Millinger, M., Meisel, K., **Thrän, D.** (2019):
Greenhouse gas abatement optimal deployment of biofuels from crops in Germany
Transport. Res. Part D-Transport. Environ. **69** , 265 – 275

http://dx.doi.org/10.1016/j.trd.2019.02.005

Greenhouse gas abatement optimal deployment of biofuels from crops in Germany

M. Millinger[a,*], K.Meisel[b], D. Thrän[a,b]

[a] *Department of Bioenergy, Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany*

[b] *Department of Bioenergy Systems, Deutsches Biomasseforschungszentrum gemeinnützige GmbH—DBFZ, Torgauer Straße 116, 04347 Leipzig, Germany*

Abstract

The optimal role of biofuels from energy crops for greenhouse gas (GHG) abatement in the German transport sectors is investigated under different progressive long-term scenarios, from a set arable land area corresponding to current use. The sectors included are land passenger and goods transport, shipping and aviation. The GHG abatement from the same land area can be increased by a factor of five through switching to higher yielding biofuel options. Silage maize based biomethane and wood based Synthetic Natural Gas (SNG), in either gaseous or liquefied form are the options with the highest GHG abatement potential per arable land unit, and thus markets where such fuels are an option should be prioritised. Sector fuel restrictions combined with fuel yields resulted in the land passenger sector to be the first priority for maximising GHG abatement, followed by land goods transport, shipping and finally aviation. Only when the previous sectors have been covered by renewable options do the following become relevant and thus a large transition is required before aviation biofuels or any liquid advanced biofuel become the climate optimal use of biomass. Applying admixture quotas to sub-sectors yields a lower GHG abatement than an optimal strategy.

Keywords: biofuels, greenhouse gas abatement, GHG, optimization, transport, land use

1. Introduction

The Paris Agreement goal of staying below 1.5°C of global warming [44] requires rapid global efforts of decarbonisation [36]. Beside a goal of complete decarbonisation until 2050, the path leading there is crucial, with early system shifts potentially significantly reducing the cumulative carbon emissions over the time period.

A complete decarbonisation of the transport sector relies heavily on power based solutions, such as electric vehicles (EVs), hydrogen (H_2) and other electrofuels (Power-to-X, PtX) [1, 37, 8, 40, 27]. However, the deployment of these alternatives requires some time and the environmental advantage is dependent on the renewables development in the power mix, which determines the GHG emissions of power based transport solutions [34]. Also, some sectors, such as shipping, goods transport and aviation may be slower than personal transport in adapting to renewable modes and fuels, due to fewer available options [24, p.19].

Biofuels are another option to reduce the climate impact of transport, which are already being used. However, potential and sustainability constraints set limits for their deployment and thus biofuels may play an important role as an intermediate decarbonisation solution until other renewable options can take over.

In this paper, the optimal role of biofuels from energy crops for greenhouse gas (GHG) abatement in the German transport sectors is investigated under different long-term scenarios. The following research questions are assessed:

*Corresponding author. Tel: +49(0)3412434595
Email address: markus.millinger@ufz.de (M. Millinger)

- How would biofuels from energy crops be deployed in order to maximise GHG abatement under progressive decarbonisation scenarios?
- How do biofuel deployment, GHG abatement and costs differ under different scenarios?

The research questions are answered with the aid of an optimisation model, maximising the GHG abatement of the biomass allocation from the currently used arable land area for biofuels. Nine progressive scenarios are calculated in order to analyse the dependence of the results to variations in future developments and policy.

2. Materials and methods

In this section, the modelling is first introduced, followed by the data and assumptions and finally the assessed scenarios are described.

2.1. Modelling

For optimising the GHG abatement of biofuels, a model has been developed, building on the model BENSIM [32, 31, 33]. Instead of simulating the biofuel development, an optimisation module has been developed in GAMS. The technology and scenario data are imported and generated in BENSIM/Matlab, and then exported to GAMS. Using the Cplex solver, the optimal GHG abatement under the given restrictions is calculated and the results sent back to Matlab, where plotting is performed.

The model is fully deterministic, bottom-up and uses perfect foresight across all dimensions. The objective function used here is maximising the GHG abatement ε_{tot} [tCO_2eq] over the whole time period t, as a sum of all produced biofuels $\pi_{i,t}$ [PJ] multiplied by their net GHG abatement $\varepsilon_{i,t} - \varepsilon_{sub,t}$, with $\varepsilon_{sub,t}$= 83.8 [ktCO_2eq PJ^{-1}] (as defined in the EU renewable energy directive [13]), for all options i and time points t.

The model restrictions are as follows: the biofuel production $\pi_{i,t}$ for option i in time t is the sum of production in all sectors s, with a total demand $\delta_{s,t}$ [PJ] for each sector which sets an upper limit for the total production of all options for each sector in each time point, but must not be met. The production cannot surpass the capacity available $\kappa_{i,t}$.

The capacity is the sum of the capacity in the previous year, $\kappa_{i,t}$ [PJ] and new capacities $\kappa^+_{i,t+1}$, minus the capacities $\kappa^+_{i,t-\hat{t}_i}$ which have reached the end of their life time $\hat{t}_i$=25 [a] years. Capacities available at the beginning κ_0 are gradually decommissioned linearly over the time span of one plant life time. Capacity expansion is subject to the sum of a constant ramp factor r_{min}=0.1 [PJ a^{-1}] and the product of standing capacity and r_f=0.5, and cannot surpass r_{max}=25 [PJ a^{-1}]. This sets a system inertia and ensures that capacities cannot expand suddenly, resulting in S-curve shaped market share increases [cf. 16].

The required land for each option is given by the production, divided by yield $Y_{i,t}$ [PJ_{feed} Mha^{-1}] times conversion efficiency $\eta_{i,t}$ [PJ_{fuel} PJ^{-1}_{feed}]. The total land use cannot surpass Λ_t for each time point (=1.5 [Mha] in all but one scenario in this paper).

