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Systems assessment of biofuels – Modelling of future cost and greenhouse gas abatement competitiveness between biofuels for transport on the case of Germany

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HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

Systems assessment of biofuels

Modelling of future cost and greenhouse gas abatement competitiveness between biofuels for transport on the case of Germany

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Abstract: Biofuels are a renewable alternative for reducing the climate impact of transport. Due to the versatility of biomass and complexity of economics and impacts, biofuels are part of a complex system, which is here analysed from a systems perspective. Several models are developed in order to assess the competitiveness of various crop based biofuel options as part of a system, using different economic and environmental functional units. The scope is set to Germany until 2050.

The capital and feedstock costs were revised to higher levels compared to common assumptions. The different functional units result in different merit orders for the biofuel options. Currently used biofuels, rape seed based biodiesel and starch crop based bioethanol, were found not to be competitive when considering differentiated and increasing feedstock costs. Advanced liquid fuels were only competitive at extreme assumptions, contrary to common expectations. Instead, sugar beet based ethanol dominated for most of the time span when comparing energetic cost, whereas Synthetic Natural Gas (SNG) was competitive on a greenhouse gas abatement (GHG) cost basis, especially at a rapid decarbonisation of the power mix. With a land use GHG abatement functional unit, silage maize based biomethane was the best, with SNG converging only at very high renewables shares of the background systems.

Switching from current practise to higher yielding biofuel options can treble the abatement per land area for the present day, and potentially increase it by a factor five in the future. A focus on GHG abatement per area of arable land results in the land passenger transport sector to be of the highest priority due to the suitability of higher yielding biofuel options, followed by land goods transport, shipping and finally aviation. If gaseous fuels are not possible to introduce on a large scale, sectors where liquefied gaseous fuels are suitable become the priority, i.e. goods transport and shipping. The current practise of applying admixture quotas to sub-sectors of land transport renders a significantly lower climate benefit compared to an overall optimal usage, and a large societal transition is required before aviation biofuels become the climate optimal biomass usage.

The direct importance of land use has thus far not received enough attention in terms of the economics of biofuels from dedicated crops, as well as for the greenhouse gas emissions policy. Biofuels produced from arable land can provide a strong GHG benefit if an expansion of arable land is hindered through redirecting land use, which requires a holistic policy approach.

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Leipzig, den 19 Dezember 2017

Markus Millinger

till Bianca, Elsi och Wilma

Zur Einsicht in den geringsten Teil
ist die Übersicht über das Ganze nötig

J.W. GOETHE

Allting är mycket osäkert,
och det är just det som lugnar mig
All things are so very uncertain,
and that's exactly what makes me feel reassured

TOO-TICKI
Trollvinter by Tove Jansson

Where we're going,
we don't need roads

Dr. EMMETT BROWN
Back to the Future

Abstract

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Switching from current practise to higher yielding biofuel options can treble the abatement per land area for the present day, and potentially increase it by a factor five in the future. A focus on GHG abatement per area of arable land results in the land passenger transport sector to be of the highest priority due to the suitability of higher yielding biofuel options, followed by land goods transport, shipping and finally aviation. If gaseous fuels are not possible to introduce on a large scale, sectors where liquefied gaseous fuels are suitable become the priority, i.e. goods transport and shipping. The current practise of applying admixture quotas to sub-sectors of land transport renders a significantly lower climate benefit compared to an overall optimal usage, and a large societal transition is required before aviation biofuels become the climate optimal biomass usage.

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Keywords: biofuels; greenhouse gas; economics; competition; land use; advanced; conventional; systems perspective .

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Markus Millinger

Leipzig, December 2017

List of Publications

This thesis is based on the following appended papers:

I Millinger, M., Ponitka, J., Arendt, O. and Thrän, D. (2017) *Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany.* Energy Policy. 107, 394-402.

II Millinger, M. and Thrän, D. (2016) *Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields.* Journal of Cleaner Production. In Press.

III Millinger, M., Meisel, K., Budzinski, M. and Thrän, D. (submitted) *Relative greenhouse gas abatement cost competitiveness of biofuels in Germany.*

IV Millinger, M., Meisel, K. and Thrän, D. (submitted) *Climate optimal deployment of biofuels from crops in Germany.*

Work related to this thesis has also been presented in the following publications:

Thrän, D., Schaldach, R., **Millinger, M.**, Wolf, V., Arendt, O., Ponitka, J., Gärtner, S., Rettenmaier, N., Hennenberg, K., Schüngel, J. (2016). *The MILESTONES modeling framework: An integrated analysis of national bioenergy strategies and their global environmental impacts.* Environ. Modell. Softw. 86, 14 - 29.

Thrän, D., Arendt, O., Banse, M., Braun, J., Fritsche, U., Gärtner, S., Hennenberg, K. J., Hünneke, K., **Millinger, M.**, Ponitka, J., Rettenmaier, N., Schaldach, R., Schüngel, J., Wern, B., Wolf, V. (2017). *Strategy elements for a sustainable bioenergy policy based on scenarios and systems modeling demonstrated on the example of Germany.* Chem. Eng. Technol. 40 (2), 211-226.

Thrän, D., Arendt, O., Ponitka, J., Braun, J., **Millinger, M.**, Wolf, V., Banse, M. Schaldach, R., Schüngel, J., Gärtner, S., Rettenmaier, N., Hünnecke, K., Hennenberg, K., Wern, B., Baur, F., Fritsche, U., Gress, H.-W. (2015). *Meilensteine 2030 – Elemente und Meilensteine für die Entwicklung einer tragfähigen und nachhaltigen Bioenergiestrategie.* In: Thrän, D.; Pfeiffer, D. (Hrsg.): Schriftenreihe des BMWi-Förderprogramms „Energetische Biomassenutzung“, Band 18. Leipzig 2015. – ISSN: 2199-2762.

Millinger, M., Ponitka, J., Arendt, O., Thrän, D. (2015). *On future competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany.* Bioenergy 2015 international bioenergy exhibition and conference proceedings p.120, Jyväskylä, Finland.

List of Acronyms

BENSIM	–	BioENergy SImulation Model
BTL	–	Biomass-To-Liquid
CCS	–	Carbon Capture and Storage
CH_4	–	Methane
CHP	–	Combined Heat and Power
CO_2	–	Carbon dioxide
CO_2eq	–	Carbon dioxide equivalent
dLUC	–	direct Land Use Change
DM	–	Dry Matter
EtOH	–	Ethanol
EF	–	Emission Factor
EV	–	Electric Vehicle
FM	–	Fresh Matter
FT	–	Fischer-Tropsch
GHG	–	GreenHouse Gas
iLUC	–	indirect Land Use Change
IPCC	–	Intergovernmental Panel on Climate Change
LCA	–	Life-Cycle Assessment
LR	–	Learning Rate
LSNG	–	Liquid Synthetic Natural Gas
LUC	–	Land Use Change
MC	–	Marginal Cost
MFA	–	Material Flow Analysis
N_2O	–	Nitrous oxide
NG	–	Natural Gas
PR	–	Progress Rate
PtG	–	Power-to-Gas
PtL	–	Power-to-Liquid
PtX	–	Power-to-Anything
R&D	–	Research and Development
RED	–	Renewable Energy Directive by the European Union
RME	–	Rape seed MethylEster
SNG	–	Synthetic Natural Gas
SRC	–	Short Rotation Coppice
TC	–	Total Cost
vRES	–	variable Renewable Energy Sources
WTT	–	Well-To-Tank
WTW	–	Well-To-Wheel

Contents

Part I

Introductory chapters

Chapter 1

Background

Emissions of fossil carbon dioxide cause an increase in atmospheric radiative forcing, leading to a net warming of the earth's surface (Arrhenius, 1896). Since Arrhenius' days, anthropogenic greenhouse gas emissions have increased manifold and atmospheric CO_2 concentration has increased from pre-industrial 278ppm (IPCC, 2013, p.50) to above 400ppm (Vaughan, 2015), and the additional relevance of other greenhouse gases such as CH_4, N_2O and halocarbons has been realised (IPCC, 2013).

The critical consequences of climate change for life on earth are far better understood than only a few decades ago (Field et al., 2014; IPCC, 2013). A large majority of all countries have ratified the Paris accord, thus agreeing upon measures for curbing global warming to 1.5°C or at least less than 2°C compared to pre-industrial levels (UNFCCC, 2015).

Transport emits 14% of total anthropogenic greenhouse gas emissions (IPCC, 2014a), with an increasing trend (IPCC, 2014b, p.7). In heavily industrialised countries such as Germany, the transport share of emissions is even higher, at 21% (EEA, 2017). Measures to reduce transport emissions are in place both in Germany (BImSchG, 2014) and in the European Union (European Parliament, 2009).

Climate change mitigation in the transport sector can be divided into the following measures (IPCC, 2014b, p.9): modal shift to less emitting modes of transport; reduction of fuel carbon intensity; reduction of energy intensity of vehicles; and reduction of activity. All measures are necessary in order to substantially reduce impact, which will also be seen later on in this work.

Biofuels are a measure for reducing the fuel carbon intensity for transport modes dominated by vehicles relying on fossil hydrocarbon fuels, such as diesel, gasoline, natural gas and kerosene. Policy quota for adding biofuels to diesel and gasoline has been in place in Germany for a good decade (BioKraftQuG, 2006), and almost as long in the EU (European Parliament, 2009), setting energetic quota to be achieved. In Germany, the focus has changed from such an energetic quota to a GHG abatement quota (BImSchG, 2014). The types of feedstocks used are changing too; the use of biomass residues and wastes has increased (BLE, 2017), while limits for crop-based biofuels will be in place shortly (BImSchV, 2017).

1.1 Biofuels

In this work, biofuels denote fuels of biogenic (phyto- or zoomass, as also defined in e.g. BiomasseV, 2001) origin used in transport. Conventional biofuels denote the biofuels which use food crops, whereas advanced biofuels denote those based on biomass with a high lignocellulose content (woody biomass).

The use of biomass and agricultural land is, due to its versatility, connected to virtually all sectors of society, making it an inherently complex subject. Biomass is needed for food and feed, fibre, building materials, chemicals as well as for energy, and can potentially replace fossil resources in all sectors (Ragauskas, 2006), both directly or in cascade (Haberl and Geissler, 2000). When designing biofuel policies, this greater context needs to be taken into account, in order to avoid sub-optimal solutions.

Many long-term scenarios assume significant shares of biofuels for the future in order to achieve climate goals (Szarka et al., 2017). The presently most common conventional biofuels such as oilseed based biodiesel and grain or maize based ethanol are food crop based and use only a small share of the crops for energetic purposes, thus being both inefficient as well as competing directly with food production. Furthermore, the use of dedicated crops for biofuel production risks increasing the pressure on land, thus leading to an extension of arable land into previously unused lands, potentially leading to substantial carbon emissions which overshadow the potential GHG abatement of the fuels (Fargione et al., 2008; Searchinger et al., 2008). Therefore, focus has been turned to crops grown on agricultural so called marginal or fallow lands (Tilman et al., 2006) as well as residual biomass.

The global biomass residue potential is limited as well as highly uncertain (Thrän et al., 2010; Hoogwijk et al., 2003; Haberl et al., 2010), and for degraded or marginal lands there is no common definition (IPCC, 2011, p.234). Furthermore, strong doubts have been raised as to how feasible such a use would be (Bryngelsson and Lindgren, 2013). However, also the notion of reducing the land required for meat production, which stands for 75% of agricultural land use (Foley et al., 2011), for achieving both a direct and substantial emission reduction as well as freeing land for biofuels has been raised (Bryngelsson et al., 2017; Foley et al., 2011; Tilman et al., 2009). Thus, as biomass residue and marginal land potentials are limited and uncertain, biomass from arable land may continue to be an important source for producing biofuels.

Dedicated crops suitable for biofuel production come in many different varieties, with differing characteristics in terms of climate requirements, photosynthesis, yield, type of energy storage, structural properties, growth period etc. Among biofuels, there are numerous pathways, with varying feedstocks (with differing shares of oil, sugar and lignocellulose content), varying technological characteristics, complexity and developmental stage, as well as varying costs and end-products (diesel, ethanol, methane and hydrogen). One can distinguish between three main routes for biofuel production (McKendry, 2002; Huber et al., 2006; IPCC, 2011, p.279):

1. Mechanical extraction and (trans-) esterification, where oil is extracted from oilseeds and converted into fatty-acid methyl esters (biodiesel).
2. Bio-chemical/biological (anaerobic digestion, fermentation), where sugar monomers are converted by bacteria into ethanol, methane or hydrogen.

3. Thermo-chemical (gasification, pyrolysis, liquefaction, hydrolysis), where lignocellulose rich biomass is converted to a range of possible products, including Fischer-Tropsch (FT)-diesel, advanced bioethanol (combined with a subsequent fermentation), Synthetic Natural Gas (SNG) and hydrogen.

The first two belong to the conventional biofuels (if derived from food crops), and the thermo-chemical options belong to the advanced biofuels.

Figure 1.1 shows the different pathways which are included in this work (see e.g. Huber et al., 2006, for more information on the various biofuel production pathways). Rape seed, sugar beet, wheat and maize silage are classified as food crops, and thus fuels derived from these feedstocks belong to conventional biofuels. Poplar, willow and miscanthus are not food crops and have a high lignocellulose content; fuels derived from them belong to advanced biofuels.

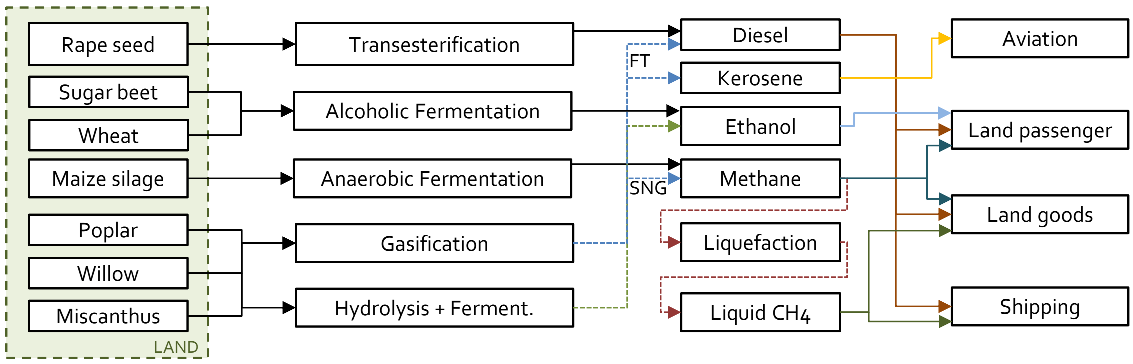

Figure 1.1: All biofuel pathways considered in this work. In paper 4, all of the shown pathways are included; in paper 1-3 only land transport and no liquefied methane; in paper 2 all pathways except advanced ethanol; in paper 1 without differentiation between lignocellulose rich feedstocks.

Diesel fuels can in this work be produced either through transesterification of rape seed or gasification and Fischer-Tropsch-synthesis of woody biomass. With the latter route, also Kerosene can be produced. Ethanol can be produced either through alcoholic fermentation of sugar beet or starch based crops such as wheat, or through hydrolysis and subsequent fermentation of woody biomass. Methane can be produced either through anaerobic fermentation of silage maize or gasification of woody biomass. The methane can then be cryogenically liquefied to liquid methane. In total, ten fuel pathways are included, although with differences between papers.

For each step in the pathway, there are differences in crops yields, inputs and costs; inputs, byproducts, costs and conversion efficiencies; fuel type suitability, demand differences and differing other types of renewable or modal split options for different sectors.

Currently, liquid conventional options are the most common biofuels, whereas neither conventional nor advanced gaseous fuels are used to a large degree in transport in Germany. The liquid advanced biofuel options have also not yet achieved a market break-through, despite reportedly promising cost competitiveness of both feedstocks and crops (IPCC, 2011, p.234) as well as of conversion options (IPCC, 2011, p.244ff & p.281f). Both economics and environmental performance are dependent on a range of parameters, bound with large uncertainties.

1.2 Technological Change and Modelling

Despite the uncertainties, policy and investment decisions need to be made. IPCC (2014a, p.872) emphasises the need for supporting technologies that are estimated to have high development potential, due to two market failures: the external costs of GHG emissions as well as of learning effects, which lead to an underestimation of future benefits or the benefits not being appropriated by the investor. For biofuels, both learning (including also initial costs) as well as environmental performance are subject to uncertainties and dependent on market competitiveness; still there is a surprising lack of systematic and detailed model-based analyses of these factors, especially in combination.

A wide range of models have been developed in order to assess the future role of biofuels for different regions of the world (summarized in Börjesson et al., 2013, p.27ff.). However, many of the models aggregate the biofuels to one or a few available options, thus not representing a competitiveness between biofuels; and many are perfect foresight models and most without endogenous technological change, thus lacking market interactions and path dependencies. For the one other model assessing biofuel competition in Germany with a high level bottom-up detail for the technologies (Martinsen et al., 2010), some factors are lacking: the feedstock cost and greenhouse gas emission developments are not detailed and technological learning is not included. All three have potentially crucial importance for the modelling results and conclusions.

The competitiveness between biofuels depends on a multitude of factors such as land use, yields, feedstock costs, conversion efficiencies, infrastructural costs and GHG abatement, as well as fit into the current system, among other factors. All of these factors are bound with more or less uncertainty and the competitiveness is always relative to the development of the other options.

In order to capture the complexity, a systems perspective is imperative, in order to consider not only the biofuels production pathways, but also the surrounding systems (Mangoyana et al., 2013; Heyne et al., 2015).

1.3 Aim and objectives

The aim of this thesis is to assess techno-economic development potentials of relevant biofuel options, and to model their competitiveness in the long-term under various scenarios and using different functional units: costs related to energy content and GHG abatement, as well as GHG abatement related to land use.

The following research questions are assessed:

1. What is the techno-economic development potential of biofuel options?
2. Which, if any, biofuels are favourable from a systems perspective?

A sound data basis is first established and a myopic simulation model is developed for assessing the competitiveness between various conventional and advanced biofuels for road transport in Germany until 2050, highlighting the influence of learning effects and feedstock cost developments. The role and potential of feedstock cost developments is highlighted in a second stage, whereupon relative GHG abatement costs are assessed and finally an overall optimisation of biofuel deployment is performed in a perfect foresight optimisation model. This thesis includes four papers, listed in Tab. 1.1.

Table 1.1: Overview of papers and their connection to the research questions. RQ=research question

Paper	RQ	Description
1	1	Techno-economic review of biofuel options, model development
2	1	Feedstock cost assessment and method development
3	1&2	GHG module development, analysis of GHG abatement costs
4	2	Multi-sector optimisation model, optimal land use

The thesis consists of two parts. Part I is a general introduction to the field and puts the appended papers into context. Part II contains the appended papers.

Chapter 2

Methodology

With the use of a systems perspective, partial analyses and thus sub-optimal solutions can be avoided, and therefore such a perspective will be used in this work in order to assess possible biofuel developments in mobility. A systems perspective does not merely consider each biofuel option independently, but their development in a system and is in the theory of industrial ecology manifested through the following areas (Lifset and Graedel, 2002; Erkman, 1997): (i) a life-cycle perspective, (ii) material and energy flow analyses, (iii) systems modelling and ideally (iv) interdisciplinary analyses. A further important aspect, (v) technological change, should also be mentioned in this context (Lifset and Graedel, 2002; Grubler, 1998). Aspects i-iii and v are considered in this work, and brought together with systems modelling.

2.1 Systems modelling

For the modelling of technological change, Grubler (1998, p.372) suggests the following elements to be included as a minimum: uncertainty and experimentation; R&D and learning; diffusion and substitution (interaction with existing technologies); economic, environmental and resource impacts and their feedbacks for technological change.

Due to uncertainty, interdependencies and unexpected growth patterns, markets can lock-in on solutions which may be sub-optimal from a systems perspective (Cowan, 1991; Grubler, 1998, p.71f.). Thus, increasing returns may lead to path dependencies, which may be difficult to break (Grubler, 1998, p.104ff.). The role of technological learning, potentially leading to cost reductions in each part of the value-chain, is also important (Grubler, 1998, p.81ff.). The diffusion of technologies in society often follows a logistic (S-shaped) curve, where technologies experience an introductory phase, a growth phase and saturation. The possible interaction of a technology with its technological environment needs to be examined to assess the potential of diffusion (Grubler, 1998, p. 49ff. and 58ff.).

Following these recommendations and in order to capture these elements, a myopic model, depicting uncertainty and market imperfection is developed. A recursive model, building on cumulative development in terms of both costs through technological learning and standing capacities is required. The competition of new options with the standing capacities that have sunk capital investment costs requires a high detail of capital and marginal costs, and thus of input and output streams, resulting in a bottom-up approach. This enables capturing path dependencies. Endogenous technological learning introduces dynamics, reinforcing the cost-competitiveness of deployed options. Through the use a partial equilibrium approach with an investment and production merit order until demand is satisfied, ensures least-cost developments.

Uncertainty (through myopic simulation), technological learning, diffusion and substitution as well as economic (learning) impacts are endogenised in the simulation model, whereas R&D, the exogenous part of technological learning, resource cost developments and environmental effects are handled exogenously. Thus, apart from stochastic elements and diverse agent behaviour, the suggested elements will all be captured in the modelling in this work.

For a national assessment covering only one of the many sectors using biomass, dynamic feedstock prices would be misleading, as both global trade and developments in other sectors would dominate the results, apart from being inherently impossible to foresee. Furthermore, although risk behaviour under uncertainty and experimentation certainly may strongly affect technological progress, such an assessment is out of the scope of an assessment of the relative competitiveness of biofuels, with the analysis aiming on normative conclusions rather than describing patterns. Instead, substantial sensitivity analyses are required. As a result of the assessment focusing on Germany, also R&D is relevant to include, as exogenous learning.

The system boundary in all papers is from Well-To-Tank (WTT), see Fig. 2.1, and thus a complete life-cycle perspective, including the use stage and beyond is out of the scope of this thesis. The status quo of biofuel production sets the starting point, with a the temporal scope until 2050 and a spatial scope limited to Germany. Energetic, GHG abatement and land use functional units are assessed.

2.2 Model description

In order to model the competition between different technology options, a simulation model has 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 (Germany) is the basis at the starting point of the modelling. For each year of the simulation, BENSIM starts by removing the plants that have reached the end of their life-time (capacities present at the beginning are assumed to be decommissioned linearly over the life-time of the plants). In the next step, the technology options are sorted in the orders of total costs (TC; equation 2.1) and in merit order after marginal costs (MC; equation 2.2). A given biofuel demand sets the limit for the production and is also the basis for calculating a minimum market price (p_{sys}), defined by the MC of the most expensive option in the merit order which is put into production. If there are options which have TC lower than the p_{sys}, capacity investments[1] 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. In order to account for e.g. regional differences, investment risk behaviour and market imperfections, options with TC within 10% of the least-cost alternative are treated equally with the least-cost option, i.e. they are also invested in during the same round. There are no capacity expansion constraints in relation to previously built capacities.

After the investment phase, biofuel production takes place following the merit order based on marginal costs of production, until the hypothetical biofuel target is fulfilled (and/or until a given biomass potential is exhausted). In the following year, the technology options that experienced an expansion are subject to learning effects, reducing the investment costs by the learning rate for each doubling of capacity. The options which were not expanded experience "exogenous" learning through a research and development mechanism, defined as one learning rate unit in a specified number of years.

