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

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Abstract

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 27.0-53.6€ 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.

Keywords: biofuels, energy crops, perennials, biofuel competition, short-rotation coppice, miscanthus

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. (Cherubini and Strømman, 2011)

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 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)).

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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., 2017) 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 (Figure 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. (2017) 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 (**?**), 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

[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.

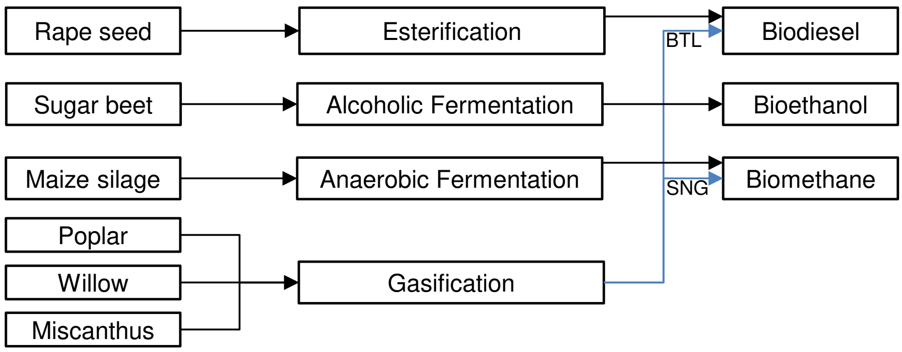

Figure 1: Feedstocks, conversion pathways and biofuel options included in the modelling.

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).

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

All perennials are assumed to provide the same and equivalent good[2], "lignocellulosic biomass", for which the 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 Figure 2. However, the average yearly price increase between 1994-2014 was about 2.1% (the equivalent 20-year historical average price change for the past ten years averages 1.8% year^{-1}) and between 2004-2014 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) to 400PJ by 2050, corresponding to 16% of the current end energy demand of the

[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)

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

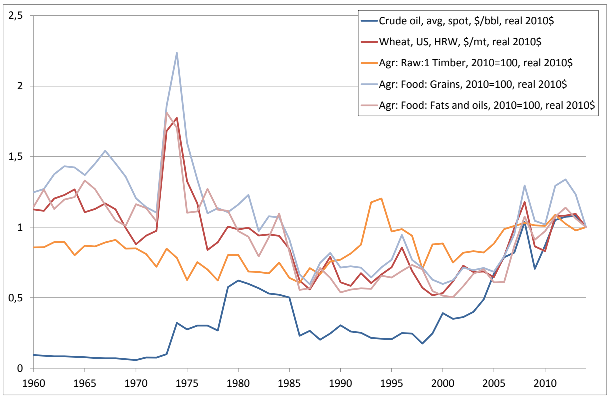

Figure 2: World market price development of wheat, grains, fats and oils, timber and crude oil 1960-2014, in $\$_{2010}$ (World Bank, 2016), normalized to 2014.

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 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 Figure 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 3-4.6, 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

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%

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.

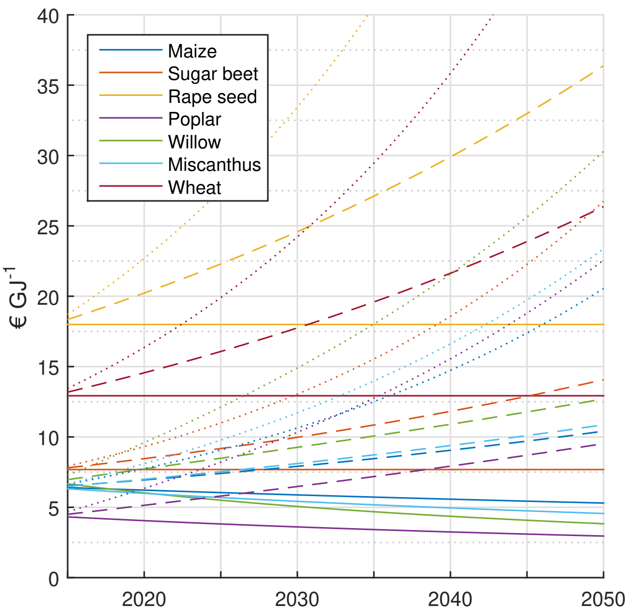

Figure 3: Feedstock cost developments in the assessed cases. Solid, dashed and dotted lines are for the cases where the wheat price remains constant and increases by 2% and 4% yearly, respectively. In the latter case, the prices of wheat and rape seed continue rising to 53.1 and 72.9 € GJ^{-1}, respectively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

