate. Transports of raw materials and intermediate products to the fertilizer plant were included as well as the transport of the fertilizer product from the factory to the regional department store. Production and waste treatment of catalysts, coating and packaging of the final fertilizer products were not included. Infrastructure was included by means of a proxy module.

Geography

According to the reference of this inventory, the European average is derived from mean values of several fertilizer plants within Europe. The production of raw materials and/or intermediates outside Europe was taken into account by considering the production technology in the respective country and the relative import shares.

Technology

Production inventory was derived from detailed literature studies and specifications from the manufacturer, relevant for the European production.

The substance with the greatest contribution to the carcinogens category is arsenic. Arsenic is present in phosphate fertilizers (as P_2O_5). In order to verify if other phosphorous fertilizers have smaller environmental impact a comparison of the 3 types of phosphate fertilizer from the ecoinvent, with the same system boundaries is presented in Figure 25.

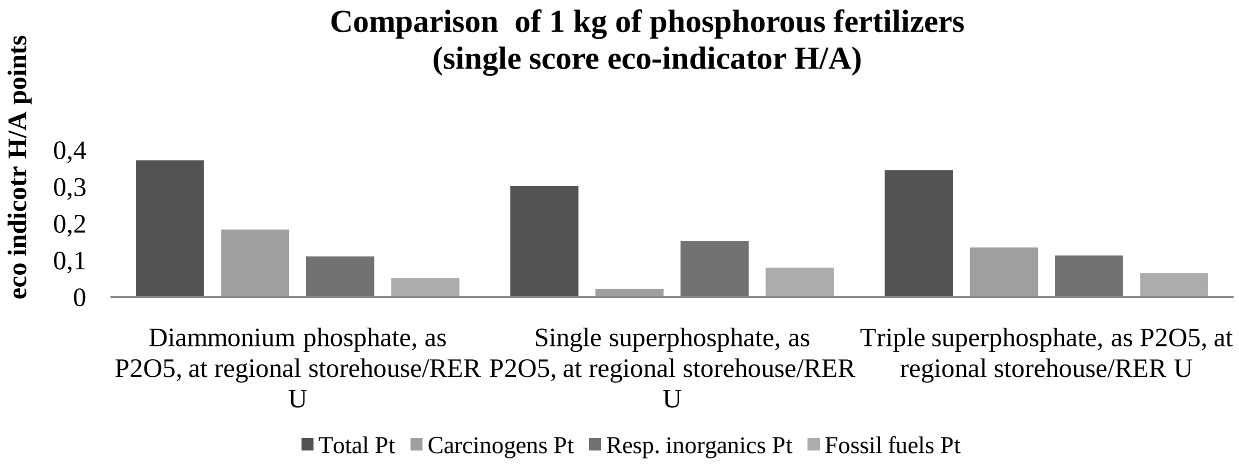

Figure 25 comparison of 1 kg of 3 types of phosphate and its environmental impacts (eco-indicator 99 H/A).

Despite the comparison shows substantial difference on the impact for different categories across the different types of fertilizer the overall all impact (weighed results) does not significantly differ from the type of fertilizer.

4.4.4.1.1.1 Depletion of phosphorous reserves

Phosphorous is an essential mineral with depleted reserves, some author suggest that the reserves are expected to last about 100 years (Smil 2000).

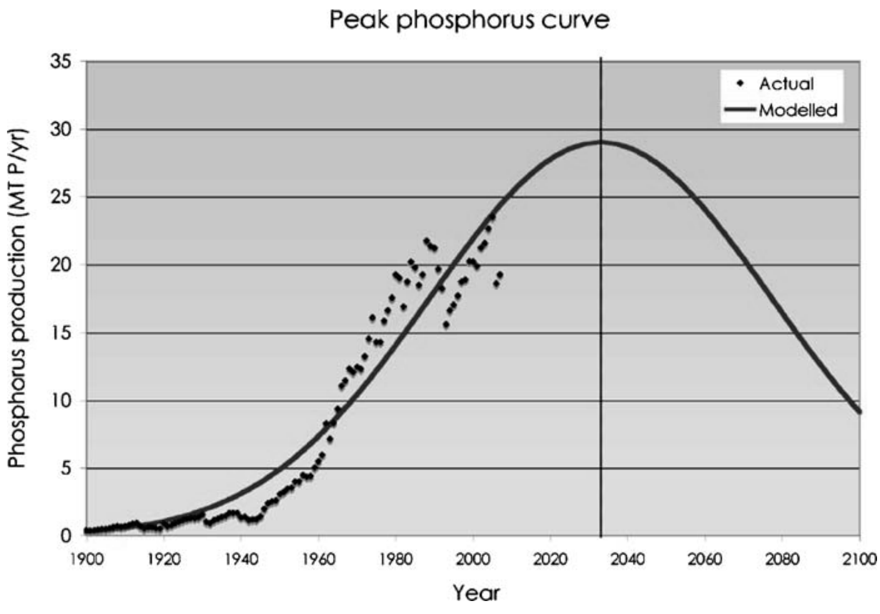

Figure 26 Projected consumption of phosphorous indicate a peak on the phosphorus curve, illustrating that global phosphorus reserves are likely to peak and suffering a significant reduction afterwards (Cordell, Drangert et al. 2009).