Biofuel costs

Eqn. 2.1 shows the investment cost $\mathrm{I}_j^{(t)}$ [€ GJ_{fuel}^{-1}] for technology j at time point t as a relationship of the initial investment cost $\mathrm{I}_j^{(0)}$ [€ $\mathrm{GJ}_{cap,fuel}^{-1}$ converted from € $\mathrm{MW}_{cap,fuel}^{-1}$] with an assumed capacity factor $\mathrm{C}_{f,j}$ and an annuity factor with an assumed discount rate i over a set time-span T, including a learning effect by a learning rate LR_j with increasing cumulative production capacity $\mathrm{k}_j^{(t)}$ divided by the initial capacity $\mathrm{k}_j^{(0)}$ (see Grubler (1998, p81ff) and IEA (2000)). This relationship holds with the assumption that relative expansion in the region in focus is equal to the relative expansion globally. In order to have a nonzero denominator, a virtual initial capacity $\mathrm{k}_j^{(0)}$ for options not presently at the market is set at 2 PJ in this work, whereas actual initial capacities are set to zero. As the starting capacity for these options is relatively small, the capacities multiply relatively quickly in case of investments and thus can experience substantial learning.[2]

$$I_j^{(t)} = \frac{I_j^{(0)}}{C_{f,j}} \frac{i(1+i)^T}{(1+i)^T - 1} \left(\frac{\kappa_j^{(t)}}{\kappa_j^{(0)}} \right)^{-\log_2(1-LR_j)} \tag{2.1}$$

[1]Investments take place in units of 1 PJ_{cap} a^{-1} (ca 35 MW_{cap} at 8000 full-load hours), an assumption which enables a competition on equal terms. Typical plant sizes for the included options range between 7-250 MW (Ponitka et al., 2016) and thus the model units do not correspond to whole plants, but in some cases more and in some less. However, as the additional demand to be fulfilled surpasses at least 8 PJ a^{-1}, options with typically large plants may reach realistic capacity increments, especially when taking the development over time into account. Similarly, for options with typically small plant sizes the model unit corresponds to several plants.

[2]The set biofuel target influences the amount of expansion possible, thus limiting the possible cost reductions through technological learning. If the final biofuel target of 400 PJ is met by one of these technologies, about 9 virtual capacity doublings are possible, translating into a ca 60% investment cost reduction with a 10% learning rate, which may be seen as a rather high reduction but in line with some estimates for future costs (see e.g. Haarlemmer et al. (2012) and Hamelinck et al. (2005)).

$$MC_j^{(t)} = c_{om,j}^{(t)} + \frac{p_f^{(t)}}{e_f \eta_j^{(t)}} + p_{f2}^{(t)} \dot{m}_{f2,j} + p_{el}^{(t)} \dot{m}_{el,j} + p_{th}^{(t)} \dot{m}_{th,j}$$
$$+ c_{log,j}^{(t)} - p_{bp,j}^{(t)} \dot{m}_{bp,j} + p_{CO_2}^{(t)} \dot{m}_{CO_2,j} \quad (2.2)$$

Eqn. 2.2 shows the marginal cost $\mathrm{MC}_j^{(t)}$ [€ GJ_{fuel}^{-1}] for technology j at time point t as a sum of operation and maintenance costs and personnel costs $\mathrm{c}_{om,j}^{(t)}$, costs for main feedstock ($\mathrm{p}_f^{(t)}$ [€ t_{DM}^{-1}] divided by feedstock specific energy content e_f [GJ t_{DM}^{-1}] and conversion efficiency $\eta_j^{(t)}$), secondary inputs $\mathrm{p}_{f2}^{(t)}$ [€ t^{-1}], electricity ($\mathrm{p}_{el}^{(t)}$ [€ kWh^{-1}] multiplied by amount required, $\dot{m}_{el,j}$ [kWh GJ^{-1}]), process heat ($\mathrm{p}_{th}^{(t)}$ [€ kWh^{-1}] multiplied by amount required, $\dot{m}_{th,j}$), logistic cost $\mathrm{c}_{log,j}^{(t)}$, a credit for by-products $\mathrm{p}_{bp,j}^{(t)}$ and a cost of GHG emissions (the price of emissions $\mathrm{p}_{CO_2}^{(t)}$ multiplied by amount emitted $\dot{m}_{CO_2,j}$).

The by-product income (tied to the respective feedstock cost developments), as well as input and infrastructure costs are elaborated in Paper 1.

Eqn. 2.3 shows the constitution of total costs as a sum of investment and marginal costs.

$$TC_j^{(t)} = I_j^{(t)} + MC_j^{(t)} \quad (2.3)$$

Technologies are assumed to improve their efficiencies linearly, with the end-point being set as a technical limit, to be reached in 2050. Initial plant investment costs are set per unit output in the starting year with further investment cost developments being independent of the efficiency improvements (ceteris paribus, this would mean that plant prices per input feedstock increase in line with the efficiency improvement, the sum being zero).

Economies of scale are applicable to biofuel plants, with larger plants having lower relative investment costs (see e.g. Lange, 2001; Bridgwater, 2009). However, the counteracting effect of feedstock availability and supply-chains affects the optimal sizing of a plant and is site specific, for which a more spatially detailed model would be appropriate. Thus, costs for relatively large-scale plants are assumed from the beginning of the simulation and economies of scale are not explicitly highlighted in the modelling.

Feedstock costs

A common methodology for estimating the costs of energy crops is to add the per hectare profit of a benchmark crop to the per hectare production cost of the energy crop(s) (Witzel and Finger, 2016). This opportunity cost also serves as the shadow price of land, whereas published land rents may rather be seen as marginal land rents (Ericsson et al., 2009). Common benchmark crops include cereals (Krasuska and Rosenqvist, 2012; Faasch and Patenaude, 2012; Ericsson et al., 2009), corn (James et al., 2010; Khanna et al., 2008), soybeans (Khanna et al., 2008) and rape seed (Faasch and Patenaude, 2012). Usually, the most common crop in the region is selected, but sometimes also the one(s) deemed most likely to be replaced by energy crops. In Germany, by far the most common crop is wheat (Destatis, 2017), which is therefore used as a benchmark for all other crops in this work.

The hectare profit for wheat is calculated as the market price $p_w^{(t)}$ [€ t_{FM}^{-1}] times yield $Y_w^{(t)}$ [t_{FM} ha^{-1}] minus production costs $c_w^{(t)}$ [€ ha^{-1}]. Other crops are to achieve this profit per ha, adding production costs $c_i^{(t)}$ [€ ha^{-1}]. The prices are then divided with the yield $Y_i^{(t)}$ [t_{FM} ha^{-1}] to come up with a market price $p_i^{(t)}$ [€ t_{DM}^{-1}] of feedstock i. Over time, this results in a market price development including opportunity costs for each feedstock (Eqn. 2.4).

$$p_i^{(t)} = \left(p_w^{(t)} Y_w^{(t)} - c_w^{(t)} + c_i^{(t)}\right) {Y_i^{(t)}}^{-1} \tag{2.4}$$

All perennials are assumed to provide the same and equivalent good[3], "lignocellulosic biomass", for which the least-cost perennial crop sets the price on an annual basis. Thus, the marginal cost formulation is slightly transformed (Eqn. 2.5)

$$MC_j^{(t)} = c_{om,j}^{(t)} + \min_{\forall i \in f_j} \frac{p_i^{(t)}}{e_i} \frac{1}{\eta_j^{(t)}} + p_{f2}^{(t)} \dot{m}_{f2,j} + p_{el}^{(t)} \dot{m}_{el,j} + p_{th}^{(t)} \dot{m}_{th,j} + c_{log,j}^{(t)} - p_{bp,j}^{(t)} \dot{m}_{bp,j} \tag{2.5}$$

Greenhouse gas abatement

In order to model greenhouse gas cost competitiveness, the model is transformed to have 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 (Millinger et al., 2017a), with the feedstock costs calculated according to (Millinger and Thrän, 2018). 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 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. The system boundaries are shown in Fig. 2.1.

Eqn. 2.6 shows the total GHG emissions $\varepsilon_{tot,j}^{(t)}$ [$kgCO_{2eq}$ GJ_{fuel}^{-1}] 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 $t_{FM^{-1}}$] 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

[3] i.e. the energy content part in the different lignocellulosic biomass types can be used equivalently, e.g. without needing to adapt the conversion step

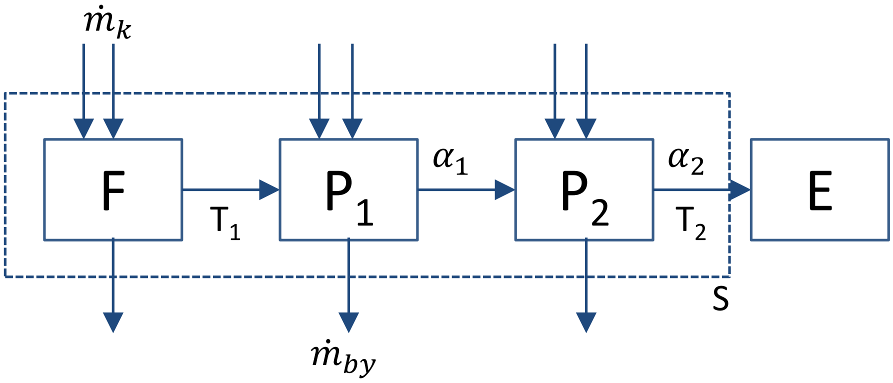

Figure 2.1: System boundaries of the Well-To-Tank (WTT) assessment from feedstock cultivation to tank for each pathway, shown by the dashed line S. The resulting abatement is compared on the basis of different functional units, such as GHG abatement per energy unit, cost per GHG abatement and GHG abatement 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, based on which the preceding greenhouse gas emissions are allocated to the main product, weighted based on the energy content of the different process outputs. 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.

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. The allocation factors are weighted based on the energy content of the different process outputs.

$$\begin{aligned}\varepsilon_{tot,j}^{(t)} =& \frac{\alpha_1\alpha_2}{e_j\eta_j}\left(\frac{1}{Y_j^{(t)}}\sum_{k\in F}\dot{m}_{k,j}^{(t)}\varepsilon_k^{(t)} + \sum_{k\in T_1}\dot{m}_{k,j}^{(t)}\varepsilon_k^{(t)} + \sum_{k\in P_1}\dot{m}_{k,j}^{(t)}\varepsilon_k^{(t)} - \dot{m}_{cr,j}^{(t)}\varepsilon_{cr}^{(t)}\right) \\ &+ \frac{\alpha_2}{e_j\eta_j}\left(\sum_{k\in P_2}\dot{m}_{k,j}^{(t)}\varepsilon_k^{(t)} - \dot{m}_{cr,j}^{(t)}\varepsilon_{cr}^{(t)}\right) + \sum_{k\in T_2}\dot{m}_{k,j}^{(t)}\varepsilon_k^{(t)}\end{aligned} \tag{2.6}$$

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

The total costs $TC_{j,e}^{(t)}$ are divided by the avoided fossil GHG emissions minus the biofuel pathway GHG emissions $\varepsilon_{tot,j}^{(t)}$, in order to come up with the GHG abatement cost $TC_{j,\Delta\varepsilon}^{(t)}$ [€ $\text{kgCO}_{2eq}{}^{-1}$] for time point (t) of option j (Eqn. 2.7).

$$TC_{j,\Delta\varepsilon}^{(t)} = TC_{j,e}^{(t)}\left(\varepsilon_{ref} - \varepsilon_{tot,k}^{(t)}\right)^{-1} \tag{2.7}$$

Allocation optimisation

Complementing the simulation model, 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. 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}], 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. 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]. Capacities available at the beginning κ_0 are decommissioned linearly over their 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. Grubler, 1998).

The required land for each option is given by the production, divided by yield $Y_{i,t}$ times conversion efficiency $\eta_{i,t}$. The total land use cannot surpass Λ_t=1.5 [Mha] (in most scenarios in this paper) for each time point.

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 $i \in I_{pe}$.

$$\max_{\varepsilon} \quad \varepsilon_{tot} = \sum_{i,t} (\varepsilon_{i,t} - \varepsilon_{sub,t}) \cdot \pi_{i,t} \tag{2.8a}$$

s.t.

$$\pi_{i,t} = \sum_{s} \pi_{i,t,s}, \qquad \forall (i,t,s) \in (I,S,T), \tag{2.8b}$$

$$\delta_{s,t} \geqslant \sum_{i \in s} \pi_{i,s,t}, \qquad \forall (i,s,t) \in (I,S,T), \tag{2.8c}$$

$$\pi_{i,t} \leqslant \kappa_{i,t}, \qquad \forall (i,t) \in (I,T), \tag{2.8d}$$

$$\kappa_{i,t+1} \leqslant \kappa_{i,t} + \kappa^{+}_{i,t+1} - \kappa^{+}_{i,t-\hat{t}_i}, \forall (i,t) \in (I,T), \tag{2.8e}$$

$$\kappa^{+}_{i,t+1} \leqslant r_{min} + r_f \cdot \kappa_{i,t}, \qquad \forall (i,t) \in (I,T), \tag{2.8f}$$

$$\kappa^{+}_{i,t+1} \geqslant r_{max}, \qquad \forall (i,t) \in (I,T), \tag{2.8g}$$

$$\Lambda_t \geqslant \sum_{i,s} \pi_{i,s,t} \left(Y_{i,t} \eta_{i,t}\right)^{-1}, \qquad \forall (i,s,t) \in (I,S,T), \tag{2.8h}$$

$$q_t \sum_{i \in I_{pe}} \pi_{i,s_{pl},t} = \sum_{i \in I_{di}} \pi_{i,s_{pl},t}, \quad \forall (i,s,t) \in (I,S,T) \tag{2.8i}$$

The costs are in this case calculated ex-post, according to Millinger et al. (2017a), including technological learning effects based on the resulting expansion of the technologies in each scenario. The feedstock costs were calculated according to (Millinger and Thrän, 2018), with an annual reference feedstock cost increase of 4%.

Chapter 3

Results and discussion

Modelling of the competitiveness of selected biofuels was carried out in this work, with foci on crop-based biofuel costs and GHG abatement. The role of technological learning effects and feedstock cost developments, as well as the development of GHG abatement and GHG abatement cost were analysed under German conditions. Finally, a GHG optimal allocation between transport sectors was carried out. The results differ from both current practice as well as from common expectations on advanced liquid biofuels. The main findings from the modelling and papers are here related to the research questions and then discussed from a systems perspective. For the details, please consult the respective papers.

3.1 Biofuel techno-economic potential and competitiveness

The techno-economic development of biofuel options depends on the competitiveness compared to other options and is thus best analysed in a competitive context. However, in contrast to e.g. wind and solar power, the potential cost reductions through technological learning are limited, and feedstock costs contribute to a large share of the total costs. Under a global decarbonisation, the feedstock cost is in the long-term likely to be determined by the land required.

In Paper 1, it was found that the investment cost of advanced biofuels has commonly been underrated, through optimistic assumptions for both initial investment costs, conversion efficiencies as well as for learning rates. Also, the feedstock cost developments have commonly been assumed to decrease, due to both optimistically assumed high yields (Haberl et al., 2010; Witzel and Finger, 2016; Searle and Malins, 2014), as well as learning effects for the cultivation. Instead, what is argued in Paper 2 is that the feedstock costs should be expected to increase, due to the fact that this has been the trend for the past several decades, as well as due to the high expectations on biomass in a global decarbonisation. A large scale deployment of biofuels for greenhouse gas abatement only makes sense in a large scale global transition, and thus such a development should be assumed when designing policy. The role of uncertain future feedstock prices is characteristic for any usage of biomass, in stark contrast to other renewable options such as wind and solar photovoltaics which have no operational resource costs, and must be considered when designing policy for any sector of the bioeconomy. These results are all relevant also in a global context.

Through the application of a method commonly used for estimating minimum selling prices for energy crops, four main findings can be highlighted (Paper 2): currently common biofuels (rape seed based biodiesel and starch crop based bioethanol) were quickly displaced (by sugar beet based bioethanol); all feedstock costs were found to increase even at moderate price increases (2% a^{-1}) well below developments in the recent decade (4% a^{-1}), in stark contrast to assumptions found in literature; some conventional biofuels (sugar beet based bioethanol and silage maize based biomethane) were found to be more competitive than both currently common options as well as the advanced ones; gaseous biofuels (silage maize based biomethane and advanced Synthetic Natural Gas), especially among advanced options, were found to be highly competitive, also in stark contrast to current focus in literature and policy.

Investment cost reductions through technological learning were found to be overshadowed by feedstock cost developments, which presents a considerable market barrier, as the feedstock costs are not under the control of the investors. Focusing on optimising conversion efficiencies may thus prove more fruitful compared to reducing investment costs. However for some pathways, such as liquid advanced biofuels, thermodynamic limits set important limitations for the potential compared to gaseous biofuel pathways.

In Paper 3, combining these developments with detailed GHG abatement scenarios, the picture changed somewhat in that SNG was found more competitive than when compared with an energetic functional unit, with sugar beet based bioethanol and silage maize based biomethane being strong competitors. Currently common biofuels as well as advanced liquid options were found to be at least 40% more expensive. Overall lower yields and conversion efficiencies increase costs as well as at the same time reducing the GHG abatement, creating a double effect on the GHG abatement costs. Through switching from currently most common biofuels, rape seed based biodiesel and wheat based bioethanol to biomethane and SNG, the GHG abatement per land area can potentially be increased by a factor five. For present day, a switch to biomethane and sugar beet based bioethanol with renewable heat sources would double the spatial GHG abatement, despite the fact that the heat source requires substantial amounts of land.

In Paper 4, a focus on high yielding biofuels in terms of GHG abatement per area of arable land resulted in the following prioritisation for Germany, when taking current fuel suitability restrictions into account: land passenger transport sector would be of the highest priority due to the suitability of higher yielding biofuel options, followed by land goods transport, shipping and finally, when all other sectors have been covered by renewables, aviation.

An important finding of this work is that the direct importance of land use has thus far not received enough attention in terms of the economics of biofuels (Paper 2), as well as for the greenhouse gas emissions policy (Paper 3). Further effects related to land use which are of high concern in public debate, such as land use change, competition with food production and the potential of freeing land for conservation, result in strong arguments across the triple bottom line (social, economic, ecologic) for a stronger focus on land use of biofuels in policy and including the required arable land in the functional unit, instead of merely energy or GHG abatement as is presently the case. As could be expected in light of previous results, the total cost differences between scenarios in Paper 4 were rather small, despite having no cost restrictions, and thus the greenhouse gas abatement per land area would be an important long-term indicator for crop-based biofuels.

Currently, substantial uncertainties lead to sub-optimal solutions being practised in each part of the pathway: uncertain policy leads to short-term and market-available, easily transportable and tradable feedstocks to be used, instead of using those which would result in lower cost as well as lower greenhouse gas emissions. Furthermore, investment uncertainties lead to low-cost conversion options being invested in, leading to simpler processes which require a larger share of the conversion to a usable fuel to be performed on the field (especially rape seed based biodiesel), which leads to lower yields.

An optimal GHG abatement through biofuels thus requires substantial policy in all parts of the pathway: on the feedstock side in assuring the availability of high yielding crop types while at the same time assuring a sustainable humus balance and a curbing of soil N_2O emissions; on the conversion side in assuring that long-term investments are made feasible despite high uncertainties regarding feedstock costs, market demands and feedstock availability; on the demand side in assuring that a market for high yielding fuels exists through a higher deployment on flex fuel vehicles which allow for higher bioethanol and biomethane shares. Due to these barriers, a technology neutral policy is unlikely to result in high shares of these fuels; instead directed action would be required.

The current practise of applying admixture quotas to sub-sectors of land transport renders a significantly lower climate benefit compared to an overall optimal usage, and 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 remain of importance for the longer term.

3.2 Discussion

Thus far, competitiveness modelling results between biofuels have been assessed. However, the question under which circumstances biofuels are the best usage of biomass is important in this context. The answer to the question demands a systems perspective, as it depends essentially on the resource base, climate benefits in different sectors and competing renewable alternatives:

1. The biomass demand for food and feed
2. The biomass demand for all other non-food/feed sectors
3. The development of the fossil solutions which are to be substituted by biomass in each sector
4. The development of other non-biomass and non-fossil solutions for those sectors

3.2.1 Resource base

The role of biomass in a successful societal decarbonisation transition will change drastically. Current practise and demand for biomass is dominated by producing feed for meat production, with 75% of agricultural land used for raising animals (Foley et al., 2011), with an increasing trend (FAO, 2017), which adds pressure on land use, leading to an extension of agriculture into previously largely pristine areas such as rain forests (Foley, 2005). Due to this added pressure, previously bounded soil carbon is emitted, leading to vast CO_2 emissions (Fargione et al., 2008), beside heavy biodiversity loss (Foley, 2005) among other effects. In order to avoid these effects - termed direct and indirect land use change - increased uses of biomass crops in any sector, such as for bioenergy, require an equivalent reduction of demand in other sectors. This is mainly achievable through a reduction of land required for meat production (Tilman et al., 2009; Bryngelsson et al., 2017; Foley et al., 2011) as well as thorough land use governance policy (Popp et al., 2012; Thrän et al., 2017), the latter which may prove difficult to implement on a global scale (Bryngelsson and Lindgren, 2013). In fact, a reduction of ruminant meat production is necessary in order to achieve climate goals (Bryngelsson et al., 2017), and the double effect of being able to use the land areas for replacing fossil fuels further enhances the positive effect (Tilman et al., 2009; Bryngelsson et al., 2017). Thus, an increase of bioenergy from dedicated crops relies on a redirection of currently used biomass or the lands used therefore (Tomei and Helliwell, 2016).

Current land required for producing biofuels used in Germany (including imports) amounts to ca 1.5 Mha (see Paper 4), while it has been estimated that 8.4 Mha (including imports) is needed for German meat consumption (Witzke et al., 2011). Thus, a reduction of land used for meat consumption by a fifth, through demand reduction or switching to less land intensive meat would, in addition to reducing GHG emissions resulting from ruminant meat production (Bryngelsson et al., 2017), allow for a doubling of the assumed area used for biofuels today, and thus essentially double the direct climate benefit resulting from biofuels.

3.2.2 Biomass climate benefit in other sectors

For the other non-food and feed sectors, biomass is a viable alternative to reduce GHG emissions through replacement of fossil options. Presently, the transport sectors stand for 21% of German GHG emissions (in total 926 Mton a^{-1}), power production stands for 33%, manufacturing, construction and industrial processes stand for 24%, commercial and residential energy (mainly heating) 14% and agriculture 7% (EEA, 2017).

As a benchmark, the permissible carbon budget in order to achieve certain climate goals can be allocated per capita (WWF, 2017). 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. In the best scenario in Paper 4, the power and transport sectors emit ca 170 Mton a^{-1}, leaving 121 Mton a^{-1} for the other sectors. These sectors combined today emit ca 431 Mton (EEA, 2017), and thus a dramatic transition is required there as well.

The energy demand of some of the sectors can be reduced through efficiency measures (e.g. room and water heating), whereas e.g. construction requires a shift towards renewable materials where biomass can play a large role (Peñaloza, 2017; Rockström et al., 2017). For some industrial processes, the most suitable renewable options are biomass also in the long run (e.g. where the chemical properties of hydrocarbons are sought, such as in steel production and hydrocarbon chemistry). These sectors all compete with the transport sector for the limited biomass available and more research is needed regarding optimal allocations of biomass across all sectors.