Resulting from the feedstock cost developments, the biofuel developments in the six main cases can be seen in Figure 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 Figure 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 Figure 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

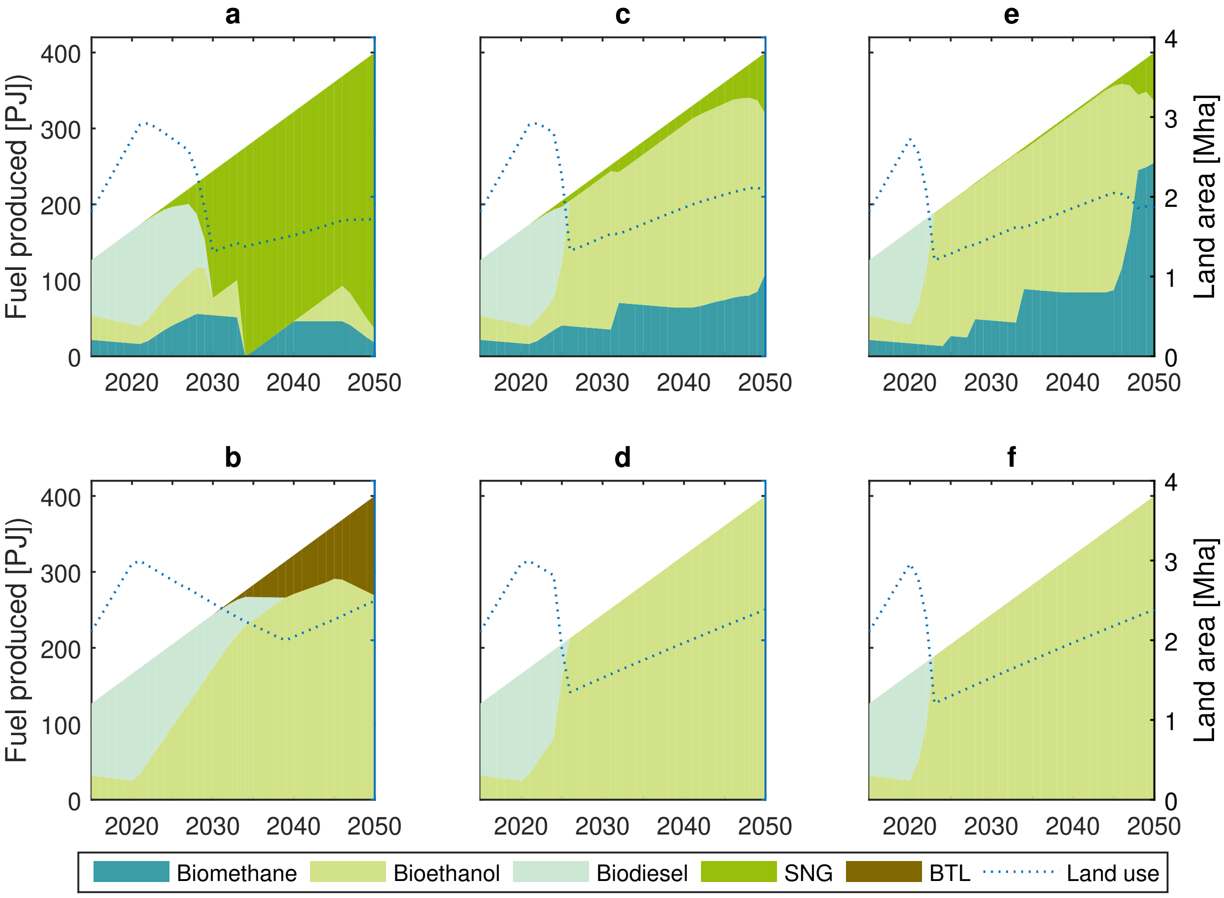

Figure 4: Production structures as well as land use (line, right axis) in the six main scenarios. Cases (a) and (b) with a constant wheat price, cases (c) and (d) with a 2% annual wheat price increase and cases (e) and (f) with a 2% annual wheat price increase. Cases (a), (c) and (e) include all fuels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

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 Figure 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 10-20%. 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%.

