Land use, greenhouse gas emissions and fossil fuel substitution of biofuels compared to bioelectricity production for electric cars in Austria

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Abstract: Bioenergy is one way of achieving the indicative target of 10% renewable energy outlined in the EU Directive 2009/28/EC. This paper assesses the consequences for land use, greenhouse gas (GHG) emissions and fossil fuel substitution of increasing the use of bioenergy for road transportation. Different technologies, including first and second generation fuels and electric cars fuelled by bio-electricity are assessed in relation to existing bioenergy uses for heat and power production. The paper applies a spatially explicit energy system model that is coupled with a biomass production model to allow estimating impacts of increased biomass utilization for energy production on agriculture and forestry. Uncertainty is explicitly considered with the help of Monte-Carlo simulations of input parameters. Results indicate that second generation fuels perform better with respect to land use than first generation ethanol and that costs are lower. Biodiesel is also a cheap option, although the total potential is limited at a low level due to constraints in feedstock production. Electric vehicle mobility minimizes land use, however, costs are still high and prohibitive. First generation ethanol production is effective in reducing domestic GHG emissions because it does not induce feedstock competition with existing bioenergy uses (i.e. heat and power production). However, land use change is significant.

Keywords: *biofuels, electric cars, e-mobility, 2020 goals, spatially explicit optimization*

1. Introduction

Directive 2009/28/EC requires all member states of the EU to guarantee a share of 10% of renewable fuels in transportation by 2020. The target may be reached by various measures, including an increase in the share of biofuels and an increase in the share of renewably produced electricity in the transportation sector. However, since the large scale introduction of biofuels in the US and Europe an extensive discussion has evolved because the large land requirements were identified as cause for direct and indirect greenhouse gas (GHG) emissions [1], [2] and as the driver for increasing competition between food and fuels [3], [4]. In Austria, bioenergy has played traditionally an important role. It provided around 8% of the primary energy demand in 2006, mainly for heating purposes [5]. Other uses of bioenergy developed in recent years, include biofuel and power production. Austria has complied with the 5.75% indicative EU biofuel target since late 2008 and used around 4.00 TWh of biodiesel and 0.60 TWh of ethanol in 2008 [6]. A further increase of the supply of biofuels will be difficult to achieve, particularly if only domestic biomass supply is considered. However, new technologies are emerging that aim to increase biofuel productivity and diversify feedstock supply. Second generation biofuels that may use ligno-cellulosic feedstock for fuel production are regarded as a sustainable alternative to first generation biofuels which are mainly produced from food and feed crops [2], [7]. A technological alternative is electric cars. Technical and economical barriers currently prevent the large scale introduction of electric cars, however, future potentials are considered significant [8], [9]. Electric cars will only contribute to renewable energy targets if the electricity for cars is produced in a renewable manner. Biomass is one possible source for this purpose. An existing study estimates [10] that the utilization of biomass resources for electricity generation and subsequent utilization in electric cars is a far more effective way of using limited land resources for transportation than the conversion of food and feed crops to first generation ethanol. However, the assessment relied merely on technical details without considering economics and alternative uses of biomass in the energy sector – e.g. for heating. This paper contributes to research by applying a spatially explicit agricultural-bioenergy-system model to evaluate several technological options for the transportation sector, including first and second generation fuels and electric cars, with respect to land use, GHG emissions and fossil fuel substitution. The techno-economic characteristics of future biofuel production as well as of electric cars are not well known yet. Also, high uncertainty is attached to future price energy scenarios. We therefore apply a Monte-Carlo simulation of input parameters to explicitly include uncertainty in the modeling process.

