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Article

Relative Greenhouse Gas Abatement Cost Competitiveness of Biofuels in Germany

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Abstract: Transport biofuels derived from biogenic material are used for substituting fossil fuels, thereby abating greenhouse gas (GHG) emissions. Numerous competing conversion options exist to produce biofuels, with differing GHG emissions and costs. In this paper analysis and modelling of the long-term development of GHG abatement and relative GHG abatement cost competitiveness between crop-based biofuels in Germany is carried out. Presently dominant conventional biofuels and advanced liquid biofuels were found not to be competitive compared to the substantially higher yielding options available: sugar beet based ethanol for the short to medium term least-cost option and Substitute Natural Gas (SNG) for the medium to long term. The competitiveness of SNG was found to depend highly on the emissions development of the power mix. Silage maize based biomethane was found competitive on a land area basis, but not on an energetic basis. Due to land limitations as well as cost and GHG uncertainty, a stronger focus on the land use of crop-based biofuels should be laid in policy.

Keywords: biofuels; greenhouse gas; ghg; abatement cost; modelling; competition

1. Introduction

Biofuels are one way to reduce the GHG emissions of transport, which in Germany stands for 21% of total societal emissions [1]. Germany has, as the currently only EU country, set a goal of reducing the greenhouse gas (GHG) emissions of land transport through biofuels or other renewable options, instead of an energetic biofuel goal which was previously in place, in common with the other countries.

Currently, both biomass residues as well as dedicated crops are used for biofuels production in Germany. Rape seed based biodiesel (RME) and starch crop based bioethanol, both conventional biofuels, are the most common pathways [2]. However, these have a low overall yield and thus limited potential compared to other available options, which also makes them not competitive in the long run on an energetic basis [3]. The cost-competitiveness on a GHG abatement basis is also in focus [e.g. 4], thus making the GHG abatement cost developments of biofuels highly relevant.

The GHG abatement cost of different biofuels is highly variable between options, time-points and regions. A long-term cost-effective greenhouse gas abatement through the deployment of biofuels requires a thorough analysis on both the highly uncertain future potential costs [3,5] as well as on the uncertain biofuel pathway emissions [6–8], both of which depend on numerous factors, with land use as one combining factor. Particularly for biofuels from dedicated crops, the GHG abatement on a land use basis is an important indicator [7] and the discussion around land use has lead Germany to set a limit for conventional biofuels [9], albeit on an energetic basis.

Although both life-cycle emissions [6,7,10,11] as well as costs [3,5,12–15] of different biofuels have been well covered in literature, a combined detailed assessment of GHG abatement cost relations to date has not. For instance, Tomaschek *et al.* [16] performed such a study on the case of South Africa for conventional biofuels and Schmidt *et al.* [17] performed a comparison of different energetic usages of woody biomass in Austria, both for one single year. However, to our knowledge studies assessing

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relative GHG abatement costs and competitiveness developments over time for both conventional and advanced biofuels have not been published to date.

In this paper, these aspects are combined into an investigation on potential relative GHG abatement cost developments and uncertainties of biofuels from dedicated crops in a German context. The following research questions are assessed:

- How may the greenhouse gas abatement of crop based biofuels develop in a German context, and are there differences between energetic and land use functional units?
- How may the relative greenhouse gas abatement costs of German crop based biofuels develop in the future?
- How would the biofuel deployment develop if GHG abatement costs are the sole deciding factor, and how sensitive are the results to parameter variations?

2. Materials and methods

2.1. Modelling

In order to model the competition between different technology options, a simulation model has previously been developed. BENSIM (BioENergy SImulation Model) is a myopic recursive dynamic bottom-up least-cost simulation model with endogenous technological learning, seeking the least-cost mix of biofuel production options on a yearly basis for fulfilling a set demand. Through the recursive elements of learning effects and previously built capacities, path dependencies can be captured by the model.

The existing biofuel plant infrastructure in the region in focus (here Germany) is the basis at the initial time point of the modelling. For each year of the simulation, BENSIM first removes the plants that have reached the end of their life-time (assumed at 25 years). A minimum market price (p_{sys}) is then calculated, defined by the marginal cost (MC) of the most expensive option in the merit order[1] which is put into production to meet the given biofuel demand. If there are options which have total costs (TC = levelised capital cost + MC) lower than the p_{sys}, capacity investments take place, beginning with the option with the lowest TC. This continues until the market price adjusts on a level below the TC of still available options and the system reaches a (partial) equilibrium. After the investment phase, biofuel production takes place following the merit order based on marginal costs of production, until the given biofuel target is fulfilled. It is assumed that the biofuel demand can adapt in order to accommodate a cost-optimal deployment, and that it is not restricted by quota. BENSIM has been more thoroughly described in Millinger *et al.* [5]. For the feedstock costs, BENSIM was expanded with a methodology for estimating the costs of energy crops, through adding the per hectare profit of a benchmark crop (wheat) to the per hectare production cost of the energy crop [3].

The model is here transformed to have relative GHG abatement cost (instead of an energetic cost used previously) as the deciding factor, with a GHG abatement goal (instead an energetic goal) to be reached through substituting fossil fuels by the deployment of biofuels. The costs of the options on an energetic basis [€ GJ^{-1}] are calculated according to [5], with the feedstock costs calculated according to [3]. The costs are an output of the modelling, as learning effects affect the investment costs of the options if they expand due to their relative competitiveness. Feedstock costs are exogenous, with scenario differences.

In order to come up with the relative GHG abatement costs, some additional calculations are required. Firstly, the GHG emissions of each biofuel pathway need to be calculated and secondly, the total costs per GHG abatement unit need to be derived.

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[1] All options with existing capacities are sorted by ascending marginal cost, with the capacities brought into use in that order until the given demand is met.

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Equation 1 shows the total GHG emissions $\varepsilon^{(t)}_{tot,j}$ [kgCO$_{2eq}$ GJ$^{-1}_{fuel}$] of option j at time-point (t) as a sum of all emissions in the different stages of the process: F, feedstock cultivation; T_1, transport of the biomass to the conversion facility; P_1, first process step (with allocation factor α_1); P_2, second process step (α_2); transport of the fuel to the fuelling station T_2. The input data is all related to the feedstock input [t$_{FM}$], except for the final fuel transport, whereby a conversion to GJ$_{fuel}$ is performed through division by feedstock energy content e_j [GJ t$^{-1}_{FM}$] multiplied by fuel conversion efficiency η_j. The inputs for the feedstock cultivation are on a hectare basis, thus a division by yield Y_j [t$_{FM}$ ha^{-1}] is necessary. The emissions of all process steps preceding the end of P_1 are allocated to the fuel according to α_1, whereas those preceding the end of P_2 are additionally allocated according to α_2.