If a biofuel quota is in place, the quota q_t=0.5 is the fraction of diesel fuels $i \in I_{di}$ to ethanol $i \in I_{pe}$. Parameters and decision variables are summarised in Table 1.

$$\max_{\varepsilon} \quad \varepsilon_{tot} = \sum_{i,t} (\varepsilon_{i,t} - \varepsilon_{sub,t}) \cdot \pi_{i,t} \tag{1a}$$

s.t.

$$\pi_{i,t} = \sum_{s} \pi_{i,t,s}, \qquad \forall (i,t,s) \in (I,S,T), \tag{1b}$$

$$\delta_{s,t} \geqslant \sum_{i \in s} \pi_{i,s,t}, \qquad \forall (i,s,t) \in (I,S,T), \tag{1c}$$

$$\pi_{i,t} \leqslant \kappa_{i,t}, \qquad \forall (i,t) \in (I,T), \tag{1d}$$

$$\kappa_{i,t+1} \leqslant \kappa_{i,t} + \kappa^{+}_{i,t+1} - \kappa^{+}_{i,t-\hat{t}_i}, \forall (i,t) \in (I,T), \tag{1e}$$

$$\kappa^{+}_{i,t+1} \leqslant r_{min} + r_f \cdot \kappa_{i,t}, \qquad \forall (i,t) \in (I,T), \tag{1f}$$

$$\kappa^{+}_{i,t+1} \geqslant r_{max}, \qquad \forall (i,t) \in (I,T), \tag{1g}$$

$$\Lambda_t \geqslant \sum_{i,s} \pi_{i,s,t} \left(Y_{i,t} \eta_{i,t}\right)^{-1}, \qquad \forall (i,s,t) \in (I,S,T), \tag{1h}$$

$$q_t \sum_{i \in I_{pe}} \pi_{i,s_{pl},t} = \sum_{i \in I_{di}} \pi_{i,s_{pl},t}, \quad \forall (i,s,t) \in (I,S,T) \tag{1i}$$

Table 1: Parameters and decision variables in the modelling. Values are given if they are constant across all dimensions (I=biofuel option; S=sector; T=time) and scenarios. If the values differ between dimensions and/or scenarios, "Diff" is stated. Decision variables are "Free".

Parameters	**Symbol**	**Value**	**Unit**
Pathway emissions	$\varepsilon_{i,t}$	Diff	$ktCO_2eq\ PJ^{-1}$
Fossil substitute emission	$\varepsilon_{sub,t}$	83.8	$ktCO_2eq\ PJ^{-1}$
Ramp minimum	r_{min}	0.1	$PJ\ a^{-1}$
Ramp factor	r_f	0.5	-
Ramp maximum	r_{max}	25	$PJ\ a^{-1}$
Initial capacity	κ_0	Diff	PJ
Yield	$Y_{i,t}$	Diff	$PJ_{feed}\ Mha^{-1}$
Conversion efficiency	$\eta_{i,t}$	Diff	$PJ_{fuel}\ PJ^{-1}_{feed}$
Land use	Λ_t	Diff	Mha
Demand upper limit	$\delta_{s,t}$	Diff	PJ
Biofuel quota (scen. ii only)	q_t	0.5	-
Decision variables			
Total GHG abatement	ε_{tot}	Free	tCO_2eq
Production	$\pi_{i,t}$	Free	PJ
Capacity	$\kappa_{i,t}$	Free	PJ

The costs are calculated ex-post, according to [32], including technological learning effects based on the resulting expansion of the technologies in each scenario. The feedstock costs were calculated according to [31], with an annual reference feedstock cost increase of 4%.

2.2. Data and assumptions

The biofuel options included are biomethane ($BioCH_4$, based on maize silage), bioethanol (BeetEtOH, sugar beet; StarchEtOH, wheat; LignoEtOH, poplar), biodiesel (RME, rape seed), substitute natural gas (SNG, poplar), advanced biodiesel (Fischer-Tropsch, FT, poplar), biokerosene (KER, poplar), liquefied biomethane (LBM, maize silage) and liquefied SNG (LSNG, poplar).

The process data can be found in [32], except data for StarchEtOH [35, p.40f]. Biokerosene is assumed to have the same process characteristics as FT-diesel, and the biomethane and SNG pathways can be liquefied (LBM and LSNG), with a gas loss of 2% and an additional power requirement of 12 kWh GJ^{-1}_{fuel} [2, p.39 & p.43]. Table 4 summaries some key process data.

The GHG abatement data and background system developments (power mix, fertiliser, heat input and fuel input emission factors) are elaborated in [33]. For the main background system developments, the power mix emissions are assumed to decrease towards an almost fully renewable power system in 2050 (see Scenarios), fertiliser is assumed to be increasingly renewable (with the emission factor decreasing linearly to 20% of initial value until 2050), the heat input is assumed to be of renewable poplar origin (with an additional land use requirement) and diesel fuel inputs are assumed to be increasingly renewable (with the emission factor decreasing linearly to 20% of initial value until 2050). The reference emission for the transport sector is set at 83.8 $kgCO_2eq\ GJ^{-1}$, according to [13].

The land use attributable to biofuels used in Germany can be estimated to ca. 1.5 Mha, which was the average for the years 2014-2016 (own calculation based on crop use statistics from German biofuels monitoring [3], combined with yields from KTBL [29] and IPCC [23] and conversion efficiencies from [32]). This is assumed to continue to be available for biofuels production and thus an upper allowable limit is set to 1.5 Mha, in all but one scenario.

Table 2: Sector permitted fuels and relative size in terms of GHG emissions (total 228 $MtCO_2$) in 2010, assumed for the start year. Land individual and public transport is combined to one sector ("Passenger"). Apart from international shipping, absolute emissions stem from Hütter [17]. International shipping emissions were weighted for Germany by ton shipped using statistics from Hütter [17, p.12] for Germany and UNCTAD [43, p.5] for the world, with freight emissions from IMO [22]. The energy used has been estimated using 83.8 $kgCO_2eq\ GJ^{-1}$ (sum total 2725 PJ). The passenger sector is normed for the first year to the resulting energy use. Abbreviations: CH_4=methane ($BioCH_4$ or SNG); EtOH=ethanol (BeetEtOH, StarchEtOH or LignoEtOH); Dsl=diesel (RME or FT-diesel); LCH_4=liquid methane (LBM or LSNG); Ker=kerosene.

	CH_4	EtOH	Dsl	LCH_4	Ker	Share	PJ
Passenger	×	×	×			57.1%	1546
Goods	×		×	×		20.4%	555
Shipping			×	×		12.9%	351
Aviation					×	10%	273

For the transport sector, some basic data are assumed and used throughout all scenarios, unless explicitly otherwise specified. Passenger land transport demand (person-kilometres) until 2030 is assumed according to BMVI [4], with the demand between 2030-2050 assumed to level out and remain constant. 45 million passenger cars were registered as of 2017 [25], with 3 million new registrations each year [20, p.15]. The individual and public passenger sectors are grouped together for the modelling.

For the specific emissions of the current vehicle fleet, the average specific emissions of new personal internal combustion engine vehicles (ICEVs) in Germany for the years 2001-2015 were used from [20]. Between 2001-2015, passenger cars in the EU reduced their specific CO_2-emissions by on average 30%, at the same time as increasing engine power by 25% and weight by 10% [19]. At least 65 $gCO_2\ km^{-1}$ can be achieved until 2025 through vehicle mass reduction only [30]. Based on this, targets of 95 [13], 70 and 50 $gCO_2\ km^{-1}$ are assumed for the years 2021, 2030 and 2040, respectively, with linear interpolation in between and a levelling out after 2040. The annual specific emissions are approximated as the average taken over the past 15 years. The energy demand is then estimated using 83.8 $kgCO_2eq\ GJ^{-1}$, combined with the passenger land transport demand. The specific emissions are used to measure the efficiency of the vehicle fleet.