2. Methodology

2.1. Model and Model Boundaries

A spatially explicit, techno-economic mixed integer program is developed and applied to assess the costs, land use and GHG emissions of different bioenergy conversion routes. The model minimizes the costs of supplying Austria with transportation fuels, heat and electricity from either bioenergy or fossil fuels. It is static and simulates one year of operation. The current model version considers domestic biomass supply and energy demand only and does not allow imports and exports of biomass or bioenergy commodities. The model determines which bioenergy plants of a specific size and specific location shall be built and which demand regions are supplied with bioenergy and/or with fossil fuels. Each plant produces various energy commodities, e.g. the heat produced in a combined heat and power (CHP) may be delivered to district heating networks (Figure 1). By-products of biofuel plants are sold as animal feed. Biomass supply curves endogenously determine the price of feedstock from forestry and agriculture, while prices of fossil fuels and energy demand are defined exogenously. Taxes currently applied to both fossil and bioenergy fuels are not included in the model.

2.2. Technologies

We assess several bioenergy technologies which are able to replace fossil fuels in the transportation sector along with technologies that convert biomass to heat and power. First generation biofuels are classified into ethanol produced from fermentation of starchy and sugar crops (e.g. wheat and corn) and biodiesel which is produced from vegetable oil derived

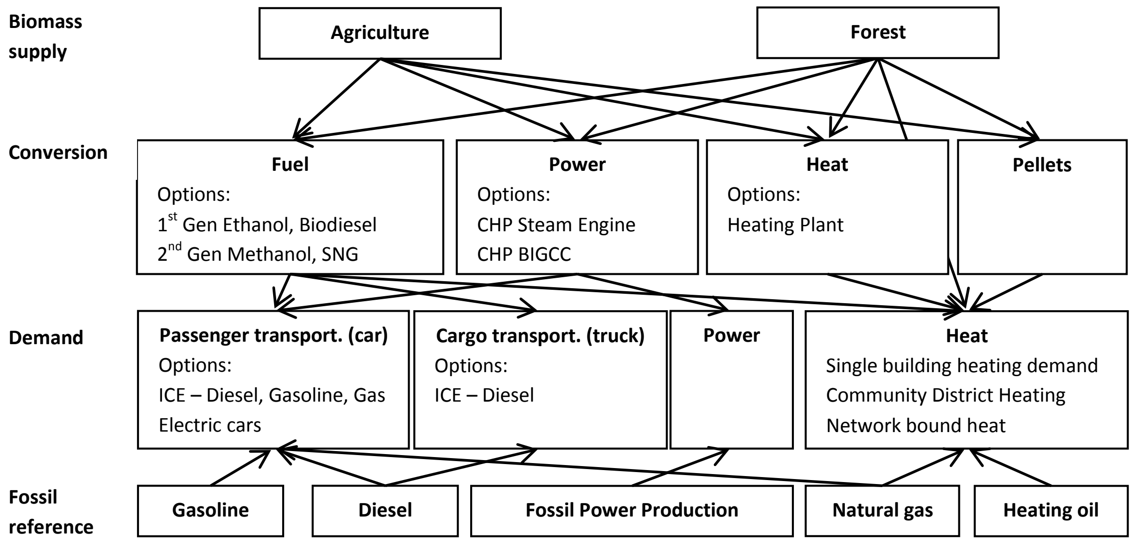

Figure 1: Diagram of the mixed integer programming model.