For each input to any process, for all inputs k belonging to the respective process steps, the input amount $\dot{m}^{(t)}_{k,j}$ is multiplied by its emission factor $\varepsilon^{(t)}_k$. Byproducts which are not considered in the allocation, but through a credit, are denoted cr.

$$\begin{aligned}\varepsilon^{(t)}_{tot,j} = & \frac{\alpha_1\alpha_2}{e_j\eta_j}\left(\frac{1}{Y^{(t)}_j}\sum_{k\in F}\dot{m}^{(t)}_{k,j}\varepsilon^{(t)}_k + \sum_{k\in T_1}\dot{m}^{(t)}_{k,j}\varepsilon^{(t)}_k + \sum_{k\in P_1}\dot{m}^{(t)}_{k,j}\varepsilon^{(t)}_k - \dot{m}^{(t)}_{cr,j}\varepsilon^{(t)}_{cr}\right) \\ & + \frac{\alpha_2}{e_j\eta_j}\left(\sum_{k\in P_2}\dot{m}^{(t)}_{k,j}\varepsilon^{(t)}_k - \dot{m}^{(t)}_{cr,j}\varepsilon^{(t)}_{cr}\right) + \sum_{k\in T_2}\dot{m}^{(t)}_{k,j}\varepsilon^{(t)}_k\end{aligned} \tag{1}$$

The total costs $TC^{(t)}_{j,e}$ are divided by the avoided fossil GHG emissions minus the biofuel pathway GHG emissions $\varepsilon^{(t)}_{tot,j}$, in order to come up with the relative[2] GHG abatement cost $TC^{(t)}_{j,\Delta\varepsilon}$ [€ kgCO$^{-1}_{2eq}$] for time point (t) of option j (Equation 2).

$$TC^{(t)}_{j,\Delta\varepsilon} = TC^{(t)}_{j,e}\left(\varepsilon_{ref} - \varepsilon^{(t)}_{tot,k}\right)^{-1} \tag{2}$$

2.2. Data and assumptions

The biofuels options included are the same as in Millinger *et al.* [5], where the techno-economic data are described in detail, with the addition of starch based (wheat) bioethanol, data for which is described in Ponitka *et al.* [18, p.40f]. The feedstock data are elaborated in Millinger and Thrän [3].

The GHG emissions are calculated on a well-to-tank (WTT) basis (see Figure 1). Thus, end-use efficiencies are not included, as these developments are dependent on numerous vehicle market factors which are outside of the scope of this paper to assess. It can be noted that specific emissions of average diesel and gasoline driven passenger cars have almost converged in the past decade [19, p.34].

2 i.e. without the avoided cost of the substituted fossil fuel

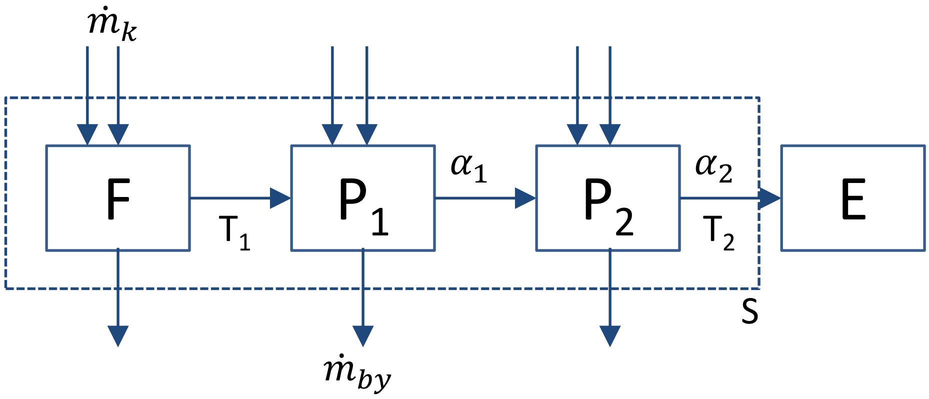

Figure 1. System boundaries of the Well-To-Tank (WTT) assessment from feedstock cultivation to tank for each pathway, shown by the dashed line S. The resulting abatement is compared on the basis of different functional units, such as GHG abatement per energy unit, cost per GHG abatement and GHG abatement per land area used. F=feedstock cultivation; T= transport; P_1= process one; P_2= process two; E= end use; $\dot{m}_k$= process inputs; $\dot{m}_{by}$= process by-products; α = allocation factor. The end use as well as potential indirect land use effects are not included. The biofuel combustion is assumed to be carbon neutral, as the carbon absorbed during plant growth is emitted, thus closing the cycle.

For the GHG-emissions of the pathways, detailed references for rape-seed based biodiesel (RME) [20], sugar beet based bioethanol [21] and silage maize based biomethane [22] were used as a basis. For biofuels based on short-rotation coppice (SRC), data from KTBL [23] and Neeft and Ludwiczek [24] were used for poplar, which was used to represent SRCs. For all options, the medium yields were assumed, as in Millinger and Thrän [3].

In the literature, a byproduct credit is included for liquid CO_2, which is output from the BeetEtOH process. Although this is based on a real plant (from where it is used for beverage carbonation), it can be argued that a large scale substitution of liquid fossil CO_2 is not feasible due to small scale uses of CO_2 (a large share of which is in the fossil industry) and a potentially large future oversupply [25, p.81ff]. Therefore, since the scope of this paper is on a systems level and not on the individual plant level, this credit is removed.

Switching from natural gas to wood chips for heating provides a significant contribution for heat intensive processes (the biomethane process was already in the literature assumed to be heated through wood chips). However, the wood chips cannot be assumed to be residual biomass, as the total German heat demand alone by far surpasses the wood residue potential[3]. Instead, poplar is assumed to be the biomass for the heat source (with an efficiency of η_{th}=80%), with price developments from Millinger and Thrän [3] consistent with the other biomass types and GHG emissions presented here.

For RME, an additional emission source is the methanol input, which can be assumed to be of renewable origin, with BeetEtOH as an approximation for the costs, emissions and land requirement.

The other main options to reduce the pathway GHG emissions are to swap from fossil diesel to biodiesel (or another biofuel) input for farming and transport, swapping to a fertiliser with less production emissions, as well as reducing the power emissions. All three options are assumed to rely largely on system improvements and not to be within the scope of producers' individual decision, and thus for all three an improvement over time is assumed.

For the N_2O emissions, the BioGrace I [28] and II [24] tools were used for the conventional and advanced options, respectively. The variation of field N_2O emissions is both crop specific as well as spatially dependent, and is highly variable. Thus, this factor must be included in a sensitivity analysis.

Land use change emissions as well as infrastructural emissions for conversion plants were excluded.

[3] The residual wood potential has been estimated to ca. 800 PJ [26]. Total current German heat demand amounts to ca 5000 PJ [27, p.C9]

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The absolute GHG abatement cost is dependent on the cost development of the substituted fossil fuel. In this paper modelling, focus lies on the relative GHG abatement costs and competitiveness, i.e. ignoring the fossil fuel cost. The same fossil fuel reference is used for all biofuels [83.8 kgCO_{2eq} GJ^{-1} 29]. While the emissions of this reference are relatively foreseeable, the cost developments are not: as a decoupling of agricultural products and fossil fuels is conceivable under a large global transition away from fossil fuels, developing consistent scenarios merging these two potentially independent variables is bound with perverse uncertainties. It is therefore in this paper abstained from assessing the absolute GHG abatement costs, as the results are likely misleading in the long term.

