Global, regional and local environmental impacts: LCA indicators for energy & mobility

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Abstract

Because of its reliance to oil, the automotive industry is facing new environmental challenges. Therefore, alternative fuels are being developed: biofuels, synthetic fuels, electricity, hydrogen, etc. To assess their sustainability, life cycle assessment is probably the most appropriate tool. In this article, we compare fossil fuels (gasoline and Diesel fuel) to electricity coming from coal and rapeseed biodiesel. Various environmental impacts are compared using CML2001, ReCiPe2008 and USEtox indicators. Since USEtox considers the distinction between rural and urban atmospheric emissions, a geographical information system was used to assess the urban share of emissions during the production stage of the fuels. The eleven indicators have been aggregated to seven impacts, exhaustively showing the various environmental advantages / drawbacks of each pathway.

1 Introduction

The internal combustion engine (ICE), along with fuels coming from oil, has lead to the development and the generalisation of individual mobility, which can be considered as one of the major progress of mankind during the twentieth century. However, as more and more kilometres are travelled using individual cars, environmental, political and economical issues have risen: dependency of Europe to crude oil producing countries, high costs of oil, depletion of fossil fuels, anthropogenic global warming and air pollution. To challenge these issues, new alternative fuels and powertrains are now being developed: biofuels, synthetic fuel, hydrogen, fuel cells, electric engine, etc.

This article specifically deals with the environmental impacts of fossil and alternative fuels. To assess them, Life Cycle Analysis (LCA) has been chosen as the best tool. In this study, we will present a choice of indicators to exhaustively represent these environmental issues. We will also propose a Geographical Information System to introduce the differentiation between rural and urban emissions for USEtox.

2 Materials and methods

2.1 Studied fuels

Four fuels are studied: Diesel fuel, gasoline, Rape Methyl Ester (RME) and electricity from coal. Diesel fuel and gasoline emissions inventories come from [1] while electricity from coal comes from Querini et al. (submitted to Int J LCA, 2011). RME was calculated using various data from literature [2,3,4,5]. The following figure summarises the production of RME:

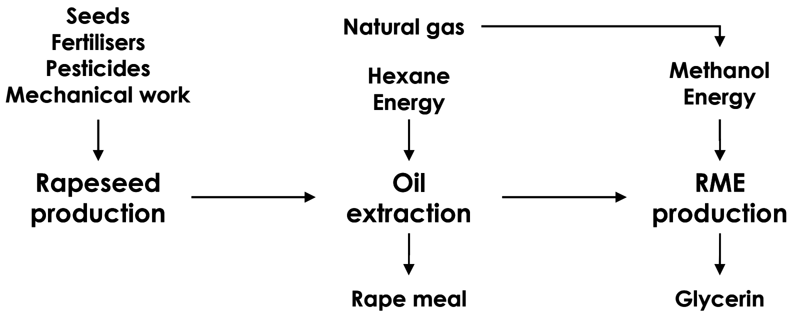

Fig.1: Rapeseed Oil Methyl ester (RME) production pathway

As shown on figure 1, RME production can be separated in three steps: rapeseed production, oil extraction and RME production. For the rapeseed production stage, inputs were taken from [2,3,4,5]. The values were obtained by calculating the mean. Fertiliser and pesticide composition is taken from [2]. For N_2O emissions, the IPCC factors were used, according to [6]. Oil extraction and RME production are calculated using mean factors coming from [2,3,4]. Transport distances between stages are taken from [4]. Atmospheric emissions linked with combustion are calculated using EMEP/EEA register [7] and volatile organic compounds speciation comes from [8]. Emission allocations associated with the numerous by-products were done according to [6]. Finally, no land-use change were taken into account as it raises too many methodological and political issues. GaBi software (www.gabi-software.com) has been used to do all the calculations.

2.2 Selected cars and resulting pathways

The impacts linked to the consumption of fuels can be complex to assess. Indeed, for ICE cars, the pollutants emitted strongly depend on the use of the car: motorway, urban, congestion, hard or smooth acceleration, load of the car, etc. Moreover, the ageing of the car also has a strong influence on pollutant emissions since aftertreatment systems are progressively more efficient because of Euro regulations.

