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Life cycle assessment of mobility options using wood based fuels – Comparison of selected environmental effects and costs

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HIGHLIGHTS

- Methane production and utilization has lowest environmental impacts and costs.
- Mobility costs are dominated by car purchase, especially for electric cars.
- LCA results and costs of electric concepts today are high compared to other options.
- Technical and cost improvements lead to competitive results for future electric cars.

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ABSTRACT

An environmental assessment and a cost analysis were conducted for mobility options using electricity, hydrogen, ethanol, Fischer–Tropsch diesel and methane derived from wood. Therefore, the overall life cycle with regard to greenhouse gas emissions, acidifying emissions and fossil energy demand as well as costs is analysed. The investigation is carried out for mobility options in 2010 and gives an outlook to the year 2030.

Results show that methane utilization in the car is beneficial with regard to environmental impacts (e.g. 58.5 g CO_2-eq./km) and costs (23.1 €-ct./km) in 2010, especially in comparison to hydrogen usage (132.4 g CO_2-eq./km and 63.9 €-ct./km).

The electric vehicle construction has high environmental impacts and costs compared to conventional vehicles today, but with technical improvements and further market penetration, battery electric vehicles can reach the level of concepts with combustion engines in future applications (e.g. cost decrease from 38.7 to 23.4 €-ct./km).

1. Introduction

Globally the demand of fossil energy carriers (e.g. crude oil, natural gas, hard coal) grows due to an increasing population as well as a growing need for energy due to further industrialisation and mobility. This is directly linked to increased emission of greenhouse gases (GHGs) that are released during combustion of fossil fuels. In Germany approximately 20% of energy induced emissions come from road traffic (Federal Environment Agency, 2012). In order to reduce the contribution of traffic to climate change, the European Commission has adopted the Renewable Energy Directive claiming a share of 10% renewable energy within the mobility sector until 2020 (European commission, 2009). Today this target is partly reached by conventional biofuels based on rape oil (i.e. biodiesel) and plants containing sugar or starch (i.e. ethanol). Due to food versus fuel debate, especially fuels from wastes and residues as well as fuels based on lignocellulosic biomass are promoted recently. One of the measures to bring such options into the market is by accounting the double amount on biofuel ratings (European Commission, 2009).

Many efforts have been undertaken to develop technologies to convert wooden biomass to liquid or gaseous fuels like ethanol, diesel fuel (Fischer Tropsch (FT) diesel) or methane. First small scale demonstration plants have been installed, e.g. a plant for methane production of 1 MW gas capacity in Güssing, Austria, or the bioethanol plant in Straubing, Germany, which produces ethanol from straw since 2012 (see e.g. Steubing et al. (2011)).

Simultaneously numerous studies have been prepared with focus on the modelling and simulation of large scale fuel generation from wood or other lignocellulosic biomasses like straw (Kravanja

Abbreviations: GHG, greenhouse gas; FT, fischer tropsch; CHP, combined heat and power plant; BEV, battery electric vehicle; FCEV, fuel cell electric vehicle; ICE, internal combustion engine; RME, rape methyl ester.

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et al., 2012; Wagner and Kaltschmitt, 2011). For different technology options or for different lignocellulosic biomasses often the fuel production of one specific fuel has been evaluated with regard to environmental or economic performance (Han et al., 2013; Littlewood et al., 2013; Pucker et al., 2012; Kabir and Kumar, 2012). However, there is only a very limited number of investigations that collate the different fuels ethanol, diesel and methane in order to help deciding, which fuel should be generated from one kind of wooden biomass. For this step the use of the fuel has to be regarded as well, due to different energy demand for propulsion in diesel and petrol engines (Han et al., 2013).

Instead of producing fuels for combustion engines the fuel production for electric drive trains (i.e. electricity or hydrogen to be converted to electricity in fuel cells) is possible and might be favourable due to higher efficiencies in the car (Hawkins et al., 2013). However, the investigation of comparable fuel pathways from wood for conventional cars and alternative mobility concepts like battery electric vehicles or fuel cell electric vehicles is seldom a subject in up to date analyses.

Therefore, the scope of this analysis is to compare the environmental and economic performance of the production and use of wood based fuels for cars with conventional combustion engines as well as for electric cars driven with electricity stored in batteries and with hydrogen converted to electricity in fuel cells. The whole life cycle of biomass production, conversion and use including the car production and disposal is investigated.