While the impact assessment methods eco-indicator 99 H/A as well as e.g. impact assessment 2002+, do not have characterization factors for resource depletion of phosphate, EPS 2000 accounts 4,47 ELU/kg of ‘phosphorous, in ground’.

However, due to the small participation on the electricity mix and the characterization factors of the other electricity mix, and the burden on depletion of reserves of natural gas and diesel, the bagasse contribution to this category turn out not to have a great contribution when compared to all the other electricity types of the Brazilian mix.

4.4.4.1.2 Aldrin

As expressed in session 4.3.1, the pesticide aldrin is no longer in use for sugar cane production. This session investigate the consequences of the exclusion of this input in the inventory of the sugar cane production.

The LCA-tox calculator(IERE 2009), is a toxicity indicator application that measures the toxicity of emissions based on their aquatic toxicity, persistence and bioaccumulation. The LCA-tox is a life cycle impact indicator that uses the same approach as USE-tox. The USE-tox model was initiated by the United Nations Environment Program (UNEP) and SETAC Life Cycle Initiative (Rosenbaum, Bachmann et al. 2008). The LCA-tox calculator does present values for aldrin.

If on one hand, the eco-indicator 99H/A does not present a characterization factor for the substance aldrin, the elimination of this input will not have a difference in the outcome of the impact assessment; on the other hand EPS 2000 does contain characterization factor for aldrin. Therefore the impact assessment comparing the bagasse derived electricity with sugar cane at farm been produced with and without the usage of aldrin is presented in Figure 27.

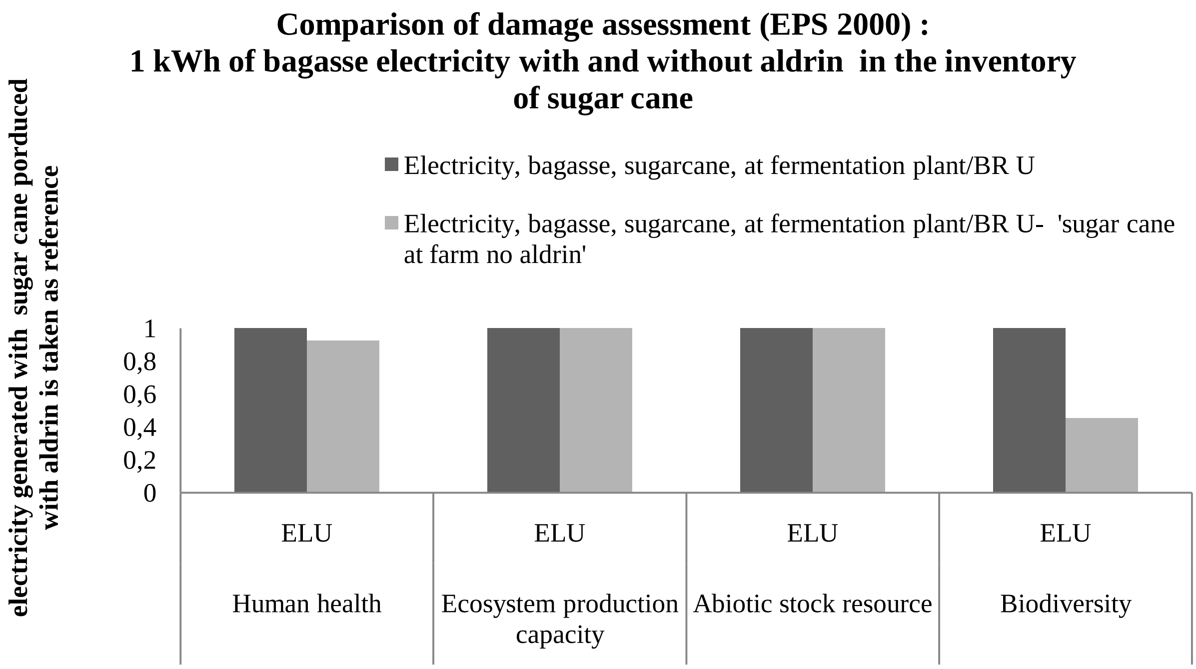

Figure 27 comparison of damage assessment of 1 kWh of bagasse electricity production normalized to the ecoinvent process with the aldrin in the inventory of sugar cane. Impact assessment method EPS 2000.