In case (c), both SNG and biomethane are spread out with significant shares between 0-80%. SNG remains below 10% in about a third of the cases and between 50-80% in a third of the cases. Biomethane remains below 20% in about half of the cases and rather evenly spread out between 20-80% 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 20-70%. Biomethane is rather evenly spread out between 10-80% 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 Figure 7. Comparing to Figure 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

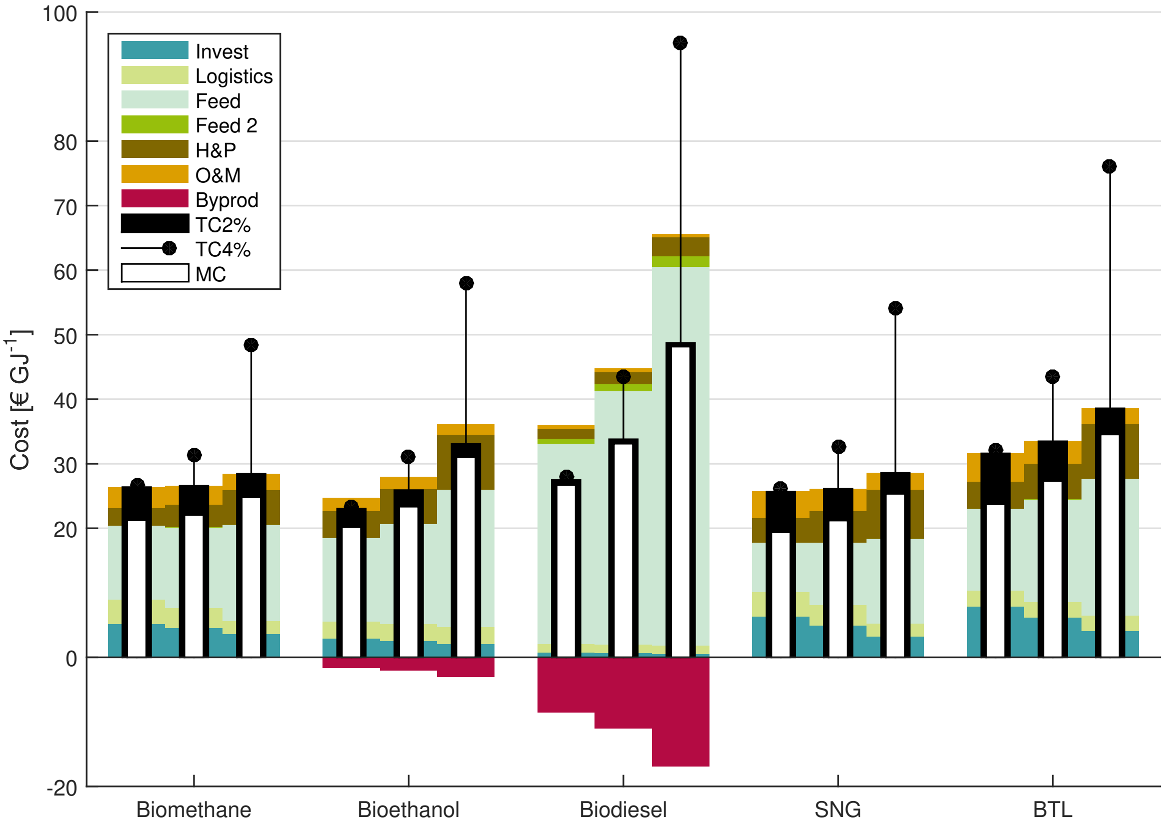

Figure 5: Cost break-down and development for the biofuel options, in the case of a 2% annual wheat price increase, for the years 2015, 2030 and 2050, respectively. Abbreviations: Invest=investment cost; Logistics=logistic cost; Feed=main (biogenic) feedstock cost; Feed 2=secondary feedstock cost (i.e. 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.

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. (2017), 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 Figure 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.