from oil crops (e.g. sunflower and rapeseed). Both technologies are commercially available and are currently used for the production of biofuels in Austria**.** Ethanol is blended with gasoline. A blend of 5% ethanol and 95% gasoline is considered safe to be used in all cars, while all cars sold currently on the market are also able to handle a blend of 10% of ethanol. Similar limitations apply to biodiesel [11]. Second Generation biofuels are able to use cellulosic feedstock and even waste for the production of biofuels. There are two major technological options [7]. The biomass can be gasified and subsequently upgraded to liquid transportation fuels such as methanol or synthetic natural gas (SNG) which can also be used as transportation fuel. The second option is the hydrolysis of cellulose to sugars that are fermented to ethanol afterwards. We assess gasification only as it is estimated to be economically more viable than hydrolysis with fermentation [12], [7]. Second generation production technologies are currently under research and first pre-commercial installations are being built. US legislation requires 572 TWh of yearly cellulosic biofuel production until 2022 [13], therefore a rapid increase in the construction of second generation facilities can be expected. Current cars cannot run solely on methanol and the amount of methanol that may be blended to gasoline is, similar to ethanol, limited. SNG requires significant modifications to the car, including the installation of a gas tank. Electric cars are currently globally under research, however, costs and ranges of batteries are major economic and technical obstacles to full implementation of the technology. Ranges of above 150 km are currently only achieved at very high costs [9]. Also, electric cars need the large scale deployment of charging stations. Metering of power and billing still has to be developed. The model considers investment costs for electric cars. Costs associated with additional infrastructure necessary for electric cars are not included. With respect to power production, the model allows two technologies: steam engines and biomass integrated gasification combined cycle (BIGCC) plants. While steam engines are well established in Austria and the installed capacity exceeded 300 MW in 2007 [5], BIGCC is a technology that is still under research. It allows higher electrical conversion efficiencies than steam engines but capital costs are also significantly higher. We assume that power can be either used to fuel electric cars or that it is simply sold on the electricity market at a fixed price. Heating technologies modelled include fuel wood furnaces, pellet furnaces and heating plants for district heating networks.

2.2.1. Total Cost of Ownership – Cars

We use the concept of total cost of ownership (*tco*) to assign different costs to different cars in the model. Costs for fuels are endogenously determined by the model and are therefore not included in the calculations of *tco*. The *tco* per km is described by equations (1)-(3):

$$tco = \frac{C\frac{i(1+i)^t}{(1+i)^t-1}+B}{km} + om \qquad (1)$$

$$t = \min(\frac{maxKm}{km}, 10) \qquad (2)$$

$$B = \frac{i(1+i)^{tb}}{(1+i)^{tb}-1}\sum_{tb\in y}\frac{bc}{(1+i)^{t'}} \qquad (3)$$

The *tco* is determined by the annuity of capital costs *C* of the car, assuming an interest rate *i* and a lifetime *t*. For electric cars, the battery cost *B* is additionally considered as explained below. Total necessary yearly investment costs are divided by the kilometres *km* driven annualy. Additionally, operation & management costs per km of *om* are assumed. These costs are assumed to be lower for electric cars because maintenance of the electric motor is less complex than for an internal combustion engine (ICE) [9]. The lifetime of the car is limited to ten years, however, if the car is driven a lot (i.e. more than *maxKm*), the lifetime is further reduced as indicated by equation (2). The lifetime of a battery is significantly less than that of the carriage. A change of the battery within the lifetime is therefore probable and is modelled by equation (3): the annuity of battery costs is derived by adding up the discounted battery costs over the whole life time, assuming that one battery costs *bc*. The battery is changed in year *y* when the driven kilometres since the last change exceed the lifetime of the battery. The *tco* depends significantly on the kilometres driven each year. A higher amount of kilometres implies lower specific capital costs per km. We therefore estimate ten classes of annual car utilization based on data provided by ÖAMTC. ÖAMTC, the biggest Austrian Automobile Association, checks approximately 10% of all cars for their technical liability each year. The total driven kilometers and the year of the first registration of the car are collected in the examination of the cars. An approximate estimate of the yearly driven kilometers can be derived from this data. We classified the cars by the annual driven kilometers into ten classes (0 km - 10,000 km, 10,001 km - 20,000 km, …, 90,000 km – 100,000 km). For each class, the mean of the yearly driven kilometers by car and the mean of the sum of driven kilometers by all cars in the class are determined. The sum of driven kilometers is linearly extrapolated from the ÖAMTC data with data of total Austrian car ownership from Statistik-Austria to allow an estimate for whole Austria as ÖAMTC data only covers around 10% of all registered cars.