Table 1. Summarised important metrics for the biofuel options included. Some small contributions to the emissions come from other minor sources, which can be found in the respective detailed sources. The heat and power input data has been adapted from [5] for $BioCH_4$ [22], BeetEtOH [21] and RME [20], in order to fit with the detailed GHG calculation and allocation steps. For BeetEtOH (P1 dried beet pulp; P2 vinasse), StarchEtOH (Distillers Grains with Solubles, DDGS) and RME (P1 rape seed meal; P2 glycerol) co-products are produced, for which the emissions up until that point are allocated according to below. Emissions factors (EF): diesel 3.14 $kgCO_2\ l^{-1}$, sinking linearly to 20% of that value in 2050; N fertiliser 5.88 $kgCO_2\ kgN^{-1}$, sinking linearly to 20% in 2050; N_2O 298 $kgCO_2\ kgN_2O^{-1}$; power mix 0.47 $kgCO_{2eq}\ kWh^{-1}$ in the beginning, sinking according to [30, p.120]; heat 0.067 $kgCO_2\ MJ_{NG}^{-1}$ or wood chips calculated internally with η =0.8. For the transport of the biomass, 24 t_{FM} are transported, with 80 km loaded and 20 km empty, with fuel a consumption of 0.41 and 0.24 $l\ km^{-1}$, respectively. For the transport of the fuel, 50 t are transported, with 150 km loaded and 50 km empty and the same fuel consumption. For the gaseous fuels, 4.625 $kWh_{el}\ GJ^{-1}$ and 1.6 $MJ_{th}\ GJ^{-1}$ are assumed to be required for the injection into the gas grid. The transport assumptions were all used from Majer *et al.* [20], Meisel *et al.* [21], Oehmichen *et al.* [22]

Fuel		**$BioCH_4$**	**BeetEtOH**	**StarchEtOH**	**RME**	**BioSNG**	**LignoEtOH**	**FT**
Feedstock		Maize silage	Sugar beet	Wheat	Rape seed	Poplar	Poplar	Poplar
Yield medium	$GJ_{feed}\ ha^{-1}$	268-327	254	115	84	143-214	143-214	143-214
Yield low	$GJ_{feed}\ ha^{-1}$	208-268	176-215					
N fertilizer	$kgN\ (ha\text{-}a)^{-1}$	63.2	119.7	109.3	137.4			
Diesel equivalent	$l\ (ha\text{-}a)^{-1}$	96	175.9	106	82.6	2.1	2.1	2.1
N_2O field emis avg	$kgN_2O\ (ha\text{-}a)^{-1}$	4.66	4.59	2.92	4.19	1.28	1.28	1.28
N_2O field emis low	$kgN_2O\ (ha\text{-}a)^{-1}$	1.06	1.11	0.71	1.0	0.28	0.28	0.28
N_2O field emis high	$kgN_2O\ (ha\text{-}a)^{-1}$	23.37	20.78	13.27	19.45	6.72	6.72	6.72
Alloc. factor P1	[frac]		0.94	0.595	0.65			
Alloc. factor P2	[frac]		0.7		0.96			
Conv. eff. tot	η	0.56 -0.70	0.6-0.66	0.48-0.53	0.59-0.62	0.58-0.73	0.36-0.44	0.35-0.45
2^{nd} feedstock	$kg\ GJ^{-1}$				3.3 (MeOH)			
Net heat input	$kWh\ \ GJ^{-1}$	65	134	123	22	0	0	0
Net power input	$kWh\ \ GJ^{-1}$	14	10	17	1.6	31	35	35

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2.3. Scenarios

For all scenarios, the GHG abatement target for crop-based biofuels is set at 4 $MtCO_{2eq}$ for the beginning[4], or 2.5% of the current 160 $MtCO_{2eq}$ total German transport emissions [31], increasing linearly by a factor of five to 20 $MtCO_{2eq}$ in 2050 (or about 12.5% of current fuel demand). The mostly relevant GHG inputs (fertiliser, process heat) are assumed to be optimised already in the base case, as compared to literature.

All scenarios include all biofuels, both liquid and gaseous. Cases including only liquid fuels are assessed in the sensitivity analysis, in order to assess the competitiveness if gaseous fuels are not a large-scale solution. A 4% a^{-1} reference feedstock price increase is assumed as a basis, in line with developments in the past decade [3].

The power mix contributes significantly to the GHG emissions of biofuels. Within the goals of the German energy transition, different pathways can be taken in order to achieve the set GHG reductions and renewables targets. A near linear development [30, p.123] can be contrasted to one where coal power is quickly decommissioned [30, p.120], leading to earlier reductions despite the end point goal being the same. The effect of this is assessed, with a moderate power mix in scenario a, and a progressive power mix in scenarios b-c.

Silage maize and sugar beet have a high humus requirement, which in the long run may be detrimental to the land fertility if not curbed, through reducing yields and a combination with other crops which have a net negative humus requirement [23, p.272ff.]. With the medium yields assumed, this can to some extent be assured, but it is still interesting to assess the effect on the competitiveness if low yield spans are assumed for these two crops (see Table 1). Lower yields are assumed in scenario c.

Table 2 summarises the main scenarios.

Table 2. Scenario summary. The base case (a) includes both liquid and gaseous fuels and assumes a moderate power mix development according to [30, p.123], a wheat price increase of 4% a^{-1}, GHG optimised process heat and medium yields for all crops. Scenario variations compared to base case are listed.

	Description
a	Base - all fuels, moderate power mix
b	Progressive power mix development [30, p.120]
c	Prog. power mix, low yields for sugar beet and maize

2.4. Sensitivity analysis

The sensitivity analysis is in this paper performed through Monte Carlo simulation, which is a way of mapping out the solution space depending on variance in input variables without calculating all possible combinations. The method used here is elaborated in Millinger and Thrän [3].

Table 3 summarises the parameters which are varied in the sensitivity analysis. The first nine parameters are the same as in Millinger and Thrän [3], and are motivated there. Additionally, some parameters relevant for the GHG emissions are necessary. The soil N_2O emissions [8] are varied between the low and high values (Table 1), with a uniform probability distribution. All parameters in Table 3 are varied simultaneously, in a random fashion.

As the power mix and feedstock cost increases as well as the inclusion of gaseous biofuels have a significant impact on the competitiveness, the results are shown over these three dimensions, independent of the main scenarios in Section 2.3: moderate and progressive power mix developments; reference feedstock price increases of 3% and 4% a^{-1}; including all fuels or only liquid fuels. Four main sensitivity

[4] Corresponding to the average for crop-based biofuels used in Germany 2014-2016 [2], with assumed GHG abatement values for the crop shares of 63% for EtOH and 55% for RME, compared to a reference of 83.8 $kgCO_{2eq}$ GJ^{-1}.