A similar analyzes is carried out for the Brazilian mix, i.e. comparing the Brazilian mix 2007-updated altering the inventory of sugar cane at farm with aldrin (as presented in the current inventory) and without aldrin (Figure 28).

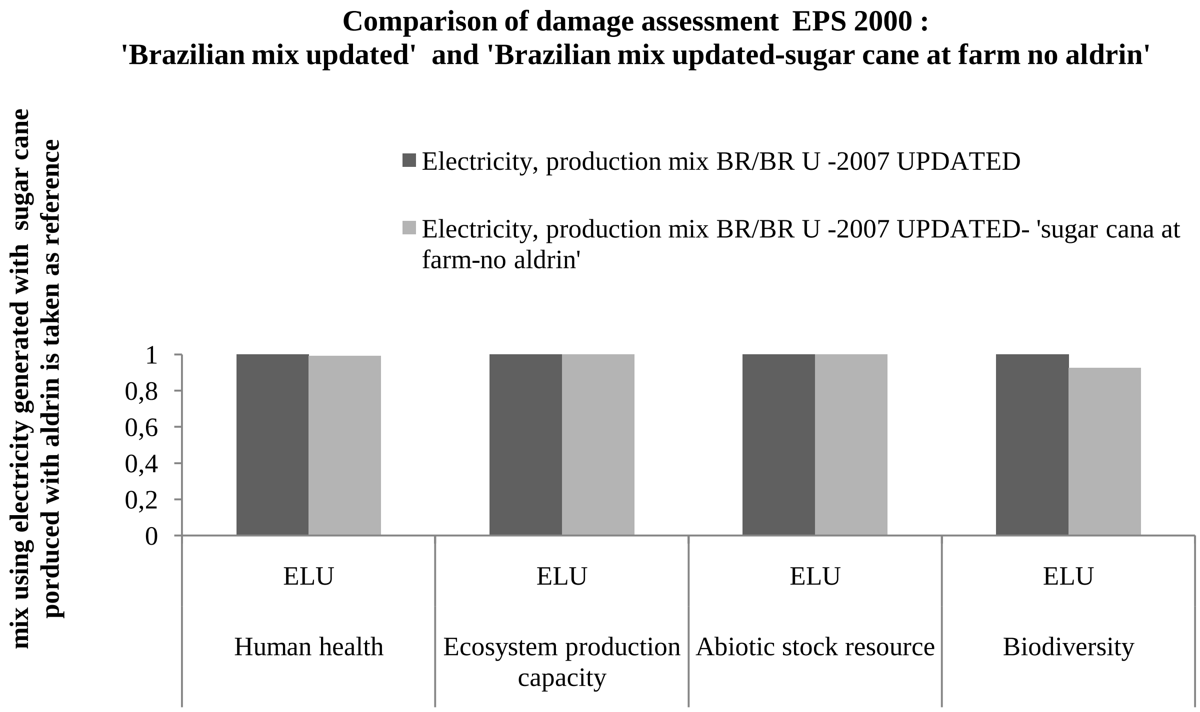

Figure 28 comparison of damage assessment of 1 kWh of the Brazilian mix 2007 with updated installed capacity and Brazilian mix updated with the aldrin elimination on the inventory of sugar cane, according to the method EPS 2000.

4.4.5 Hard coal

The Brazilian electricity mix available in the ecoinvent uses the UCTE hard coal derived electricity mix in the ecoinvent. The UCTE hard coal derived electricity system description according to (Dones, Bauer et al. 2007):

Functional unit

1 kWh in the power plant.

Included processes

The module represents the electricity output at busbar produced by the average hard coal power plant in UCTE in year 2000.

The average for UCTE hard coal power plant mix is calculated using country-specific average units weighted by the share of net electricity output. The countries are those composing UCTE in year 2000, consistently with the UCTE electricity mix.

Geography

UCTE in year 2000 which is Austria, Belgium, Germany, Spain, France, Italy, Hungary, Netherlands and Portugal.

Technology

Average installed technology.

This session aim is to evaluate which are the implications of altering the type of coal mining since the Brazilian mining is exclusively open mine. The processes included in the generation of hard coal electricity are represented in Figure 29.