2.3. Demand

We estimate current transportation demand from the ÖAMTC data and assume that the demand for transportation remains constant until 2020. We assume a total of 60 billion annual kilometres for personal transportation and total of 24 billion tonne kilometres for cargo transportation by truck. Although transportation fuel consumption has historically seen significant increases in the last years, the increase was significantly caused by “tank tourism” due to lower fuel taxes in Austria. We exclude demand from “tank tourism” from our analysis and also assume that public transportation will take a higher share of the overall transportation supply, thus allowing that road transportation remains constant. While the model allocates biomass resources to various conversion routes depending on energy prices and production costs, the demand for biomass heating is assumed to not fall under 17 TWh in the simulations. This is a possible decline of 5 TWh from current consumption levels. Setting a lower bound for biomass consumption for heating is reasonable because adjustment of individual heating devices to new economic conditions generally takes a lot of time.

2.4. Uncertainty

Most of the parameters in the study are of high uncertainty. Uncertainties on the performance and costs of various technologies as well as uncertainty about future energy prices are high. We explicitly address this issue by performing Monte-Carlo simulations of the MIP model and conducting an extensive sensitivity analysis. We first define plausible ranges for the uncertain parameters from a literature research and assume that the parameters are distributed uniformly within that range. For energy and CO_2 prices, correlation between the prices of oil, gas, gasoline and CO_2 are determined from historical spot prices**.** The input data for the Monte-Carlo simulation is generated by performing a Latin Hypercube Sampling procedure and combining it with the Iman-Conover method to guarantee correlation of correlated parameters in the procedure [14]. Latin Hypercube Sampling is used to guarantee that the whole parameter range is covered in the Monte-Carlo simulations. Results are given in form of probability distributions and a stepwise regression analysis is performed to examine the sensitivity of results to input parameters. The assumption on the distribution of the most important parameters is reported in Table 1. Further parameters modelled stochastically are biomass costs, conversion efficiencies and investment costs of bioenergy plants.

Table 1: Main model parameters and uncertainty ranges

	Lower Bound	Upper Bound
Price of oil (€ MWh^{-1})	40	60
Price of gas (€ MWh^{-1})	30	50
Price of gasoline (€ MWh^{-1})	42	62
Price of electricity (€ MWh^{-1})	54	74
Price of carbon (€ MWh^{-1} tCO_2^{-1})	21	55
Battery costs (€)	4,000	6,500
Replacement distance battery (km)	70,000	90,000
Investment costs electric cars (w/o battery) (€)	14,000	16,500
Investment costs gasoline cars (€)	16,500	16,500
Investment costs diesel cars (€)	17,000	17,000
Investment costs gas cars (€)	17,500	17,500
O&M costs electric car (€ km^{-1})	0.02	0.025
Conversion efficiency car – Gasoline (km MWh_{fuel}^{-1})	2,000	2,200
Conversion efficiency car – Diesel (km MWh_{fuel}^{-1})	2,250	2,450
Conversion efficiency electric car (km MWh_{elec}^{-1})	5,600	7,000

2.5. Scenarios

We model one baseline scenario, that assumes no policy intervention at all, and 7 policy scenarios. Three of the scenarios assume that 5% (*S5*), 10% (*S10*) and 15% (*S15*) of the transportation sector are supplied by bioenergy, allowing all technologies to be selected by the model. The other four scenarios examine the impact of a 10% target of renewable transportation fuels, if only single technologies (i.e. ethanol (*eth*), methanol (*met*), sng (*sng*), electric mobility (*emo*)) are allowed. Biodiesel is not modelled in these scenarios because domestic feedstock production is too low to supply 10% of the transportation sector with biofuels.

3. Results

3.1. Technologies and fuel utilization

The first three scenarios allow free choice of technologies. Biodiesel and methanol supply the biofuels in these scenarios. Biodiesel is however limited at around 0.5 TWh due to restrictions in feedstock supply of oil-crops. Second generation methanol is the supplement to biodiesel to complete the full target. E-Mobility plays a role in the first three scenarios - however, variation is very high and the contribution is significantly lower than that of methanol. Ethanol and SNG are not selected in the first three scenarios. These results indicate that methanol production can be considered superior to ethanol in terms of costs – although the variation of results is generally high, the dominance of methanol over ethanol is stable. Competing bioenergy technologies (i.e. heating and power production) are mainly reduced in *S15, met* and *SNG.* This is due to the high demands for woody biomass for biofuel production which increases prices for the feedstock and therefore makes production of power and heat partly unprofitable. The ethanol scenario has less influence on the woody biomass market as ethanol feedstock competes with food and feed crops. Biodiesel is mainly used in the freight sector where it substitutes diesel. Ethanol and methanol are used for personal transportation in driving classes with low annual distances because fixed capital costs contribute more to the total costs of transportation in those classes than the distance dependent fuel costs. Higher classes with higher annual driving distances are more likely to be supplied by electric cars where the influence of the high capital costs of the car and the battery decrease and the fuel costs become more important.