In this article, we selected three vehicles: a Renault Fluence (mid-sized sedan car) Electric Vehicle (EV) and two ICE vehicles representative of the average car sold in 2011 (gasoline and Diesel). Car consumptions and pollutant emissions are calculated on the New European Driving Cycle, following the methodology given by [1]. The composition of unburt hydrocarbon species was taken from the COPERT software [9]. Diesel fuel and gasoline are used as pure fuels in ICE engines and RME is incorporated to 30% in Diesel (leading to a fuel called B30, which is used in the same car as conventional Diesel). As coal electricity can be considered as an "environmental worst case", a mix consisting in 50% coal - 50% renewable (renewable energy has, in a simplistic approach here, no impact) was defined, in order to show the strong dependence of the EV to the origin of electricity.

We thus obtain the five following pathways: Average Sold (AS) Diesel car with pure Diesel (B0), AS gasoline car with pure gasoline (E0), EV with coal electricity, EV with 50% coal / 50% renewable electricity and AS Diesel car with B30. To ensure the relevance of the results, the functional unit is the same for all vehicles and defined as "15,000 km in one year". For the EV, the battery conception is neglected, though it has a strong environmental impact. This is due to a lack of reliable data.

2.3 Environmental indicators

Two midpoint methodologies were retained for the environmental assessment of the studied fuels. These two methodologies are CML2001 [10] and ReCipe2008 [11]. We selected a significant number of impact indicators in order to build an indicator set representative of our system. Some of these indicators are retained from [1]: CML2001 Acidification Potential (AP, kg SO_2 $_{eq.}$), CML2001 Photochemical Oxidation Creation Potential (POCP, kg C_2H_4 $_{eq.}$), ReCiPe2008 Ozone Formation Potential (OFP, kg VOC $_{eq.}$), ReCiPe2008 Marine Water Eutrophication Potential (MWEP, kg N $_{eq.}$) and ReCiPe2008 Particulate Matter Formation Potential (PMFP, kg PM_{10} $_{eq.}$). Since our study also includes one biofuel, we decided to add indicators that would represent the side effects associated: greenhouse gas benefits, freshwater eutrophication and presumably less fossil fuel consumption. To represent these impacts, the following impact indicators were retained: CML2001 Global Warming Potential (GWP100, kg CO_2 $_{eq.}$), ReCiPe2008 Fresh Water Eutrophication Potential (FWEP, kg P $_{eq.}$), CML2001 Abiotic Depletion Potential (ADP, kg Sb $_{eq.}$) and Fossil Energy Consumption (FEC, MJ $_{eq.}$).

For human health (HH) and aquatic ecotoxicity (ECO), USEtox [10] was retained as it offers a consensus [13] between the various toxicity and ecotoxicity methodologies. However, values for inorganics are still interim and Querini et al. (submitted, 2011) have shown the difficulties associated with their use while [14] has concluded that toxicity and ecotoxicity methods for heavy metals tend to over evaluate their impact. That is why only factors for organics were retained in our study. Emissions compartments include air (especially significant for the emissions associated with the fuel combustion), water and agricultural soil (affected by crops for biofuel production). USEtox introduces the distinction between rural and urban air compartments. Therefore, to take account of this distinction, it is necessary to know where the pollutants are emitted. For the car emissions (Diesel and gasoline), we considered two cases: 100% in rural environment or 100% in urban environment, using the same pollutant amounts emitted. For the fuel production, a Geographical Information System (GIS) has been developed.

2.4 Geographical Information System

The GIS tool was developed thanks to Quantum GIS open source software (http://www.qgis.org). Using maps from the Global Rural-Urban Mapping Project (GRUMP) [15], it is possible to know whether a plant is localised in a rural or urban environment according to its geographical coordinates. This method was used by Querini et al (submitted, 2011) for crude oil based fuel and hard coal electricity. The feasibility of this tool was here tested for the RME pathway. The main steps of the RME pathway, which occur in Europe, have been localised. Lime, fertilisers, methanol and pesticides production plants coordinates were obtained from the European Pollutant Release and Transfer Register (E-PRTR) [16] while RME production plants were localised using internet researches and Google Maps (http://maps.google.com/). The following figure shows the localisation of fertiliser (circles), pesticide (diamonds), oil (triangles) and RME (stars) production plants in Europe.