The specific emissions of average diesel and gasoline driven passenger cars have almost converged in the past decade [19, p.34] and are therefore assumed to be the same. The diesel share of new passenger cars in Germany was slightly below 50% for years, but has significantly reduced since 2015 (Dieselgate) [20, p.3]. Of the current total passenger vehicle fleet, 65% are petrol driven, 33% diesel driven, 1.2% gas driven, 0.36% hybrids and 0.07% EVs [25].

For EVs, an initial average power consumption of 0.2 $kWh\ km^{-1}$ is assumed, with a linear decrease to 10 $kWh\ km^{-1}$ in 2050. A yearly 50% increase of EVs is assumed in line with the average development in the past five years [26]. A maximum of 3 million new EVs a^{-1} can be deployed annually, in which case no new ICEVs are deployed. A life-time of 15 years is assumed for all vehicles, and each EV is assumed to be driven equivalently to one ICEV.

For the fuel demand developments of the different sub-sectors, ambitious transformation scenarios are formulated based on available options according to IPCC [24].

The fuel demand of the land goods sector is assumed to decrease linearly to a tenth of current demand by 2050, through a combination of modal shift to rail transport, electrification and possibly a shift to hydrogen, as well as transport and logistics efficiency improvements [24, p.17&28]. Allowed biofuels are either diesel as well as gaseous and liquefied methane, in line with expectations for heavy goods transport, which is less easily electrified than e.g. light-duty vehicles [21].

Fuel demand for shipping is assumed to decrease linearly to half of current demand by 2050, through efficiency improvements, in line with the IPCC projections [24, p.18&62]. Allowed biofuels are diesel and liquefied methane, according to expectations by IMO [22].

The fuel demand for the aviation sector is expected to increase or at best remain at the same level, despite efficiency improvements [18, 24, p.62f.]. Biokerosene is assumed to be the only option for aviation in this paper.

An optimistic development for the power system is assumed according to the WWF fast coal decommission scenario [45, p.120], where the power mix emissions initially rapidly decrease from the initial level of 500 $gCO_2eq\ kWh^{-1}$ and then sink towards near zero in 2050. Infrastructure emissions from the construction of the conversion facilities are set at 3 $kgCO_2eq\ GJ_{cap}^{-1}$, independent of conversion route, which is in line with values for ethanol [10] and biodiesel [9] plants. These emissions are almost negligible compared to operative emissions, but the assumption prevents over-capacities in the model.

2.3. Scenarios

Under these conditions, several scenarios of biofuel deployment are assessed (Table 3), with varying degree of electrification, yields, quota, land available and other important parameters. It is thereby attempted to assess the dependence of the results to different future development deviations regarding demands, policy and diffusion of EVs. All scenarios should be seen as highly progressive towards climate goals.

In scenario i, the effect of adding biofuels from energy crops from 1.5 Mha of arable land to the system is assessed, with all fuels allowed according to Table 2.

Scenario ii restricts all gaseous biofuels to zero, as well as introducing biofuel admixture quotas in the land passenger sector for Otto and diesel fuels, according to current shares of petrol and diesel fuelled vehicles. This scenario reflects current policy for road transport in Germany.

Scenario iii reduces the yields of sugar beet and silage maize to the lower span stated in Millinger et al. [33], as these crops risk being detrimental to the soil humus balance, especially at higher yields [29, p.272ff.].

Scenario iv assesses the effect of a higher average usage of electric passenger cars, equivalent to 1.5 ICEVs for each EV. A higher usage of especially EVs can become reality through the diffusion of self-driving cars combined with e.g. modern IT solutions [see e.g. 11], for which the effect is interesting to assess.

Scenario v reduces the annual EV increase to 30% and scenario vi assesses the effect of no EVs in the passenger transport sector. The effect of EVs failing to diffuse into passenger road transport is important to assess.

Scenario vii reduces the land goods transport fuel demand linearly to zero (e.g. through a combination of modal shift and electrification) and the ship freight linearly to one fourth (e.g. through demand reduction and efficiency improvements). If very ambitious goals are pursued within goods transport, more room is left for the aviation sector, where alternatives are lacking.

Scenario viii doubles the available arable land linearly to 3 Mha in 2050. If land is freed through mainly a decrease in meat production, this can possibly be used for biofuels without causing land use change emissions [15, 46, 6]. Such a development would be consistent with the progressive societal transformation assumed.

Scenario ix assumes a less progressive power mix improvement according to the fourth scenario in WWF [45, p.123], with an almost linear power mix emission reduction towards near zero in 2050. A fast coal decommissioning may be politically difficult to achieve in Germany, why the effect of variations to this within the goals of the energy transition need to be assessed.

The fuel demand in all scenarios surpasses the potential biofuel supply from the available arable land area for the beginning, with differing reduction rates for the sectors, dependent on the scenarios.

Table 3: Scenarios summary. The base scenario assumes developments as described in Section 2.2. The other scenarios are variations on the base scenario according to the description. Abbreviations: EV= electric vehicle; ICEV= internal combustion engine vehicle.

Scenario	Description
i	Base
ii	No gaseous fuels + diesel/gasoline quota
iii	Lower yields: sugar beet and silage maize
iv	EVs = 1.5 ICEVs
v	EV growth rate of 30% a^{-1}
vi	No passenger EVs
vii	Goods & shipping fuel demand reduction
viii	Arable land linearly increasing to 3 Mha
ix	Moderate power mix [45, p.123]

3. Results and discussion

In this section, the resulting development of electric vehicles in the passenger car sector is presented, followed by scenario results for optimal biofuel deployment and discussions of various important topics and potential sensitivities.

3.1. Electric vehicle development

The resulting EV deployment resembles an S-curve [cf. 16, p.50f.], with 172000 EVs in 2020 (0.38% of current fleet), 9.6 million (21%) in 2030, 38 million (85%) in 2040 and a fully electrified passenger car fleet by 2044. Under the given circumstances, from 2030 onwards, only EVs are deployed. Figure 1 shows some relevant metric developments for passenger cars.