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cases result, for which the developments of key options are shown, with and without gaseous fuels included.

Table 3. Parameters varied in the Monte Carlo sensitivity analysis. All parameters have a uniform distribution over the span. The distributions which vary between the technology specific minimum and maximum values start at a random point along the span and increase linearly to a value randomly between the starting point and the maximum value. The technology-specific values are individually randomised for each technology option. The yields are varied within the medium ranges for all crops.

Parameter	Unit	Span
Initial investment cost	M€ MW_{cap}^{-1}	±25%
Exogenous learning	years	3-10
Discount rate	%	5-10
Conversion efficiency	η	min-max
Yield	t_{FM} ha^{-1}	min-max
Establishment cost (perennials)	€ ha^{-1}	±25%
Investment distribution limit	%	10-20
Path dependency factor	%	15-25
Capacity ramp	%	100-200%
Soil N_2O emissions	%	low-high

3. Results

The results are shown first for the biofuel GHG emissions, then for the relative GHG abatement costs, followed by the scenario modelling and finally sensitivity analysis.

3.1. Biofuel GHG emissions

The resulting GHG emissions are shown in Figure 2. For each biofuel option, the far left bar is the standard literature case (for reference; not used in the scenarios). The second bar shows the present pathway emissions in the base case when correcting for practises that can be sustained on a larger scale and assuming biomass from dedicated crops for the heat and secondary feedstocks. The third bar shows the pathway emissions in the last year of the base scenario (a), where the power mix is nearly fully renewable, and renewable fuels and fertiliser are used as inputs.

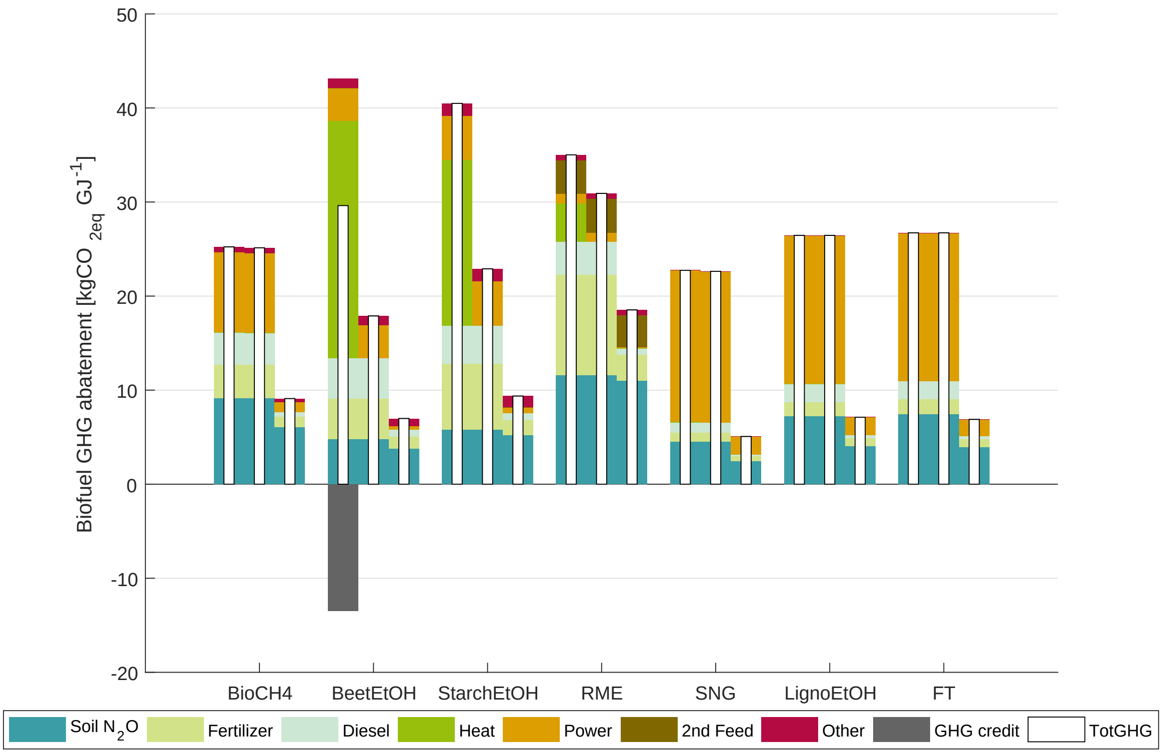

Figure 2. GHG emissions for the biofuel options, broken down to their sources [$kgCO_{2eq}$ GJ^{-1}]. The leftmost bar for each option is the reference literature case; the middle bar shows the results for the start year of the base case, with renewable heat input; the rightmost bar shows the results for the last year of the base case, where the power mix is cleaner, yields and conversions efficiencies improved, and renewable fuel and fertiliser inputs assumed.

In the beginning, thus BeetEtOH is the better performing option in terms of GHG abatement per energy unit, with SNG second and StarchEtOH third best. Currently dominant RME is in fact the worst option. Through the system improvements, the advanced options gradually improve and overtake BeetEtOH (Figures 2 & 3). Assuming a fast power mix emission improvement through coal decommission as in scenarios (b) and (c), SNG is fast the best option, whereas at moderate power mix developments this takes considerably longer. Of the advanced options, SNG performs clearly better due to higher conversion efficiencies and lower power demand, whereas LignoEtOH and FT-diesel perform similarly to each other. It should however be noted that the options, with the exception of RME, achieve between 67-79% GHG abatement in the beginning, and again excepting RME, between 88-96% GHG abatement in the end. Thus, the differences are relatively small, leaving ample room for cost developments to change the priority order when comparing relative GHG abatement costs.

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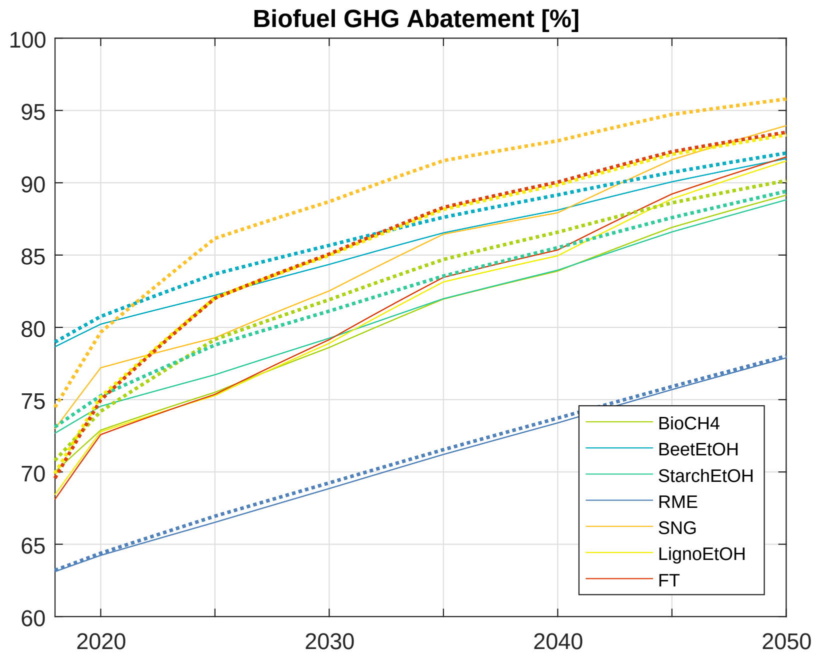

Figure 3. Biofuel GHG abatement development, compared on an energetic basis with the fossil reference. The solid lines show the development at a moderate power mix development, whereas the dotted lines show the development at a more progressive power mix development.