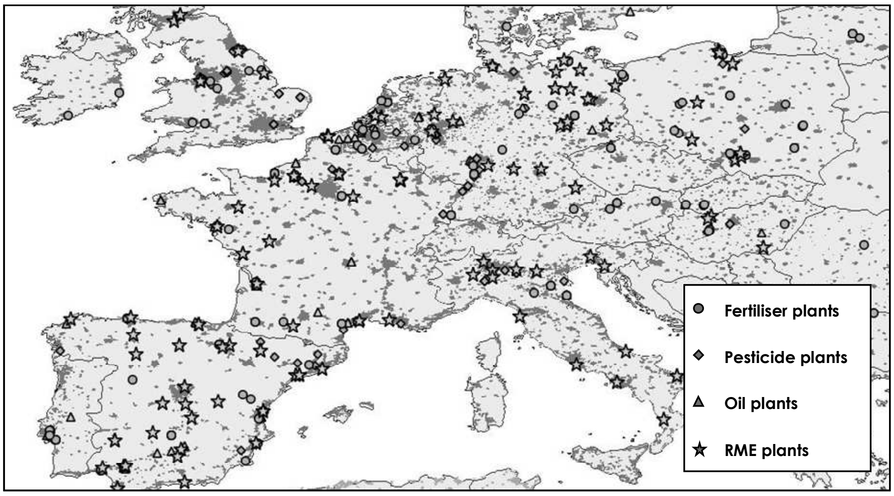

Fig.2: Localisation of fertiliser, pesticide, oil and RME production plants, using the GIS tool

The GIS developed gives the following urban shares of emissions: fertiliser production (78%), lime production (50%), pesticide production (73%), oil production (84%) and RME production (98%).

2.5 Indicator normalisation and aggregation

The environmental impact indicators were grouped into 7 categories. To aggregate the selected impacts, a normalisation method had to be used, since the various indicators do not share the same units. We chose to normalise the results into a European average inhabitant, using values given by CML [17,18]. For ReCiPe indicators, since OFP, PMFP, FWEP and MWEP are based on a small number of substances, it was possible to calculate the normalisation factors using [18]. Normalisation factors are taken for Western Europe (1995) , converted to EU25 using Gross Domestic Products. The following table lists the substance emissions taken into account for ReCiPe2008 normalisation:

Tab.1: Substances taken into account for ReCiPe2008 normalisation

Impact	Substances (to air, unless mentioned)
OFP	Nitrogen oxides, volatil organic compounds
PMFP	Dust (PM10), nitrogen oxides, sulphur dioxide, ammonia
FWEP	Phosphorus (to air and to soil)
MWEP	Ammonia, nitrogen oxides, nitrogen (to water)

For HH, two values for normalisation can be obtained. Indeed, USEtox provides characterisation factors that differentiate urban from rural emissions and default value in [16] is calculated using rural emissions. We decided to calculate the same normalisation figure using urban factors instead of rural ones. However, we do not know the share between urban and rural emissions. Thus, we applied a 75/25 ratio between the two ($(4.75 \times 10^{-3}$ cases.yr^{-1}) x 0.25 + 3.54×10^{4} cases.yr^{-1}) x 0.75) in order to obtain a new normalisation factor. This ratio is probably conservative, as most industrial activities are located around urban areas.

To obtain the 7 impacts, we arbitrarily summed up CML and ReCiPe indicators as follows:

- resource consumption: ADP;
- global warming: GWP;
- acidification: AP;
- eutrophication: 0.5(FWEP) + 0.5(MWEP);
- tropospheric ozone formation: 0.5(POCP) + 0.5(OFP);
- human health: 0.5(PMFP) + 0.5(HH);
- aquatic ecotoxicity: ECO.

3 Results

3.1 Raw normalised results

Figure 3 presents the results for the gasoline, Diesel (used in urban and rural environments, with the same emissions values but with different HH factors), electricity and B30 pathways (in a rural context). Diesel and gasoline vehicles have a strong impact on ADP and FEC (which are correlated), respectively equal to 0.40 and 0.48 inhabitant equivalent. B30 allows small cuts in these impacts while EV can offer strong benefits, even using coal electricity. Conclusions are similar for GWP. For AP, the impact is far inferior (0.07 for Diesel, 0.04 for gasoline). EV using coal and B30 increase this impact, though they remain low (0.11). The same conclusions tend to be similar for MWEP (though EV is a little less impacting) save for B30, which is strongly impacting (0.43). For FWEP and ECO, Diesel, gasoline and EV have a negligible impact. However, B30 shows a weak impact on FWEP (0.04), caused by phosphorus fertilisers, and a strong impact on ECO (0.43). This strong impact on ECO can be explained by the use of pesticides (whose impact factors are high), directly emitted to the soil by rapeseed crops. POCP impact is low for all fuel pathways, especially for EV, even using 100% coal electricity (0.02). OFP and PMFP impacts are moderate and caused by NOx (even for PMFP). This explains that ranking is similar between the two impacts. EV using coal is more impacting though it remains moderate (0.18). This is caused by the combustion of coal. However, using 50% of coal in the electric mix (the other 50% being e.g. renewable or nuclear) leads to the same impact as Diesel fuel (0.1). For human health, all fuels have a small impact when the car is driven in a rural environment. The worst fuel is then B30 (0.04) with issues associated with pesticides. Nonetheless, results are different in urban environment. While EV impact stays negligible (no emission during the car use stage), gasoline impact slightly rises to 0.05 and Diesel increases to 0.66. B30, which is the same as Diesel during the car use phase, would also increase (not shown on figure 3).