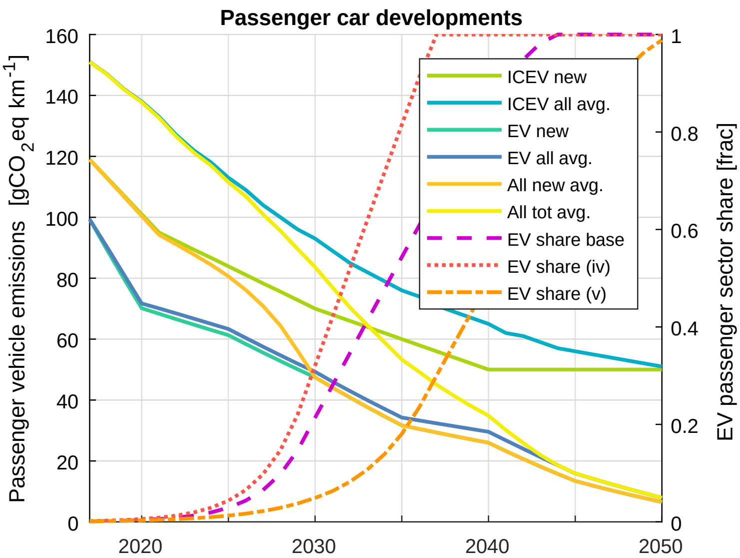

Figure 1: Passenger car sector developments. Average vehicle and fleet emissions are shown in solid lines [$gCO_2eq\ km^{-1}$, left axis]. The passenger sector market shares of EVs are shown in dotted lines [frac, right axis], for the base case as well as for scenarios (iv) where EVs have a 50% higher usage rate and (v) where the EV growth rate is at 30% a^{-1}. From 2030 onwards, EVs make up all new passenger cars. The fleet emissions including EVs compared to with only ICEVs diverge at higher shares of EVs, combined with a cleaner power system and the fact that also older EVs improve their driving emissions according to the changing power system.

3.2. Scenario results

The resulting GHG optimal biofuel developments in the scenarios are shown in Figure 2. In the base scenario (i), the presently common RME and StarchEtOH are phased out within a few years, with BeetEtOH gaining market shares during a decade. Then, $BioCH_4$ as well as LBM, both of silage maize origin, together with SNG come strong for another decade. $BioCH_4$ fully dominates for a few years and is then gradually replaced by LBM as the sectors using gaseous fuels become increasingly renewable. SNG and LSNG as well as biokerosene start coming towards the end.

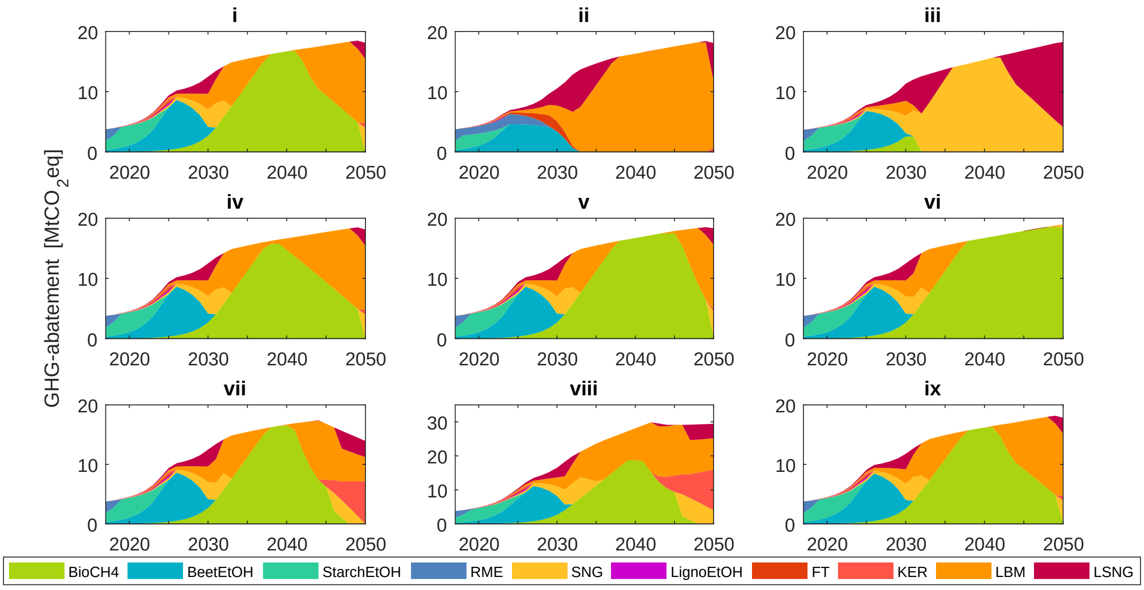

Figure 2: Total biofuel GHG abatement mix development in scenarios. The base scenario i assumes developments as described in Section 2.2, with the other scenarios being variations of the base scenario. Scenario ii: exclusion of gaseous fuels and quota for diesel and gasoline; iii: lower yields for sugar beet and silage maize; iv: a higher usage of EVs; v: a lower EV market growth rate; vi: no EVs; vii: more progressive developments in the goods and shipping sectors; viii: doubling of arable land over time; ix: less progressive power mix development. Abbreviations: BioCH4: silage maize based methane; BeetEtOH: sugar beet based ethanol; StarchEtOH: starch crop based ethanol; RME: rape seed methyl ester; SNG: poplar based substitute natural gas; LignoEtOH: poplar based ethanol; FT: poplar based Fischer-Tropsch-diesel; KER: poplar based Fischer-Tropsch kerosene; LBM: silage maize based liquefied biomethane; LSNG: poplar based liquefied SNG. The GHG abatement through other renewable options such as electric vehicles (EVs) are not shown in this figure.

If biofuel quotas for land passenger transport are in place and gaseous fuels are not permitted (scenario ii), RME stays on for a decade longer but is replaced by FT-diesel for a short while until the passenger land transport fuel demand drops to zero. Instead of gaseous fuels, liquefied gaseous fuels (mainly LBM) dominate in the long term, making goods transport and shipping the priority sectors. This scenario achieves the lowest GHG abatement, as well as having the highest total GHG abatement cost (Figure 3).

If low yields are assumed for sugar beet and silage maize (scenario iii), BeetEtOH still dominates the passenger land transport sector, while $BioCH_4$ does not achieve substantial market shares. Instead, SNG and when the land goods sector fuel demand drops, LSNG for shipping come strongly.

If EVs take over a larger share of total passenger land transports through higher usage of each EV (scenario iv), only marginal differences to the base scenario can be observed, as $BioCH_4$ is used also in land goods transport. If the EV development is slower than in the base case (scenario v), $BioCH_4$ dominates for a longer period and aviation is not supplied with biofuels. If EVs are assumed not to break through (scenario vi), $BioCH_4$ dominates until the end, and shipping as well as aviation are not supplied with biofuels. In this scenario, the highest cumulative emissions for transport are achieved (Figure 4), and transport remains at ca 80 $MtCO_2$eq in the end (Figure 5), more than twice as much as in all other scenarios, which include EVs.