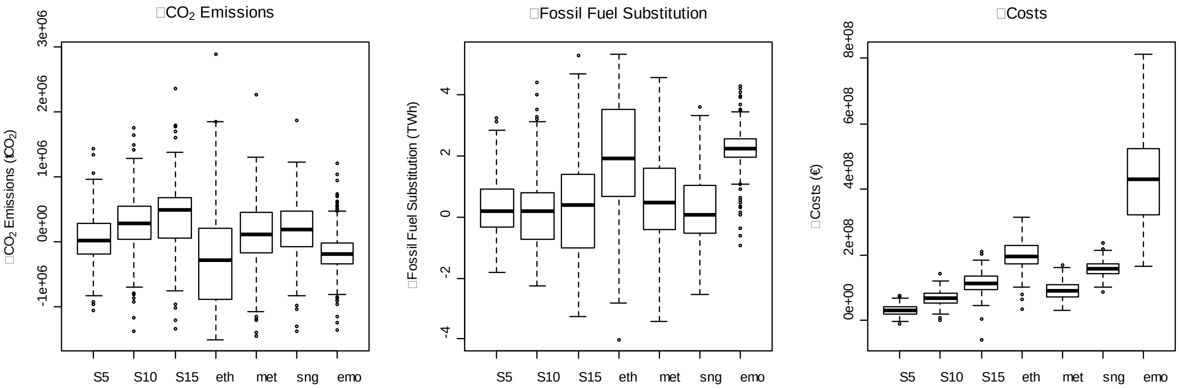

Fig. 2: Differences in CO_2-Emissions, Fossil Fuel Substitution and Costs between the baseline and the biofuel scenarios.

3.2. CO_2 Emissions, Fossil Fuel Substitution and Costs

Figure 2 shows CO_2 emissions, fossil fuel substitution and costs calculated as the difference from the baseline scenario. A significant reduction in CO_2 emissions and an increase in fossil fuel substitution are achieved by the *eth* and the *emo* scenario. These two scenarios also have highest costs. The variance of costs is highest in *emo* due to the large uncertainties in the development of the costs of electric vehicles. However, the model only considers domestic GHG emissions while effects of indirect land use change on GHG emissions are not modeled.

3.3. Land use

While the *eth* policy substitutes a lot of fossil fuels, the land use effects are also substantial in comparison to the other policy scenarios (See Figure 3). Up to 200,000 ha of agricultural land are converted to energy crop production while all other scenarios stay well below 50,000 ha. This implies that food and feed production is reduced significantly in the *eth* scenario while all other policies have rather low impacts on the production of other agricultural products. There are two reasons for this: first, productivity is higher for second generation fuels and for electric mobility due to higher total conversion efficiencies (see Figure 3). Second, these technologies rely on lignocellulose resources that may come from additional forest harvesting or that may otherwise be used for power and heat production (see Figure 3, bottom-right). There are also important differences between the *S10*, *met*, *sng* and *emo* scenarios. Combining biodiesel and methanol for the biofuel goals as in *S10* reduces land use change in comparison to the methanol only scenario. Biodiesel therefore plays a small, but important role in the technological portfolio. Figure 3 shows that *SNG* is more efficient in converting biomass than methanol. Electric mobility has by far the lowest impact on land use change and on additional forest wood utilization.