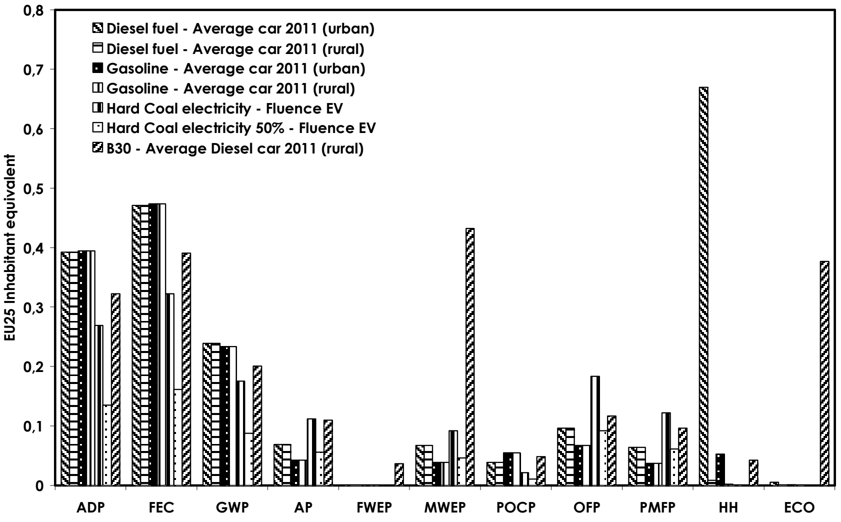

Fig.3: Results for each environmental impact, normalized using EU25 inhabitant equivalent

3.2 Aggregated normalised environmental impacts

Aggregated impacts are presented on the following figure 4:

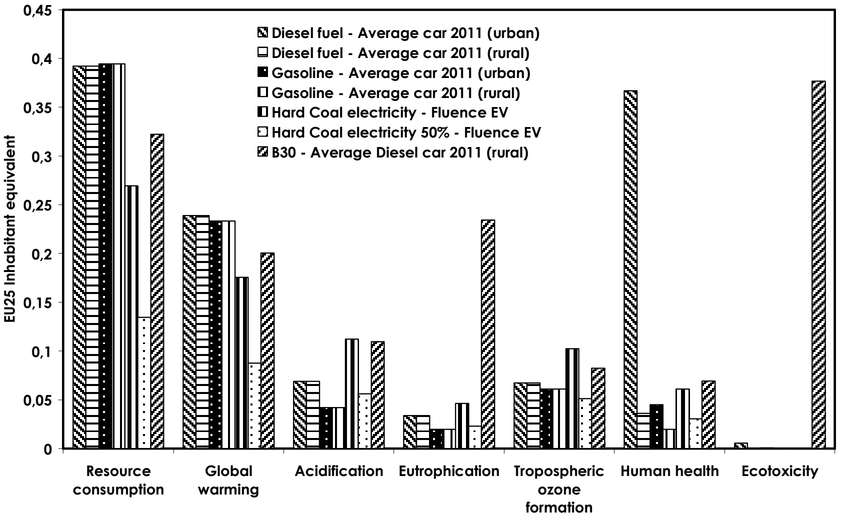

Fig.4: Results for each aggregated environmental category

Resource consumption, global warming, acidification and ecotoxicity results are the same as ADP, GWP, AP and ECO on figure 3, since they are not aggregated indicators. Eutrophication appears weak for all fuels (0.02 - 0.05) except for B30 (0.23). Tropospheric ozone formation is moderate (0.06 - 0.1) with EV using coal being slightly more impacting. Human health issues are low for all fuels except for Diesel used in a urban context.