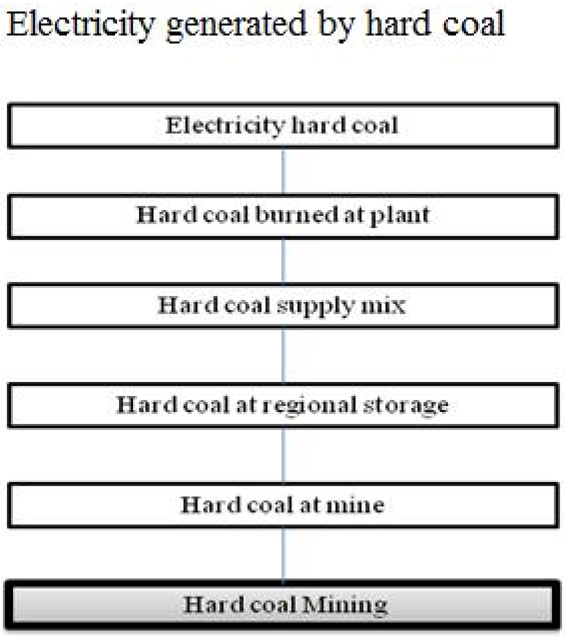

Figure 29 process included in the hard coal electricity production of the countries of the UCTE.

On the available version of ecoinvent database, there was no hard coal electricity mix produced exclusively with coal from open case mine. The hard coal minning is the only process which has been altered to open mine only in order to better represent the Brazilian hard coal electricity production.

The open cast mine of hard coal is used into the supply mix of the following regions: Australia, South Africa, Latin America and Caribbean (RLA), Russian Federation, Asia and China and North America. The hard coal supplied for the 'hard coal at mine' for RLA only had input from 'open cast mine', is the only supply mix composed exclusively from open mined hard coal.

The biggest mine in Brazil, called Candiota is a open cast mine located in the South region.Candiota is the largest mine and it accounts for about 40% of the Brazilian coal (Gomes, Cruz et al. 2003). Other significant mines are also open cast, making it reasonable to assume the Brazilian coal is extracted exclusively from open mine.

The first impact assessment is made to evaluate if there are differences on the type of mining: underground or open mine.

The following description suits both open cast mine and the underground systems in ecoinvent (Dones et al. 2007).

Functional unit

1 hard coal mining plant.

Included processes

This module includes an estimation of the most important construction materials and energy use for a model mine. The land use for the infrastructure is also included. The machinery used for mining operation has been included in this module.

Information was available only for a few mines. The module has to be considered as a first approximation and may not reflect specific mines. Lifetime is assumed to be 30 years to take into account the lifetime of machinery.

For defining the total production of a unit model mine, one million ton per year has been estimated as an average worldwide (excluding small mines in China).

The estimation includes open pit as well as underground mines. Therefore the total lifetime production of 30 million tones shall be considered as a normalization factor more than an actual average value for the real mines. Explosives are assumed to be used only during operation.

Geography

Average European conditions.

The comparison of the two types in overall point for eco-indicator 99H/A is presented in Figure 30.

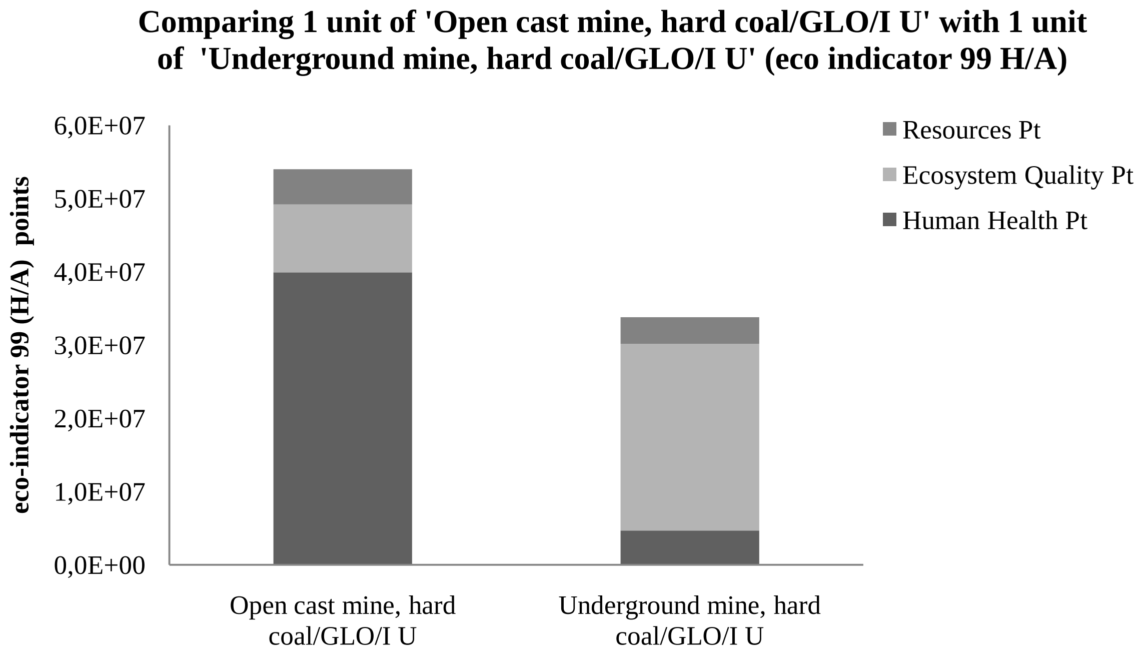

Figure 30 comparing one unit of open cast mine and one unit of underground mine for hard coal under the eco-indicator 99 H/A.