It can be noted that the "other" factors are relatively marginal in comparison to the other sources (Figure 2). Thus, simplified calculations excluding the other inputs where data are not available (such as for the advanced options) provide a sufficient estimate for the total GHG emissions.

As a consequence of switching from natural gas to wood chips from dedicated crops for the heat input, the land required for the options increases corresponding to the heat requirement (Figure 4). For BeetEtOH, the land requirement increases by 49% while at the same time increasing the GHG abatement by 22%; for StarchEtOH the land required increases by 36% with a 41% GHG abatement increase; for $BioCH_4$ land use increases by 24% (the reference already assumed renewable heat). For RME, the land use increases by 9% through a renewable heat input, with an additional 3% through the methanol input, while increasing GHG abatement by 8%.

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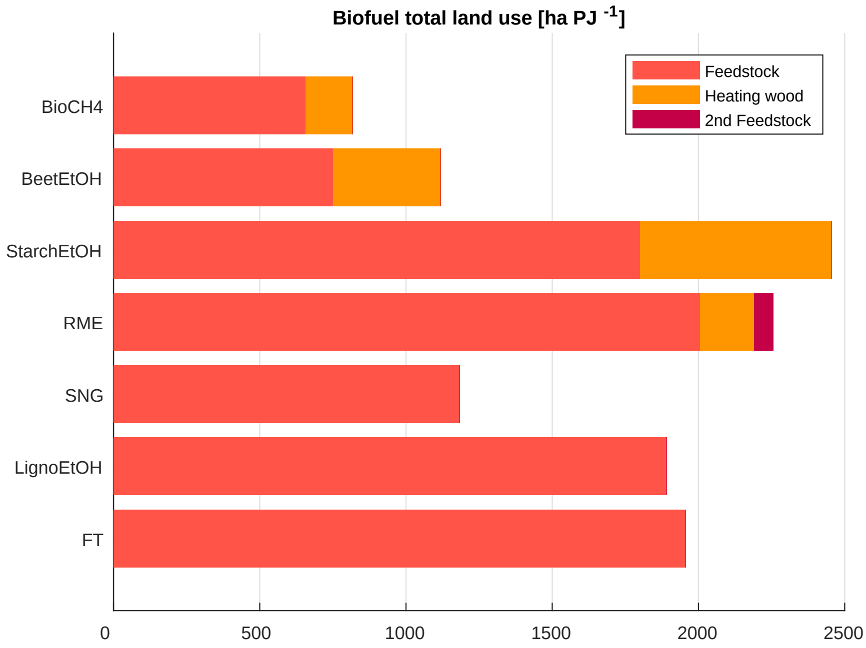

Figure 4. Biofuel land requirement by source in the first year of the base case.

The GHG abatement per hectare is shown for the base case in Figure 5. RME and StarchEtOH can abate 2-3 tCO_{2eq} ha^{-1}, whereas $BioCH_4$ and BeetEtOH are the present day best, with 6-7 tCO_{2eq} ha^{-1}. With a clean power mix and renewable input fertiliser and fuel, in addition to yield and conversion efficiency improvements, $BioCH_4$ and SNG can potentially achieve over 12 tCO_{2eq} ha^{-1}. BeetEtOH can achieve a maximal 8 tCO_{2eq} ha^{-1}, somewhat more than the liquid advanced biofuel options.

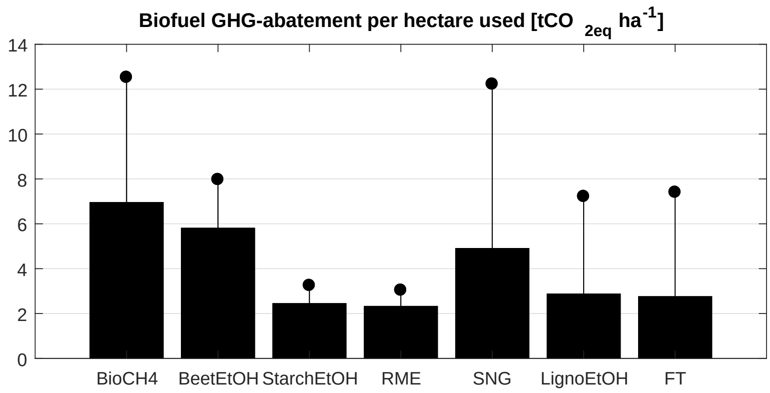

Figure 5. Biofuel GHG abatement per hectare in the base case with medium yields for all crops. The bar shows the initial GHG abatement, whereas the whisker extends to the GHG abatement in the last year.

Notably, the merit order of the fuels differs when compared on a hectare basis and an energetic basis. Whereas $BioCH_4$ is the best both for the beginning of the simulation in the base scenario in terms of GHG abatement per hectare as well as in the long run (Figure 5), it is only fourth best in terms of GHG abatement on an energetic basis for the beginning (Figure 3) - even after StarchEtOH - and it is only fifth best in the long run.

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3.2. Biofuel relative GHG abatement cost

From the competition modelling, relative GHG abatement cost developments emerge, which are highly different between scenarios. In Figure 6, the extreme span of possible outcomes in the scenarios is sketched between scenarios (a) and (c), with a more progressive power mix development and lower sugar beet and silage maize yields in the latter case.

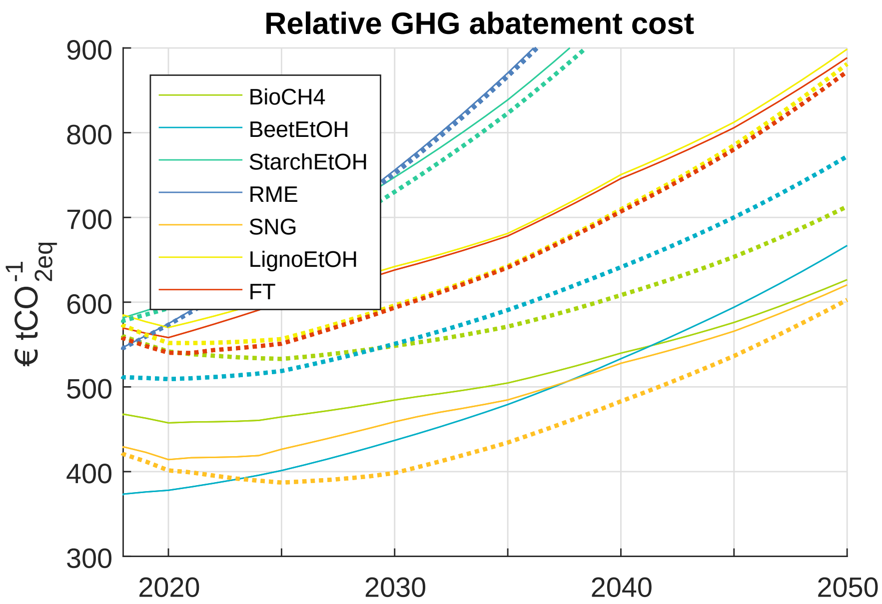

Figure 6. Biofuel relative GHG abatement cost developments [€ tCO_{2eq}^{-1}] in scenarios (a, solid lines) and (c, dotted lines). Some developments are outside of the plot: the cost of RME increases to ca. 1350 € tCO_{2eq}^{-1} and the cost of StarchEtOH increases to ca. 1230 € tCO_{2eq}^{-1} in both cases.