As long as there are options in the power mix, as well as in heat production and industrial applications, which emit more CO_2 than the transport fuel fossil reference, and can be replaced by biomass application with sufficient efficiency to achieve a higher climate benefit than through biofuels, then clearly these applications are to be prioritised from a climate perspective. This is for instance the case as long as coal power can be replaced by biomass in the power mix (i.e. as long as coal is the power generation option on the margin in terms of relative GHG emissions), especially by combined heat and power (CHP) processes with higher overall efficiencies and the possibility to serve both the power and heat sectors. Seasonal variations in demand and vRES supply may result in coal as an option in the winter to remain longer, for which biomass also may become important due to a lack of low-cost seasonal storage options (Millinger et al., 2017b).

When coal is no longer used and natural gas is the fossil option on the power (and heat) mix GHG margin, biofuels would substitute more fossil GHG emissions (Tab. 3.1). In this case however, efficiencies are important, as the difference between producing methane and liquid fuels may flip the advantage if gaseous biofuels are not viable in transport. As an example for wood-based advanced biofuels, conversion efficiencies of η =0.58-0.73 for SNG would require advanced liquid equivalents of η =0.39-0.49 in order to achieve the same GHG benchmark under RED - ceteris paribus - when excluding the process emissions, which are to the disadvantage of advanced liquid biofuel options. If the IPCC default values are used, this disadvantage is larger.

Table 3.1: Default emission factors for selected fossil fuels in stationary and mobile combustion (IPCC, 2006). The higher end of the range for the liquid fuels is the standard emission factor from the EU Renewable Energy Directive (European Parliament, 2009).

	$tCO_2\ TJ^{-1}$
Lignite	101.0
Anthracite	98.3
Liquid fuels	69.3-83.8
Natural gas	56.1

3.2.3 Other renewable fuel options

In the case of mobility, the two most viable alternatives to biofuels are electric (Armaroli and Balzani, 2011) and hydrogen (from water electrolysis) (Dunn, 2002) mobility, both of which could be supplied renewably in sufficient quantities (Jacobson and Delucchi, 2011) and without the use of hydrocarbons. For these options, the GHG emissions rely on those of the power mix. For the fuel versions, the combination with conversion losses (Sterner, 2009, p.109f.) renders those alternatives superior to biofuels only at very high shares of variable renewables (vRES). Alternatively, excess power produced could be utilised, with the advantage of (near) zero GHG emissions, but with a limited amount available, possibly even at very high vRES shares (Schill, 2013; Tafarte et al., 2014). Such high levels may even be infeasible due to decreasing marginal values of vRES leading to a heavy reliance on dedicated subsidies, with high CO_2-prices potentially counteracting vRES throughput by favouring baseline options such as CCS and - if permitted - nuclear power (Hirth, 2014). If an (almost) fully renewable power mix is achieved, for the hydrocarbon options the question remains as to where a cost-competitive source of carbon is to be found, as the fossil options would be largely phased out by then. Thus, possibly hydrogen may be the long-term competitor to biofuels in transport modes where battery storage based propulsion is not an option - and potentially even a serious competitor to battery EVs (van der Zwaan et al., 2013).

For solar and wind power, the direct usage of the generated power for producing fuels (often called Power-to-X, PtX, or electrofuels) is an alternative which would circumvent the relatively slow progress in the power mix. Thus substantially higher yields per land area can be achieved (Larkum, 2010), but there are at least three caveats: firstly, due to the variable nature of vRES leading to low capacity usage and the high cost of PtX facilities (Albrecht et al., 2016), the solutions to produce fuels are costly; secondly, the power is better used directly, and without substantial conversion losses, in a system-friendly manner (Tafarte et al., 2014; Millinger et al., 2017b) in the power mix as long as it can replace any fossil fuels there; thirdly, photovoltaic modules can be installed on non-arable areas and thus compete directly for the arable land only when these have been saturated. Nevertheless, this is a field which grants further research.

3.2.4 Summary

Thus, solutions which may appear elusive, such as liquid lignocellulose based fuels, lignocellulosic crops from marginal lands, aviation fuels as well as PtX, are not necessarily the immediately best options for transport, when viewed from a systems perspective.

Table 3.2: A sketch of possible short, medium and long-term priorities of biomass allocation, summarising this section.

	Options
Short-term	replacing coal, CHP, fuels fitting into current system
Medium-term	gaseous biofuels (possibly of perennial origin), seasonal storage
Long-term	building materials, aviation, hydrocarbon based chemicals and materials

The overall priorities emerging from this discussion are shown in Tab. 3.2, where the options relevant in the short, medium and long terms are sketched. Some of the options which are relevant also in the long-term, such as building materials, are relevant immediately. Others, such as gaseous biofuels would require an early policy to stimulate supply and demand.

3.2.5 Applicability of results to other regions

Although this work is based on Germany, several key findings can be generalised for a global context. The results for investment costs and technological learning are applicable globally. Expectation on advanced biofuels are high, due to expected learning in each part of the chain. However, the findings in this work suggest that the expectations are set too high.

Furthermore, the importance of feedstock costs for the cost developments has been underrated, due to often assumed decreasing feedstock costs, especially for short rotation coppice. As instead demand for biomass is likely to increase, the general increasing feedstock cost trend in the past decades is likely to continue, perhaps even at higher rates. The feedstock cost developments overshadow potential investment cost reductions. This in turn inhibits investments due to high uncertainties and as the feedstock costs are not in the control of the investors, and thus no technological learning takes place.

German per capita arable land corresponds roughly to the global average[1], and is thus a relevant measure also in a global context - albeit with significantly higher than average yields (FAO, 2017). As the supply side is not significantly skewed, the results from a German study can thus to some extent be scaled up or transferred to other regions.

The best biofuels differ between regions, due to different climate, crop suitability, yields, as well as differing power mix and other background systems. In addition, the availability of biomass residues is an important difference between regions. Also, the role of electric mobility and electrofuels, especially in regions with a high share of renewables in the power mix, may differ, as does the composition of the vehicle fleet. Thus, although some results can be generalised, important differences would lead to other optimal biofuel developments.

[1] World arable land is 1530 Mha (Foley et al., 2011). A current population of 7.6 billion gives 0.20 ha cap^{-1}. German arable land is ca 12 Mha, with ca 82 million capita (Destatis, 2017), giving 0.15 ha cap^{-1}. As the global population increases while the German one is relatively stagnant, the per capita arable land will converge.

Chapter 4

Conclusions

By applying a systems perspective, some common preconceptions about biofuel futures have in this work been scrutinised in terms of economic developments and greenhouse gas abatement, using energetic, GHG abatement and land use functional units. The results differ from both current practice as well as from common expectations on advanced liquid biofuels.

It was found that the costs of advanced biofuels have commonly been underrated, through optimistic assumptions for the feedstocks (optimistic high yields, learning effects, baseline cost reductions) and conversion step (initial investment costs, conversion efficiencies, learning rates). Through a thorough data and plausible assumption set, all of these factors were revised compared to common assumptions, leading to some interesting conclusions.

Currently most common practise, i.e. rape seed based biodiesel and wheat based bioethanol was found not to be economical when considering differentiated and increasing feedstock costs. Instead, sugar beet based bioethanol in the short to medium term, and silage maize based biomethane as well as lignocellulosic crop based SNG in the medium to long-term were found to be the more economical options, both with energetic and GHG abatement functional units. Notably, advanced liquid fuels were found substantially inferior to these three options. Switching from current practise to higher yielding biofuel options can treble the abatement per land area for the present day, and potentially increase it by a factor five in the future.

Notably, the different functional units result in different merit orders for the biofuel options. With an energetic cost functional unit, sugar beet based ethanol dominated for most of the time span, whereas a relative GHG abatement cost functional unit resulted in SNG being a strong option, especially at a rapid decarbonisation of the power mix. With a land use GHG abatement functional unit, silage maize based biomethane was the best, with SNG converging only at very high renewables shares of the background systems.

The land use of biofuels perspectively decides large parts of both economics and GHG emissions and thus in an optimal development, current practise would be rapidly replaced by higher yielding options. However, some important market barriers require dedicated policy in order for this to take place: investment cost reductions through technological learning are overshadowed by feedstock cost developments, which inhibits investments as the feedstock costs are not under the control of the investors; perennial crops are a long-term investment for farmers with increased risks, which would likely need to be circumvented through policy; for gaseous biofuels as well as for higher bioethanol shares, the vehicle market needs to be stimulated. Furthermore, other ecological parameters need to be monitored in order to ensure sustainable practises.

Due to differences in available options, it is likely that the transport sub-sectors are transformed at different paces, and thus biofuels would wander between them in order to perform incremental improvements until larger transformations occur. A focus on high yielding biofuels in terms of GHG abatement per area of arable land results in the land passenger transport sector to be of the highest priority due to the suitability of higher yielding biofuel options, followed by land goods transport, shipping and finally aviation. The current practise of applying admixture quotas to sub-sectors of land transport renders a significantly lower climate benefit compared to an overall optimal usage, and a large societal transition is required before aviation biofuels become the best biomass usage for mitigating climate change. If gaseous fuels are not possible to introduce on a large scale, sectors allowing liquefied gaseous fuels become the priority, e.g. goods transport and shipping.

The direct importance of land use has thus far not received enough attention in terms of the economics of biofuels from dedicated crops, as well as for the greenhouse gas emissions policy. Biofuels produced from arable land can provide a strong GHG benefit if an expansion of arable land is hindered through redirecting land use, which requires a holistic policy approach.

4.1 Future research

As the topic at hand spans a multitude of disciplines, future work identified through this work is divided into work related to modelling as well as to other issues. Each identified area grants substantial further research.

Future research related directly to the modelling includes:

1. Analysis across regions (e.g. EU), with differing yields, potentials, power mix etc.
2. Spatially explicit extension of the model and assessment of optimal locations of biofuel conversion facilities
3. Analysis across more societal sectors (e.g. power, heat, industry)
4. Competitiveness and potential of PtX/electrofuels compared to biofuels
5. Biofuels from perennials grown on marginal lands
6. Technological learning effects and endogenous efficiency developments in the perfect forecast model
7. Comparison of the myopic and perfect forecast models
8. Assessment of vehicle market developments, extending the analysis to Well-to-Wheel and analysing the potential role of differences between drive trains on the competitiveness.

Thus, the spatial scope and detail, the sectors, technology and feedstock options included, system boundary extensions and model technical aspects can all be extended in order to provide answers to further questions regarding this topic.

Future research related to surrounding issues includes:

1. Sustainable high yielding biofuel crop practises possibly allowing for land conservation and the resulting ecological trade-offs
2. Regional assessment of soil N_2O emissions, and practises curbing these
3. Feedstock cost developments under a global energy and bioeconomy transition
4. Investment costs and conversion efficiencies of advanced biofuel options as well as yields and costs of perennials

More holistic research is required in order to come up with practises combining high yields across the whole value-chain, while assuring ecologically sustainable practises. The notion of assessing land use as a basket of goods rather than on an individual pathway level would include the possibility of land conservation enabled through higher yielding practises, which locally may not be the best practise but globally perhaps optimal. Thus trade-offs could be analysed from a systems perspective.

The N_2O balance of agricultural practises are highly variable, dependent on regional characteristics such as climate, soil and weather (Bouwman et al., 1993), but is also dependent on farming and can be curbed through more sustainable practises (Skenhall et al., 2013). Both should be monitored and regulated, as these emissions show a large span (Crutzen et al., 2008; Cherubini and Strømman, 2011; Menten et al., 2013) and thus present considerable uncertainties for any given biofuel.

Future feedstock cost developments are an uncertain field, which cannot viably be analysed through the use of historical developments in a previously unprecedented global transition to a bioeconomy. Mere market models are also not sufficient, as bio-physical limits are of crucial importance (Bryngelsson and Lindgren, 2013; Millinger and Thrän, 2018), and assumptions of learning effects for some feedstocks without including overall feedstock cost developments are not sufficient. The notion of feedstock costs decreasing over long periods of time (in stark contrast to the developments in past decades) simultaneously with a global decarbonisation must be held to be absurd. Since this parameter was found to be of utmost importance, the field must receive more attention.

Investment costs of advanced biofuel options show a large span in literature (Haarlemmer et al., 2014), as do the yields and costs of perennial crops (Witzel and Finger, 2016; Searle and Malins, 2014), as well as the conversion efficiencies (Millinger et al., 2017a). This therefore requires more research, as the uncertainties, together with those of the feedstock costs, are detrimental to investment as well as policy decisions.

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Contribution to Appended Papers

The authors' contribution to the work reported in the appended papers were as follows:

I Millinger, M., Ponitka, J., Arendt, O. and Thrän, D. (2017) *Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany.* Energy Policy. 107, 394-402.

Millinger had the idea, developed the model, carried out all the modelling and calculations and wrote the paper. Ponitka and Arendt provided feedback on the model, data and manuscript. Thrän provided expert guidance and feedback on the model results and manuscript.

II Millinger, M. and Thrän, D. (2016) *Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields.* Journal of Cleaner Production. In Press.

Millinger had the idea, developed the model, carried out all the modelling and calculations and wrote the paper. Thrän provided feedback on the manuscript.

III Millinger, M., Meisel, K., Budzinski, M. and Thrän, D. (submitted) *Relative greenhouse gas abatement cost competitiveness development of biofuels in Germany.*

Millinger had the idea, developed the model, carried out all the modelling and wrote the paper. Meisel provided LCA and legislature expert feedback and contributed to the GHG calculations as well as to the new goal function. Budzinski provided some LCA data and feedback on the manuscript. Thrän provided feedback on the manuscript.

IV Millinger, M., Meisel, K. and Thrän, D. (submitted) *Climate optimal deployment of biofuels from crops in Germany.*

Millinger had the idea, developed the model, carried out all the modelling and calculations and wrote the paper. Meisel provided LCA expert and manuscript feedback. Thrän provided feedback on the manuscript.

Part II

Appended papers

Paper 1

Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany

Millinger, M., Ponitka, J., Arendt, O. and Thrän, D.

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Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany

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ABSTRACT

Techno-economic variables for advanced biofuels produced from lignocellulosic biomass have been scrutinized and combined with a newly developed transparent model for simulating the competitiveness between conventional and advanced biofuels for road transport in the medium to long term in Germany. The influence of learning effects and feedstock cost developments has been highlighted, including also gaseous fuels. Thorough sensitivity analyses were undertaken. Previously reported cost assumptions for advanced biofuels were found to have been too optimistic. The most cost-competitive biofuels for most of the time period remained conventional biodiesel and bioethanol, but the costs of these options and biomethane and Synthetic Natural Gas (bio-SNG) converged in the medium term and thus other factors will play a decisive role for market developments of biofuels. Feedstock cost uncertainties for the future remain a challenge for long-term planning, and low-cost short-rotation coppice may change the picture more than any other parameter. Of the advanced biofuels, bio-SNG was found significantly more cost-competitive and resource efficient than Fischer-Tropsch-diesel and lignocellulose-based ethanol, but still requiring a dedicated long-term policy. The results and the large sensitivities of biofuel competitiveness stress the need for more data transparency and for thorough sensitivity analyses of the results in similar system studies.

1. Introduction

Global concern for climate change calls for alternatives in the transport sector, which accounts for 14% of global anthropogenic (IPCC, 2014) and 20% of German GHG-emissions (BMWi, 2013). Germany aims to reduce transport emissions by 6% until 2020 (BImSchG, 2014), with subsequent further emission reductions required in order to meet overall climate targets (UNFCCC, 2015). Aside from demand reduction and modal shift, biofuels and a switch to electric mobility are the main renewable solutions for road transport, with biofuels fitting comparably well into the current vehicle fleet.

The presently dominant biofuels in the German road transport sector are biodiesel from oil bearing crops and bioethanol from sugar beet or grains. These conventional biofuels compete with food production (see e.g. Foley et al., 2011) and have a limited GHG-abatement even when excluding indirect land use effects (Cherubini et al., 2009). Advanced biofuels derived from biomass with a high share of cellulose, hemicellulose and/or lignocellulose potentially avoid these problems and are thus often proposed as a solution, with promising future cost estimates reported (Chum et al., 2011, p.282; Eisentraut et al., 2011, p.32; IEA, 2008, p.335). However, to date advanced biofuels have not yet become commercially available, and large-scale attempts have failed (Hogan, 2011).

The capital investment and production costs of advanced biofuels have been subject to a large range of estimates (Haarlemmer et al., 2012). The future cost development is subject to the development of feedstock costs and to learning effects, both being uncertain. At any point in time, the biofuel options are also subject to competition between each other to fulfill biofuel mandates. Yet - to our knowledge - the effect of these uncertainties on cost developments and competitiveness of biofuels have not been thoroughly assessed before.

There is a large number of future modelling studies including biofuels, with a wide array of different scopes and results (Börjesson et al., 2013). The models are often large and the focus often on whether to use biomass in the power or transport sector (as Martinsen et al. (2010) did for Germany) and thus the techno-economic details of the different biofuels have not been central (Börjesson et al., 2013). Wit et al. (2010) performed a modelling study including learning and competition between biofuels for transport in Europe. However, the model did not build the yearly development on prevalent capacities,

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thus missing out on path-dependencies, gaseous biofuels were excluded and advanced liquid fuels were seemingly assumed to be lower cost than conventional biofuels already from the beginning of the time-period, indicating a need for further scrutiny of the data basis. Most other models are optimisation models with perfect foresight, thus losing information regarding learning effects and path dependencies, which are of value to policy makers. Also, there is a lack of thorough sensitivity assessments to results in energy systems modelling (Hedenus et al., 2012). This is perhaps of particular importance in the bioenergy sector, which is subject to influence from numerous parameters.

To address the open points mentioned above, a sound data set has been developed and used as a basis for a newly developed least-cost myopic simulation model in order to answer the research question: Which liquid or gaseous biofuel options from domestic biomass are potentially most cost-competitive in Germany in the medium to long term?

2. Methodology, scenarios and data

Three pathways of conventional biofuels (biomethane produced from maize, bioethanol from sugar beet and biodiesel from rape seed) and three pathways as advanced biofuel counterparts (Synthetic Natural Gas (bio-SNG), bioethanol from lignocellulosic biomass (Ligno-EtOH) and Biomass-to-Liquid (BtL)/Fischer-Tropsch (FT)-diesel, all produced from biomass with high lignocellulosic content) were included in the simulation. All biofuels were assumed to be equivalent at the end user stage (with some differences regarding transport and storage costs).

Vehicle costs are neglected in this paper, as various and possibly fuel type specific strategies for implementing biofuels can be foreseen in a likely rapidly changing market (see e.g. Economist (2016)), which highly affect vehicle usage rates and efficiencies and have large consequences for the vehicle cost added to the fuel cost.

Germany has relatively much experience with the conventional biofuel options biomethane, bioethanol and biodiesel, the data for which are elaborated in Thrän et al. (2015). For advanced biofuel options there is less experience, why a literature review was additionally performed in order to come up with estimates for techno-economic parameters. All costs used in the modelling were converted to $€_{2010}$.

2.1. Model description

In order to model the competition between different technology options, a simulation model has 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 starting point of the modelling. For each year of the simulation, BENSIM starts by removing the plants that have reached the end of their life-time (capacities present at the beginning are assumed to be decommissioned linearly over the life-time of the plants). In the next step, the technology options are sorted in the orders of total costs (TC; Eq. (1)) and in merit order after marginal costs (MC; Eq. (2)). A given biofuel demand sets the limit for the production and is also the basis for calculating a minimum market price (p_{sys}), defined by the MC of the most expensive option in the merit order which is put into production. If there are options which have TC lower than the p_{sys}, capacity investments[1] 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. In order to account for e.g. regional differences, investment risk behaviour and market imperfections, options with TC within 10% of the least-cost alternative are treated equally with the least-cost option, i.e. they are also invested in during the same round. There are no capacity expansion constraints in relation to previously built capacities.

After the investment phase, biofuel production takes place following the merit order based on marginal costs of production, until the hypothetical biofuel target is fulfilled (and/or until a given biomass potential is exhausted). In the following year, the technology options that experienced an expansion are subject to learning effects, reducing the investment costs by the learning rate for each doubling of capacity. The options which were not expanded experience "exogenous" learning through a research and development mechanism, defined as one learning rate unit in a specified number of years.

Eq. (1) shows the investment cost $I_j^{(t)}$ [€ GJ $^{-1}_{fuel}$] for technology j at timepoint t as a relationship of the initial investment cost $I_j^{(0)}$ [€ GJ $^{-1}_{cap,fuel}$ converted from € MW $^{-1}_{cap,fuel}$] with an assumed capacity factor $C_{f,j}$ and an annuity factor with an assumed discount rate i over a set time-span T, including a learning effect by a learning rate LR_j with increasing cumulative production capacity $k_j^{(t)}$ divided by the initial capacity $k_j^{(0)}$ (see Grubler (1998, p81ff) and IEA (2000)). This relationship holds with the assumption that relative expansion in the region in focus (Germany) is equal to the relative expansion globally. In order to have a nonzero denominator, a virtual initial capacity $k_j^{(0)}$ for options not presently at the market is set at 2 PJ in this paper, whereas actual initial capacities are set to zero. As the starting capacity for these options is relatively small, the capacities multiply relatively quickly in case of investments and thus can experience substantial learning.[2]

$$I_j^{(t)} = \frac{I_j^{(0)}}{C_{f,j}} \frac{i(1+i)^T}{(1+i)^T - 1} \left(\frac{k_j^{(t)}}{k_j^{(0)}} \right)^{-\log_2(1-LR_j)} \quad (1)$$

$$MC_j^{(t)} = c_{om,j}^{(t)} + \frac{p_f^{(t)}}{e_f \eta_j^{(t)}} + p_{f2}^{(t)} \dot{m}_{f2,j} + p_{el}^{(t)} \dot{m}_{el,j} + p_{th}^{(t)} \dot{m}_{th,j} + c_{log,j}^{(t)} - p_{bp,j}^{(t)} \dot{m}_{bp,j} + p_{CO_2}^{(t)} \dot{m}_{CO_2,j} \quad (2)$$

Eq. (2) shows the marginal cost $MC_j^{(t)}$ [€ GJ $^{-1}_{fuel}$] for technology j at timepoint t as a sum of operation and maintenance costs and personnel costs $c_{om,j}^{(t)}$, costs for main feedstock ($p_f^{(t)}$ [€ t $^{-1}_{DM}$] divided by feedstock specific energy content e_f [GJ t $^{-1}_{DM}$] and conversion efficiency $\eta_j^{(t)}$), secondary inputs $p_{f2}^{(t)}$ [€ t^{-1}], electricity ($p_{el}^{(t)}$ [€ kWh^{-1}] multiplied by amount required, $\dot{m}_{el,j}$ [kWh GJ^{-1}]), process heat ($p_{th}^{(t)}$ [€ kWh^{-1}] multiplied by amount required, $\dot{m}_{th,j}$), logistic cost $c_{log,j}^{(t)}$, a credit for by-products $p_{bp,j}^{(t)}$ and a cost of GHG-emissions (the price of emissions $p_{CO_2}^{(t)}$ multiplied by amount emitted $\dot{m}_{CO_2,j}$).

Eq. (3) shows the constitution of total costs as a sum of investment and marginal costs.