Thus, the coal input of all the hard coal electricity mixes composing the UCTE in ecoinvent, were modified to 'hard coal at mine/RLA' evaluating what are the differences of the change in the mining type, maintaining all the other parameters as it is on the UCTE hard coal mix; Figure 31

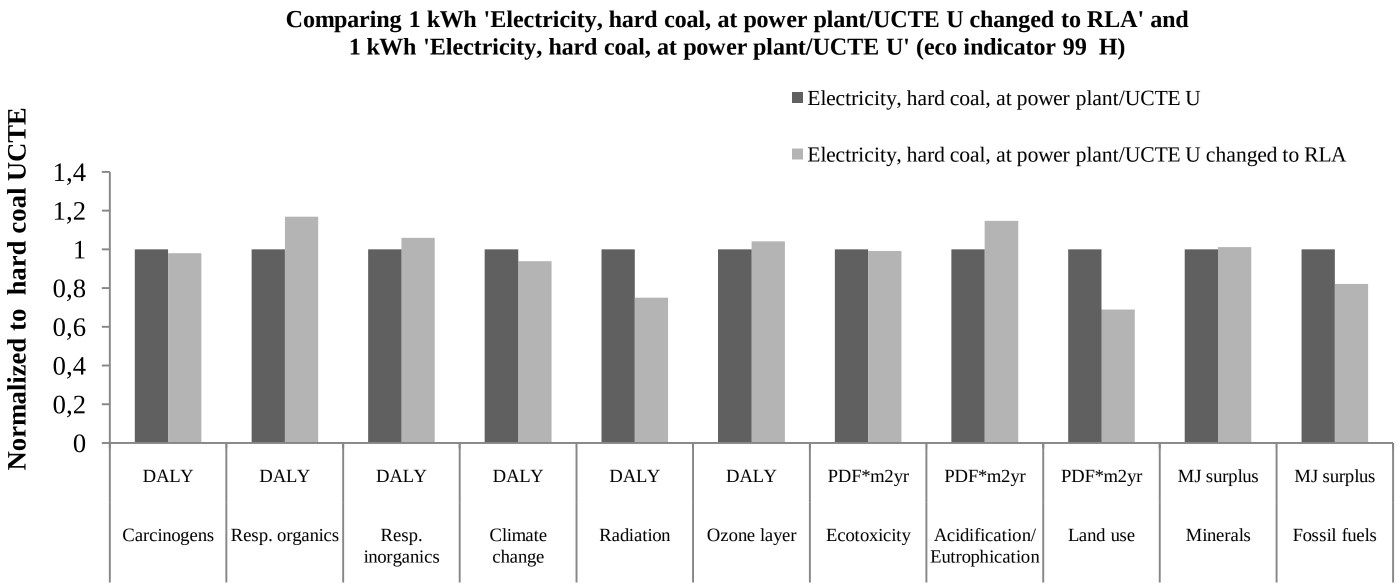

Figure 31 comparing 1kWh of hard coal electricity generation method eco indicator 99H/A, for the UCTE mix and UCTE mix with hard coal exclusively from open cast mines named RLA, per impact category. The impact is normalized to UCTE mix.

The weighted result from eco-indicator 99H/A are presented in Table 6, showing that when using the single score approach, the difference of hard coal mined from underground or open mine maintaining the remaining conditions of the UCTE hard coal derived electricity, the overall impact have a only a slight difference.

Table 6 Single score points (method eco indicator 99H/A), results comparing 1kWh of hard coal electricity generated with hard coal from underground and open cast mine.

Electricity, hard coal	Weighted impact (single score) Total (Pt)
Open cast mine (RLA)	0,0271
Underground mine (UCTE)	0,0275

The impact assessment of the Brazilian mix, as used in ecoinvent and a new mix altering the hard coal input for the new process hard coal changed to RLA (i.e. hard coal being exclusively mined from open mine), for the methods eco-indicator 99 H/A the mining type alteration did not present variation on the impact result.

5 Discussion

As stated on the session 2, Research objective, the objective of the study was to:

1. identify which are the most relevant aspect*s* related to the Brazilian electricity production environmental impacts, for which aspects adaptation would be required, and uncertainties and difficulties to perform such adaptation,
2. to evaluate how much adaptation of current inventories would be necessary in order to obtain sound data for LCA,
3. and on a more general level, if is possible to obtain a recommendation for new datasets analyzing the weakness and strengths of different approaches when carrying out an inventory adaptation.