Since either the fuel production technology (i.e. for liquid and gaseous fuels) or the car technology (i.e. with electric drive trains) is immature and in an early stage of commercialisation, a future perspective on the development of these technologies is given – especially with regard to cost reduction potentials.

2. Methods and database

2.1. Methods

The scope of this analysis is to compare mobility concepts using fuels based on poplar wood with regard to environmental and economic performance. The pathways, that are investigated are *electricity* from a combined heat and power (CHP) plant for a battery electric vehicle (BEV), *hydrogen* from wood gasification for a fuel cell electric vehicle (FCEV), *ethanol* from C6 sugar fermentation for a vehicle with internal combustion engine (ICE), *FT-diesel* from wood gasification for an ICE vehicle and *methane* from wood gasification for an ICE vehicle.

All pathways include the pre-chains of the material and energy supply as well as the infrastructure – if not mentioned otherwise – for the following steps:

- Wood cultivation and transport of the wood to the conversion plant
- Fuel production
- Fuel distribution
- Use of the fuel in the car.

The results for the various fuel production processes are presented, discussed and compared to conventional fuel. Afterwards, all environmental as well as economic key figures are referred to one kilometre driven by the specific car in order to identify the pathways of wood use for mobility purposes with relative environmental and cost benefits.

It is assumed that production and use of the fuel is realised in Germany in the year 2010. In order to show possible future developments of technologies not fully market mature today, an outlook for the year 2030 is given. Therefore, technological as well as cost developments are taken into consideration.

For the determination of the influence of important or uncertain parameters on the results a sensitivity analysis is carried out.

2.1.1. Life cycle assessment

The environmental assessment is carried out according to ISO 14040 and 14044. Impact categories that are considered are climate change according to IPCC 2007 on a baseline of 100 years, acidification according to CML 2001 and cumulative energy demand of fossil resources based on their lower heating value, addressed in CO_2-eq., in SO_2-eq. and in MJ-eq. respectively (Guinée et al., 2002; Ecoinvent, 2010).

CO_2 emissions from biomass or biofuel combustion are not counted for, because they are of biogenic origin.

If by-products occur, allocation according to the exergy content is carried out. For heat (Q in MJ) as a by-product a temperature level of T_o = 363 K (90 °C) and an ambient temperature of T_u = 288 K (15 °C) is assumed to determine the exergy Ex_Q (in MJ) according to Eq. 1.

$$Ex_Q = Q \cdot (1 - T_u/T_o) \tag{1}$$

Especially during the production of liquid fuels energy carriers like lignin or sugar might be formed as by-products. In this study they are assumed to be utilized to cover heat and electricity demand of the process. The remaining heat and electricity are counted for as by-products.

Data for environmental assessment are taken from the ecoinvent database (Ecoinvent, 2010) if not mentioned otherwise. Electricity that is used as operating supply for fuel production is modelled according to the German electricity mix 2010 with a share of 17% renewables, see Table 1.

2.1.2. Cost assessment

Cost analysis is carried out according to annuity method. Cost groups that are assessed are capital bound, consumables, operating costs and other costs. Onetime costs (i.e. investments) are apportioned into yearly costs (capital bound costs) by a rate of interest of 4% (Kaltschmitt et al., 2007). For cleaning and maintenance of the conversion plant (operating costs) yearly costs of 1.5% of the investment are assumed. Administration and insurance costs (other costs) are assumed to be yearly 2% of the investment. Employee costs are assumed to be 50,000 €/(pers.∗a). Taxes or subsidies are neglected.

Future cost development of investments is investigated by applying experience curves according to equation 2 (Grübler et al., 1999):

$$I_n = I_0 (C_n/C_0)^{log2(r)} \tag{2}$$

where I_n and I_0 are the specific investments of the nth and the first plant, C_n is the accumulated installed capacity and C_0 is the capacity of the first plant. The factor r describes the progress ratio.

Table 1
Electricity mix in 2010 (Wulf and Kaltschmitt, 2012) and assumption for 2030.

	2010 in%	2030 in%
Hard coal	19.3	9.1
Lignite	24.8	6.1
Natural gas	15.1	21.8
Nuclear	23.9	-
Wind	6.7	38.0
Biomass	4.5	9.1
Hydropower	3.6	4.6
Solar	2.1	11.1