Evaluation and comparison of bio-fuelled mobility with all-electric solutions using Life Cycle Assessment

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Abstract

In a post-fossil-carbon energy future mobility will have to be based on new forms of energy cycles. An attractive energy source being intrinsically renewable is the solar radiation. The various options for harvesting, storing, transmitting and final use for services of solar energy requires a chain of conversion steps between different energy carriers. This chain ultimately defines the technical, economical and environmental efficiency of a certain 'energy path' – even carbon neutral renewable energy sources are accompanied for instance by net emissions of greenhouse gases. Harvesting solar energy in general and most obviously using photovoltaics and photosynthesis implies land use. On an industrial level the areas needed are immense, possibly leading to conflicts between different stakeholders and their land use requirements.

Biofuel based mobility is compared in this study with all-electric solutions using the same car body (Golf 4) and power trains according to the propelling energy carrier i.e. either an internal combustion engine or an electric motor with battery and inverter.

Life Cycle Assessment (LCA) is a proven method for the analysis and comparison of different mobility options [1]. Using SimaPro as LCA software and the ecoinvent database [2] as a reviewed source for data the study compares 3 impacts widely discussed today and linked with mobility: 1) the required land area for the necessary energy yield, 2) the total non-renewable energy content and 3) the total green house gas emissions despite using a renewable energy source and carbon free or neutral energy carriers.

Keywords: life cycle assessment, biofuels, land to wheel, land use, ghg emission,

1 Introduction

There is growing interest to use bioenergy to help combat problems in both the areas of a perceived scarcity of fossil fuels and climate change. Biofuels are currently the most important renewable energy form used in road traffic and they are promoted to receive a central role in reducing our dependency on fossil fuels at least in the short to medium term. Therefore important political decisions are pending, for instance in Switzerland as to what extent tax preferences should be given to biogenic energy utilization in view of promoting biofuels.

Although biofuels are by definition made from renewable biomass, they are not harmless and can cause a wider spectrum of environmental impacts than fossil fuels. These additional impacts include a wide range of adverse issues i.e. from the excessive use of fertilizer, eutrophication, biodiversity loss till smoke induced respiratory ailments caused by slash-and-burn clearing of forest areas. Therefore the energetic efficiency and greenhouse gas emissions do not suffice as criteria for evaluating the environmental impacts of biofuels.

Converting and storing solar energy by photosynthesis in biomass and converting it to biofuels is just one possibility for moving cars. All-electric (plug-in) or hybrid drive systems show improved tank to wheel efficiencies. However to conclude on a broader basis whether the electric drive train is favorable compared to an internal combustion engine, the entire pathway including electricity gen-