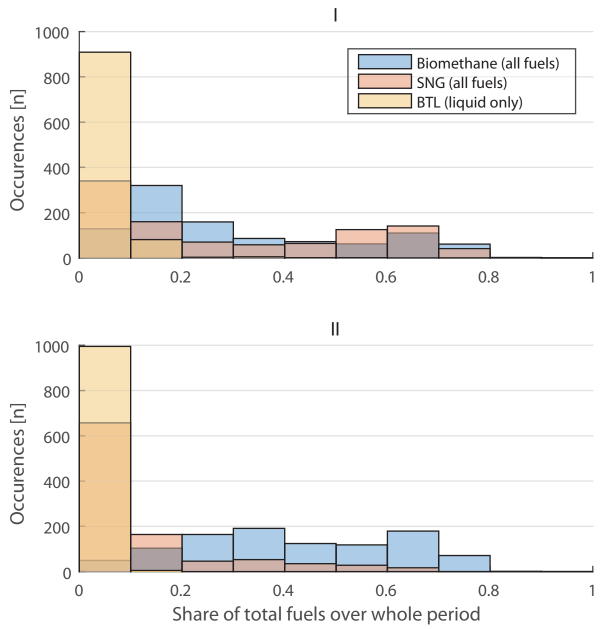

Figure 6: Sensitivity of biofuel production shares, (I) at an annual 2% wheat price increase and (II) at an annual 4% wheat price increase, for the cases where all fuels as well as liquid fuels only were included. Thus, (I) and (II) correspond to the sensitivity in (c-d) and (e-f), respectively. The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

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 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 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. (2017) 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

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

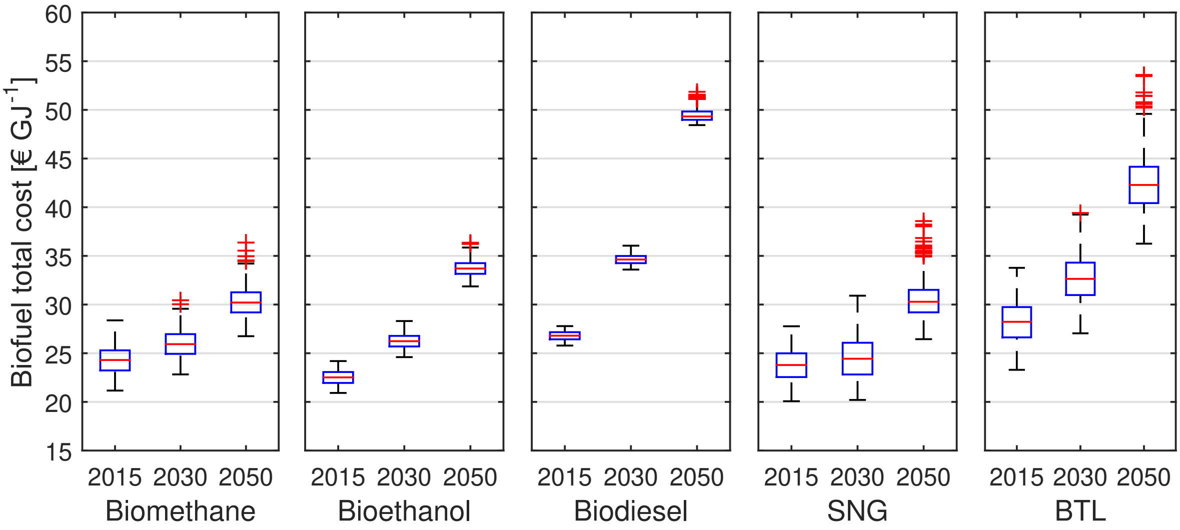

Figure 7: Sensitivity of total cost of biofuels in 2015, 2030 and 2050 in case (c), at an annual 2% wheat price increase with all fuels included. The red lines show the median, the bottom and top edges of the blue box show the 25th and 75th percentiles, respectively, the whiskers extend to a maximum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

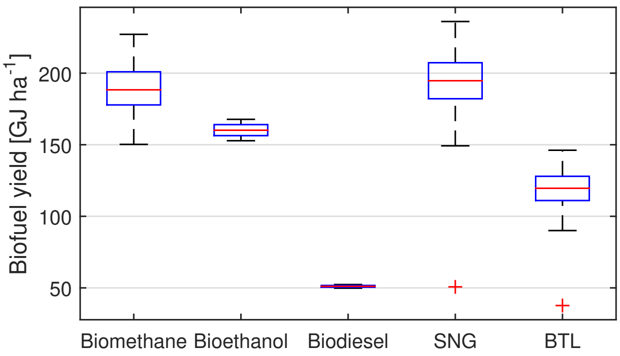

Figure 8: Sensitivity of biofuel yield. The red line shows the median, the bottom and top edges of the blue box show the 25th and 75th percentiles, respectively, the whiskers extend to a maximum of 1.5 times the length of the box and outside of this interval outliers are plotted.

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.

[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.

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 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 27.0-53.6€ 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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