The three impact assessment methods used point out different electricity types as being more critical from the environmental point of view. Hydro power is the greatest electricity source in Brazil and played an important role in many categories in all impact assessment methods.

5.1 Relevant aspects

In regards to the relevant aspects of electricity generation, it was possible to indentify that hydro-power played a significant role according to all the impact methods, if in the one hand this could be expected since the electricity has such high participation on the mix, on the other hand hydro several times is perceived as an emission-free electricity source. The most significant aspect is the methane emissions from the reservoirs, having a substantial difference across reservoir and countries. Great difficulty is faced in what concerns values of methane emission, since data is limited and methodology on accounting those emissions still under discussion.

Also, a significant input for the generation of bagasse derived energy is fertilizers containing carcinogenic substances. It was not possible to identify any aspect which could be altered from an inventory point of view when considering Brazil usage of the fertilizer. Alternative types of the similar fertilizers were investigated, despite they presented different impacts across categories, the overall impact to human health remained fairly the same. On the inventory level, the current dataset investigated has input of substances for the sugar cane production (namely aldrin) which have its use prohibited for almost 25 years in Brazil.

The EPS method does have a characterization factor for this substance, therefore assuming that its use is no longer in practice, the input was eliminated in the inventory, but the overall impact of the mix did not have a significant alteration. The result is in line with the expectation since bagasse did not contribute substantially in the overall impact for this method.

Mining is a relevant impact on the life cycle of the hard coal electricity. As coal mining in Brazil is open mine, and the comparative analysis of underground and open cast mine, showed difference in the impact (within categories and overall impact) this parameter was changed maintaining all the other characteristics of the system. The overall impact of electricity produced with hard coal open mine was the same as hard coal from underground mine.

The diagram presented in Figure 32 was drawn to illustrate a summary of the parameters altered.

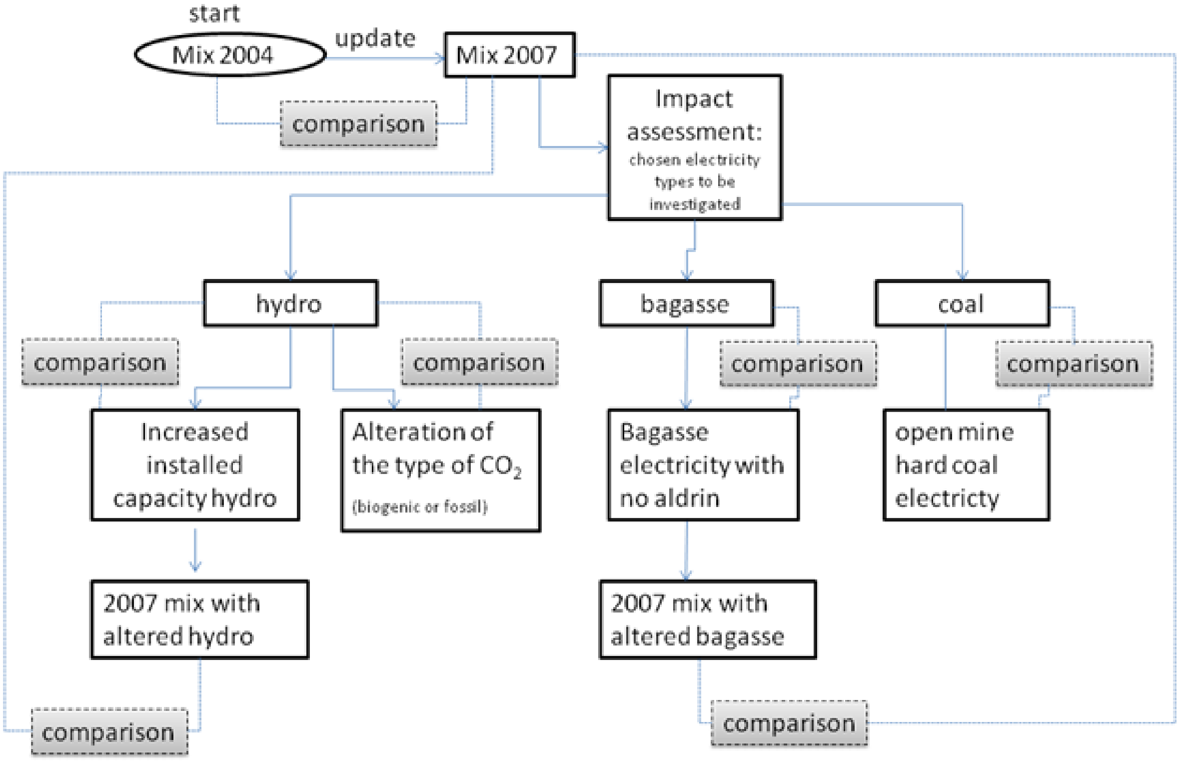

Figure 32 summary of the alterations and comparisons carried out in this work

5.2 Adaptation

As an attempt to fulfill the second goal the Table 7 parameters identified as in need of adaptation on the inventory or assessment level was drawn, pointing out the aspects and impacts which were identified to be relevant for making LCA of electricity generation more site specific.