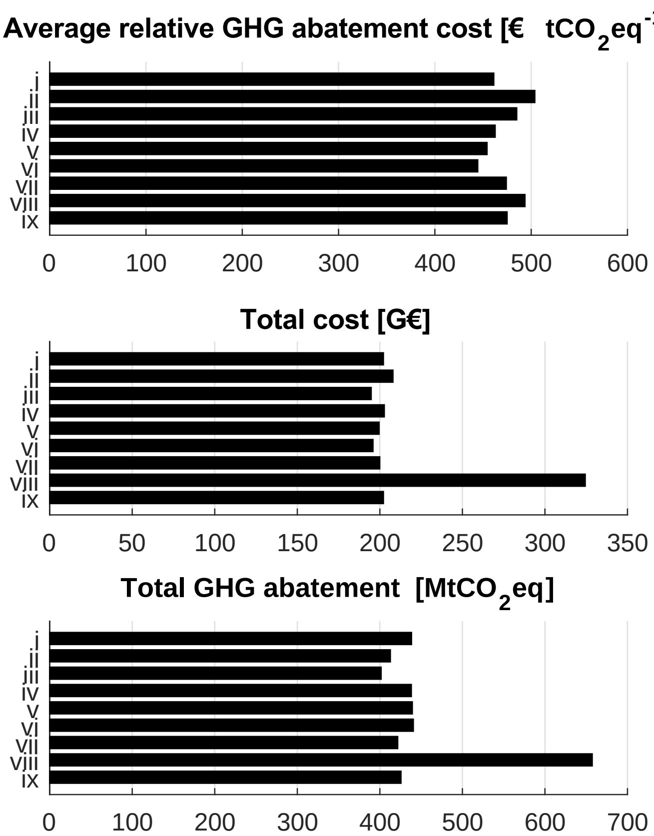

Figure 3: Average biofuel GHG abatement cost, total cumulative biofuel cost (excluding the avoided cost of the substituted fossil fuels) and total cumulative GHG abatement through fossil fuel substitution by biofuels, summed for all transport sectors in each scenario.

This is the result despite the assumed substantial improvements to the ICEV vehicle park emissions, with only a third of the relative emissions in the end compared to at the start (Figure 1).

If on the other hand the fuel demand in land goods transport and shipping is reduced more progressively (scenario vii), biokerosene comes strongly towards the end, as all other sectors are met by other means to a sufficient extent. The same effect occurs if more arable land is available (scenario viii), as more fossil fuels can be replaced. These two scenarios are the ones with the lowest cumulative emissions (Figure 4), as well as the lowest emissions at the end of the time span (Figure 5).

A more moderate power mix development has only minor consequences for the types of fuels produced, with a slight reduction in $BioCH_4$. However, the increased cumulative emissions are substantial (Figure 4), indicating the need for prioritising early emission reductions in the power system.

In all scenarios, one can observe a general trend: the order in which biofuels are optimally deployed is first land passenger transport, followed by land goods transport, shipping and finally aviation.

3.3. Aviation biofuels

Aviation biofuels from dedicated crops in Germany only perform a climate benefit when other biofuel usages with higher pathway GHG abatement have been displaced. This displacement requires substantial changes in all sectors, through efficiency improvements and EVs (or for that matter PtX) in the passenger transport

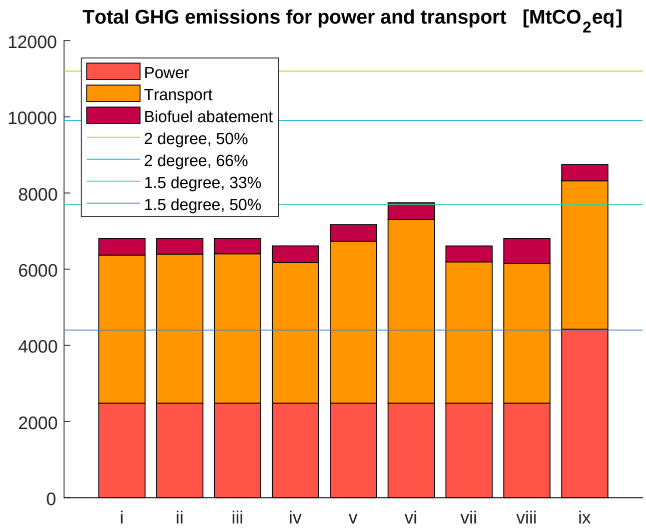

Figure 4: Total greenhouse gas (GHG) emissions for the power and transport sectors in the scenarios, including the GHG abatement through biofuels. The lines show permissible German GHG budgets at different likelihoods of reaching 1.5°C and 2°C climate targets, if the global GHG budgets are allocated per capita [45].

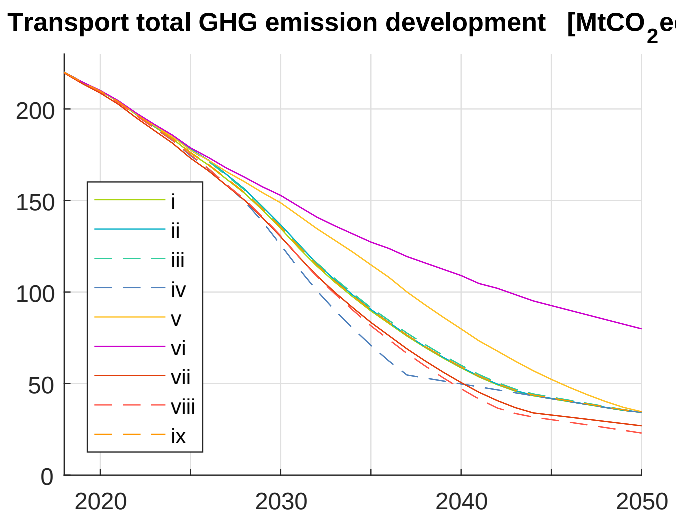

Figure 5: Total GHG emission development [$MtCO_2eq\ a^{-1}$] for transport over the modelled time span in the scenarios.

sector; modal shift, efficiency and logistics improvements as well as demand reduction and possibly PtX in the land goods transport and shipping sectors. Only in the most progressive scenarios where all sectors improve substantially were aviation biofuels found to achieve any substantial market shares, and even then only towards the end. Keeping in mind that biomass may potentially render a higher GHG abatement in the sectors which were not included here, in sum a large transition is required before aviation biofuels become relevant from the perspective of optimising GHG abatement.

Alcohol-to-jet options were not included, but may play a role in the long term. If so, the conversion efficiency from ethanol to jet fuel needs to be >70% in order to compete with KER in terms of GHG abatement per hectare. Direct alcohol applications and gaseous alternatives are still better performing, and thus an addition of such options would not change the overall priority conclusions.

3.4. Costs

The total biofuel costs in all 1.5 Mha scenarios amount to around 200 billion € (Figure 3), or an annual 0.2% of current German GDP of 3.1 trillion € [7], excluding the avoided cost of the substituted fossil fuels. The total cost differences between these scenarios are small, despite costs not being in the goal function and only calculated ex-post. It can be argued that a focus on land use efficiency to some extent implies cost efficiency in the long run [31, 33], which is confirmed by this result. Some of the deployment behaviour observed (with some options being used for a few years only) would likely disappear if cost optimal strategies were to be assessed, which is interesting for future research.