[1] Investments take place in units of 1 PJ_{cap} a^{-1} (ca $35MW_{cap}$ at 8000 full-load hours), an assumption which enables a competition on equal terms. Typical plant sizes for the included options range between 7-250 MW (Ponitka et al., 2016) and thus the model units do not correspond to whole plants, but in some cases more and in some less. However, as the additional demand to be fulfilled surpasses at least 8 PJ a^{-1}, options with typically large plants may reach realistic capacity increments, especially when taking the development over time into account. Similarly, for options with typically small plant sizes the model unit corresponds to several plants.

[2] The set biofuel target influences the amount of expansion possible, thus limiting the possible cost reductions through technological learning. If the final biofuel target of 400 PJ is met by one of these technologies, about 9 virtual capacity doublings are possible, translating into a ca. 60% investment cost reduction with a 10% learning rate, which may be seen as a rather high reduction but in line with some estimates for future costs (see e.g. Haarlemmer et al. (2012) and Hamelinck et al. (2005)).

$$TC_j^{(t)} = I_j^{(t)} + MC_j^{(t)} \quad (3)$$

Technologies are assumed to improve their efficiencies linearly, with the end-point being set as a technical limit, to be reached in 2050. Initial plant investment costs are set per unit output in the starting year with further investment cost developments being independent of the efficiency improvements (ceteris paribus, this would mean that plant prices per input feedstock increase in line with the efficiency improvement, the sum being zero).

Economies of scale are applicable to biofuel plants, with larger plants having lower relative investment costs (see e.g. Lange, 2001; Bridgwater, 2009). However, the counteracting effect of feedstock availability and supply-chains affects the optimal sizing of a plant and is site specific, for which a more spatially detailed model would be appropriate. Thus, costs for relatively large-scale plants are assumed from the beginning of the simulation and economies of scale are not explicitly highlighted in the modelling.

In principle, other flows can be included, one notable example being life-cycle emission data. These can be coupled with a GHG-cost to indicate the competitiveness including such effects. A thorough analysis of GHG abatement potentials of the biofuel options (which are highly uncertain due to their sensitivity to highly varying assumptions along the pathway) is beyond the scope of this paper, and therefore greenhouse gases are only considered tentatively in one sensitivity run. Future extensions and applications of the model will have to cover this crucial aspect more in detail, as greenhouse gas abatement is the main objective of introducing biofuels in Germany.

2.2. Data

Techno-economic data for advanced biofuel options are presented in detail, with a summary of all data used at the end of this section.

2.3. Initial ligno-cellulosic feedstock cost

Short-rotation coppice (SRC) is a promising and potentially high-yielding source of ligneous biomass. Faasch and Patenaude (2012) estimate production costs for SRCs in Germany of 58€ t^{-1}_{DM}, which would set a minimum, break-even selling price. For a farmer to decide to grow SRCs however, the profit per hectare would need to at least match that of other possible options. For instance, at wheat prices of 140€ t^{-1}, the minimum selling price for wood chips from SRCs would be around 100€ t^{-1}_{DM} in order for it to be the more profitable alternative (Schaerff, 2007). Wheat cost 203€ t^{-1} on average on the world market in 2014 (World Bank, 2016), which would increase the minimum selling price of SRCs further. In 2015, SRC wood chips cost 131 € t^{-1}_{DM} (122€$_{2010}$ t^{-1}_{DM}), lower than forest wood chips, at 153 € t^{-1}_{DM} (CARMEN, 2015).

Thus, an initial wood chip price of 122€ t^{-1}_{DM} (6.6€ GJ^{-1}) is assumed. This can be compared to assumptions between 2€ GJ^{-1} and 5€ GJ^{-1} in other biofuel studies reviewed by Sunde et al. (2011).

2.3.1. Investment costs for advanced biofuels

Haarlemmer et al. (2012) reviewed 14 studies on thermochemical FT-diesel production from biomass published between 2000 and 2011, concluding that the depreciable investment cost is likely to be toward the upper limit of a range of between 1.25 and 2.5 M€$_{2011}$ MW^{-1}_{cap}. Bridgwater (2009) analysed 23 data sets for BtL plants and came up with a relationship according to plant size (Eq. (4)), which renders the investment costs in Table 1, where the costs for the 400 MW_{cap} plant are comparable to those in Haarlemmer et al. (2012). Bridgwater (2009, p24.) also contends that the investment costs for new technologies are invariably underestimated.

$$I_c = 0.535\cdot(\dot{m}_{fuel,out})^{0.574} \quad (4)$$

Lange (2001) has proposed some simple methodologies for estimating investment costs for thermo-chemical plants, one being based on heat of reaction, using the total energy loss of a process[3] (Eq. (5))

Table 1
Investment costs for BtL plants of different sizes according to Bridgwater (2009). For the conversion from MW_{cap} to liquid hydrocarbons, a lower heating value of 42 GJ t^{-1} and a capacity factor of 1 have been assumed. Costs have been converted to €$_{2010}$.

MW_{cap}	Hydrocarbon [kt a^{-1}]	Cost (Eq. (4)) [M€]	M€$_{2010}$ MW^{-1}_{cap}
20	15	134	6.6
100	75	336	3.3
200	150	501	2.5
400	300	746	1.8
1000	750	1262	1.2

$$I_c = 3.0\cdot(h_{LHV,in,feed} - h_{LHV,out,fuel})^{0.84} \quad (5)$$

In combination with process efficiencies of between 34.6 – 46.7% (see below), the investment cost of a BtL plant using Eq. (5) would amount to between 2.0–2.4 M€ MW^{-1}_{cap}. Similarly, a bio-SNG plant with process efficiencies of between 57.9 – 72.6% would have an investment cost of 1.2 – 1.7 M€ MW^{-1}_{cap}.

Although the initial costs may be higher for the first commercial plants, 2.5 M€ MW^{-1}_{cap} is used as a conservative base assumption. For bio-SNG plants, the investment cost is set at 2 M€ MW^{-1}_{cap}, due to higher conversion efficiencies.

Initial investment costs of Ligno-EtOH plants have been reviewed and estimated at 2.1 M€$_{2003}$ $MW^{-1}_{cap,HHV}$ (Hamelinck et al., 2005), corresponding to 2.7 M€$_{2010}$ $MW^{-1}_{cap,LHV}$[4].

2.3.2. Technological learning

The rate at which investment costs are reduced with increasing experience is an uncertain and highly sensitive parameter in modelling (Yeh and Rubin, 2012). Lacking historical data, learning rates for plant investments are estimated according to the maturity and complexity of the technologies.

Biomethane, bioethanol and biodiesel are mature and relatively simple technologies, with large installed capacities in Germany and world-wide. Bio-SNG, Ligno-EtOH and BtL on the other hand have not yet been introduced on a commercial scale. The SNG and BtL processes have however been used since the first half of the 20th century, albeit with fossil coal as feedstock (Dry, 2002), and can thus not be said to be new and unproven technologies (Sims and Taylor, 2008). However, as the processes have not been applied on a large scale and as energy companies particularly in Germany have little experience with these technologies, some learning can be expected. As a basis for simulations, learning rates of 5% for the conventional options are used (in line with Neij, 2008; Chen et al., 2012). With the above reasoning, we assume somewhat higher learning rates for the advanced options, at 10%.

2.3.3. Conversion efficiencies for advanced biouels

Conversion efficiencies of advanced biofuels are subject to theoretical limits which are dependent on the feedstock used, but give an orientation for what can be realistically expected. Müller-Langer (2011, p.8 & 166ff) arrives at a theoretical limit of 49% for BtL, 90% for bio-SNG and 66% for Ligno-EtOH, using standard enthalpies of formation with willow as feedstock. Hamelinck et al. (2005) reports a theoretical limit of 52% for Ligno-EtOH on a HHV basis, corresponding to 49.7% on a LHV basis.[5] Process simulations give lower estimates, ranging from 34.6% to 46.7% for BtL, 57.9–72.6% for bio-SNG and 36.3–

[3] with the addition of a Chemical Engineering Plant Cost Index (CEPCI, 2015) between 1993 and 2010 of 550.8/359.2 = 1.53 and a subsequent conversion to €

[4] Using the CEPCI (2015) for 2003 of 402 (with a previous conversion to $ $_{2003}$ and a subsequent conversion back to €$_{2010}$) as well as 26.95 MJ_{LHV} kg $^{-1}_{DM}$ and 29.85 MJ_{HHV} kg $^{-1}_{DM}$ for ethanol

[5] Assuming 18.5 MJ_{LHV} kg $^{-1}_{DM}$ and 19.6 MJ_{HHV} kg $^{-1}_{DM}$ for the lignocellulosic feedstock

Table 2
Conversion efficiencies of BtL, bio-SNG and Ligno-EtOH processes from process simulations. The values from Hamelinck et al. (2005) were converted to an LHV basis.

Fuel	η	Sources
BtL	34.6%, 42.1%, 46.7%	Prins and Ptasinski (2005),Manganaro et al. (2011),Tijmensen (2002)
Bio-SNG	57.9%, 70.3%, 72.6%	Duret et al. (2005),van der Meijden et al. (2010),Juraščík et al. (2009)
Ligno-EtOH	36.3–44.0%	Hamelinck et al. (2005)

demand side, and (ii) where only liquid biofuels were considered. As methane is neglected as an option in many studies, the comparability to these studies is better in the liquid biofuels only case.

For all scenarios, a continuously increasing amount of biofuels in the transport sector is assumed, rising from current 119PJ (BMWi, 2016) to 400PJ by 2050, corresponding to 16% of the current end energy demand of the German transport sector and in line with sustainable agricultural biofuel potentials (Simon and Wiegmann, 2009) and long-term strategies (Pregger et al., 2013).

The prices of rape seed and wheat in Germany increased by on average 2.1% a^{-1} and 2.4% a^{-1}, respectively, between 2009–2015,[6] whereas the prices for wood pellets and wood chips in Germany during the same time period increased by 5.1% a^{-1} and 4.9% a^{-1}, respectively.[7] SRCs could possibly dampen the steep price increase but are also connected to a counteracting long-term investment risk for the farmer (Ericsson et al., 2009) and are still subject to opportunity costs. The price of maize silage in Germany is set dependent on the wheat price, with an almost identical price development (Toews, 2009, p18ff.). Price setting on the German sugar market is more complicated (Georg, 2008, p8ff.), but as the maize silage and sugar beet yields are rather similar (KTBL, 2012), we assume that similar price developments compared to wheat can be expected as an approximation.

In keeping with the logic of favouring the advanced options where there is data uncertainty, we assume all feedstock costs to increase by 2% a^{-1}. An increase is assumed, as this is consistent with the increased demand for biomass as a consequence of the full-scale energy transition which biofuels would likely be part of. Prices for secondary inputs

Table 3
Cost, material and energy flow summary for the biofuel options in this study. Data for the conventional biofuels (biomethane, bioethanol and biodiesel) are taken unchanged from Thrän et al. (2015) unless otherwise noted. Equal capacity factors (0.91 or 8000 full-load hours) and plant life times (25 years) have been assumed for all technologies. Maintenance costs are assumed at an annual 4% of the investment cost and operational costs at 15% of maintenance costs, throughout all options. Only byproducts with an assumed significant market value are shown here. Net power input for BtL has been halved compared to Thrän et al. (2015) in order to relativise the effect of this parameter, for Ligno-EtOH the value has been reduced to be the same as for BtL, whereas for bio-SNG the former value has been kept. The advanced options are assumed to be self-sufficient in their heat demand. GHG emissions for conventional biofuels were taken from EU RED values (EU, 2009). For BtL and Ligno-EtOH, a review by Menten et al. (2013) has been used (mean values 19.45 and 19.7 $tCO_2eq\ GJ^{-1}$, respectively) and for bio-SNG the value for BtL was used as an approximation and for biomethane Westerkamp et al. (2014) was used. Transport and storage (logistics) costs stem from Cazzola et al. (2013). Unless otherwise noted, the values given are the initial values used in the modelling, per GJ_{fuel}.

Fuel		Biomethane	Bioethanol	Biodiesel	BioSNG	Ligno-EtOH	BtL
Feedstock		Maize silage	Sugar beet	Rape seed	Wood	Wood	Wood
Energy content	$GJ\ t^{-1}_{DM}$	17	16.3	26.5	18.5	18.5	18.5
Cost	$€\ t^{-1}_{DM}$	106	116	366	122	122	122
Conv. eff. (init.)	η	0.56	0.6	0.59	0.58	0.36	0.35
Conv. eff. (final)	η	0.70	0.66	0.62	0.73	0.44	0.45
2^{nd} feed.		–	–	Methanol	–	–	–
Amount	GJ^{-1}	–	–	3.3kgDM	–	–	–
Cost	$€\ t^{-1}$	–	–	250	–	–	–
Net heat input	$kWh\ GJ^{-1}$	0	69	34.8	0	0	0
Net power input	$kWh\ GJ^{-1}$	22	17.3	3.1	31	35	35
1^{st} byprod.		–	Vinasse	Rape seed meal	–	–	–
Amount	GJ^{-1}	–	23.7 kg_{FM}	33 kg_{DM}	–	–	–
Credit	$€\ t^{-1}$	–	70	211	–	–	–
2^{nd} byprod.		–	–	Pharmaglycerine	–	–	–
Amount	GJ^{-1}	–	–	2.5 kg_{DM}	–	–	–
Credit	$€\ t^{-1}$	–	–	600	–	–	–
Tot. credit	$€\ GJ^{-1}$	0	1.7	8.4	0	0	0
GHG emissions	$kgCO_{2eq}\ GJ^{-1}$	23.7	40	52	18.7	26.6	18.7
Investment cost	$€\ kW^{-1}_{cap}$	1600	900	240	2000	3200	2500
Learning rate	%	5	5	5	10	15	10
Capacity	PJ_{cap}	22.4	33.1	195	0	0	0
Staff cost	$€\ GJ^{-1}$	0.7	0.6	0.3	1.0	1.1	0.6
Transport cost	$€\ GJ^{-1}$	1.7	2.6	1.2	1.7	2.6	2.4
Storage cost	$€\ GJ^{-1}$	2.2	0.08	0.06	2.2	0.07	0.05

44.0% for Ligno-EtOH (Table 2). In this study, the lower process simulation results are used for the initial conversion efficiencies, increasing linearly towards the higher ones in 2050.

2.3.4. Logistic costs

For logistic costs, the average of the "current" (high) and "mature" (low) cost scenarios for fuel transport, distribution and refuelling infrastructure found in Cazzola et al. (2013) are used. These costs are mostly relevant for methane, as they are much higher than for liquid biofuels in the "current" scenario (which is not Germany specific). As methane as a fuel is relatively widespread in Germany, with 879 fuelling stations (Statista, 2015) of ca 14500 in total (EID, 2015), the needed minimum infrastructure is assumed to be at hand.

2.3.5. Data summary

The techno-economic data for all biofuel options in this study are summarized in Table 3.

2.4. Scenarios

With the techno-economical data as a basis, two base scenarios are modelled: (i) where all biofuels were considered equal from the

[6] Using price information from finanzennet (2016), which was subsequently inflation adjusted
[7] Using price information from CARMEN (2015), subsequently inflation adjusted

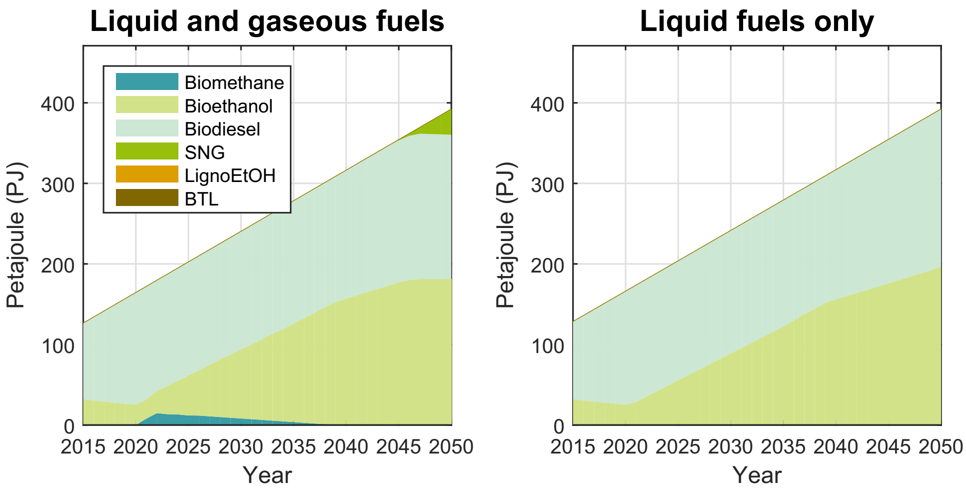

Fig. 1. Resulting production structures of biofuels from the modelling of the two main scenarios.

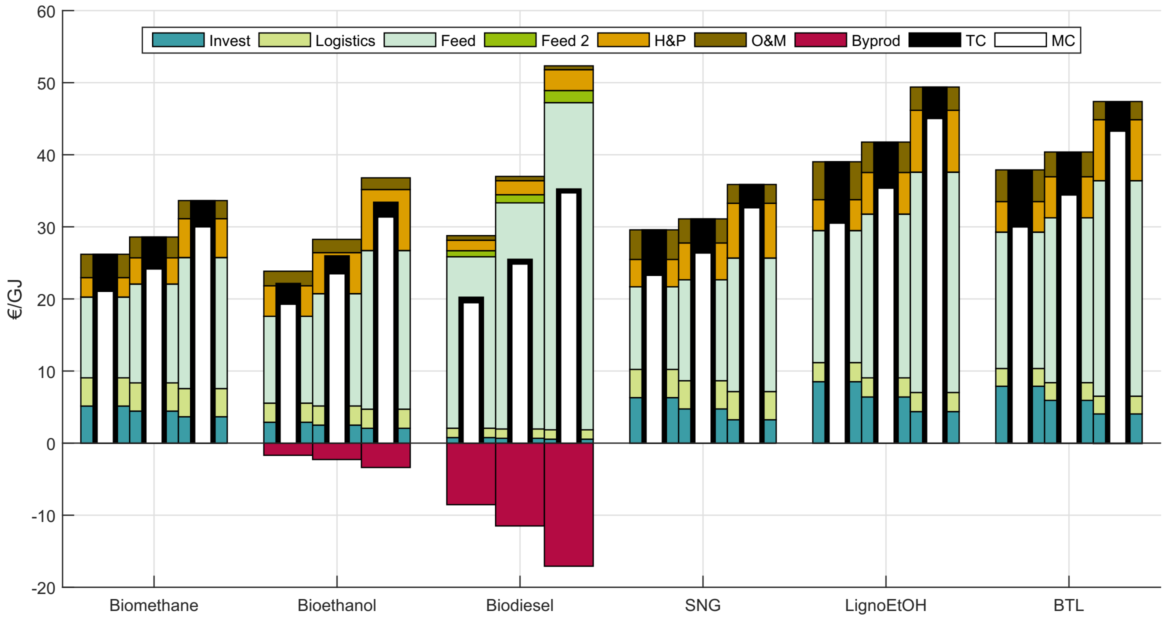

Fig. 2. Cost structures for the different options for the years 2015, 2030 and 2050, respectively. Abbreviations: Invest=investment cost; Logistics=logistic cost; Feed=main (biogenic) feedstock cost; Feed 2=secondary feedstock cost (i.e. methanol for biodiesel); H & P=heat and power; O & M=operation and maintenance; Byprod=by-product credit; TC=total cost; MC=marginal cost.

(including heat and power) and by-products are assumed to develop in parity with the other feedstock prices.

A discount rate of 7% with a payback time of 20 years is used (a medium assumption, see Chum et al., 2011, for a comparison of the effect of different discount rates). One could argue that the advanced options carry more risk and would therefore require higher discount rates than the other options. Also in this case, we choose not to discriminate between the options and thereby favour the advanced options. R & D-learning is set at a rate of one learning rate (technology specific) for each five years. All costs in the modelling are in $€_{2010}$ and inflation is excluded. In order for the results for cost-competitiveness to be as transparent as possible, we do not include restrictions and quota from current biofuel policy.

3. Results and discussion

The results for the modelling of the two main scenarios can be seen in Fig. 1. Biodiesel starts off as the least-cost fuel (starting at 20.2€ GJ^{-1} in 2015, with the costs increasing by 74% until 2050), followed by bioethanol (22.2€, increasing by 51%), biomethane (26.2€, 28%), bio-SNG (29.6€, 21%), ligno-EtOH (39.0€, 27%) and BtL (37.9€, 25%). Fig. 2 shows the cost break-downs and developments over time.

In both scenarios bioethanol and biodiesel virtually share the market, purely due to similar costs (there are no assumed quota for different biofuel options in the scenarios). In the case where gaseous fuels are included, some biomethane and bio-SNG can be seen, but the proportion is small and bio-SNG increases only towards the very end of the time span, resulting in a small total share of gaseous biofuels over the whole time period. In the case where gaseous biofuels are excluded, notably no advanced biofuels show up.

Interestingly, the total costs of the first four options largely converged around 30€ GJ^{-1} in the 2040s (Fig. 2). Learning effects can be observed for all options, being largest for the advanced biofuels, the investment cost of which are almost halved over the time period. Despite investment cost reductions and thus O & M cost reductions (due to their coupling), as well as conversion efficiency increases, no price reductions can be seen, due to increased feedstock and power costs.

The large share of power costs may motivate process-internal power production, especially for the BtL option. In that case, there is a trade-off: fuel conversion efficiency would likely decrease and investment costs relative to the produced fuel would increase. Moreover, one can note that the biodiesel cost is dominated by the cost of rape seed. The increased price is somewhat balanced by increasing credits for the by-products, but still increased by 76% until 2050.

In this paper, economies of scale were omitted in the modelling, and the investment costs were assumed for relatively large-scale plants. The optimal sizing of plants depends on feedstock availability and cost, which are site specific attributes. Furthermore, as the included feedstocks have different energy densities and thus transport costs, the options also have differing optimal sizes, ceteris paribus. Economy of scale aspects are therefore mostly relevant for the advanced options, which rely on feedstocks which can potentially be viably transported over longer distances, as well as having a higher absolute investment cost reduction potential. As these options were found rather uncompetitive even with optimistic assumptions, economies of scale are not so central to the results. A spatial extension of the model would be interesting for future research on the optimal sizing of plants considering spatially explicit conditions.

The large range of investment and production cost estimates (Haarlemmer et al., 2012), uncertainties regarding learning rates (Yeh and Rubin, 2012) and the assumptions for initial feedstock costs (Sunde et al., 2011) and their future development generates a large span of possible outcomes for studies such as this one. As an example, the cost of BtL in this paper increased to 40€ GJ^{-1} in 2030, comparable with a span of 7–26$€_{2010}$ GJ^{-1} (8–30$\$_{2005}$ GJ^{-1}) for 2030 in other studies (Chum et al., 2011, p.282) and 7.1–46$€_{2010}$ GJ^{-1} (9.4–61$\$_{2010}$ GJ^{-1}) for developing countries (van Eijck et al., 2014). Wit et al. (2010) assumed costs of lignocellulosic feedstocks to start at 1.8 $€_{2010}$ GJ^{-1}, compared to 6.6$€_{2010}$ GJ^{-1} in this paper and initial investment costs for FT-diesel were about half compared to in this paper. As a result, the cost of advanced liquid biofuels started off much lower than in this paper (22$€_{2010}$ GJ^{-1}, compared to 37.9€ GJ^{-1}) and then decreased due to technolocal learning and feedstock cost reductions, which should explain the large discrepancy in results.