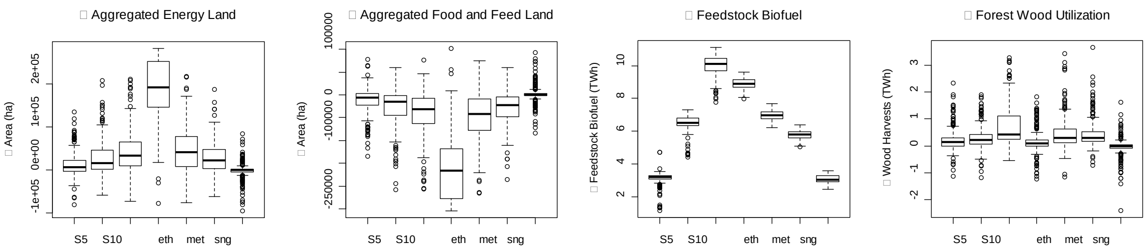

Fig. 3: Differences in Land Use, Feedstock Utilization and Forest Wood utilization between the baseline and policy scenarios.

3.4. Sensitivity Analysis

Table 2 show the results of the sensitivity analysis performed on the results of the *S15* scenario. We checked for the influence of parameters on the deployment of electric mobility to show which factors mainly influence the competition between second generation fuels and electric mobility by performing a regression of the input parameters on the output variables (a stepwise regression procedure is used). The regression coefficients are normalized. The most important input parameters regard the cost for the electric car (i.e. battery costs, investment costs, O&M). The carbon price and the kilometers until replacement of battery also prove to significantly influence the results while the gasoline price does not show significant influence on results.

4. Discussion

Results of our study are in line with other studies that estimate lower land use for bio-electric-cars than for biofuel production [10]. They are also in line with studies that come to the conclusion that battery replacement costs are currently the biggest economic barrier to the large scale introduction of electric mobility in the transportation sector [8], [9]. However, there are additional barriers to electro-mobility that were not modelled within this study: the change from cars that are refuelled at gas stations in very short time to cars that need hours of recharging and that have a comparably low driving range probably plays a more important role than sole considerations of the *tco*. The model results indicate that drivers who use their car a lot are more likely to choose electric cars than those with low car utilization because of lower fuel costs. However, technical reasons may impede the utilization of electric cars for those drivers: the low range and the high recharging times may render electric cars impractical for them. With respect to economics, renewable electricity production from wind or small water power plants may produce electricity at much more competitive costs than biomass powered thermal plants. Therefore, electric cars may be more competitive than stated in this study due to lower fuel costs from renewables. The GHG emission effects of biofuel policies have to be considered in conjunction with the land use change that is caused by the expansion of biofuel production. The GHG emissions stated in this paper do not include indirect or leakage effects of the policies. However, it can be clearly stated that fuelling electric cars with electricity produced from biomass induces by far the least change of land use and can therefore be considered to also minimize leakage effects.

*Table 2: Results of sensitivity analysis. Confidence levels: *** 0.999, ** 0.99 and * 0.95*

	Coefficient	
Amount of electric mobility (R^2 0.49)		
Battery Costs	-0.54	***
Investment costs electric car	-0.28	***
O&M costs electric car	-0.12	*
Gasoline price	0.08	
Kilometers until replacement of battery	0.15	**
Carbon price	0.17	**

5. Conclusions

Second generation biofuels have less impact on land use than first generation ethanol due to two reasons: yields of biofuel per hectare are higher for agricultural land and the feedstock may additionally come from forests. Biodiesel has high yields per hectare, but the total domestic potential is limited at a low level. The lowest land use is implied by the utilization of electric cars, which, at current technological standards, are still very costly in comparison to cars fuelled by liquid fuels. With respect to policies for promoting second generation biofuel production, one has to consider that investments in second generation biofuel production will have a long-term effect on the utilization of biomass resources. The results of the study indicate, however, that the gains in efficiency in relation to first generation fuels are relatively low while significant efficiency increases can only be expected when developing a transportation system based on electricity. A large scale introduction of second generation biofuels has to be considered very carefully therefore and in the light of a possible total restructuring of the transportation sector within the next 20 to 30 years.

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