4 Discussion and conclusions

4.1 Comparison between fuels

When looking at a significant number of environmental impacts, conclusions can be complex to drawn. In this study, we focused on eleven impacts, reduced to seven afterwards. Normalisation can help to know how significant an impact is when compared to global anthropogenic activities but not if one impact can be considered more important than another. This is the role of weighing, which we chose not to do here. The following conclusions can be drawn:

1) Fossil fuels (gasoline and Diesel) are especially impacting on resource consumption and global warming. The impact is similar between Diesel and gasoline because, though Diesel ICE tends to use less energy than gasoline ICE for the same distance traveled, people tend to use more powerful Diesel cars than gasoline ones. Their role on tropospheric ozone formation is moderate (0.06 - 0.07) and low for eutrophication, acidification and aquatic ecotoxicity (this article does not study events such as oil spills). For human health, gasoline has a small impact, as well as Diesel fuel used in a rural context. The USEtox characterization factor for aldehydes in urban context being high, Diesel fuel has a higher impact when the car is driven exclusively in a urban environment. Finally, it is interesting to notice that, since the Diesel car studied possess a Euro5 compliant aftertreatment system, PMFP is more caused by NO_x emissions than particulate matter.
2) RME, when soil transformation is not considered, can help to reduce GWP. However, for one vehicle, the benefit is low as RME is blended to 30%. These benefits come with environmental drawbacks, especially EP and ECO. These impacts are respectively caused by fertilisers and pesticides and are linked with intensive agriculture. Thus, a decrease in

the use of these products would immediately lead to a decrease in environmental impacts. Nonetheless, for HH, B30 suffers of the same issues as conventional Diesel fuel, since the car use stages are similar.

3) EV, even using hard coal electricity, leads to a decrease in resource consumption and global warming. The drawback is an increase in acidification, eutrophication and ozone formation, though the impacts are still low. Nonetheless, EV leads to negligible ecotoxicity and low human health issues, even in urban driving. It must be emphasized that the EV studied here uses electricity coming from coal, which is one of the worst environmental way to produce electric power. Using 50% coal - 50% renewable leads to environmental impacts equal or smaller to conventional fuels. EV is thus an alternative that can lead to a decrease of all environmental impacts, depending on the sources used. Yet, the impact of the battery should be further investigated in order to validate or invalidate these conclusions.

4.2 Methodology

Methodology for tropospheric ozone formation (using POCP and OFP) can be discussed. Ozone formation in the troposphere is a complex phenomenon involving interactions mainly between sunlight, NO_x and VOC. Thus, no indicator perfectly describes it. Using both ReCiPe and CML instead of only CML prevent from minimizing the role of NO_x. However, the choice to equally weigh the two indicators is arbitrarily and not without consequences, since with CML gasoline AS car appears more impacting than Diesel AS car and EV while with ReCiPe, Diesel and EV are more impacting. For Eutrophication, marine (coasts and estuaries) and freshwater are considered equal. In our study, aggregation did not change the conclusion, as RME is more impacting than other fuels for both MWEP and FWEP. Finally, the aggregation of PMFP and HH is also arbitrary. However, this allows to have an impact that both represent the health impacts of the substances included in USEtox and NO_x and particulate matter in PMFP. For HH, the GIS used to localize the impacts of the fuel production has no effect, since all impacts are linked to the car and pesticides used for RME.

4.3 Further research

Further research should be done in different directions. First, a distinction between rural and urban emissions should be applied to PMFP and even to POCP and OFP. Normalisation value for USEtox should also be explored in order to correctly define the ratio between rural and urban emissions. To extend the distinction between rural and urban emissions, research should be done to see if the GIS can be used for other systems than fuel production. In order to have a more exhaustive energy panorama, other fuels, such as ethanol or other electricity sources, should be studied. Finally, aggregation should be done in a less arbitrarily way in order to relevantly reduce the number of environmental impacts.

5 Glossary

ADP: Abiotic Depletion Potential (CML 2001)
AP: Acidification Potential (CML 2001)
AS: Average Sold (car)
ECO: aquatic ECOtoxicity (USEtox 2010)
EV: Electric Vehicle
FWEP: Fresh Water Eutrophication Potential (ReCiPe 2008)
GIS: Geographical Information System
GWP: Global Warming Potential (CML 2001)
HH: Human Health (USEtox 2010)
ICE: Internal Combustion Engine
LCA: Life Cycle Assessment
MWEP: Marine Water Eutrophication Potential (ReCiPe 2008)
OFP: Ozone Formation Potential (ReCiPe 2008)
PMFP: Particulate Matter Formation Potential (ReCiPe 2008)
POCP: Photochemical Oxidation Creation Potential (CML 2001)
RME: Rape Methyl Ester

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