3.1. Sensitivitiy analysis

In the sensitivity analysis, parameters subject to large uncertainty and/or which may affect the costs of biofuels significantly were varied. The parameters were varied in the direction for which the system is more sensitive or in which a change is more likely. The performed sensitivity analyses are summarized in Table 4:

Table 4
Sensitivity cases performed.

Abbreviation	Description
NoRise	Constant biofuel demand (121 PJ a^{-1}).
WdLow	Wood prices starting at −40%.
WdCnst	Wood prices constant at 122€ t_{DM}^{-1}.
Adv−25%	Initial investment costs for advanced biofuel plants - 25%
Bme−25%	Initial investment costs for conventional biomethane plants −25%
i=3%	Discount rate at 3%
LogLow	Storage and logistics costs lower (from the "mature" scenario in Cazzola et al. (2013))
LR20%	Technological learning rate for advanced options 20% (a doubling), which also doubles R & D learning.
NoR & D	No R & D learning.
η_{max}	Conversion efficiencies constant at the technical limit throughout the time period.
Feed4%	Feedstock price increase of 4% a^{-1}.
ByCnst	Price of all byproducts constant over the time period.
GHG	GHG-price of 100€ $t_{CO_2eq}^{-1}$ which is added as a cost based on the GHG emissions of each option. The values are assumed constant over time.
H & PAdv	The external heat and electricity inputs to the advanced processes are reduced by half.
Combi	A combination of an initial investment cost reduction of 25%, a 20% learning rate and a constant conversion efficiency at the technical limit, for the advanced options.
Base	Base run.

Compared to the base case, it can be seen that the results are in fact relatively sensitive to some parameters when gaseous fuels are included (Fig. 3). However, advanced biofuel options do not appear in any large amounts in 2030, in any of the sensitivity runs, and for most cases in relatively small amounts in 2040, and thus the share over the whole time period remains rather small.

In the case of a constant biofuel target, some dynamics can be observed. Biomethane retains the same amount and biodiesel has a larger share for 2030 compared to the base case. Between 2040 and 2050 no change occurs, whereas in the base case bio-SNG increases, thus covering mainly the increased demand. Thus, as can be expected, a non-increasing biofuel target leads to a slight lock-in effect, keeping new technologies out of the market.

When the initial wood chip costs are decreased by 40%, bio-SNG increases steadily and dominates towards the end, and a similar result emerges when assuming constant wood prices, with a stronger effect towards the end of the time-period. In the case where initial investment costs for advanced biofuels are decreased, some increase of bio-SNG can be observed.

Throughout all cases, only conventional biomethane stands out as having the same absolute amount in 2030, which originates from the initially available capacity. This indicates that high investment costs deter a further break-through, and a reduction of the investment cost for conventional biomethane does in fact lead to a significant increase of the option, interestingly at the cost of mainly bio-SNG.

A decrease of the discount rate to 3% increases the amount of bio-SNG and biomethane somewhat, while decreasing the amount of biodiesel towards the end of the time-period. The initial costs are in this case reduced by 1.1% (2.0%) for biodiesel, 3.8% (6.7%) for bioethanol, 5.7% (10.0%) for biomethane, 6.1% (10.8%) for bio-SNG, 6.3% (11.0%) for Ligno-EtOH and 6.0% (10.6%) for BtL compared to with a 7% (10%) discount rate.

Decreased logistic costs from the beginning increases the amount of both bio-SNG and biomethane, as the cost reduction potential for the logistic costs of gaseous fuels is larger than for the liquid fuels. An increase of the learning rate for advanced biofuels has some effect for bio-SNG, but perhaps not as much as may have been expected. If no investment cost reduction through R & D learning is assumed to take place, bio-SNG and biomethane (apart from already present capacities) do not appear on the market. If the maximum conversion efficiencies are assumed already from the beginning for all options, a neglible increase of bio-SNG can be observed.

A feedstock cost increase of 4% has a large effect on the development towards the end, as all other fuels vanish and biomethane dominates. Holding by-product credits constant has a similar effect for the development of biomethane (the latter two are also the only cases where an unlimited diffusion rate in the modelling has a significant effect compared to a limitation to 50% new capacity per year). Thus, technology investments and improvements are highly sensitive to feedstock and by-product cost developments. As these are uncertain and volatile, this may deter investment efforts and also serve to render policy decisions uncertain.

In the case where GHG emissions are coupled with a 100€ $t_{CO_2eq}^{-1}$ cost, both bio-SNG and biomethane increase. However, again only moderate effects can be seen until in the 2040 s. Halving the external power input requirement for the advanced biofuel options compared to the base case leads to an increase of bio-SNG, indicating that a trade-off may take place here between internal power production and high conversion efficiencies for bio-SNG. No effect can be observed for the liquid biofuels only case. A combination of investment cost decreases and learning rate and conversion efficiency increases for advanced

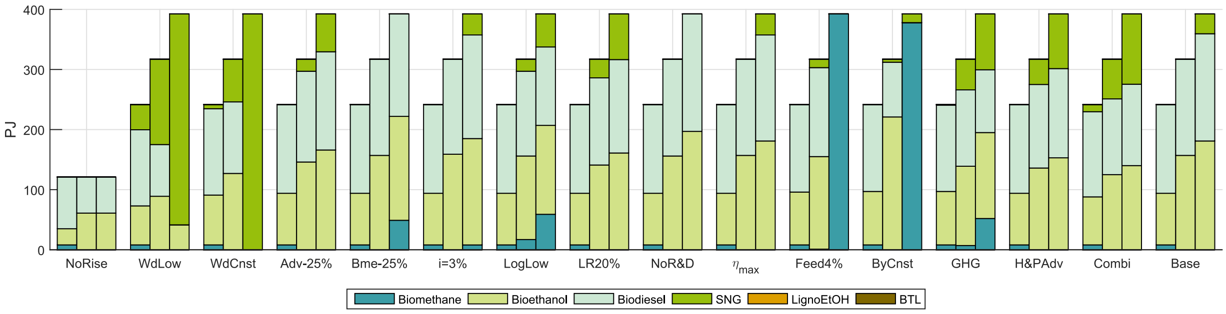

Fig. 3. Sensitivity simulations for the case where methane is included as a fuel. For each sensitivity run, the biofuel production pattern for the years 2030, 2040 and 2050 is shown.

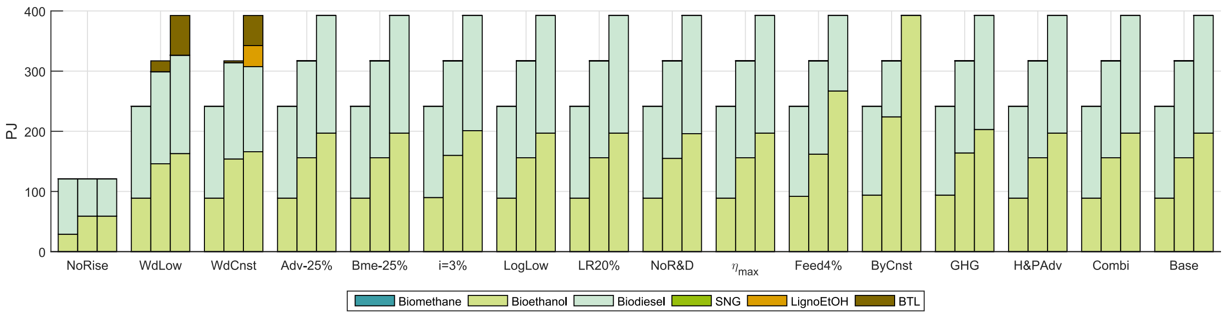

Fig. 4. Sensitivity simulations for the liquid biofuels only case. For each sensitivity run, the biofuel production for the years 2030, 2040 and 2050 is shown. See Table 4 for explanation of abbreviations.

biofuel options has a moderate effect in increasing bio-SNG, but still such R & D efforts do not have the strong effect which may be expected, and the development is still subject to feedstock cost developments which are largely out of the control of investors.

For the case where only liquid biofuels are included, it can be observed that advanced liquid fuels only show up in two of the investigated cases (Fig. 4): where wood chip prices are reduced by 40% (to an initial 73€ t $_{DM}^{-1}$) as well as where wood prices are held constant throughout the simulated time period. In the former case BtL emerges towards the end, and in the latter case both BtL and LignoEtOH emerge towards the end. The effect of a higher learning rate is not enough to bring BtL to the market, not even in combination with lower initial investment costs and higher conversion efficiencies. In the cases where the feedstock costs increase by 4% a^{-1} and especially when the byproduct price is held constant, bioethanol becomes more cost-competitive than biodiesel. Other than this, no significant changes can be seen in the other sensitivity cases and thus the liquid biofuels only system is relatively insensitive to parameter changes.

4. Conclusions and policy implications

In this paper, a sound data basis for techno-economic parameters of advanced biofuels has been investigated and used as a basis for modelling the competitiveness between conventional and advanced biofuels under German conditions. A scrutiny of central techno-economic assumptions for advanced biofuels rendered costs significantly higher than those previously reported and used in similar models, thus highlighting that previous cost assumptions are likely to have been too optimistic, which might also explain why BtL attempts have failed so far.

The most cost-competitive biofuels for most of the time period remained conventional biodiesel and bioethanol, but the costs of these options and biomethane and bio-SNG converged around 30€ GJ^{-1} in the medium term and thus other factors, such as resource availability, land use, GHG abatement, other emissions and market barriers will play a decisive role for market developments of biofuels. In fact, due to the small cost differences, the options may inhibit the development of each other as seen in the sensitivity analysis, and thus a technology neutral policy may not be optimal from a long-term perspective. Clear objectives and long-term policies would help, but may be difficult to achieve due to high uncertainties and competition about biomass from other sectors as well as competition from electric mobility.

Feedstock cost developments were found to be the single most relevant factor for the future costs of all biofuels. Assumptions regarding low and/or decreasing feedstock costs (particularly for SRCs) due to increased yields and learning effects in that part of the value chain may explain some of the prevalent optimism regarding the competitiveness of advanced biofuels. Low SRC/lignocellulosic crop costs was in fact seen to be the only case where BtL reached competitiveness towards the end of the time-period, at initial costs of 73€ t_{DM}^{-1} (3.9€ GJ^{-1}) and below, and then only in the case where gaseous fuels were excluded. However, a switch from annual to perennial crops presents a significant market barrier and the dependence on feedstock cost developments presents a considerable risk and deterrent for investors and developers, as these can counterbalance R & D-efforts.

If advanced biofuels are to be promoted through policy, the results presented in this paper indicate that the more resource and cost efficient strategy would be to go for gaseous biofuels rather than advanced liquid biofuels. For this to happen, the amount of gas powered vehicles (which are more expensive than vehicles powered with liquid fuels (Åhman, 2010), rendering the total well-to-wheel cost advantage lower) needs to increase in order to increase the demand. Thus, a policy promoting gaseous biofuels needs to stimulate both biofuel production and demand (as well as the production of perennial lignocellulosic crops) simultaneously. A technology neutral biofuel policy will likely not result in gaseous fuels due to these path-dependencies, a conclusion further enhanced by the result that cost reductions through R & D are fundamental for these options to reach competitiveness. Starting with niche applications where the usage rate of the vehicles is high (thus reducing the effect of higher-cost vehicles and new infrastructure), such as public transport may be a necessary first step. On the other hand, the produced methane can be used as fuel for combined heat and power plants which may become increasingly important to balance a power system that is foreseen to be dominated by variable renewable energy sources (wind and photovoltaics). Thus, the risk of investing in a biomethane or bio-SNG plant may be alleviated through the option to serve several markets.

In this paper, an equivalent value of different biofuels was assumed for the end-use stage (with costs for transport and fuelling stations included), but advanced liquid biofuels may become relevant in sectors where gaseous biofuels and electric mobility are no alternative, e.g. in the aviation sector. However, for the short to medium term, the results in this paper indicate that for a specific amount of biomass, the use of gaseous biofuels for land transport would replace more fossil fuels for a lower cost than using advanced liquid biofuels for aviation, due to higher conversion efficiencies. Thus, both GHG abatement and even more so GHG abatement cost are in favour of gaseous fuels as long as the land transport sector is not covered by other non-biogenic renewables.

As a final conclusion, the results and the large sensitivities of biofuel competitiveness highlighted in this paper stress the need for more data and model transparency and for thorough sensitivity analyses of the results in similar system studies.

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Paper 2

Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields

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Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields

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A B S T R A C T

The competitiveness of conventional and advanced (second generation) biofuels is a critical issue for the implementation of a sustainable transport strategy. We model biofuel competition under different feedstock cost development scenarios, assessing what costs and cost developments can be expected for energy crops in Germany and how these feedstock cost developments affect the competitiveness between biofuels. Perennial poplar was found to be the least-cost energy crop, with non-perennial silage maize being strongly competitive at increasing feedstock price developments. Assuming increasing feedstock costs for the future, neither conventional biodiesel from rape seed nor advanced biodiesel were found to be competitive in the long run. Feedstock costs were found to overshadow all other factors, leading to costs for advanced biodiesel to be between 27.0 and 53.6€ GJ^{-1} in 2030, which is above most expectations. Of the advanced biofuels, only synthetic natural gas was cost-competitive under some circumstances, but biomethane from silage maize and bioethanol from sugar beet were the strongest options, as they combine high yields with high conversion efficiencies while avoiding the high upfront costs of advanced biofuels and the risk of switching to perennial crops. However, such a transition leads to less mobile feedstocks being used than presently and in the case of gaseous fuels requires stimulation of the demand side in order to function. The high dependence on and increasing relevance of feedstock costs is characteristic for the biobased renewables only and is detrimental and inhibiting for investments and research and development efforts, in contrast to for e.g. wind and solar photovoltaics, and must be considered when designing policy for any sector of the bioeconomy.

1. Introduction

A sustainable transition of the transport sector requires renewable alternatives, where biofuels are one option fitting well into the current system. Advanced biofuels derived from perennial lignocellulosic biomass potentially perform better from an environmental perspective than presently used conventional biofuels and are therefore often put forward as a preferable solution (Tilman et al., 2006; Fargione et al., 2008; Chum et al., 2011). Fast-growing perennial biomass such as short-rotation coppice (SRC) and miscanthus could also potentially act as game-changers for the cost-competitiveness of advanced biofuels, which have yet to experience a market break-through. In this paper, focus lies on assessing the potential and uncertainties regarding the effect of feedstock costs on biofuel competitiveness in the long term, based on the example of Germany.

The production costs of feedstocks are often used as an approximation to assess the overall cost development potentials of biofuels (Chum et al., 2011). However, production costs alone are not sufficient to estimate the minimum selling price of feedstocks, as opportunity costs from alternative land uses may render other feedstocks more profitable for the farmer. Therefore, a certain market approach is necessary.

Typically, computable general equilibrium (CGE) models are useful for modelling global trade and price developments of the agricultural sector. However, for the case of bioenergy and especially advanced biofuels relying on lignocellulosic feedstock, and in particular perennial biomass, there is an insufficient data basis to date, making these sectors challenging to implement in CGE-models (Kretschmer and Peterson, 2010). Furthermore, for modelling long time-spans the high level of detail in CGE-models is subject to large uncertainties and therefore transparent models

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taking physical limitations into account are a suitable complement, if not alternative (Bryngelsson and Lindgren, 2013). As a transition away from fossil fuels towards a bioeconomy may have large implications for the economics of biomass, this arguably cannot be captured with top-down models where relationships are based on historical data only (such as in e.g. Festel et al. (2014)).

Estimates of the cost of perennial energy crops taking into account opportunity cost are widespread (Ericsson et al., 2009; Faasch and Patenaude, 2012; James et al., 2010; Khanna et al., 2008; Krasuska and Rosenqvist, 2012; Witzel and Finger, 2016), but - to our knowledge - the effect of the cost of perennials under different circumstances on biofuel costs, competitiveness and sensitivities in an integrated assessment has not been published before. Therefore, in this paper the following research questions are assessed: (i) What costs and cost developments can be expected under different scenarios for energy crops in Germany? and (ii) How do these feedstock cost developments affect the competitiveness of biofuels?

In doing this, we link an existing model for simulating biofuel competition (Millinger et al., 2016) with a crop price estimation module which is elaborated in this paper, and assess the sensitivity of the results through Monte Carlo analysis.

2. Materials and methods

Three pathways of conventional biofuels (biomethane produced from maize silage, bioethanol from sugar beet and biodiesel from rape seed) and two pathways as advanced biofuel counterparts (Biomass-to-Liquid (BTL) or Fischer-Tropsch (FT)-diesel and Synthetic Natural Gas (bio-SNG), both produced from biomass with high lignocellulosic content) were included in the simulation (Fig. 1). All biofuels were assumed to be equivalent at the end user stage on an LHV basis (with some differences regarding transport and storage costs of the fuels). The system boundary of this study thus ends at the tank (Well-to-Tank), as the future development of the mobility sector introduces further uncertainties in terms of e.g. assumed vehicle costs, usage rates and average engine efficiencies for the different types of fuel. This presents a theme of its own and is therefore out of scope for this paper. In the following we elaborate on the models, methods and data used in this paper.

2.1. Model description

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 = levelized 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. BENSIM has been more thoroughly described in Millinger et al. (2016) and is here expanded with a feedstock market module for Germany.

Three model parameters were adapted compared to the previous paper. The cost limit differential at which technologies are treated equally in the investment phase (an investment distribution factor due to e.g. market imperfections and regional differences) was set at 15% (from 10% previously). The factor at which the total cost of an emerging technology has to surpass the marginal cost of existing technologies in order to replace them (denoting a path dependency) was set at 20% (up from 15%) and the capacity ramp factor, which sets the limit of annual additional capacity dependent on the available capacity for each option was set to 100% (previously no such limit was set). The reason for these changes is that the differing feedstock cost developments in this paper introduce dynamics which under some circumstances lead to unrealistically swift market changes. These parameters together set the inertia in the model and thus the changes lead to a more balanced result. The effect of varying these parameters is further assessed in the sensitivity analysis.

2.1.1. Feedstock market

A common methodology for estimating the costs of energy crops is to add the per hectare profit of a benchmark crop to the per hectare production cost of the energy crop(s) (Witzel and Finger, 2016). This opportunity cost also serves as the shadow price of land, whereas published land rents may rather be seen as marginal land rents (Ericsson et al., 2009). Common benchmark crops include cereals (Krasuska and Rosenqvist, 2012; Faasch and Patenaude, 2012; Ericsson et al., 2009), corn (James et al., 2010; Khanna et al., 2008), soybeans (Khanna et al., 2008) and rape seed (Faasch and Patenaude, 2012). Usually, the most common crop in the region is selected, but sometimes also the one(s) deemed most likely to be replaced by energy crops. In Germany, by far the most common crop is wheat (Statistisches Bundesamt, 2016), which is therefore used as a benchmark for all other crops in this paper.

The hectare profit for wheat is calculated as the market price $p_w^{(t)}$ [€ t_{FM}^{-1}] times yield $Y_w^{(t)}$ [t_{FM} ha^{-1}] minus production costs $c_w^{(t)}$ [€ ha^{-1}]. Other crops are to achieve this profit per ha, adding production costs $c_i^{(t)}$ [€ ha^{-1}]. The prices are then divided with the yield $Y_i^{(t)}$ [t_{FM} ha^{-1}] to come up with a market price $p_i^{(t)}$ [€ t_{DM}^{-1}] of feedstock *i*. Over time, this results in a market price development including opportunity costs for each feedstock (Eqn. (1)).

$$p_i^{(t)} = \left(p_w^{(t)} Y_w^{(t)} - c_w^{(t)} + c_i^{(t)}\right) Y_i^{(t)-1} \quad (1)$$

All perennials are assumed to provide the same and equivalent

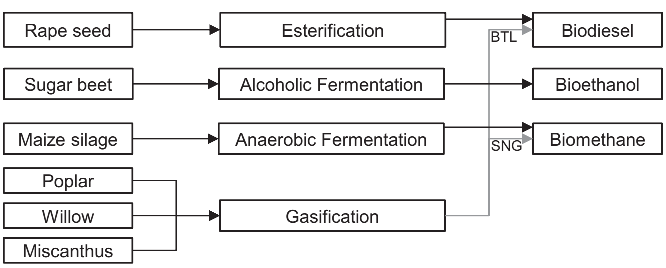

Fig. 1. Feedstocks, conversion pathways and biofuel options included in the modelling.

[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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good,[2] "lignocellulosic biomass", for which the least-cost perennial crop sets the price on an annual basis.

2.2. Data

Maize, sugar beet, rape seed and wheat are all established crops and thus yield and production cost data from KTBL (2012) are used. For yields stemming from KTBL (2012), the average yields are used (an average unit of land in Germany is assumed and thus the highest reported yields are ruled out). For the perennial crops, KTBL (2012) states a span for the average yields. In this case, the lower end of the span is used as a starting point with a linear increase towards the higher end in 2050. For non-perennial crops, constant yields are assumed for the whole time-period (bearing in mind that the quality of average land for energetic purposes is likely to decrease with increasing deployment of bio-based commodities).

For poplar and willow, yield data from KTBL (2012) is confirmed by peer-reviewed sources (Faasch and Patenaude, 2012; El Kasmioui and Ceulemans, 2012). For miscanthus, the yield assumptions are subject to a larger span in literature and therefore yield data for Europe reviewed by Witzel and Finger (2016) is used (the data in KTBL (2012) is significantly more optimistic). Establishment costs are similarly taken from the average reviewed by Witzel and Finger (2016) and annualized over 20 years. As the yields increase, establishment costs are held constant per hectare (but thus not per crop unit).

A summary of all crop data used can be found in Table 1. Farm costs for diesel (2015: 0.9€ l^{-1}) and labour (2015: 15€ h^{-1}) were assumed to increase with the same rate as the wheat price (2015: 189€$_{2010}$ t_{FM}^{-1}).[3]

2.3. Scenarios

In the scenarios, we consider different feedstock cost developments, based on both projections of historical developments and on possible future developments resulting from the implementation of a large-scale bioeconomy.

Feedstock price developments have been rather moderate and even stagnant seen over long periods of time (with large short-term fluctuations), see Fig. 2. However, the average yearly price increase between 1994 and 2014 was about 2.1% (the equivalent 20-year historical average price change for the past ten years averages 1.8% $year^{-1}$) and between 2004 and 2014 it was 3.8% $year^{-1}$ (the equivalent ten-year historical average price change for the past ten years averages 3.8% $year^{-1}$). Therefore, scenarios of stagnant wheat prices are complemented with annual increases of 2% and 4%.

The effect of these price developments is assessed in cases where (i) only liquid biofuels and (ii) both liquid and gaseous biofuels are considered, in order to ease comparison with other studies. The effects are assessed for the medium to long term and thus a time horizon until 2050 is simulated. For all scenarios, a continuously increasing amount of biofuels in the transport sector is assumed, rising from current 119PJ (BMWi, 2016) to 400PJ by 2050, corresponding to 16% of the current end energy demand of the German transport sector and in line with sustainable agricultural biofuel potentials (Simon and Wiegmann, 2009) and long-term strategies (Pregger et al., 2013).

R&D-learning is set at a rate of one learning rate for each five years for options that are not invested in. All costs in the modelling are in real €$_{2010}$.