Table 7 parameters identified as in need of adaptation on the inventory or assessment level, session where the problem is presented and comments.

Parameter	Session	Process	Problem	Comments
Phosforous fertilizer	4.4.4.1.1.1	sugar cane at farm	no charaterization factor	No characterization factor for eco-indicator 99 (H);
Aldrin	4.4.4.1.2	sugar cane at farm	outdated inventory	The inclusion of this input have a significant on Biodiversity (EPS 2000) when analyzing the bagasse derived electricity
N_2O, emissions	4.3.2.2.4.2	hydropower reservoir	lack of inventory	Studies suggest that this could be relevant GHG emission source but surveys are still lacking
Mercury, from soils	4.3.3	hydropower reservoir	lack of inventory	extremely difficult to quantify; few studies; difficult to obtain a number for the 'mercury emissions from soil accumulated in the reservoir'
Mercury, from soils	-	hydropower reservoir	lack of characterization factor	Another difficulty is that there is not characterization factor for this type of emissions
Methane	4.3.2.2	hydropower reservoir	very few data and lack of consensus	few reservoirs emissions have been investigated
Methane	4.4.3	hydropower reservoir	differences across reservoirs	there are significant differences across reservoirs in Brazil

Alteration of parameters of the electricity types into the grid did present in some cases variation in at least some impact categories, but not for all of them. In the overall impact sometimes it did not present a significant variation.

5.2.1 Methane emissions data availability

Despite there are data for Brazilian reservoirs emissions is difficult to bring into a comparison with other reservoirs or achieve a justifiable average value.

Brazilian methane emissions inventories usually do not take for granted the natural emission, the decay with time and the values are considered per unit of electricity produced (kWh). Natural emissions are relevant to be included as well as the decay with time, at least for some reservoirs. Also assuming an efficiency factor (how many hours of electricity will be produced by the power plants) is also another factor that may be relevant in case of studying the impact per kWh, which is frequently the case in LCA.

The use of the current values of methane emissions must be carefully reviewed. In case the GHG emissions are overestimated, any product's LCA carried out using that data will have an extreme disadvantage with regards to other country mixes or maybe leading to the choice of a, in reality, much more impacting energy source.

5.2.2 Phosphate scarcity

Phosphate is an essential mineral and reserves are considered to be depleted. From the two methods studied here which have categories for resource depletion only one had characterization factor for this mineral consumption (obviously IPCC does not have a characterization factor, since is a single use impact assessment). In this case adaptation for a sound LCA of bagasse derived electricity could be implemented on the impact assessment level, i.e. inclusion of characterization factor for phosphorous for impact assessment methods.

5.2.3 The sugar cane bagasse

As the pesticide aldrin is no longer in use, it is reasonable to recommend that this substance should not be included in the life cycle of sugar cane production and suggests that more careful look on up to date values, and for even of other substances could be valuable.

Change on the harvest system is expected to alter inputs and outputs of the sugar cane farming. Therefore it is fundamental to assess the changes which will come once the current inputs are likely to go out of date due to this change in the harvesting system.

5.3 Recommendation

If in one hand the approach of adapting existing inventories can be useful in order to identify the hot spots of a different mix of electricity within the existing impact assessment methods. On the other hand is remarkable that the impact of methane emissions from tropical reservoirs, as well as the carcinogen impact from bagasse derived electricity, would probably be difficult to identify without having specific data. Therefore these two aspects support local data collection.

Simply looking at hydropower and agricultural products it is easy to identify that land use must be a consideration, but as showed in the comparison of different hydropower plants, the energy density of the reservoirs have a considerable variation among them. Therefore suggesting that for electricity production from hydropower the energy density is one of the far most relevant factors.

While for bagasse derived electricity the results here studied suggests that special attention should be given to the yield and fertilizer used.

From this study the overall recommendation is:

- for the life cycle assessment of agricultural product derived electricity if specific data for fertilizers for the specific inputs are not available, the investigation of soil characteristics considering its phosphorous content or other crops on the same area could be used as an indicator of the phosphorous requirement of the soil, therefore indicating that this electricity type (or agricultural product) will contribute to the carcinogens category.
- for hydropower in tropical areas the assessment of methane emissions is indeed fundamental. Filing up reservoirs without appropriate the removal of living biomass as well the existence of aerating devices can be seen as a red flag to methane generation.