In scenario (a), BeetEtOH is the least cost option until 2037, when it is overtaken by SNG due to the combined effects of input emission improvements, conversion efficiency and yield increases and technological learning. SNG remains the least-cost option, slowly diverging with, but never surpassed by $BioCH_4$. Due to the annual 4% reference feedstock price increase, the minimum selling prices of all options generally increase. The exception to this are all advanced fuels in the first few years, when mainly the power mix emission reductions lead to slight overall relative GHG abatement cost reductions.

The least cost option over time increases from ca 370 to 620€ tCO_{2eq}^{-1}. The two liquid advanced biofuel options start from ca. 570€ and increase towards 900€, while the currently dominant biofuels RME and StarchEtOH increase from around 550 and 580 € to over 1300 and 1200 € tCO_{2eq}^{-1}, respectively. The advanced liquid fuels remain at an around 50% higher cost than the least-cost fuel, whereas for RME and StarchEtOH, the difference increases substantially over time.

In scenario (c), significant differences compared to (a) can be seen. Primarily, SNG starts off as the least cost option, or compared to with medium sugar beet yields, quickly surpasses BeetEtOH. Due to a combination of more rapid input GHG emission decreases and technological learning, minimum selling prices remain around 400 € tCO_{2eq}^{-1} until 2030, with a subsequent increase to 600 € tCO_{2eq}^{-1} towards the end.

The two liquid advanced biofuel options increase towards 870€, while RME and StarchEtOH develop similarly to in scenario (a). The advanced liquid fuels also in this case remain at an around 50% higher cost than the least-cost fuel, while the difference increases over time for RME and StarchEtOH. For the advanced liquid fuels, it can be observed (Figure 6) that they remain at higher cost than BeetEtOH even in scenario (c).

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Notably, between diesel fuels, FT-diesel is quickly competitive with RME in any case, and thus sub-quota for diesel and petrol would favour advanced options, albeit at a higher cost than without sub-quota.

3.3. Scenario modelling

From the GHG abatement cost competition, the resulting production developments can be seen in Figure 7. In all cases, both StarchEtOH and RME fall out of the market rather quickly. Instead BeetEtOH, as well as in the scenarios where all fuels are included SNG and $BioCH_4$, gain market shares in differing proportions between the scenarios. The advanced liquid options do not achieve significant market shares in any scenario.

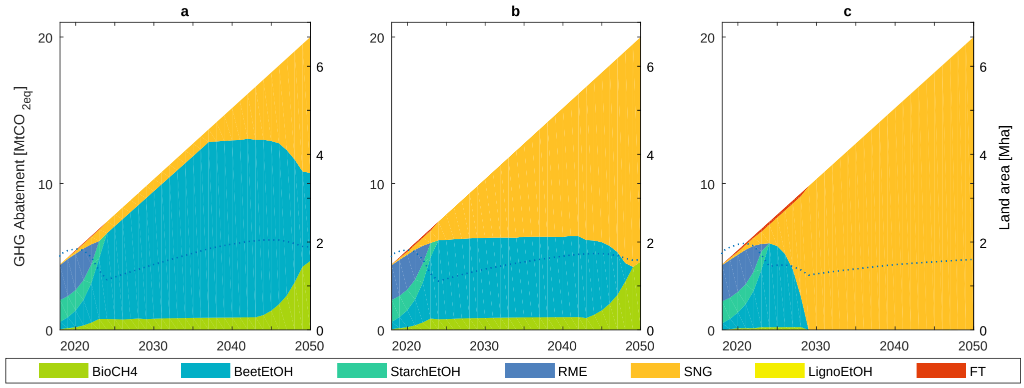

Figure 7. Biofuel competitiveness based on relative GHG abatement cost in the scenarios. The areas show the total performed GHG abatement through each option (left axis), whereas the dotted line shows the total arable land required (right axis). The base scenario (a) includes both liquid and gaseous fuels and assumes a moderate power mix development according to [30, p.123], a wheat price increase of 4% a^{-1}, GHG optimised process heat and medium yields for all crops. In scenario (b), the power mix is more progressive and in scenario (c), additionally the sugar beet and silage maize yields are assumed within the low range in Table 1.

In the base case (a), BeetEtOH dominates in the medium term, with SNG and $BioCH_4$ both gaining market shares, respectively from ca. 2035 and 2040 onwards. At a more progressive power mix (b), SNG starts gaining market shares more rapidly, while $BioCH_4$ remains almost the same as in the base case. Gaseous fuels dominate fully towards the end. If additionally low yields for silage maize and sugar beet are assumed (c), SNG fully dominates the market within a decade.

The resulting required total arable land (including for heating purposes and secondary feedstocks) differs marginally between the scenarios, with an almost constant ca. 2 Mha used once RME and StarchEtOH are displaced (Figure 7). Thus, yield and conversion efficiency improvements compensate for the GHG abatement target increase.

3.4. Sensitivity analysis

From the sensitivity analysis, the resulting occurrences at different total market shares are shown for four cases (Figure 8), where the reference feedstock costs increase by 3% ("1") and 4% ("2") a^{-1}, while the power mix is either moderate (A) or progressive (B). At moderate power developments, BeetEtOH dominates, with $BioCH_4$ more often emerging at slightly higher cumulative market shares at higher feedstock cost increases. SNG remains at below 10% total market share in around 80% of the cases, with a slightly higher occurrence of market shares of over 10%. For SNG, there is a jump in the amount of occurrences at over 50% cumulative market shares, indicating that under favourable conditions, a threshold is surpassed early, leading to learning effects and increasing returns.