2.4. Sensitivity analysis

The sensitivity analysis is in this paper performed through Monte Carlo analysis, which is a way of mapping out the solution space depending on variance in input variables without calculating all possible combinations. In energy systems modelling, Monte Carlo sensitivity analysis is often not implemented due to long computation times (Hedenus et al., 2012). With regard to biofuels, where both crops and conversion technologies of advanced biofuel options are subject to large variances, a thorough sensitivity analysis is necessary for showing the robustness of results and different biofuel options.

In BENSIM, a module for Monte Carlo analysis was developed as follows. Crucial and non-correlated parameters with large parameter variance were identified and ranges of possible values quantified with a connected distribution function (uniform). The parameters are then randomized using the "rand" Matlab function and a simulation run in BENSIM for a 1000 random parameter settings. As the resulting output from the model is a system development, shares of SNG, biomethane and BTL over the whole time-period were chosen as simple indicators to depict the distribution.

The parameters varied in the sensitivity analysis were chosen as follows. Maize, sugar beet, rape seed and wheat are all established crops and are therefore not varied in the sensitivity analysis. The parameters for perennial energy crops on the other hand are rather uncertain. This goes in particular for establishment costs (particularly rhizome costs for miscanthus (Witzel and Finger, 2016)) and yields.

The cost development of wheat, which here sets the benchmark for the costs of the other crops, is highly uncertain but overshadows

Table 1
Summary of feedstock parameters. For rape seed, the energy content reflects the total energy content and not of the oil share. The conversion efficiency of the plant is suited to the value presented here. Wheat (winter wheat) is not used as an energy crop in this study, but only serves as a comparison for the economics of the other crops.

Feedstock		Silo Maize	Sugar beet	Rape seed	Poplar	Willow	Miscanthus	Wheat
Energy content	GJ t_{DM}^{-1}	17	16.3	26.5	17.6	17.6	17.6	17.0
Dry matter content	t_{DM} t_{FM}^{-1}	0.35	0.23	0.91	0.45	0.45	0.8	0.86
Yield	t_{FM} ha^{-1}	45–55	65	3.5	18–27	11–20	12–17	7.89
Farm labour demand	hours ha^{-1}	10.8	7.8	5.5	0.3	0.3	4.8	5.4
Diesel demand	liter ha^{-1}	112	111	73	2.1	2.1	37.8	73
Fix machine cost	€ ha^{-1}	292	318	176	5.39	5.45	130	164
Variable machine cost	€ ha^{-1}	248	291	148	7.09	7.12	85.9	146
Direct cost	€ ha^{-1}	406	600	520	86.6	61.3	283	508

[2] i.e. the energy content part in the different lignocellulosic biomass types can be used equivalently, e.g. without needing to adapt the conversion step.

[3] calculated from daily wheat prices for five years 13.04.2011–14.04.2016 (finanzen.net, 2016), inflation adjusted to €$_{2010}$ with annual HICP data (Eurostat, 2016).

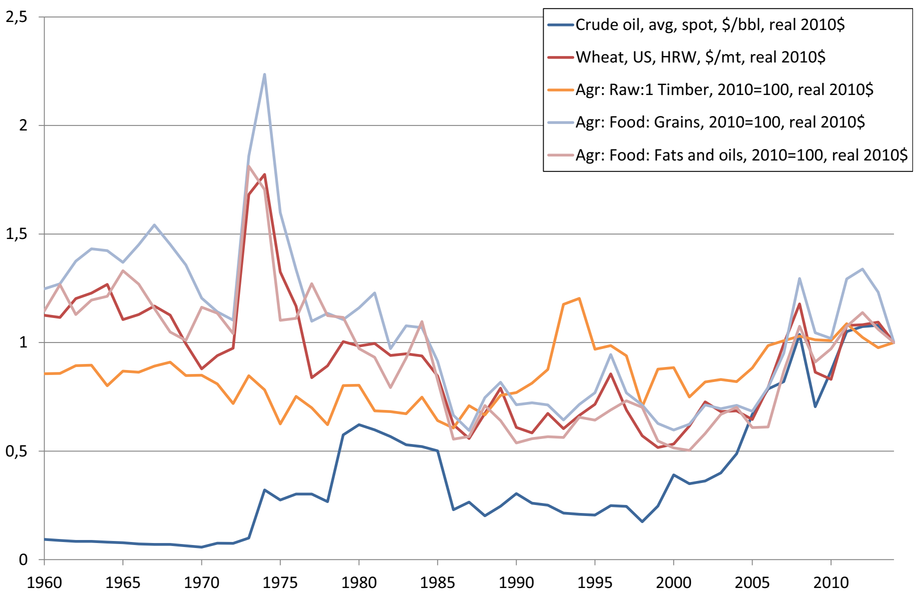

Fig. 2. World market price development of wheat, grains, fats and oils, timber and crude oil 1960–2014, in $_{2010}$ (World Bank, 2016), normalized to 2014.

all other parameters and is therefore held constant in four separate sensitivity runs, at 2% and 4% annual wheat price increases, with or without gaseous fuels.

For the conversion part, the investment costs, discount rate and learning rates affect the competitiveness. However, as the investment cost and learning rate are somewhat correlated (a low assumed initial investment cost is coupled with a low learning rate), only the investment cost is varied. Exogenous learning through R&D was however varied. Conversion efficiencies can also strongly affect the cost and are therefore varied. Three model parameters were varied: the investment distribution factor, the path dependency factor and the capacity ramp factor.

Table 2 summarizes the parameters which were varied in the Monte-Carlo sensitivity analysis.

3. Results

The resulting feedstock costs are shown in Fig. 3. It can be seen that the least cost perennial crop is poplar, with miscanthus coming close in the cases where the wheat price is increasing, as high deployment costs are somewhat compensated by land-use efficiency. The resulting lowest price for perennials in 2015 is 4.4–6.8€ GJ^{-1} (77–120€ t_{DM}^{-1}), whereas the price spans between 3 and 4.6,

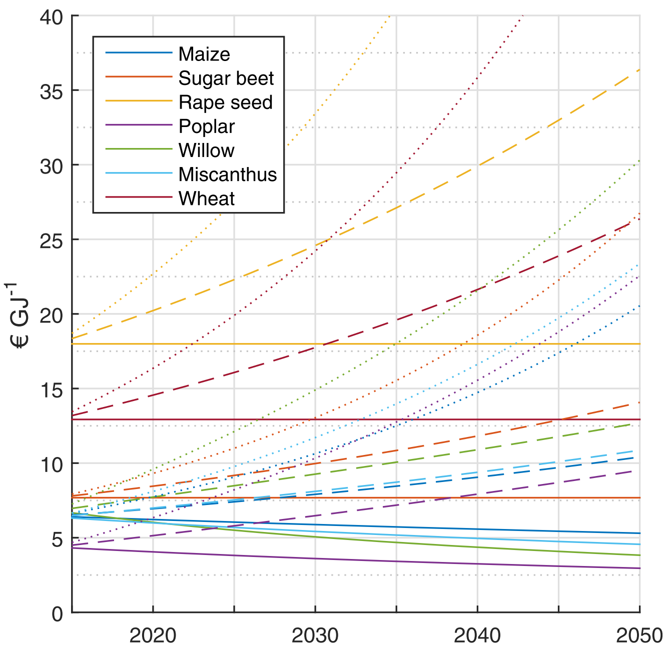

Fig. 3. Feedstock cost developments in the assessed cases. Solid, dashed and dotted lines are for the cases where the wheat price remains constant and increases by 2% and 4% yearly, respectively. In the latter case, the prices of wheat and rape seed continue rising to 53.1 and 72.9 € GJ^{-1}, respectively (outside of the graph).

9.5–12.7 and 22.6-20-3€ GJ^{-1} (53–81, 167–224 and 397–533€ t_{DM}^{-1}) for 2050 in the cases with constant, 2% and 4% increasing wheat prices, respectively. The initial costs are at the higher end of or above the 2–5€ GJ^{-1} found in other studies (Sunde et al., 2011).

Of the annual crops, maize fares rather well. In the case of 2% annually increasing wheat prices, maize is only 9% more expensive than poplar on an energy basis towards the end, and less expensive than willow and miscanthus. At a 4% annual increase, maize becomes the least-cost crop in the medium term. However, the competitiveness in this context only becomes clear when considering the conversion step.

Table 2
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 randomized for each technology option.

Parameter	Unit	Span
Conversion plant 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%

Resulting from the feedstock cost developments, the biofuel developments in the six main cases can be seen in Fig. 4. Common for all cases is that biodiesel dominates the market in the beginning, only to disappear in the short to medium term, depending on the level of feedstock cost increase and on the competition. Bioethanol dominates over-all in five scenarios, especially where gaseous fuels are not allowed. In case (a), SNG rapidly expands from 2025 onwards and after 2035 almost exclusively gaseous fuels remain. The reappearance of bioethanol and biomethane is due to existing capacities becoming competitive again for fulfilling the additionally emerging biofuel demand, which gives an idea of the dynamics at hand (whereby in reality such capacities would be decommissioned after some time of no production).

BTL shows up in the medium term in case (b), but overall has a small market share, and in the other cases BTL is not to be seen. Advanced biofuels thus fare a better chance of becoming competitive when gaseous fuels are included. Advanced biofuels retain smaller market shares when wheat prices increase more steeply, as the shadow price of land increases and thus the land use efficiency of fuels becomes a more relevant parameter in the pricing compared to other production costs. Thus, as biomethane from maize and bioethanol from sugar beet have biofuel yields higher than or comparable to SNG and the conversion steps are less expensive, bioethanol retains a large market share for much of the time period and biomethane increases, in order to become the dominant fuel towards the end in case (e).

Total arable land required for biofuels is also shown in Fig. 4 for each scenario. In all cases, land used peaks at about 3 Mha in 2020 and then decreases due to the decrease of biodiesel. In the cases where all fuels are included, land use thereafter stays below 2 Mha until 2050 despite increasing production of biofuels. In fact, in these cases, less or similar areas of land are required to produce more than three times the amount of biofuel. This is due to a switch to more land efficient fuels with additional yield and conversion efficiency improvements over time. In the liquid fuels only cases, the required land area increases to about 2.5 Mha in 2050.

The cost structures in Fig. 5 show that even at a an annual wheat price increase of only 2%, none of the options achieves decreasing costs with time, despite considerable reductions of investment and O&M costs through technological learning for some of the options. The thin bars show the total costs at an annual wheat price increase of 4% a^{-1}. It becomes clear that the biofuel cost is highly dependent on feedstock costs and thus high yields combined with high conversion efficiencies become increasingly relevant. In this case, biomethane is the least-cost option in the long run, with SNG being second, despite actually starting off at a slightly lower cost than biomethane, and bioethanol is third, from being the least-cost option at the start. Biodiesel is rather competitive at the start but the cost rapidly increases due to low yields for rape seed. BTL is only 15% more expensive than biodiesel at the beginning, but due to a low conversion efficiency also increases rather rapidly.

The share of the levelized capital cost of the whole biofuel cost decreases with increasing feedstock costs. For SNG and BTL, this share starts at 25% and decreases to 10–11% and 5–6% in 2050 in cases (c) and (e), respectively. Thus, also the importance of investment cost reductions through technological learning decreases substantially.

3.1. Sensitivity analysis

The results of the Monte Carlo sensitivity assessment are shown in Fig. 6. In case (d), BTL predominantly occurs in low quantities. In over 90% of the cases it remains below 10% of the total fuels over the whole time span, and in 8% of the cases between 10 and 20%. Some outliers are spread out, up to a 1/1000 occurrence at up to a 60% share. In case (f), 99.5% of cases remain below 10%.

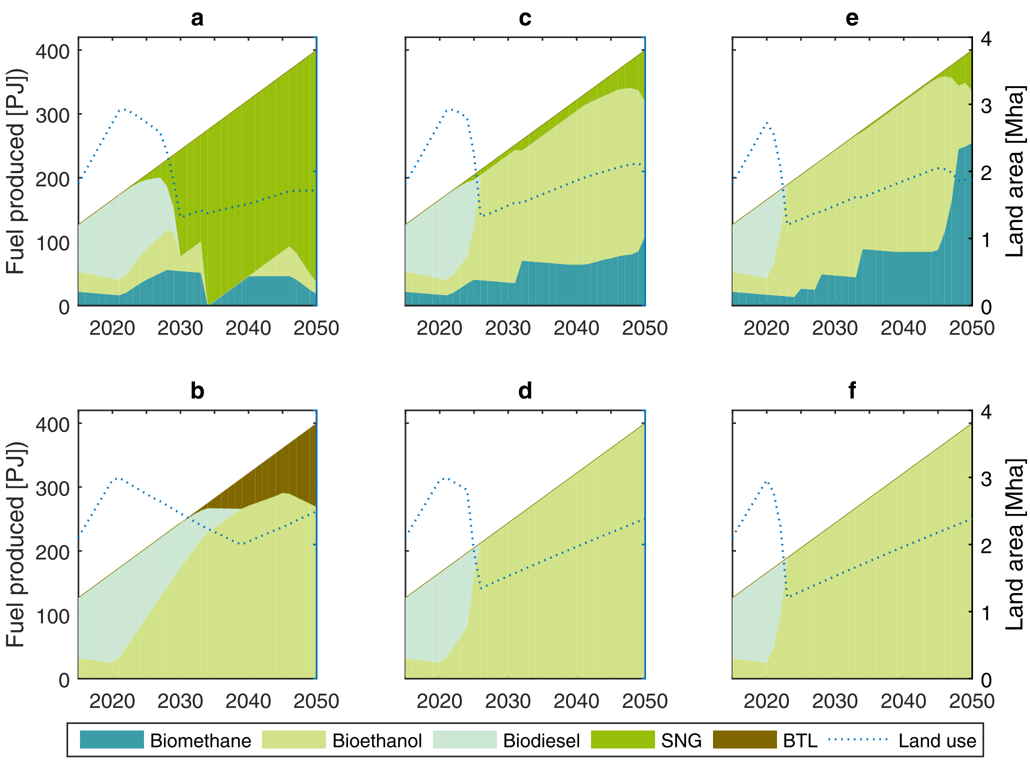

Fig. 4. Production structures as well as land use (line, right axis) in the six main scenarios. Cases (a) and (b) with a constant wheat price, cases (c) and (d) with a 2% annual wheat price increase and cases (e) and (f) with a 2% annual wheat price increase. Cases (a), (c) and (e) include all fuels whereas cases (b), (d) and (f) include only liquid fuels. The produced amount of fuels is shown in petajoule [PJ].

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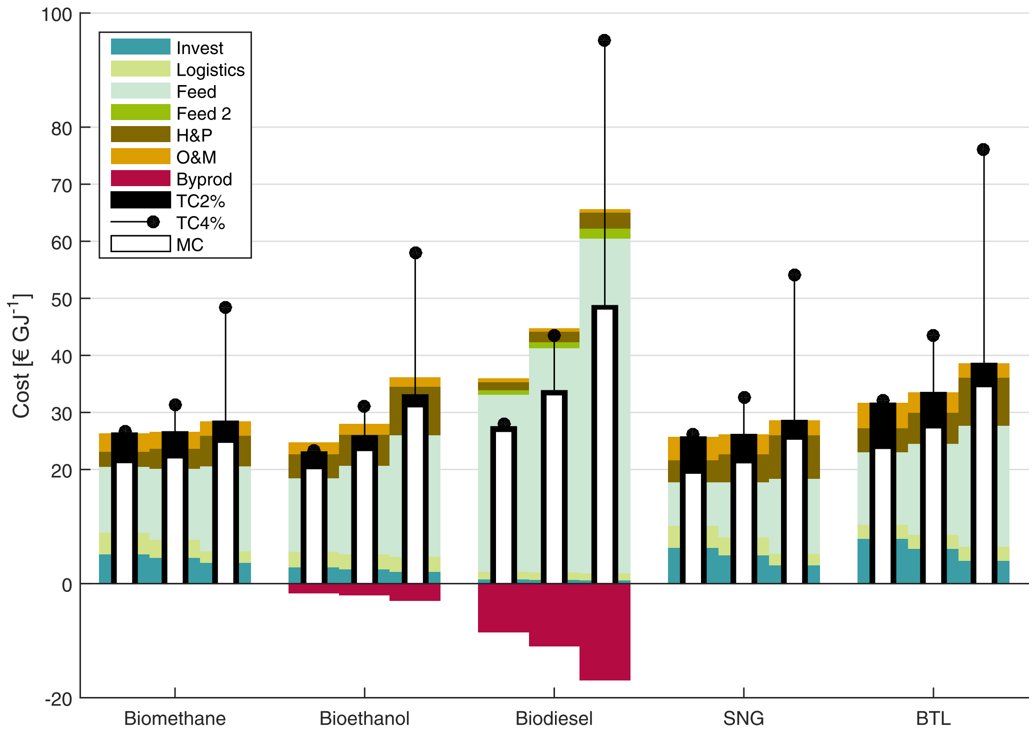

Fig. 5. Cost break-down and development for the biofuel options, in the case of a 2% annual wheat price increase, for the years 2015, 2030 and 2050, respectively. Abbreviations: Invest = investment cost; Logistics = logistic cost; Feed = main (biogenic) feedstock cost; Feed 2 = secondary feedstock cost (i.e. methanol for biodiesel); H&P = heat and power; O&M = operation and maintenance; Byprod = by-product credit; TC2% = total cost at an annual wheat price increase of 2%; TC4% = total cost at an annual wheat price increase of 4%; MC = marginal cost.

In case (c), both SNG and biomethane are spread out with significant shares between 0 and 80%. SNG remains below 10% in about a third of the cases and between 50 and 80% in a third of the cases. Biomethane remains below 20% in about half of the cases and rather evenly spread out between 20 and 80% shares. In case (e), SNG performs worse and remains below 10% in two thirds of the cases but still shows a rather even spread at low levels between 20 and 70%. Biomethane is rather evenly spread out between 10 and 80% shares, with some 40% of cases above half of the total produced biofuels. Thus, at less steeply increasing feedstock costs, SNG stands a chance of performing better than biomethane and vice versa. Clearly, BTL stands only a small chance in both cases, and more steeply increasing feedstock costs are to the disadvantage of any advanced biofuel in competition with biomethane from maize and bioethanol from sugar beet.

The biofuel cost variance at a set 2% annual wheat price increase resulting from the sensitivity assessment is shown in Fig. 7. Comparing to Fig. 5, it becomes clear that the feedstock cost development is the by far most important factor in determining future biofuel costs, as in 2050 all spans are larger when only feedstock costs are varied compared to the Monte Carlo assessment.

Biodiesel is the option most strongly determined by feedstock cost developments. Apart from that, biodiesel shows a relatively small cost span, also for the future. The largest cost span at a set feedstock cost development is exhibited by BTL, a product of high investment cost uncertainty, comparably low conversion efficiencies and feedstock yield uncertainties.

The two gaseous fuels show the lowest mean costs for 2030, with SNG being the lower one at 24.5 and biomethane at 26.0€ GJ^{-1}. Bioethanol is only slightly above with 26.2 € GJ^{-1}. The spans for the gaseous biofuels are larger than for the established liquid biofuels.

The span for BTL in 2030 in the sensitivity analysis for 2% and 4% annual wheat price increases is 27.0–53.6€ GJ^{-1} (mean 38.1€ GJ^{-1}) and can be compared to a span of 7–26$€_{2010}$ GJ^{-1} (8–30$\$_{2005}$ GJ^{-1}) for 2030 in other studies (Chum et al., 2011, p.282). The results here, even at a rather moderate 2% annual wheat price increase, are clearly above this span. The cost span of SNG is clearly lower, at 20.2–39.8€ GJ^{-1} (mean 28.5€ GJ^{-1}).

Due to low-cost perennials these options begin at substantially lower costs than in Millinger et al. (2016), where they started at 37.9 and 29.5€ GJ^{-1} and amounted to 40 and 30€ GJ^{-1} by 2030, respectively. Thus, the effect of perennial crops can be substantial for the initial costs of advanced biofuels, although it may not be enough to compete economically with some conventional biofuels, and the costs are heavily subjected to future feedstock price developments.

The sensitivities of biofuels produced per hectare are shown in Fig. 8. It can be seen that the gaseous fuels perform the best and about three to four times more biofuels can be produced per land unit compared to biodiesel and also significantly more than compared to BTL. Bioethanol, if produced from sugar beet, is the best liquid fuel in this aspect, not far behind the gaseous alternatives. For the advanced alternatives, the existence of three crops which were individually randomized in the sensitivity analysis increases the likelihood of higher yields (system resilience), but still there are cases where the yields are at the levels of biodiesel or even below.

4. Discussion

In this paper, the trade-off between feedstock energetic density and conversion complexity is tested through a combined assessment of possible future economic developments. The combination of learning effects of conversion options with a plausibly

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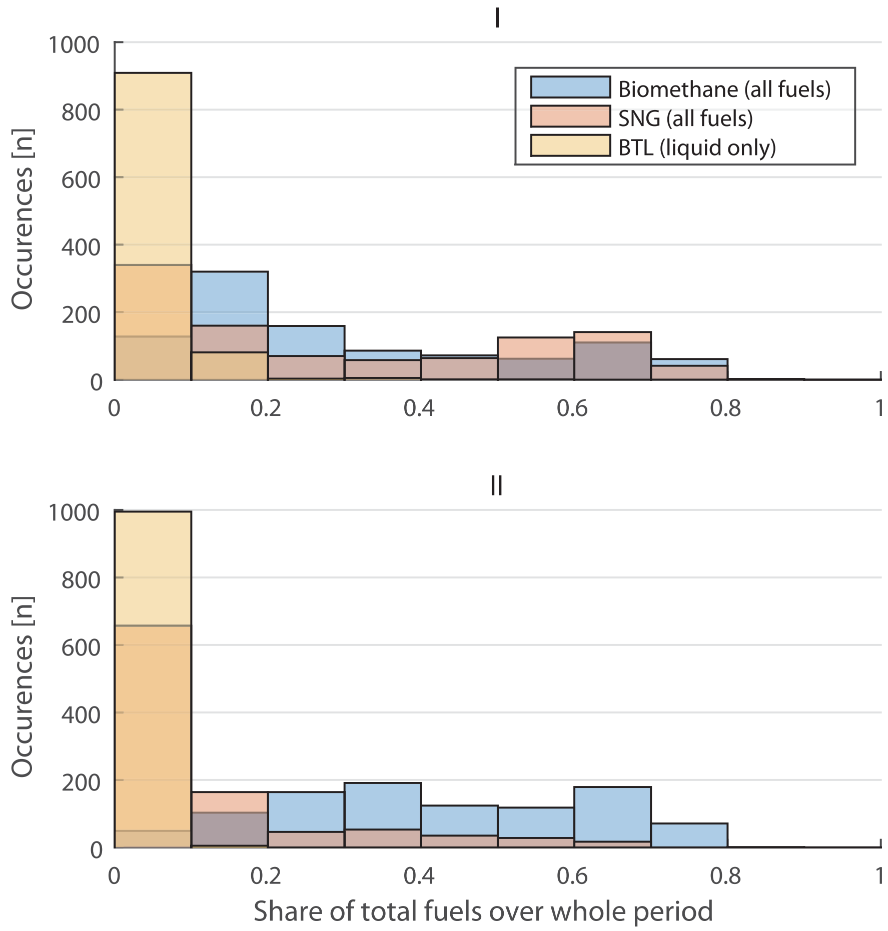

Fig. 6. Sensitivity of biofuel production shares, (I) at an annual 2% wheat price increase and (II) at an annual 4% wheat price increase, for the cases where all fuels as well as liquid fuels only were included. Thus, (I) and (II) correspond to the sensitivity in (c–d) and (e–f), respectively. The shares are of total biofuels over the whole time-period. The colour tone of the bars in the histogram is summed where they overlap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

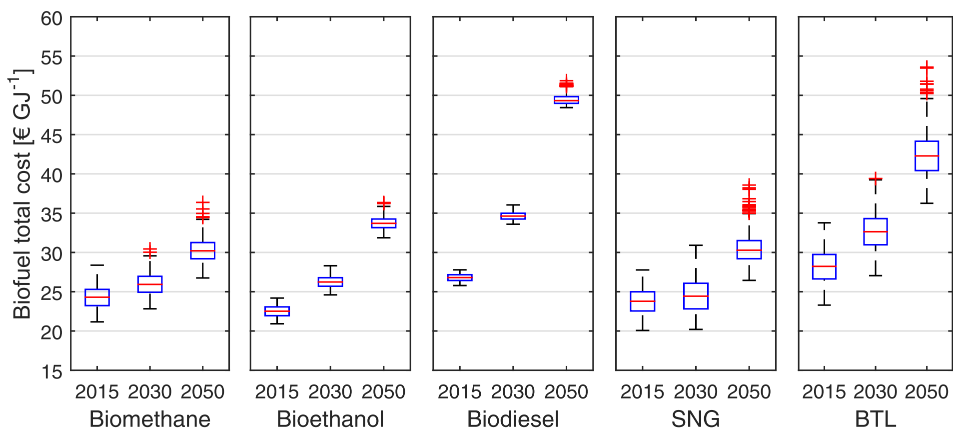

Fig. 7. Sensitivity of total cost of biofuels in 2015, 2030 and 2050 in case (c), at an annual 2% wheat price increase with all fuels included. The red lines show the median, the bottom and top edges of the blue box show the 25th and 75th percentiles, respectively, the whiskers extend to a maximum of 1.5 times the length of the box and outside of this interval outliers are plotted with a red cross. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differentiated feedstock price development leads to some striking results.