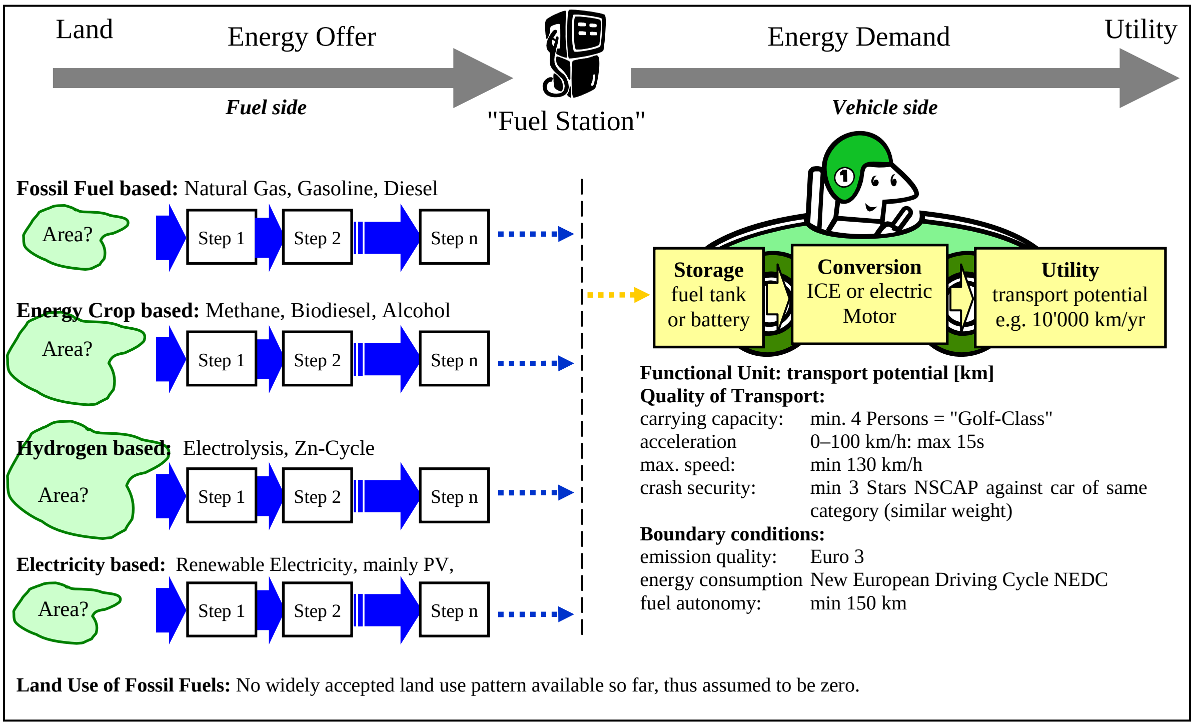

Figure 1 Overview and concept to compare the required land surfaces for various energy systems providing mobility

erating options such as off-grid photovoltaic- or natural gas fuelled combined heat and power plants need to be assessed.

The objective of this study is to evaluate and compare the environmental impacts and more specifically the land use of a variety of 'mobility solutions' ranging from those caused by the production and utilization of biofuels to those caused by an 'all-electric' solution.

2 Methodology

This study is based on a Life Cycle Assessment (LCA), a very suitable method to reach the objectives i.e. to compare the environmental impact of different energy paths used for the same mobility. As shown in Figure the same car using an appropriate engine (drive train) and storage device for the given 'fuel' is used to produce the service of 'transport potential'.

In a first step material and energy flows as well as the resource requirements for a large number of production processes for alternative fuels and electricity generation were compiled in the ecoinvent database [2].

In a second step this eco-inventory was used to evaluate the environmental impacts of each energy path using a set of chosen indicators which describe the impacts.

In a third step the land use of the different energy options were established:

- in the case of biomass based on the annual yield per hectare [kg/ha*a] and its energy content [MJ/ha*a] [3]. In the case of bio wastes the land use is allocated entirely to the original intended use e.g. food; thus the land use for the resulting biofuel is zero.
- in the case of photovoltaics (PV) based on the average annual yield [kWh/kWpeak] of all registered photovoltaic installations in Switzerland (1992-2000). The used area efficiency [m2/kWpeak] is a conservative assumption based on presently marketed standard PV-cells (Table 1).

annual yield CH	819	kWh/kW_peak
area efficiency	10	m2/kW_peak
active surface	50%	
annual energy yield	409'500	kWh/ha
annual energy yield	1'474'200	MJ/ha

Table 1 average energy yield for a large number of PV installations (approx. 1000units) in Switzerland [2].

- in the case of fossil fuels there is no obvious or accepted land use pattern established so far and thus it is assumed to be zero.

3 Comparison of energy paths

This study is restricted to:

- a selection of 6 fuel crops and a representative average of PV installations in Switzerland to determine the required land areas to produce the required energy yield. As mentioned above fossil fuels as well as biofuels from bio wastes are considered not to consume any land surface and are thus not used in this comparison.
- a selection of 9 different biofuels, 3 different fossil fuels and 3 different electricity sources to

show the non-renewable energy demand per km and the greenhouse gas (GHG) emissions per km.

- a selection of two different drive trains a) an internal combustion engine (ICE) and b) an electric motor with battery and inverter (EM&B). Both are optimised for the appropriate fuel and are fit in the same car body.