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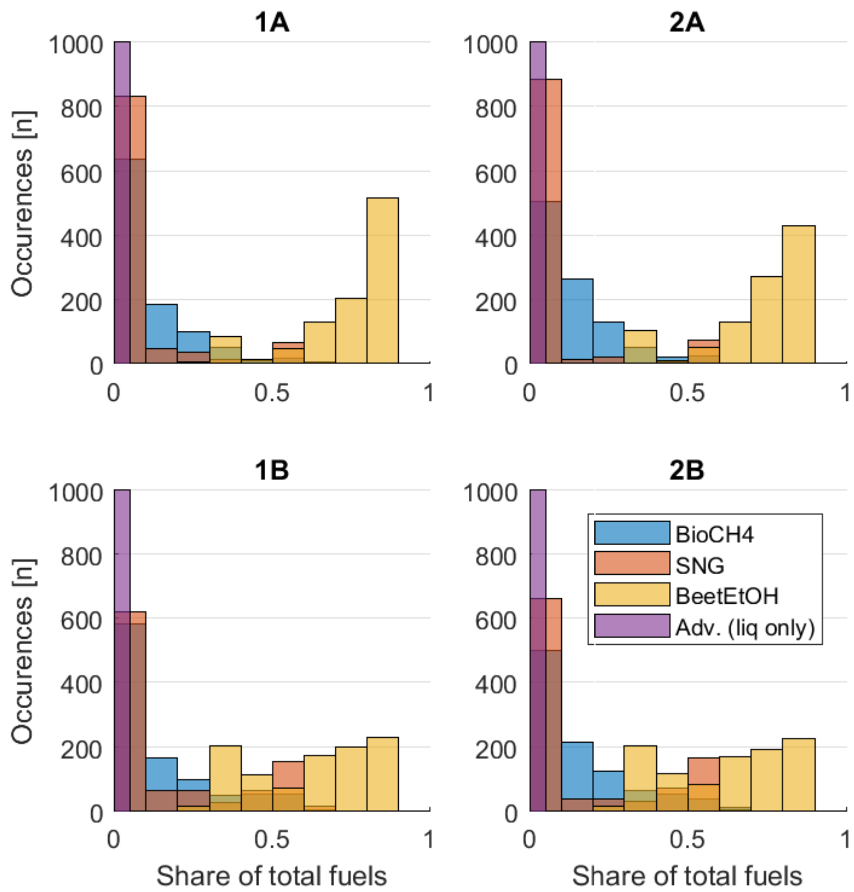

Figure 8. Sensitivity of biofuel production shares, at annual 3% (1) and 4% (2) wheat price increases, with moderate (A) and more progressive (B) power mix developments. 2A and 2B correspond to the sensitivities within scenarios (a) and (b). The number of occurrences among the 1000 runs at total cumulative biofuel shares (on an energetic basis) of between 0-10%, 10-20% etc. are shown in the histogram. The shares are of the total cumulative biofuel deployment over the whole time span. The colour tone of the bars in the histogram is summed where they overlap. In each sub-plot, the emergence of $BioCH_4$, SNG and BeetEtOH for runs with all fuels included is shown, as well as is the emergence of advanced liquid fuels (LignoEtOH and FT-diesel summed together) for runs with only liquid fuels. Thus, each sub-plot shows two separate sets of sensitivity runs with 1000 runs each, totalling 4000 runs for all subplots.

At more progressive power mix developments, BeetEtOH still dominates in most cases, but the occurrences between 30-90% market share are more uniformly distributed. $BioCH_4$ behaves similarly to in the case of a moderate power mix development, while the effect on the competitiveness of SNG is substantial, with substantially more occurrences between 10-60% cumulative market shares.

In very few of the cases do the gaseous fuels arrive at cumulative market shares of above 60%, and BeetEtOH achieves cumulative market shares of above 30% in almost all cases.

For the advanced liquid biofuels, the share remains at below 5% in all of the observed cases, despite the fact that only liquid fuels were included.

The biofuel cost sensitivity is shown in Figure 9. In contrast to on an energetic basis [3], the sensitivity of the relative GHG abatement cost of RME is high, due mainly to the uncertain soil emissions. The relative GHG abatement costs of the advanced liquid biofuels are also highly uncertain, with more than a factor of three difference for the low and high end even at the beginning. In contrast, SNG shows clearly less uncertainty, despite stemming from the same feedstock. BeetEtOH, followed by $BioCH_4$ show the lowest spans, across time-points.

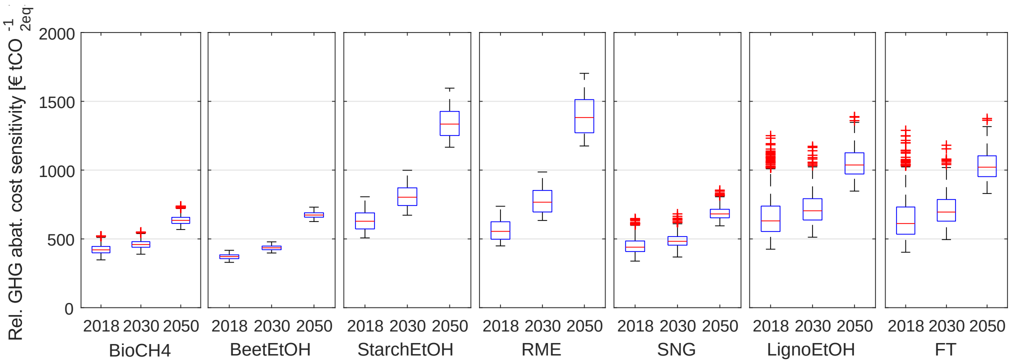

Figure 9. Sensitivity of total cost of the GHG abatement of biofuels in 2018, 2030 and 2050 in sensitivity case 1B (corresponding to the base scenario (a)), at a constant annual 4% wheat price increase and the other variables randomly varied according to Section 2.4. The red lines show the median, the bottom and top edges of the blue box show the 25th and 75th percentiles, respectively, the whiskers extend to a maximum of 1.5 times the length of the box and outside of this interval outliers are plotted with a red cross.

4. Discussion

In this paper, feedstock cost developments of biofuels have been combined with GHG abatement developments in order to estimate future spans of relative GHG abatement costs for the different options, and their competitiveness. From the point of view of a cost-optimal GHG abatement through the deployment of biofuels, the current practise emerged as increasingly divergent to the best options.

Whereas advanced biofuels were found to be competitive only at low feedstock price increases when comparing the fuels on an energetic basis [3], especially SNG was found to be competitive even at higher feedstock price increases on a GHG abatement basis. Furthermore, the power mix development is in fact more important for the competitiveness of advanced biofuels than are feedstock cost increase differences. This is due to the fact that the power mix emissions have a substantially different impact on the various biofuel options, as the power input requirements differ. Differing soil emissions result in additionally divergent GHG abatement and especially GHG abatement and thus relative GHG abatement cost uncertainty.

Liquid advanced biofuels were competitive only when gaseous fuels were not included, and even then only at very favourable conditions. In the sensitivity analysis, all relevant factors except lower sugar beet yields were varied, resulting in an almost complete absence of advanced liquid biofuels. Thus, the competitiveness of advanced liquid biofuels requires low sugar beet yields to be enforced, in addition to other favourable circumstances working together, as well as gaseous fuels being excluded.