5.4 Discussion of methodology

Analyzing a mix such as the Brazilian where the main source is hydro, followed by fossil sources with impact methods which are developed from and for Europe showed that several impacts are attributed to either fossil sources or emissions leading to the same impact as fossil sources. This result suggest that life cycle impact assessments here investigated give a greater value for impacts derived from fossil sources such as global warming then alteration of entire ecosystems or the depletion of the reserves of essential minerals.

Land transformation carbon does not have a characterization factor for some methods. Assuming that the CO_2 emitted by the reservoirs were and will be up taken by plants, the lack of characterization factor can be a positive aspect once it remains this way neutral. On the other hand if the carbon dioxide emission from the former non flooded soils and biomass is released in higher rate than is up taken global warming impact would be underestimated.

5.5 Reference to the main hypothesis

The principal hypothesis, stated on session 2.2, of this work was that an inventory adaptation approach may hide relevant parameters which can significantly affect the impact assessment once those parameters may not be indentified when analyzed for another region or technology.

It was identified that indeed starting from existing inventories my not identify some parameters which can be specific to the regional system, such as the pesticides of sugar cane, in that case justifying the site specific data collection. On the other hand certain adaptations may not lead to major differences for other impact assessments (such as the type of mining).

5.6 Uncertainties and limitations

The lack of studies of emissions in Brazilian reservoirs is indeed a limitation to sustain estimation for the methane emissions. From research on other reservoirs it is easily understandable that measurements must be taken with several concerns which were not followed in the Brazilian studies from 1998 and 1999. However, given the later development of the science in the field it is reasonable to expect that the future surveys will be more consistent. Also, due to the discussions in the topic concerning reliability and biasness is likely that measurements will be carried out by third parties, making data more trustworthy.

An additional uncertainty in regards to reservoirs emissions is the extrapolation, once measurements are taken at certain points of the reservoir and must be extrapolated for the entire area and considering depth variations since bubbling is depth dependent.

Also in what concerns the data samples and extrapolation for the whole system is important to note that Brazil over 500 reservoirs and the largest survey so far covers 9 reservoirs. Even thought the reservoirs were located different regions of the country and with different age, as certainly an attempt to have a better representativeness, the samples and amount of surveys are clearly limited.

Usage factor and installed capacity played an import role since the emissions are calculated per electricity unit. As showed in this study the increased installed capacity of major hydro power sources had a rather relevant contribution, therefore it can be also expected that the usage factor (here taken as 60%) would have a strong influence on the environmental assessment.

For bagasse electricity generation the variations among sugar cane plantations may not differ among each other since the fields are fairly concentrated in one region. Uncertainties rise when looking at the future and that the harvest system has been changing and this change will modify the inputs of the sugar cane plantation.

The fossil emissions were maintained as the current mix suggested in ecoinvent. Due to the difficulty on gathering data for emission and inputs it is expected that overall emissions of fossil derived energy do not have a great variation. This assumption is considered to be sufficient for an estimation of the impact of the Brazilian grid.

6 Conclusion

From the research findings it is possible to conclude that the main aspects contributing to the impact of electricity production in Brazil which are covered in the current impact methods could need some adaptation and updating. The lack of science and consensus in some areas makes such adaptation more difficult and beyond the scope of this study. The greatest difference seems to come from alteration of characterization factors or usage of worse case emissions. Another problem arises when characterization factors are lacking: clearly the impacts will not appear regardless of the approach (i.e. if it starts from existing inventories or starting the inventory data collection from ground zero).

Even though there is no agreement for the methane emissions for tropical reservoirs, it is certain that these emissions are greater than in boreal or temperate regions. Despite that phosphorous is an essential mineral and that phosphorous fertilizer contains arsenic regardless the region it is produced or used, the input quantities are site and crop specific, especially when looking at the region (e.g. phosphorous rich or poor soil). Under the methods studied, for coal it was clear that alteration of the mining type results in almost no alteration of the impact. When assessing the impact of hydropower, GHG emissions played an important role.

As the Petite Saut reservoir in French Guiana has aerating weirs this can be considered a different technology, it renders the values unsuitable to be used as standard values for tropical reservoirs. On the other hand what can be stated is that even thought the geographical region of the reservoir is the same as some of the Brazilian reservoirs, or other tropical reservoirs the technological difference plays a much more significant role on the emissions processes. Also, considerable regional differences can also be observed in Brazilian reservoirs' methane emissions (either per kWh or area unit).

And finally, there is no guarantee that inventories starting from scratch would include relevant impacts which are also not included in the existing inventories. Since the life cycle inventories data collection are time consuming it is more likely that less usual inputs would be excluded. Therefore the approach of starting from existing inventories and making adaptations of most relevant aspects when applicable can be an alternative for researching other relevant aspects that could be different to the production of the same good.

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