First, the currently dominant[4] biofuel in Germany, biodiesel derived from rape seed, is outcompeted in the short to medium term, showing that the low land use efficiency is not compensated by low-cost conversion. However, the rape seed price estimated with the method used here is ca 12% higher than the actual market price (with the reference rape seed price derived similarly to the base wheat price). Possible reasons for this discrepancy are that the

[4] bioethanol produced from grains (wheat) was sorted out pre-simulation for this paper due to poor economic performance; see Thrän et al. (2015).

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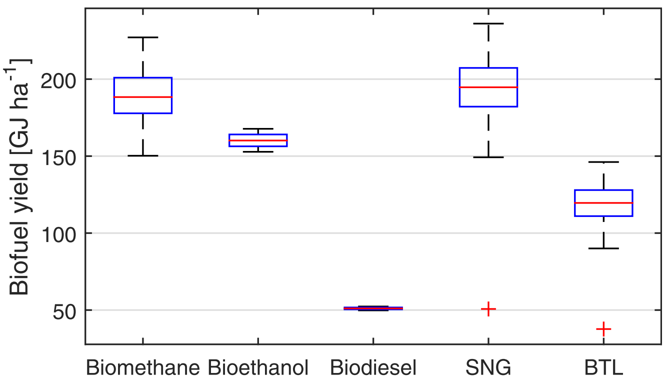

Fig. 8. Sensitivity of biofuel yield. The red line shows the median, the bottom and top edges of the blue box show the 25th and 75th percentiles, respectively, the whiskers extend to a maximum of 1.5 times the length of the box and outside of this interval outliers are plotted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

price of rape seed is heavily influenced by the global market for oil seeds due to the global tradability of the crop, as well as biofuel policies and crop-rotation practices influencing the cultivation of rape seed. Running the same scenarios with 12% lower rape seed prices throughout the whole time-period, biodiesel stays on for a slightly longer period of time, but is still displaced in the medium term in all scenarios except (b), where it remains in rather constant quantities throughout, at the cost of bioethanol. Nevertheless, based on these results and due to the low energetic yields, the shadow cost of growing rape seed for biodiesel production will increase more than for the other options in this assessment, and more complex conversion options using higher-yielding feedstocks are therefore likely to become economically preferable in the future.

Second, however, there is an end to the complexity required for a least-cost development. Advanced fuels may in fact not be required, as biomethane derived from whole-crop maize and bioethanol derived from sugar beet fare rather well even under moderate price development assumptions and even better if assuming increasing shadow costs of land use, as they have comparably high yields with less uncertainty and lower market barriers than perennial crops. This holds even though the prices for perennials are conservative (low) estimates, as farmers' risk considerations for investing land in switching to perennial crops (Ericsson et al., 2009) have not been included.

Third, the results presented here make it clear that stimulating markets for gaseous biofuels would increase the likelihood of a more biomass, land use and cost efficient biofuel development compared to focusing on liquid fuels, and especially if advanced biofuels are strived for. The result from Millinger et al. (2016) is thus further confirmed. The large and even spread of gaseous fuels seen in the sensitivity analysis further indicates the need for directed policy measures if such fuels are to achieve large market shares with a higher certainty.

Fourth, however, a consequence of a transition away from rape seed and grains with high energy density, is that the viable transport distances of feedstocks used for energetic purposes will decrease and thus biofuel conversion would likely need to take place in a nearer vicinity of the used arable areas. There may be a trade-off between the development towards biofuel conversion near the used land plots and the higher efficiency of gaseous fuels. If available land is scarce in the vicinity, increased imports of biofuels may become a necessity, in which case gaseous fuels are less economically transported in the absence of a gas network, such as is the case for overseas imports. In such a case, liquefaction or other densification is likely necessary, which however decreases the pathway efficiency and increases costs.

In this work, scenarios of either stagnant or different levels of increasing reference feedstock costs have been assessed, but which feedstock cost developments should be expected when designing long-term policy? In the past 20 years, the average annual cost increase was 2.1% and in the past ten years 3.8% (see Section, and this may be expected to continue for the following reasons.

A transition away from fossil resources with a simultaneous global population increase and improved living standards is likely to hugely increase the demand for biomass from many sectors, such as heat, power and materials as well as fuels. Some studies have come to the conclusion that biomass would contribute to more GHG abatement in combined heat and power production (Steubing et al., 2012) and do this more cost-effectively (Grahn et al., 2007; Martinsen et al., 2010) than in the transport sector. Sectors relying on hydrocarbons (e.g. some material use) are bound to rely on biomass as there are no other renewable alternatives (in contrast to for the energy and transport sectors), all the while global demand for more land extensive foodstuffs is increasing.

Land use is also connected with emissions from land use change, further enhanced through forests being converted to arable land due to increased land pressure (indirect land use change), and land use change is also connected to numerous other environmental effects such as biodiversity loss, soil erosion, albedo changes, etc. Furthermore, climate change, freshwater and phosphorous scarcities are likely to decrease the available suitable arable land as well as yields (Foley, 2005).

Therefore, due to an expected increase in biomass demand and simultaneous land use restrictions, it appears sensible to assume increasing prices of established crops, and thus an increasing shadow cost of land, when designing a resilient biofuel policy. In this case, the somewhat unexpected result of this study is that perennial biomass and advanced biofuels are not as competitive as some conventional biofuels under German conditions. This finding should apply to other regions with similar climate and soil characteristics to Germany, whereas the increasing importance of higher yielding biofuel options is globally applicable, with regional differences regarding which biofuels perform best.

Some aspects that have been left out of this study need mentioning. It was assumed that the derived market price applies at the gate of the conversion plant. Transport and storage costs of biomass have thus been omitted for the sake of simplicity and methodological transparency, as they depend on factors which are hardly foreseeable, such as where the energy crops are grown, how sparsely spread out the land plots are, how far away conversion plants are, how large they are and thus how large the catchment area needs to be[5]. For options using the same crop, the difference is bound to be smaller, as it mainly depends on the size of the plants. Still, the spread of biomass has an effect. On the one extreme, a perfect circle of biomass around the conversion plant can be assumed, in which case the transport cost would decrease with increasing plant size (as the area increases with the square of the radius). On the other hand, if biomass is assumed to be more heterogeneously spread out in the landscape, smaller conversion plants may be more economical, depending on the shape of the

[5] As an estimate, transport costs for cellulosic feedstocks typically are estimated at ca 3–16$/t (Miranowski and Rosburg, 2010; Haque et al., 2014; Wang, 2009), depending largely on the distance, which at 14 GJ t^{-1} would translate to ca. 0.16–0.86€ t_{DM}^{-1}. Compared to the costs and cost developments derived in this paper, this does little towards the economical comparison with the conventional biofuel crops.

spread. A spatial extension of the model with landscape data is therefore interesting for future research.

Growing perennials on marginal land for energetic purposes has been proposed as a solution which competes less with food production and displaces less land, thus avoiding indirect land use change (e.g. Tilman et al., 2006; Fargione et al., 2008), but has not been investigated here. Assessing the effect of this would also be an interesting extension of the study in combination with spatial data, as the marginal lands are likely to be even more sparsely spread out than presently used arable land. In combination with lower yields (Searle and Malins, 2014) and thus larger catchment areas, the transport costs are therefore more relevant for such an assessment.

Other future work includes expanding the model with more environmental aspects, widening the spatial scope to a larger area such as the EU, and assessing the role of biofuels in the wider context of the bioeconomy, including also biorefineries. With the cost developments found in this paper, the GHG abatement costs of biofuels compared with other usages of biomass is also an interesting and important topic which grants a further assessment.

5. Conclusions

In this paper, future biofuel competitiveness in Germany has been modelled under different feedstock cost development scenarios, leading to some important results and conclusions.

The initial lowest potential price of perennial crops was found to be 4.4 € GJ^{-1} (77€ t_{DM}^{-1}) for poplar, within the range found in other studies. The price of willow was 6.8, and of miscanthus 6.4 € GJ^{-1}, the same as for maize, which is not a perennial crop. Considering the development in the past decades and an expected increasing demand for biomass, the scenarios of increasing biomass prices should be considered when designing policy. At the higher feedstock cost developments considered in this paper (corresponding to the development in the last decade), maize emerged as the least-cost feedstock on an energy basis in the medium term.

Combining these price scenarios with a market competition model, some important results emerged. Currently dominant biofuels in Germany, biodiesel from rape seed and bioethanol from grains, were found not to remain cost-competitive in the short to medium term. However, despite current focus in research, advanced biofuels were found not to be the most competitive biofuels even in the long term when considering increasing feedstock costs. For instance, BTL was found to cost between 27.0 and 53.6€ GJ^{-1} in 2030, which is above most expectations. Rather, bioethanol from sugar beet and biomethane from maize are strong competitors, with biomethane increasingly so with higher feedstock prices, due to higher yields combined with high conversion efficiencies, all the while avoiding the high upfront costs of advanced biofuels and the risk of switching to perennial crops. However, such a transition leads to less mobile feedstocks being used than presently and in the case of gaseous fuels requires stimulation of the demand side in order to be successful.

The sensitivity analysis further confirmed that feedstock costs are by far the most important determining factor of the future costs of biofuels, which makes investments in biofuels in general and advanced biofuels in particular a highly risky endeavour. The share of levelized capital costs of the total biofuel costs were also seen to substantially decrease with increasing feedstock costs. As feedstock cost developments are out of the control of investors, this inhibits investments and R&D efforts (with the possible exception of conversion efficiency improvements). This is characteristic for any usage of biomass, in stark contrast to other renewable options such as wind and solar photovoltaics which have no operational resource costs, and must be considered when designing policy for any sector of the bioeconomy.

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Paper 3

Relative greenhouse gas abatement cost competitiveness of biofuels in Germany

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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 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

[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.

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.

Equation 1 shows the total GHG emissions $\varepsilon_{tot,j}^{(t)}$ [kgCO$_{2eq}$ GJ$_{fuel}^{-1}$] 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$_{FM}^{-1}$] 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 $\dot{m}_{k,j}^{(t)}$ is multiplied by its emission factor $\varepsilon_k^{(t)}$. Byproducts which are not considered in the allocation, but through a credit, are denoted cr.

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

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

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

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

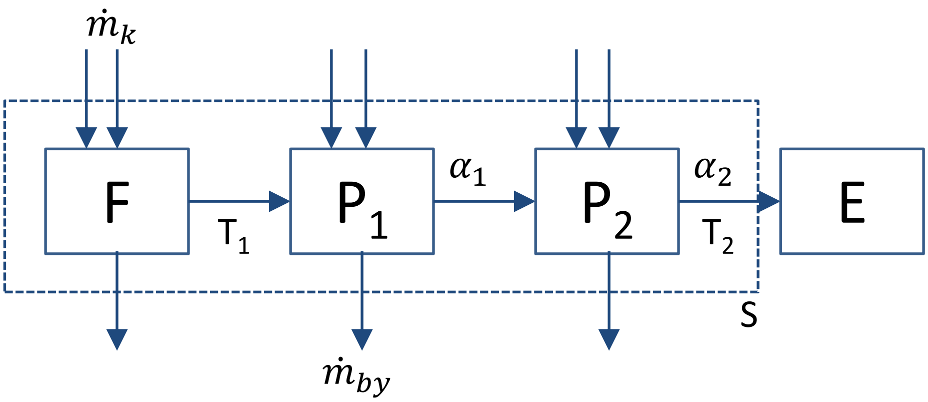

Figure 1. System boundaries of the Well-To-Tank (WTT) assessment from feedstock cultivation to tank for each pathway, shown by the dashed line S. The resulting abatement is compared on the basis of different functional units, such as GHG abatement per energy unit, cost per GHG abatement and GHG abatement 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]

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

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}.

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.

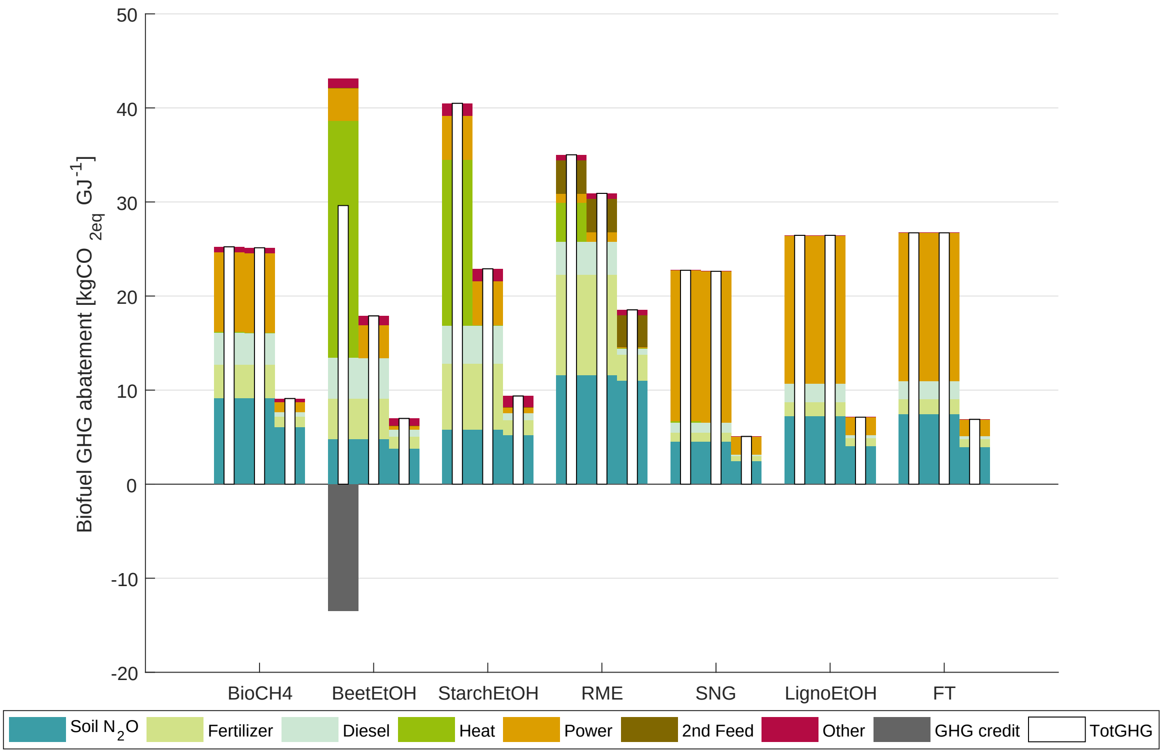

Figure 2. GHG emissions for the biofuel options, broken down to their sources [$kgCO_{2eq}$ GJ^{-1}]. The leftmost bar for each option is the reference literature case; the middle bar shows the results for the start year of the base case, with renewable heat input; the rightmost bar shows the results 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.

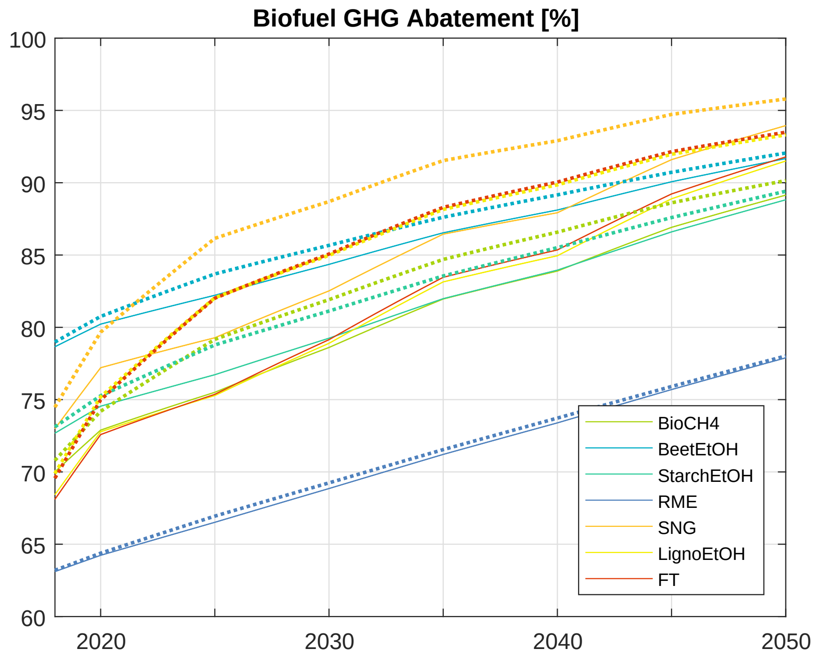

Figure 3. Biofuel GHG abatement development, compared on an energetic basis with the fossil reference. The solid lines show the development at a moderate power mix development, whereas the dotted lines show the development at a more progressive power mix development.

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%.

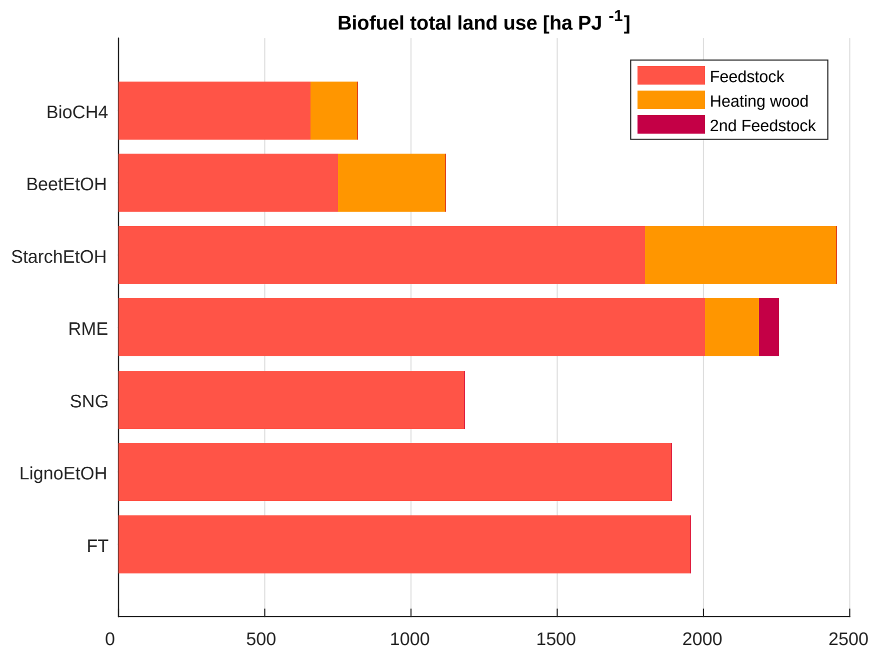

Figure 4. Biofuel land requirement by source in the first year of the base case.

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.

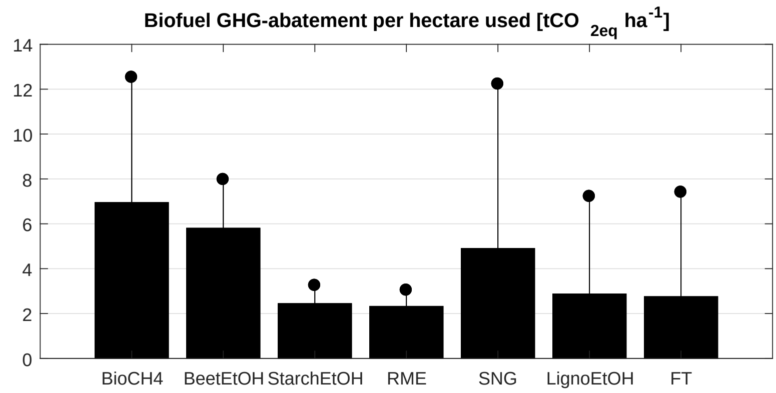

Figure 5. Biofuel GHG abatement per hectare in the base case with medium yields for all crops. The bar shows the initial GHG abatement, whereas the whisker extends to the GHG abatement in the last year.

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.

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.

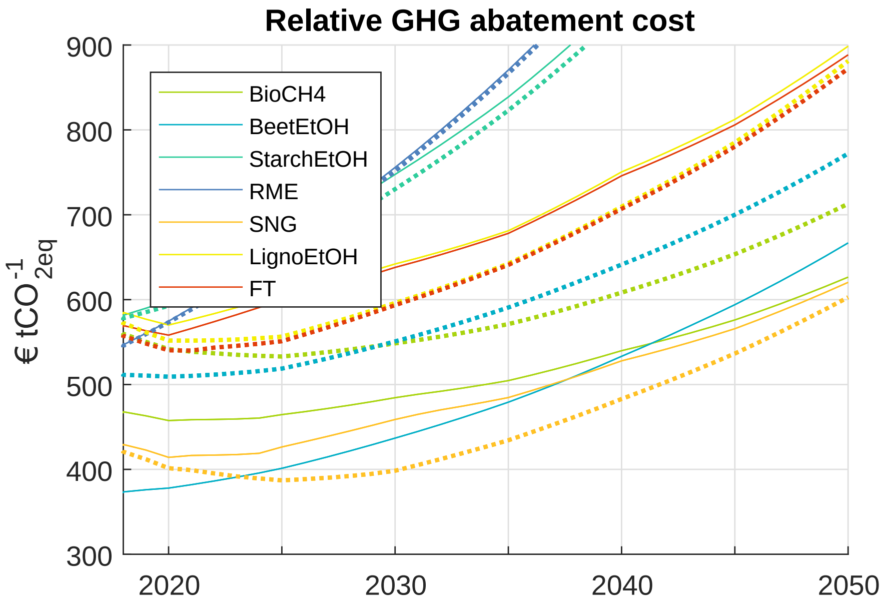

Figure 6. Biofuel relative GHG abatement cost developments [€ tCO_{2eq}^{-1}] in scenarios (a, solid lines) and (c, dotted lines). Some developments are outside of the plot: the cost of RME increases to ca. 1350 € tCO_{2eq}^{-1} and the cost of StarchEtOH increases to ca. 1230 € tCO_{2eq}^{-1} in both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

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.