3.5. Land use

Figure 6 shows the development of GHG abatement per land unit. The most promising options are $BioCH_4$ and LBM, throughout the time span. BeetEtOH is the best liquid option and is never surpassed by advanced liquid options. SNG and LSNG surpass BeetEtOH within a few years and slowly converge with the silage maize based options, as the power mix becomes increasingly renewable. The reason for the best options not dominating directly is system inertia, with ramp factors setting expansion limits. It can also be observed that, compared to current practise, the GHG abatement per hectare can be potentially enhanced by a factor five or more, through a combination of yield and conversion efficiency improvements as well as renewable input streams [33]. The potentially best performing fuels in this regard are maize silage based $BioCH_4$ and LBM.

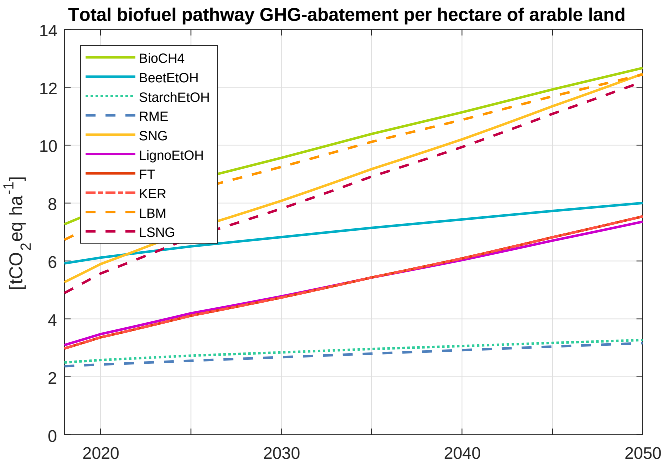

Figure 6: Development of greenhouse gas abatement per hectare [$tCO_2eq\ ha^{-1}$] for the biofuels included over the modelled time span, in the base scenario. Fischer-Tropsch-diesel shows exactly the same development as KER, and is therefore not visible in the graph.

The notable fuel shifts taking place across all scenarios obviously have consequences for the landscape, as crops are shifting from rape seed and wheat in the beginning, to a full sugar beet domination, replaced by a full domination of maize, which under some circumstances was replaced by a large share of lignocellulosic perennials. Whereas the conventional crops can rotate between different areas (potentially restricted by transportability), the perennials would remain in the same spot for a longer time span.

Land use change emissions have not been assessed here, with the reasoning that currently required arable land for production of biofuels used in Germany is not extended, thus reflecting a business as usual baseline. However, this is a question of what the assumed reference is, as the required arable land has decreased in the past few years through the use of more residual biomass [3]. In this study, no reference use of the land was assumed, as only the absolute climate effect of the bioenergy system is assessed [cf. 28].

In the scenario where the available arable land is assumed to increase, the additional land would need to be offset in order to avoid land use change issues, through reducing the demand from other sectors, such as (ruminant) meat production [6, 15, 42, 46, 39]. If this is not done, a land area extension for energy purposes beside possibly marginal lands [41] risks leading to more emissions than are offset through replacing fossil fuels [14, 38].

3.6. Other factors

Since the reference fossil fuel emission is assumed to be the same for all options, changes in this value would not change the result. The differences between fossil reference options (diesel, gasoline, kerosene) are small [12]. However, the emissions of natural gas are lower than those of liquid fossil options [12], whereby a comparison of gaseous biofuel options with a natural gas reference would likely affect the result. This has not been done here, as a liquid fossil reference baseline is assumed in line with [13], reflecting business as usual. The method of estimating the energy demand based on emission data for each sector combined with the fuel emission factor is bound with some uncertainty, which however does not affect the general analysis and conclusions in this paper.

Even though engine efficiency scenarios were not included, the possible GHG abatement per hectare of arable land (Figure 6) shows large enough GHG abatement differences to favour Otto engine options (ethanol and methane) in those sectors where such fuels are permissible. For the goods transport sector this is particularly clear, where a stronger focus on ethanol than presently would be beneficial.

Biomass residues may play an important role in increasing the resource basis for producing biofuels. Some 1000 PJ of biomass residues of different types have been estimated to be available [5]. As no emissions for cultivation as well as no arable land would be attributed to biofuels using such resources, there are strong advantages and therefore this is already being implemented in Germany to some extent [3]. If an average conversion efficiency of 65% and an average GHG abatement of 60 kgCO_2eq GJ^{-1} are assumed, some 40 Mton CO_2eq a^{-1} could be abated, or over the whole time span a cumulative 1.3 Gton; more than three times the GHG abatement in the 1.5 Mha scenarios. In such a case, the resource basis sets which options are produced; the domination of wood residues [5] would thus require advanced biofuel options, but this resource may yield a higher GHG abatement in other sectors, such as power, heat and industry. Thus, the optimal usage of biomass residues across sectors should be further assessed.

BioCH_4 is advantageous already in the beginning, but due to system inertia, the initial development is relatively slow. A higher ramp factor leads to an earlier deployment of BioCH_4, whereas a lower ramp factor has the opposite effect. Further research as to the possibility of large-scale deployment of vehicles using gaseous fuels is necessary considering the current small size of the gaseous vehicle market.

Other environmental factors than GHG emissions have not been assessed here. Yields of silage maize were found to be of strong importance for the competition between BioCH_4 and SNG. Thus possible soil management schemes reducing silage maize yields would render poplar based SNG a better option.

3.7. Biofuel role towards meeting carbon budgets

As a benchmark, the permissible carbon budget in order to achieve certain climate goals can be allocated per capita [45]. For example, in order to achieve a 2°C target with a 66% likelihood, 9.9 Gton CO_2eq (on average 291 Mton CO_2eq a^{-1}, assuming carbon neutrality after 2050) would be permissible for Germany (Figure 4), in which case the GHG reduction through biofuels from 1.5 Mha amounts to around 4% of the total carbon budget. The relative importance of biofuels increases with higher climate ambition (as long as land use change effects can be curbed), but so does the competition from other sectors where biomass may perform a higher climate benefit. For the allocation of biomass across all relevant sectors, more research is called for.

4. Conclusions

In this paper, progressive scenarios for the transport sectors have been assessed in order to investigate the resulting biofuel deployment for an optimal GHG abatement from the arable land currently used for biofuels.

The GHG abatement per land area can potentially be increased by a factor of five, by switching to more promising biofuel options with higher yield and conversion efficiencies while the background system (power mix, fertiliser, renewable heat) becomes increasingly renewable. In order for this to be realised, the use of gaseous or liquefied gaseous fuels needs to increase substantially compared to today. If a substantial market for gaseous fuels should not be realisable, sectors which can use liquefied gaseous fuels, i.e. goods transport and shipping, are the climate best usage of biomass.