3.1 Compared energy options

The LCA compares the following energy paths for the GHG emissions and the energy demand (both per km):

a) ICE

Bio Methane:

- Biogas from anaerobic manure digestion (CH)
- Biogas from anaerobic biowaste digestion (CH)
- Biogas from waste wood gasification (CH)

Bio Ethanol:

- Ethanol from sugarcane (BR)
- Ethanol from grass and sugar beet (CH)
- Ethanol from corn (US)

Bio Diesel:

- Biodiesel from used vegetable oil (CH)
- Biodiesel from palmoil (MY)
- Biodiesel from Rape (CH)

Fossil Fuels:

- Natural Gas
- Gasoline
- Diesel

b) EM&B:

- Electricity-Mix from the European grid (UCTE-mix)
- Electricity produced in a natural gas fuelled combined heat and power (CHP) plant
- Production mix of photovoltaic (PV) electricity in Switzerland.

The LCA to determine the GHG emissions and the non renewable energy demand using biofuels was part of a study [1] to evaluate the environmental impacts of fuel consumption in Switzerland which led amongst many others to the following conclusions:

- For many biofuel paths most of the GHG emissions result from the agricultural processes to grow the feedstock, though the specific contributions vary considerably. The most sensitive parameters are the per area yields (e.g. high for Brazilian sugar cane, low for Swiss potatoes), the nitrous oxide emissions (e.g. 30% of all GHG emissions in the case of US corn and CH potatoes) and last but not least the slashing and burning of rain forests (relevant for Malaysian palm oil and Brazilian soy oil). The way of cultivating energy crops is a decisive factor not only for GHG emissions but for most of the environmental impacts of bio fuels.
- Compared to specific fuel crops, biofuels from 'bio wastes' (e.g. crop residues, organic household waste, food industry wastes) often show a better performance since the environmental impacts to produce the initial biomass (e.g. food crop) is not allocated to the resulting biofuel. For instance the lowest GHG emissions can be achieved by using bio Diesel from used vegetable oils, bio ethanol from whey or methane from liquid manure.
- In an average the processes to generate biofuels cause much less GHG emissions than the agricultural processes to provide the feedstock. Oil extraction and esterification to biodiesel produce very low emissions. During the fermentation to bioethanol emissions are varying considerably as different fuels are used for the processes: fossil fuel in the case of US corn or bio residues in the case of Brazilian sugar cane. The highest GHG emissions occur during bio methane production due to leakages as well as methane / nitrous oxide emissions from the digester residues.
- Emissions due to the transport of the fuels to fuelling stations are minor (in a Swiss case they contribute less than 10% to the total).
- An important aspect is the inclusion of coupling products: the production of the assessed products generates residues for which an allocation of the environmental impact is required. The oil expelling process from rape seeds produces for instance oil and cake, thus that the inputs (raw materials) and the environmental harm have to be split. This is done according to economic criteria, thus the environmental emissions e.g. are split according to the earnings of both products. And thus the results become dependent on market dynamics and have to be rechecked once in a while. The aspect of coupling plays a minor role for all-electric systems and can be neglected.

Feedstock	Yield (crop) [kg/ha*y]	Yield (fuel) [kg/ha*y]	Heating value (H_{low}) [MJ/kg]	Yield (energy) [MJ/ha*a]	Conversion efficiency [MJ/km]	Transport potential [km/ha*a]	Land need [m2/10'000km]
Methane, Wood SynGas, CH	15'000	1'800	45.8	82'440	2.564	32'153	3'110
Ethanol, Sugar Cane BR	68'700	4'371	26.8	117'143	2.564	45'688	2'189
Ethanol, Biomass CH-mix	30'708	2'870	26.8	76'924	2.564	30'002	3'333
Ethanol, Corn US	9'315	2'718	26.8	72'842	2.564	28'410	3'520
Methylester, Palm Oil MY	20'000	5'000	37.2	186'000	2.374	78'349	1'276
Methylester, Rape, CH	3'150	1'212	37.2	45'086	2.374	18'992	5'265
Photovoltaics CH-mix	n/a	n/a	n/a	1'474'200	0.547	2'695'064	37

Table 2 Comparison of the required land areas to produce 10'000km (NEDC) for energy crops and photovoltaics [1]

3.2 The transportation model

The calculation of the transport potential is based on a standardized car (Golf-class) with usual weight and safety characteristics. The construction details are not relevant for this study except for the power train conversion efficiencies. In the case of an all-electrical solution this includes battery and electronic inverter and takes into account breaking energy recuperation. Conversion efficiency values for internal combustion engines are taken from [2], the value for the electric car has been calculated with the same wheel energy demand as the ICE, but with a global efficiency of 77.8%.

