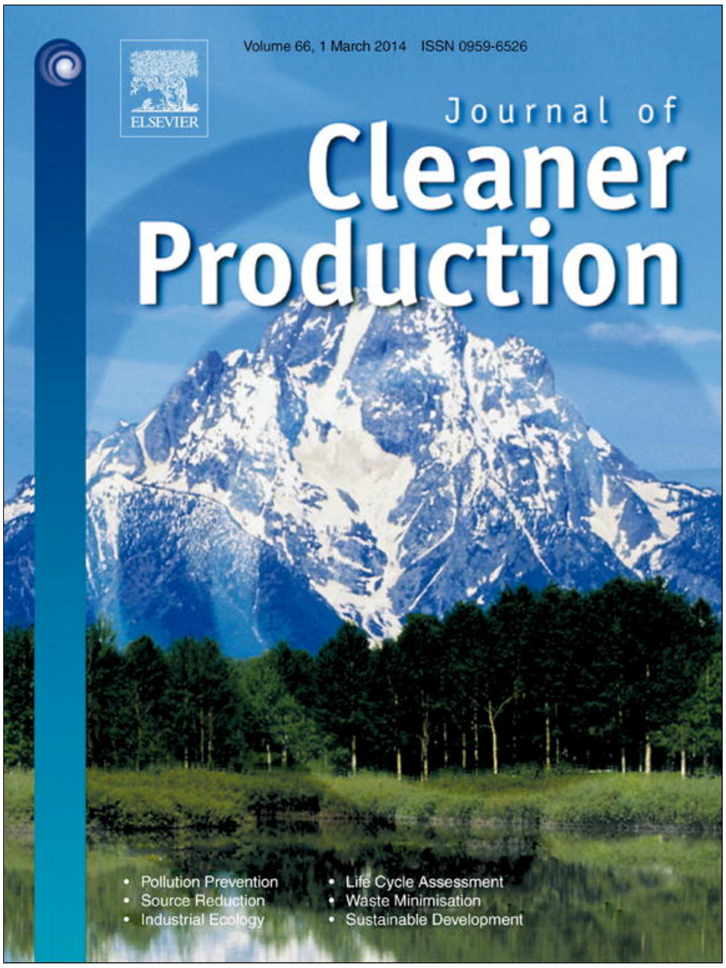
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Modelling production cost scenarios for biofuels and fossil fuels in Europe

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ABSTRACT

Competitive production costs compared to conventional fuels are imperative for biofuels to gain market shares, as current tax advantages for biofuels are only temporary. Comparing production costs of different biofuels with fossil fuels is a challenge due to the complexity of influencing factors. The objective of this research paper is threefold: 1) to project future bio-fuel feedstock prices based on the crude oil price development, the price index for agricultural products, growth in world population, growth in wealth per capita income, and change in energy consumption per capita, 2) to simulate production costs under consideration of likely economies of scale from scaling-up production size and technological learning and 3) to compare different biofuels and fossil fuels by scenario analysis. A calculation model for biofuel production is used to analyse projected production costs for different types of biofuels in Europe for 2015 and 2020. Unlike engineering oriented bottom–up approaches that are often used in other biofuel studies, the macro-economic top–down approach applied in this study enables an economic comparison and discussion of various fuel types based on reference scenarios of crude oil prices of €50, €100, €150 and €200 per barrel. Depending on the specific raw material prices as well as the conversion costs, the analysis delivered a differentiated view on the production costs and thus on the competitiveness of each individual type of fuel. The results show that 2nd generation biofuels are most likely to achieve competitive production costs mid- to long-term when taking into account the effects from technological learning and production scale size as well as crude oil price scenarios between €50 and €200 per barrel for both reference years. In all crude oil price scenarios, bioethanol from lignocellulosic raw materials as well as biodiesel from waste oil are associated with high cost saving potentials which enable them to outperform fossil fuels and 1st generation biofuels.