Under German conditions, the priority of sectors resulting from fuel suitability restrictions and GHG abatement potential of the individual biofuel options was found to be as follows: land passenger transport, land goods transport, shipping and finally aviation. Only after all other sectors of higher priority have been supplied or reduced by other means (such as electrification) do the subsequent ones become the optimal usage from a GHG abatement perspective. Sectors and scenarios where ethanol and gaseous or liquefied gaseous fuels are allowed yield the highest GHG abatement. Even at the highly ambitious electrification scenarios assessed here, land passenger transport would require renewable fuels for several decades to come.

The current practise of applying biofuel admixture quotas to sub-sectors of land transport renders a significantly lower climate benefit compared to an overall optimal usage. Ethanol based on sugar beet was found to dominate in all scenarios for land transport in the short term, with biomethane dominating in the medium term.

Aviation biofuels from dedicated crops in Germany only perform an optimal climate benefit when other biofuel usages with higher pathway climate efficiencies have been displaced, or if a substantially higher usage of arable land for biofuel production were to be permitted, which would require other demands - e.g. meat - to decrease. Including other sectors such as power, heat and industry, may postpone the relevance of aviation biofuels even further and in sum a large societal transition is required before aviation biofuels become the best biomass usage for mitigating climate change. Nevertheless, due to the lack of alternatives for aviation, such fuels do remain of importance for the longer term.

Acknowledgements

This work was funded by the Helmholtz Association of German Research Centers and supported by Helmholtz Impulse and Networking Fund through Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE). Thank you to Matthias Jordan for help with linking GAMS and Matlab. Reviewer comments are acknowledged. Declarations of interest: none.

Appendix

Table 4: Summarised important metrics for the biofuel options included. For more information, please consult [33].

Fuel		**BioCH$_4$**	**BeetEtOH**	**StarchEtOH**	**RME**	**BioSNG**	**LignoEtOH**	**FT/KER**	**LBM**	**LSNG**
Feedstock		Maize silage	Sugar beet	Wheat	Rape seed	Poplar	Poplar	Poplar	Maize silage	Poplar
Yield medium	GJ_{feed} ha^{-1}	268–327	254	115	84	143–214	143–214	143–214	268–327	143–214
Yield low	GJ_{feed} ha^{-1}	208–268	176–215						208–268	
N fertilizer	kgN $(ha\text{-}a)^{-1}$	63.2	119.7	109.3	137.4				63.2	
Diesel equivalent	l $(ha\text{-}a)^{-1}$	96	175.9	106	82.6	2.1	2.1	2.1	96	2.1
N_2O field emissions	kgN_2O $(ha\text{-}a)^{-1}$	4.66	4.59	2.92	4.19	1.28	1.28	1.28	4.66	1.28
Conversion efficiency	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	0.55–0.69	0.57–0.71
Net heat input	kWh GJ^{-1}	65	134	123	22	0	0	0	65	0
Net power input	kWh GJ^{-1}	14	10	17	1.6	31	35	35	26	43

References

[1] Nicola Armaroli and Vincenzo Balzani. Towards an electricity-powered world. *Energy & Environmental Science*, 4(9): 3193, 2011. ISSN 1754-5692. doi: \url{10.1039/c1ee01249e}.

[2] Cansu Birgen and Silvia Garcia. *Liquefied Synthetic Natural Gas from Woody Biomass: Investigation of Cryogenic Technique for Gas Upgrading*. Master Thesis, Chalmers University of Technology, Göteborg, Sweden, 2013.

[3] BLE. *Hintergrunddaten zum Evaluations- und Erfahrungsbericht 2016*. Bundesanstalt für Landwirtschaft und Ernährung, Bonn, 2017.

[4] BMVI. *Verkehrsverflechtungsprognose 2030: Zusammenfassung der Ergebnisse*. Bundesministerium für Verkehr und digitale Infrastruktur, 2014.

[5] André Brosowski, Daniela Thrän, Udo Mantau, Bernd Mahro, Georgia Erdmann, Philipp Adler, Walter Stinner, Gerd Reinhold, Thomas Hering, and Christian Blanke. A review of biomass potential and current utilisation – Status quo for 93 biogenic wastes and residues in Germany. *Biomass and Bioenergy*, 95:257–272, 2016. ISSN 09619534. doi: \url{10.1016/j.biombioe.2016.10.017}.

[6] David Bryngelsson, Fredrik Hedenus, Daniel Johansson, Christian Azar, and Stefan Wirsenius. How Do Dietary Choices Influence the Energy-System Cost of Stabilizing the Climate? *Energies*, 10(2):182, 2017. ISSN 1996-1073. doi: \url{10.3390/en10020182}.

[7] Destatis. *Statistisches Jahrbuch 2017: Deutschland und Internationales*. Statistisches Bundesamt, Wiesbaden, 1 edition, 2017. ISBN 978-3-8246-1057-0.

[8] Seth Dunn. Hydrogen futures: toward a sustainable energy system. *International Journal of Hydrogen Energy*, 2002(27): 235–264, 2002. ISSN 03603199.

[9] Ecoinvent. *Vegetable oil esterification plant: Ecoinvent database v.2.2 - www.ecoinvent.org*. Swiss Centre for life cycle inventories, Zürich, 2010.

[10] Ecoinvent. *Ethanol fermentation plant: Ecoinvent database v.3.3 - www.ecoinvent.org*. Swiss Centre for life cycle inventories, Zürich, 2016.

[11] Economist. Uberworld. *The Economist*, September 3rd 2016, 2016.

[12] European Commission. Study on actual GHG data for diesel, petrol, kerosene and natural gas: Final report: WORK ORDER: ENER/C2/2013-643.

[13] European Parliament. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, 2009.

[14] Joseph Fargione, Jason Hill, David Tilman, Stephen Polasky, and Peter Hawthorne. Land Clearing and the Biofuel Carbon Debt. *Science*, 319(5867):1235–1238, 2008. ISSN 0036-8075. doi: \url{10.1126/science.1152747}.

[15] Jonathan A. Foley, Navin Ramankutty, Kate A. Brauman, Emily S. Cassidy, James S. Gerber, Matt Johnston, Nathaniel D. Mueller, Christine O'Connell, Deepak K. Ray, Paul C. West, Christian Balzer, Elena M. Bennett, Stephen R. Carpenter, Jason Hill, Chad Monfreda, Stephen Polasky, Johan Rockström, John Sheehan, Stefan Siebert, David Tilman, and David P. M. Zaks. Solutions for a cultivated planet. *Nature*, 478(7369):337–342, 2011. ISSN 0028-0836. doi: \url{10.1038/nature10452}.

[16] Arnulf Grubler. *Technology and global change*. Cambridge University Press, Cambridge, 1998. ISBN 0521543320.

[17] Andrea Hütter. *Verkehr auf einen Blick*. Statistisches Bundesamt, Wiesbaden, 2013.

[18] IATA. *IATA Sustainable Aviation Fuel Roadmap*. International Air Transport Association, Montreal and Geneva, 2015. ISBN 978-92-9252-704-4.

[19] ICCT. *European vehicle market statistics: Pocketbook 2016/2017*. International Council on Clean Transportation Europe, 2016.