PowerTrain	Energy need MJ/km	Gasoline-equiv. l_eq./100km
ICE (Methane)	2.564	8.04
ICE (Ethanol)	2.564	8.04
ICE (Methylester)	2.374	7.45
EM&B	0.547	1.72

Table 3 conversion efficiencies from 'tank-to-wheel' [2].

3.3 The required land surface

To determine the required land areas to be covered with either fuel crops or PV installations a standard energy service has been defined: With the above mentioned vehicle an annual distance of 10'000km is covered according to the New European Driving Cycle (NEDC). This service translates into an energy demand using the respective conversion efficiencies and finally the required area using the annual energy yield (details given in Table 2).

4 Results and discussion

From a great variety of possible comparisons the following were considered important to be shown and discussed in this study (analysing whenever possible the situation in 2004):

- the land surface per 10'000 car-km required by the selected energy paths (see Figure 2)
- the total non-renewable energy demand per kilometre of the selected energy paths (see Figure 3).
- the GHG emission per kilometre for the selected energy paths (see Figure 4)

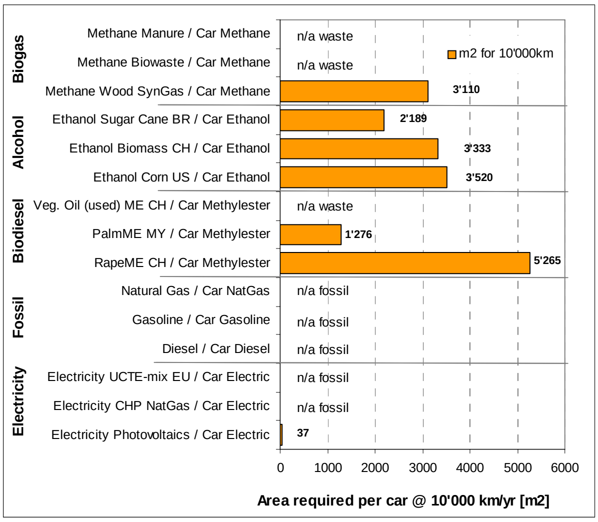

Figure 2 Comparison of the required land areas for the various energy systems

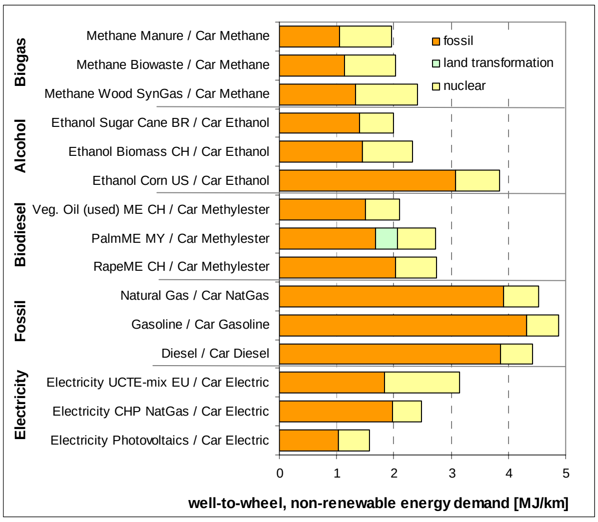

Figure 3 Comparison of cumulated non-renewable energy demand of car mobility, including all the energy investments for the car production, road construction etc.