The biofuel amounts required towards the end of the time span correspond to about 13% of current fuel demand (or in the case of large expansion of e.g. electric vehicles, a correspondingly higher market share). A continuation of the present quota would require marginally more, due to the slightly lower GHG abatement of advanced FT-diesel, but at an at least 50% higher cost compared to without sub-quota for diesel and gasoline fuels. The resulting least-cost practises would imply mixing BeetEtOH into petrol at higher shares than today, requiring some modifications to the vehicles [32, p.21], and for gaseous fuels, the current demand needs to increase manifold in order to accommodate the least-cost developments. If this is not possible, BeetEtOH is a possible long-term second-best option, albeit with significantly lower GHG abatement potential per unit of arable land compared to the gaseous options.

A slight trade-off was found between optimising the GHG emissions from the input heat and the resulting additional land required for the lignocellulosic crops used for this purpose, which in the case of BeetEtOH amounted to 49%, while increasing the GHG abatement by 22%. Thus, this additional land is motivated, but the benefits may be somewhat reduced through emissions related to land use.

Indirect Land use change (iLUC) emissions have been highlighted as a problem with crop cultivation. If applied for the attribution to the GHG abatement of the biofuel options, these emissions are a function

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of yield, as well as are to some extent direct soil emissions[5]. Thus, both are arguments for increasing the hectare GHG abatement of biofuels, through swapping from the presently used low-yielding crops to higher yielding options. The highest yielding options included here are $BioCH_4$ and SNG, both gaseous fuels. The former is based on silage maize, which (similarly to sugar beet) consumes soil humus [23, p.272ff.] and in the worst case has relatively high soil N_2O emissions. Soil erosion and N_2O emission need to be monitored and curbed in order to ensure sustainable biofuel practises. A more holistic approach including all relevant environmental factors is necessary in order to avoid sub-optimal practises, and the risk of high soil emissions needs to be taken into account and assessed.

GHG abatement cost in terms of € tCO_{2eq}^{-1} does not give the full picture, as the GHG abatement in energetic terms deviates from that in terms of required arable land, which sets a hard limit for biofuels from dedicated crops. For $BioCH_4$, the difference between the GHG abatement on an energetic basis compared to on a land use basis is particularly large (cf. Figures 3 and 5). The GHG abatement cost difference between $BioCH_4$ and BeetEtOH as well as SNG was also found to be large (Figure 6) compared to the GHG abatement per land used.

The total possible GHG abatement is limited by available arable land and residual biomass, and thus for an overall optimal GHG abatement, total yields need to be taken into account. A GHG abatement cost also ignores other relevant environmental metrics [see e.g. 34], such as biodiversity, soil erosion, pesticide use, freshwater use and land use change. In such a comparison, it would be beneficial to compare biofuel options according to land area, as some biofuels may perform worse in some metrics but through higher yields would free land which can be for instance conserved [cf. 35], thus potentially rendering the overall impact better.

Thus, in terms of several both direct and indirect environmental aspects, as well as in terms of economic [3] and social aspects (e.g. food competition), a switch to higher yielding fuels would be beneficial, especially if at the same time other relevant environmental effects are monitored and curbed. In order to achieve such a shift, presently used biofuels need to be exchanged with either bioethanol or gaseous fuels if the least-cost target and highest GHG abatement are to be achieved, or if this is proven to be infeasible, replacing RME with FT-diesel would be necessary in terms of both GHG abatement cost as well as absolute GHG abatement. For the advanced options, especially liquid ones, both unpredictable feedstock costs and highly uncertain investment costs may inhibit such a development [3]. However, in terms of GHG abatement, the benefits are more clear than in energetic terms.

As noted in Millinger and Thrän [3], perennials currently have a higher market price than those resulting with the method used, which can be at least partly explained by small markets as well as farmer risk considerations. Until the market demand for perennial lignocellulosic biomass is stable enough for the investment risk to be reduced, higher prices should be expected, thus potentially postponing the deployment of biofuels based on such crops.

The use of so called degraded or marginal lands has been suggested in order to avoid land use change emissions and food competition [36]. Although yields would be strongly affected compared to currently used arable land [37], the competitiveness compared to non-perennials is obvious, as the latter would likely not be cultivated on such lands.

5. Conclusions

In this paper, a thorough assessment of long term relative GHG abatement cost developments of biofuel options in Germany has been carried out. The better performing of the included biofuel options in terms of GHG abatement cost was sugar beet based ethanol for the short to medium term, and SNG for the medium to long term.

[5] the latter is also related to agricultural practises, which can be substantially improved [33]

The currently most common biofuels were found to have over 40% higher relative GHG abatement costs than the least cost option for the beginning, and increasing substantially over time, due to higher relative feedstock cost increases.

Liquid advanced biofuel options were only found to be competitive at a combination of favourable circumstances, and were in normal circumstances about 50% more expensive than the least-cost option throughout the whole time span.

The competitiveness of advanced biofuels was found to be more sensitive to the emissions development of the power mix than on feedstock costs, as this factor is more differentiated between the high-performing fuels.

Through switching from currently most common biofuels RME and StarchEtOH to $BioCH_4$ and SNG, the GHG abatement per land area can potentially be increased by a factor of five. For the present day, a switch to $BioCH_4$ and BeetEtOH with renewable heat sources trebles the spatial GHG abatement, despite the fact that the heat source requires substantial amounts of land.

A discrepancy between GHG abatement in relation to energetic output compared to land output was found, having important consequences especially for the competitiveness of $BioCH_4$. $BioCH_4$ was mostly not GHG abatement cost competitive and did not achieve high market shares in any scenario, while on a land use basis it was the best already in the beginning as well as in the long term. Although the land use was reflected to some extent in the cost competitiveness, larger differences and a substantially switched merit order resulted when comparing them on an area basis.

Due to the large spread of possible pathway emissions as well as cost developments, measures to quantify and curb emissions in each section of the pathway are called for in order to reduce uncertainties, starting from the specific field used, through the conversion as well as in the end use.

Finally, there are strong arguments, both social, economic and environmental, for including the required arable land for biofuels into policy and functional units, instead of merely energy or GHG abatement [cf. 9]. Such a differentiation between crop-based biofuels can potentially lead to a substantially higher GHG abatement from the same arable land area, through incentives to switch to higher yielding gaseous options.

Supplementary Materials: The following are available online at www.mdpi.com/link, Figure S1: title, Table S1: title, Video S1: title.

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Abbreviations

The following abbreviations are used in this manuscript:

BENSIM	Bioenergy simulation model
BeetEtOH	Sugar beet based bioethanol
$BioCH_4$	Silage maize based biomethane
DM	Dry matter
EF	Emission factor
FM	Fresh matter
FT	Woody biomass (poplar) based Fischer-Tropsch-diesel
GHG	Greenhouse gas
iLUC	Indirect land use change
LignoEtOH	Woody biomass (poplar) based bioethanol
LUC	Land use change
MC	Marginal cost
NG	Natural gas
RME	Rape seed methylester - biodiesel
SNG	Substitute natural gas
SRC	Short rotation coppice
StarchEtOH	Starch crop based bioethanol
TC	Total cost
WTT	Well to tank

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