[20] ICCT. *European Vehicle Market Statistics: Pocketbook 2017/2018*. International Council on Clean Transportation Europe, 2017.

[21] IEA. *The Future of Trucks - Implications for Energy and the Environment*. International Energy Agency, France, 2017.

[22] IMO. *Third IMO GHG Study 2014: Executive Summary and Final Report*. International Maritime Organization, London, 2015.

[23] IPCC. *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2011.

[24] IPCC. Climate Change 2014: Mitigation of Climate Change: Chapter 8 - Transport. In IPCC, editor, *Climate Change 2014: Mitigation of Climate Change*. IPCC, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014. ISBN 978-1-107-05821-7.

[25] KBA. *Fahrzeuge - Neuzulassungen, Bestand: www.kba.de*. Kraftfahrtbundesamt, 2017.

[26] KBA. *Umwelt - Bestand an Pkw in den Jahren 2008 bis 2017 nach ausgewählten Kraftstoffarten: www.kba.de*. Kraftfahrtbundesamt, 2017.

[27] Daniel H. König, Marcel Freiberg, Ralph-Uwe Dietrich, and Antje Wörner. Techno-economic study of the storage of fluctuating renewable energy in liquid hydrocarbons. *Fuel*, 159:289–297, 2015. ISSN 00162361. doi: \url{10.1016/j.fuel.2015.06.085}.

[28] Kati Koponen, Sampo Soimakallio, Keith L. Kline, Annette Cowie, and Miguel Brandão. Quantifying the climate effects of bioenergy – Choice of reference system. *Renewable and Sustainable Energy Reviews*, 81:2271–2280, 2018. ISSN 13640321. doi: \url{10.1016/j.rser.2017.05.292}.

[29] KTBL. *Energiepflanzen: Daten für die Planung des Energiepflanzenanbaus: KTBL Datensammlung*. KTBL, Darmstadt, 2 edition, 2012. ISBN 978-3-941583-65-8.

[30] Dan Meszler, John German, Peter Mock, and Anup Bandivadekar. *Summary of mass reduction impacts on EU cost curves: ICCT working paper 2013-1*, volume 1. International Council on Clean Transportation Europe, 2013. doi: \url{10.1002/9781118170229.ch1}.

[31] Markus Millinger and Daniela Thrän. Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields. *Journal of Cleaner Production*, 172:1654–1663, 2018. ISSN 09596526. doi: \url{10.1016/j.jclepro.2016.11.175}.

[32] Markus Millinger, Jens Ponitka, Oliver Arendt, and Daniela Thrän. Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany. *Energy Policy*, 107(107):394–402, 2017. ISSN 0301-4215. doi: \url{10.1016/j.enpol.2017.05.013}.

[33] Markus Millinger, Kathleen Meisel, Maik Budzinski, and Daniela Thrän. Relative Greenhouse Gas Abatement Cost Competitiveness of Biofuels in Germany. *Energies*, 11(3):615, 2018. ISSN 1996-1073. doi: \url{10.3390/en11030615}.

[34] Alberto Moro and Laura Lonza. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transportation Research Part D: Transport and Environment*, 2017. ISSN 13619209. doi: \url{10.1016/j.trd.2017.07.012}.

[35] Jens Ponitka, Oliver Arendt, Volker Lenz, Jaqueline Daniel-Gromke, Walter Stinner, Andreas Ortwein, Martin Zeymer, Arne Gröngröft, Franziska Müller-Langer, Marco Klemm, Julian Braun, Walther Zeug, Daniela Thrän, Sinéad O'Keeffe, and Markus Millinger. *Focus on: Bioenergy-Technologies: Conversion pathways - towards biomass energy use in the 21st century*. DBFZ, Leipzig, 2 edition, 2016. ISBN 2192-1156.

[36] Johan Rockström, Owen Gaffney, Joeri Rogelj, Malte Meinshausen, Nebojsa Nakicenovic, and Hans Joachim Schellnhuber. A roadmap for rapid decarbonization. *Science*, 355(6331):1269–1271, 2017. ISSN 0036-8075. doi: \url{10.1126/science.aah3443}.

[37] C.E. Sandy Thomas. Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles. *International Journal of Hydrogen Energy*, 34(23):9279–9296, 2009. ISSN 03603199. doi: \url{10.1016/j.ijhydene.2009.09.058}.

[38] Timothy D. Searchinger, Ralph Heimlich, R. A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot J. Hayes, and Tun-Hsiang Yu. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, 319(5867):1238–1240, 2008. ISSN 0036-8075. doi: \url{10.1126/science.1151861}.

[39] Marco Springmann, Michael Clark, Daniel Mason-D'Croz, Keith Wiebe, Benjamin Leon Bodirsky, Luis Lassaletta, Wim de Vries, Sonja J. Vermeulen, Mario Herrero, Kimberly M. Carlson, Malin Jonell, Max Troell, Fabrice DeClerck, Line J. Gordon, Rami Zurayk, Peter Scarborough, Mike Rayner, Brent Loken, Jess Fanzo, H. Charles J. Godfray, David Tilman, Johan Rockström, and Walter Willett. Options for keeping the food system within environmental limits. *Nature*, 2018. ISSN 0028-0836. doi: \url{10.1038/s41586-018-0594-0}.

[40] Michael Sterner. *Bioenergy and renewable power methane in integrated 100% renewable energy systems: Limiting global warming by transforming energy systems: Zugl.: Kassel, Univ., Diss., 2009*. Kassel Univ. Press, Kassel, 2009.

[41] David Tilman, Jason Hill, and Clarence Lehman. Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass. *Science*, 314(5805):1598–1600, 2006. ISSN 0036-8075. doi: \url{10.1126/science.1133306}.

[42] David Tilman, Robert Socolow, Jonathan A. Foley, Jason Hill, Eric D. Larson, Lee R. Lynd, Stephen Pacala, John Reilly, Timothy D. Searchinger, Chris Somerville, and Robert Williams. Beneficial Biofuels–The Food, Energy, and Environment Trilemma. *Science*, 325(5938):270–271, 2009. ISSN 0036-8075. doi: \url{10.1126/science.1177970}.

[43] UNCTAD. *Review of maritime transport 2017*. United Nations Conference on Trade and Development, Geneva, 2017. ISBN 978-92-1-112922-9.

[44] UNFCCC. *Adoption of the Paris Agreement: FCCC/CP/2015/L.9/Rev.1*. United Nations Framework Convention on Climate Change, 2015.

[45] WWF. *Zukunft Stromsystem: Kohleausstieg 2035 - vom Ziel her denken*. World Wildlife Foundation, Berlin, 2017. ISBN 978-3-946211-07-5.

[46] Konstantin Zech. *Greenhouse Gas Mitigation Through Healthy Diets: Technical and Political Potentials*. PhD Thesis, HHL - Leipzig Graduate School of Management, Leipzig, 2017.