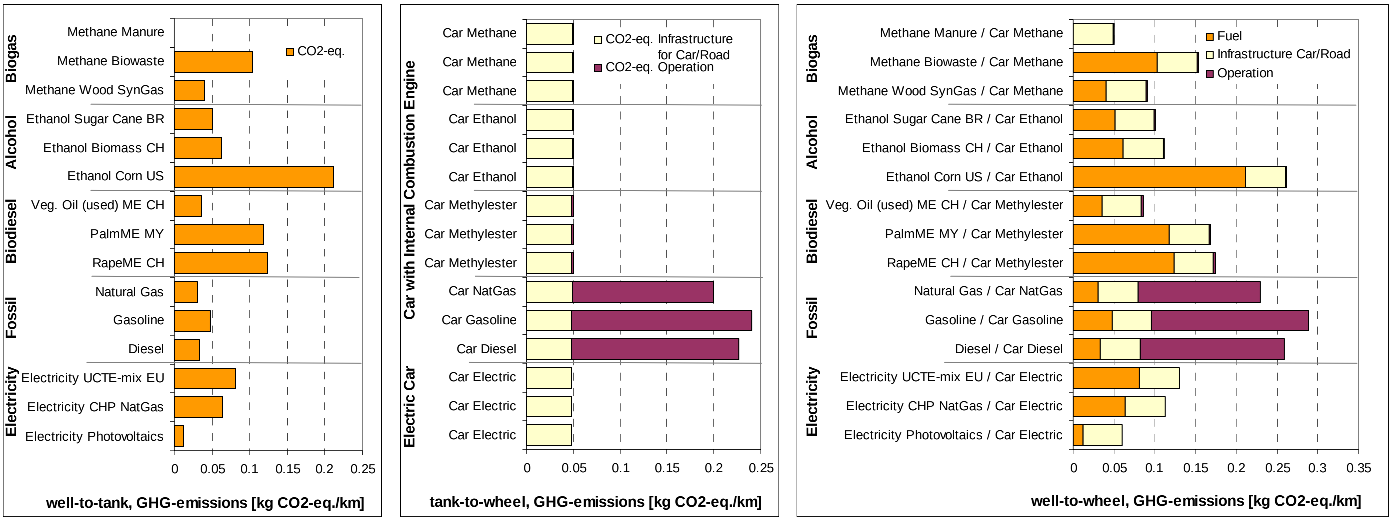

Figure 4 Comparison of GHG emissions of car mobility including all the emissions for the car and road production.

The LCA in [1] is extended in this study with the European electricity mix (UTCE), a natural gas fuelled CHP and PV electricity leading to the following conclusions:

- The required land area to propel a car for 10'000km is varying by almost a factor of 150. Based on the annual yield the option using the smallest area is PV (37m2/10'000km) compared to Bio-Diesel from Swiss rape seeds using the largest area (5'265m2/10'000km).
- PV is indeed by far the least area demanding option being a factor of more than 30 better than the 2nd in the ranking i.e. palm oil produced in Malaysia (1’276m2/10'000km). This is mainly a result of the much higher conversion efficiency of photovoltaics versus photosynthesis.
- The calculated area for the PV option is rather conservative as data is based on technologies older than 10 years and active covered area is assumed to 50% of the used area.
- a PV based car mobility is also requiring the least non-renewable energy input although the production of PV cells and panels is energy intensive.
- for the GHG emissions the PV option is ranking second lowest after the bio-methane from liquid manure option. The outstanding performance of the latter option is a typical LCA outcome: the methane is produced anyway and would reach the atmosphere as a very potent GHG; being burned in an ICE instead the total GHG emission is reduced drastically.

The used LCA methodology puts, however, some limits to the interpretation of the results:

- LCA evaluates the environmental impacts of material- and energy flows. There are no conclusions to be drawn regarding economies and social factors.
- given by the existing eco-inventories the results are related to the existing processes and cover thus the current situation; future trends are not evaluated. A partial outlook for future developments, however, is possible via a sensitivity analysis.
- the assessed processes represent only a fraction of all possible production processes. Hence many further production paths would be possible.
- the available eco-inventories match the average situation in the countries of production (Switzerland, Europe, Brasil, USA etc.) and for the average consumption in Switzerland. The results are not applicable for a single region or a particular production facility as the environmental impacts could divert considerably from the average.
- Furthermore the study will not be able to answer questions regarding the future transition to alternative fuels / electric drives, e.g. consequences for the environment if fuel crops are cultivated massively or regarding rebound effects due to changed driving behaviour (drive green = drive more).

5 Summary

In this study various mobility options for Switzerland based on alternative fuels are compared with all-electric systems. The assessment of the environmental impacts embraces a 'cradle to grave' perspective, i.e. from production (feedstock / electricity generation) to consumption (driven car kilometres) and includes the required infrastructure (cars, roads, PV-panels etc.).

The comparison of the required land areas for the studied energy pathways show a clear lowest demand by the all-electric PV system.

The comparison of cumulated non-renewable energy demand and the GHG emissions per driven kilometre also show a minimum for the PV system.

6 References

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