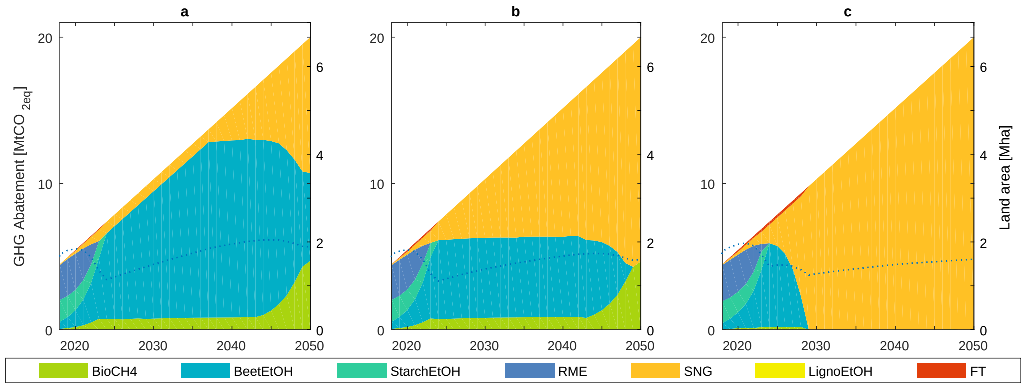

Figure 7. Biofuel competitiveness based on relative GHG abatement cost in the scenarios. The areas show the total performed GHG abatement through each option (left axis), whereas the dotted line shows the total arable land required (right axis). The base scenario (a) includes both liquid and gaseous 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.

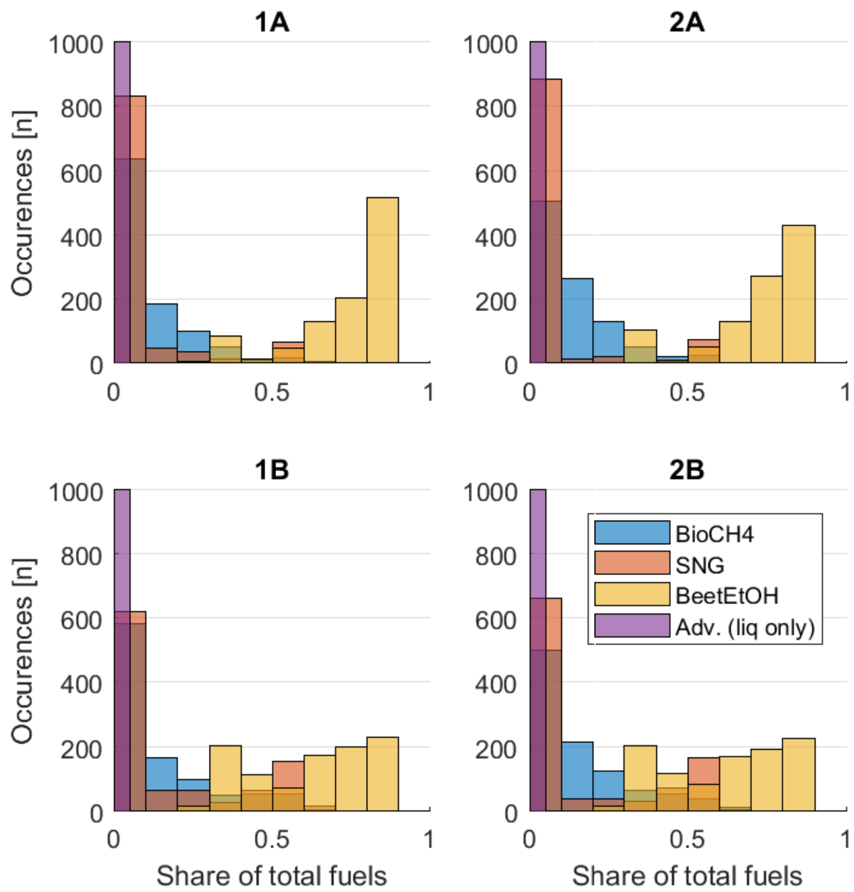

Figure 8. Sensitivity of biofuel production shares, at annual 3% (1) and 4% (2) wheat price increases, with moderate (A) and more progressive (B) power mix developments. 2A and 2B correspond to the sensitivities within scenarios (a) and (b). The number of occurrences among the 1000 runs at total cumulative 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.

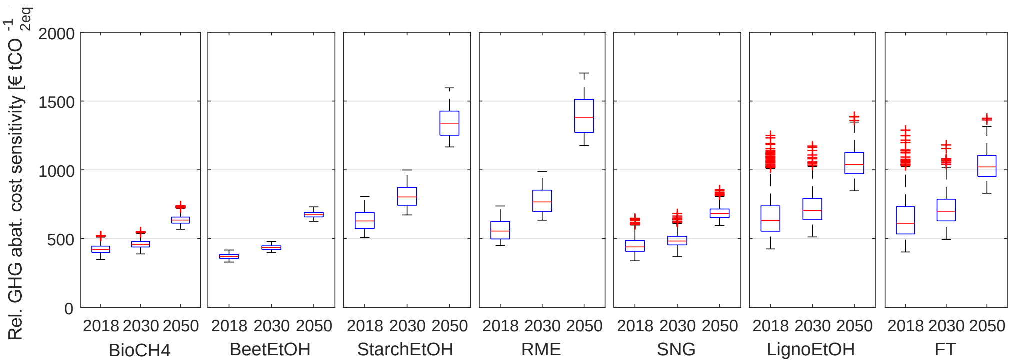

Figure 9. Sensitivity of total cost of the GHG abatement of biofuels in 2018, 2030 and 2050 in sensitivity case 1B (corresponding to the base scenario (a)), at a constant annual 4% wheat price increase and the other variables randomly varied according to Section 2.4. The red lines show the median, the 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 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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Paper 4

Climate optimal deployment of biofuels from crops in Germany

Millinger, M., Meisel, K. and Thrän, D.

Submitted

Climate optimal deployment of biofuels from crops in Germany

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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 (UNFCCC, 2015) requires rapid global efforts of decarbonisation (Rockström et al., 2017). 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) (Armaroli and Balzani, 2011; Sandy Thomas, 2009; Dunn, 2002; Sterner, 2009; König et al., 2015). 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. 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 less available options (IPCC, 2014, 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:

- 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?

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2. Materials and methods

2.1. Modelling

For optimising the GHG abatement of biofuels, a model has been developed, building on the model BENSIM (Millinger et al., 2017b; Millinger and Thrän, 2016; Millinger et al., 2017a). 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. 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}], 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. 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]. Capacities available at the beginning κ_0 are decommissioned linearly over their 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. Grubler, 1998).

The required land for each option is given by the production, divided by yield $Y_{i,t}$ times conversion efficiency $\eta_{i,t}$. The total land use cannot surpass Λ_t=1.5 [Mha] (in most scenarios in this paper) for each time point.

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 $i \in I_{pe}$.

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

s.t.

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

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

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

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

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

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

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

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

The costs are calculated ex-post, according to Millinger et al. (2017b), including technological learning effects based on the resulting expansion of the technologies in each scenario. The feedstock costs were calculated according to (Millinger and Thrän, 2016), with an annual reference feedstock cost increase of 4%.

2.2. Data and assumptions

The biofuel options included are the same as in Millinger et al. (2017b), with some additions: grain based ethanol (Ponitka et al., 2016, p.40f); biokerosene (KER), with the same characteristics assumed as for FT-diesel; and the biomethane and SNG pathways can be liquefied (LBM and LSNG). For the liquefied options, a gas loss of 2% and an additional power requirement of 12 kWh GJ_{fuel}^{-1} was assumed (Birgen and Garcia, 2013, p.39 & p.43). The GHG abatement data and background system developments (power mix, fertiliser, heat input and fuel input emission factors) are elaborated in (Millinger et al., 2017a). The reference emission for the transport sector is set at 83.8 $kgCO_{2eq}$ GJ^{-1}.

The land use attributable to biofuels used in Germany can be estimated to ca. 1.5 Mha[1]. This is assumed to continue to be available for biofuels production and thus an upper allowable limit is set to 1.5 Mha.

Table 1: 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 (2013). International shipping emissions were weighted for Germany by ton shipped using Hütter (2013, p.12) and UNCTAD (2017, p.5), with emissions from IMO (2015). 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 (2014), with the demand between 2030-2050 assumed to level out and remain constant. Ca. 45 million passenger cars were registered as of 2017 (KBA, 2017a), with ca. 3 million new registrations each year (ICCT, 2017, 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 ICCT (2017). Targets[2] of 95 (EU, 2009), 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 specific emissions of average diesel and gasoline driven passenger cars have almost converged in the past decade (ICCT, 2016, 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) (ICCT, 2017, 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 (KBA, 2017a).

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 (KBA, 2017b). 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.

The fuel demand of the land goods sector is assumed to decrease 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, in line with possible options (IPCC, 2014, p.17&28).

[1] Average for the years 2014-2016, based on own calculations. Crop use statistics were used from German biofuels monitoring (BLE, 2017), combined with yields from KTBL (2012) and IPCC (2011) and conversion efficiencies from Millinger et al. (2017b).

[2] 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 ca. 25% and weight by ca. 10% (ICCT, 2016). At least 65 gCO_2 km^{-1} can be achieved until 2025 through vehicle mass reduction only (Meszler et al., 2013).

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 (IEA, 2017).

Fuel demand for shipping is assumed to decrease to half of current demand by 2050, through efficiency improvements, in line with projections (IPCC, 2014, p.18&62). Allowed biofuels are diesel and liquefied methane, according to expectations by IMO (2015).

The fuel demand for the aviation sector is expected to increase or at best remain at the same level, despite efficiency improvements (IATA, 2015; IPCC, 2014, 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 a fast coal decommission scenario (WWF, 2017, p.120). 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 (Ecoinvent, 2016) and biodiesel (Ecoinvent, 2010) 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 2), with varying degree of electrification, yields, quota, land available and other important parameters: scenario i assesses the effect of adding biofuels from energy crops from 1.5 Mha of arable land to the system, with all fuels allowed according to Table 1. Scenario ii restricts all gaseous biofuels, 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. Scenario iii reduces the yields of sugar beet and silage maize to the lower span stated in Millinger et al. (2017a). Scenario iv assesses the effect of a higher average usage of electric passenger cars, equivalent to 1.5 ICEVs for each EV (e.g. through self-driving cars). Scenario v reduces the annual EV increase to 30%. Scenario vi assesses the effect of no EVs in the passenger transport sector. 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). Scenario viii doubles the available arable land linearly to 3 Mha in 2050. Scenario ix assumes a less progressive power mix improvement according to the fourth scenario in WWF (2017, p.123).

Table 2: 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 (WWF, 2017, p.123)

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.

3. Results

The resulting EV deployment resembles an S-curve (cf. Grubler, 1998, 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.

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

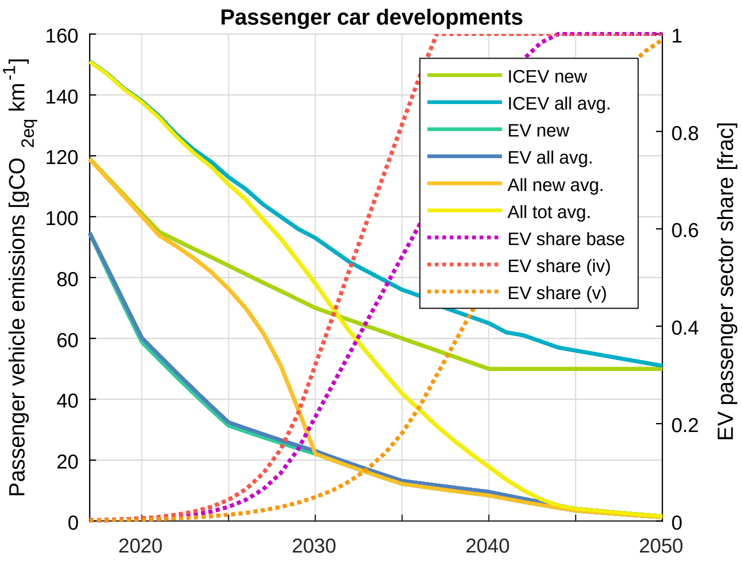

Figure 1: Passenger car sector developments. Average vehicle and fleet emissions are shown in solid lines [gCO_{2eq} km^{-1}, left axis]. The passenger sector market shares of EVs are shown in dotted lines [frac, right axis], for the base case as well as for scenarios (iv) where EVs have a 50% higher 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.

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.

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 5), and transport remains at ca 80 $MtCO_{2eq}$ in the end (Figure 6), more than twice as much as in all other scenarios, which include EVs. 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 5), as well

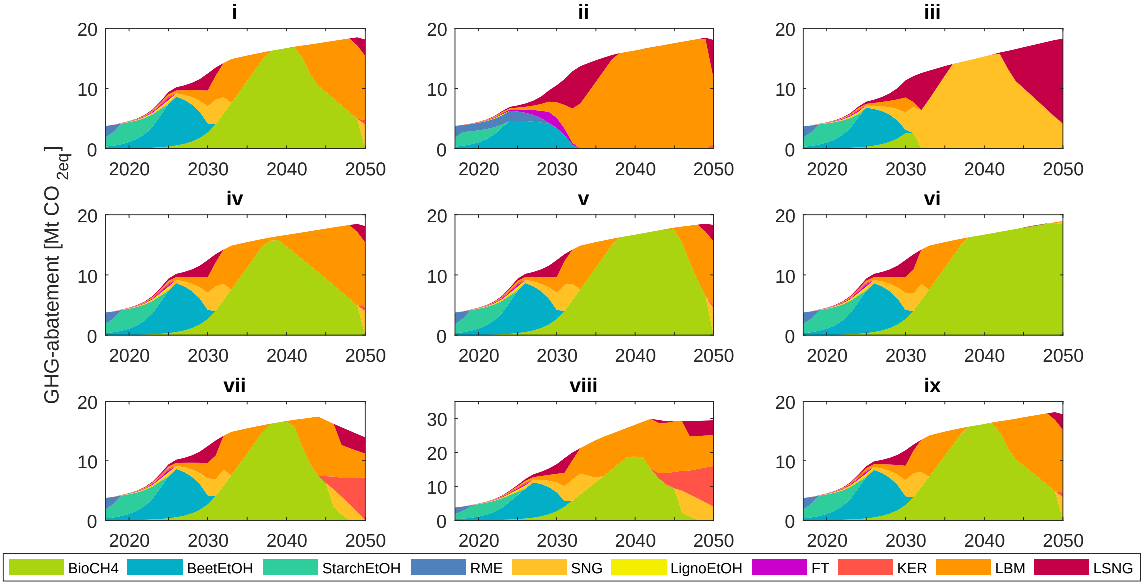

Figure 2: Total biofuel GHG abatement mix development in scenarios. The base scenario i assumes developments as described in Section 2.2, with the other scenarios being variations of the base scenario. Scenario ii: exclusion of gaseous fuels and quota for diesel and gasoline; iii: lower yields for sugar 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 synthetic 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.

as the lowest emissions at the end of the time span (Figure 6).

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 5), indicating the need for prioritising early emission reductions in the power system.

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 € (Destatis, 2017), excluding the avoided cost of the substituted fossil fuels.

Figure 4 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.

4. Discussion

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.

Aviation biofuels from dedicated crops in Germany only perform a climate benefit when other biofuel usages with higher pathway climate efficiencies 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 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

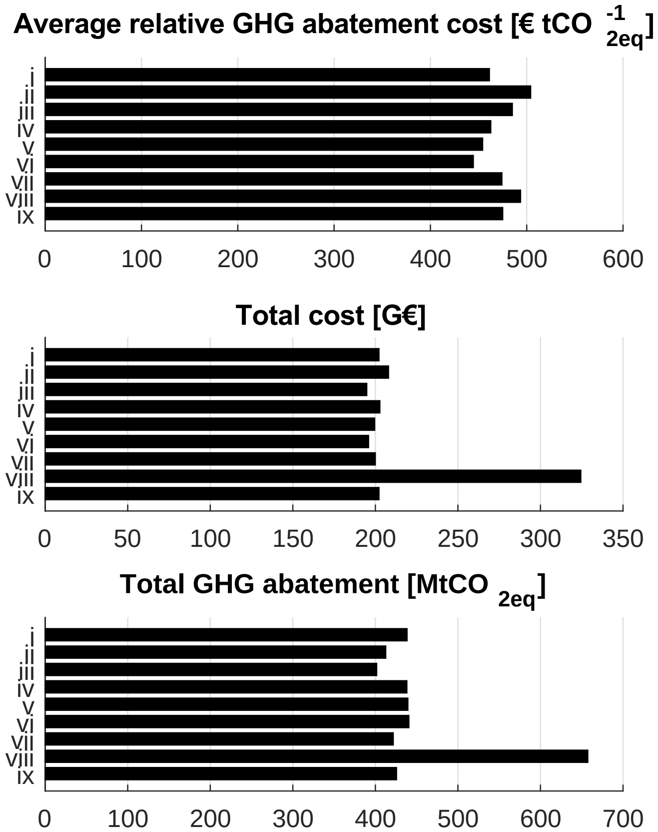

Figure 3: Average biofuel GHG abatement cost, total cumulative biofuel cost (excluding the avoided cost of the substituted fossil fuels) and total cumulative GHG abatement through fossil fuel substitution by biofuels, summed for all transport sectors in each scenario.

improvements come together were aviation biofuels found to achieve any substantial 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.

Even though engine efficiency scenarios were not included, the possible GHG abatement per hectare of arable land (Figure 4) 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. 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 (Millinger et al., 2017a). The potentially best performing fuels in this regard are maize silage based $BioCH_4$ and LBM.

The total cost differences between the 1.5 Mha scenarios were found to be small, despite costs not being

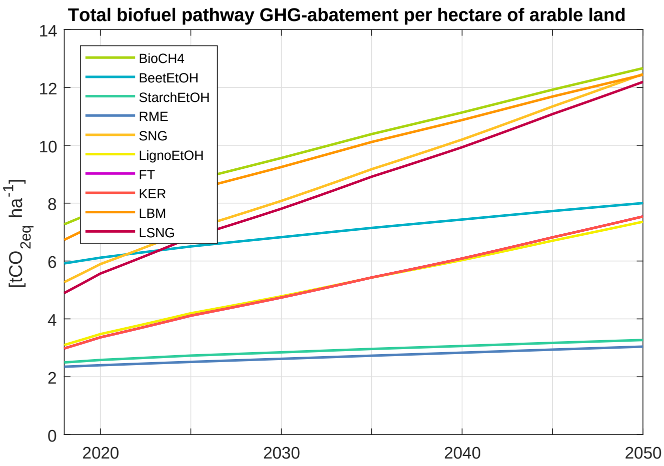

Figure 4: Development of greenhouse gas abatement per hectare [tCO_{2eq} ha^{-1}] for the biofuels included over the modelled time span, in the base scenario. Fischer-Tropsch-diesel shows exactly the same development as KER, and is therefore not visible in the graph.

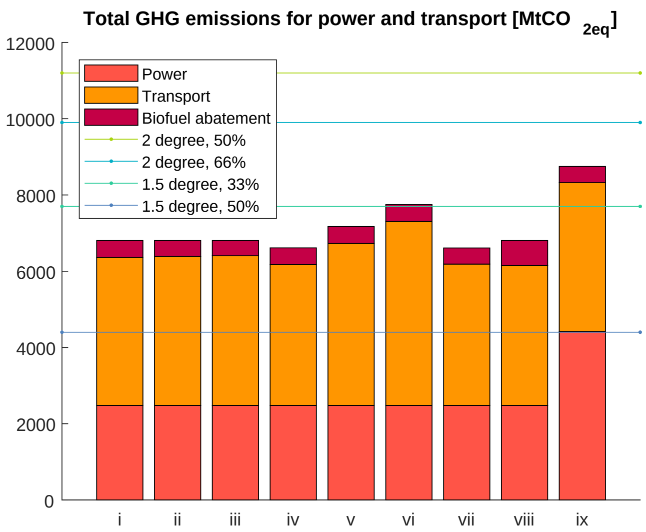

Figure 5: Total greenhouse gas (GHG) emissions for the power and transport sectors in the scenarios, including the GHG abatement through biofuels. The lines show permissible German GHG budgets at different likelihoods of reaching 1.5°C and 2°C climate targets, if the global GHG budgets are allocated per capita (WWF, 2017).

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 (Millinger and Thrän, 2016; Millinger et al., 2017a), which is confirmed by this result.

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 (Brosowski et al., 2016). 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 (BLE, 2017). 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

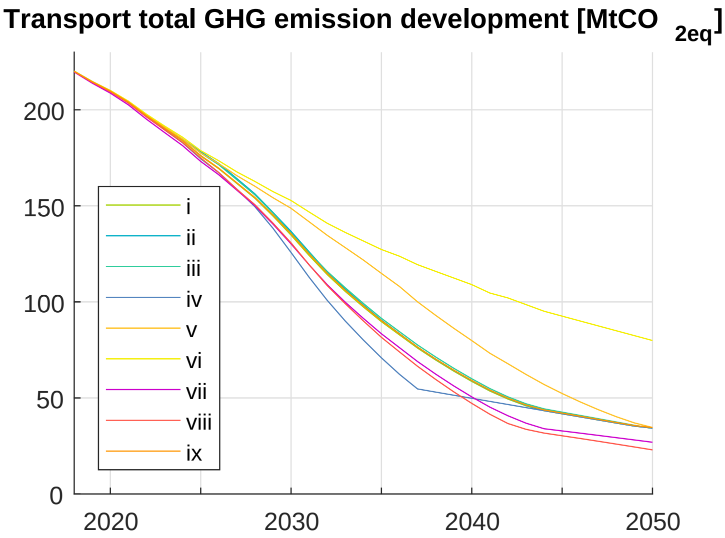

Figure 6: Total GHG emission development [$MtCO_{2eq}$ a^{-1}] for transport over the modelled time span in the scenarios.

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 thus would 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.

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.

As a benchmark, the permissible carbon budget in order to achieve certain climate goals can be allocated per capita (WWF, 2017). 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 5), 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.

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.

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. However, this is a question of what the assumed reference is, as the required arable land has reduced in the past few years through the use of more residual biomass (BLE, 2017). In the scenario where the available arable land is assumed to increase, in order to avoid land use change issues, the additional land would need to be offset through reducing the demand from other sectors, such as (ruminant) meat production (Bryngelsson et al., 2017; Foley et al., 2011; Tilman et al., 2009). If this is not done, a land area extension for energy purposes beside possibly marginal lands (Tilman et al., 2006) risks leading to more emissions than are offset through replacing fossil fuels (Fargione et al., 2008; Searchinger et al., 2008).

5. 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 do the subsequent ones become relevant. Sectors and scenarios where ethanol and gaseous fuels are allowed yield the highest GHG abatement.

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 biofuel 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.

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