1. Introduction

A large portion of worldwide energy sources and tangible products are made from fossil resources. Crude oil is the single most important source of energy accounting for approximately 35% of worldwide primary energy consumption in 2005 and is expected to slightly decrease to 32% by 2030 (IEA, 2007). Although crude oil, natural gas and coal will still remain the most important sources of energy until at least 2030 (U.S. EIA, 2011; Birol, 2010), depleting oil reserves have been recognised as a main challenge to energy supply in the next decades.

Owing to the rising crude oil price and stricter emission standards, the demand for alternative fuels is growing. Alternative fuels able to mitigate climate change and reduce the consumption of fossil resources are increasingly being promoted by governments (Gustavsson, 1997; Mizsey and Racz, 2010; Fargione et al., 2008; Balat, 2011). Among these alternative fuels, biofuels are particularly important to bridge the gap until fuel cell or electrically driven vehicles are available on a large scale. The replacement of oil with biomass as raw material for fuel and chemical production is an interesting option and a driving force for the development of so-

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called biorefineries, where almost all types of biomass feedstocks can be converted to different products (Cherubini, 2010).

Renewable resources can lead to a higher security of supply and a better environmental performance due to lower greenhouse gas (GHG) emissions (Parry et al., 1999), and may also increase income in rural regions (Leistritz and Hodur, 2008). Some authors even expect the development of a bio-based economy (Tyner and Taheripour, 2008). Of special interest is the production of biofuels, such as bioethanol, biodiesel or biomass-to-liquids (BTL) fuel using various raw materials and production processes (Naik et al., 2010). In contrast to biofuels of the 1st generation (bioethanol from sugar or starch containing plants or biodiesel from rape seed or palm oil), 2nd generation biofuels are made from raw materials which are not used for the production of food products. These raw materials mainly include lignocellulosic materials (or lignocellulosic waste), such as straw and wood as well as various agricultural and wood processing waste products, such as organic waste. Ajanovic (2011) concludes that besides the advantage related to the absence of competition for raw materials with food production, 2nd generation biofuels are associated with higher energy yields, modest use of agro-chemicals and higher reduction potential of greenhouse gas emissions compared to 1st generation biofuels. The use of biofuels has increased considerably in the European Union (EU) (Bomb et al., 2007; Dautzenberg and Hantl, 2008), although, so far, only first generation biofuels are being produced in larger scales.

The main objective of this paper is to calculate biofuel production costs for different biofuels in Europe for the two years 2015 and 2002 and compare them with production costs for fossil fuels. For this purpose, a calculation model consisting of four steps was developed: 1) definition of biofuel production scenarios in 2015 and 2020, 2) estimation of future raw material prices based on assumptions on crude oil price development and the observed relation between crude oil price and prices for biofuel raw materials in the past, 3) modelling of scale and time dependant conversion and capital costs and 4) calculation of the total production costs as sum of raw material costs, capital costs and conversion costs. The input data for the production cost model are taken from publicly available production cost data for production processes as well as single production steps which were collected during the past five years based on literature research and expert interviews (Festel, 2008, 2007). The production costs are calculated in Euro Cent per litre (€Cent/l). The accuracy of the results was enhanced by plausibility checks based on current data as well as consistency of the results across production technologies. Simultaneously, data comparability was assessed in this course and, if necessary, corresponding adjustments were performed.

Both changes in raw material costs and conversion costs as well as capital costs based on different scenarios of price development for raw materials and crude oil were considered. Raw material costs are driven by the development of the markets for biomass and fossil raw materials, like crude oil due to substitution effects. Conversion costs are driven by scale effects as well as time dependent learning effects. Demand side restrictions in the availability of biofuels due to a strongly increasing demand and rapidly raising biofuel prices are assumed as negligible for this projection period. Despite the peak oil issue, biofuels are not expected to exceed a market share of 15% on the global fuel market within the next five to ten years (Gnansounou et al., 2009; Bagheri, 2011). The EU has set a target market share of 10% in terms of all petrol and diesel transport fuels in the EU by 2020 (EU-Commission, 2003). Consequently, prices on the fuel market will still be driven by fossil fuels.

Today, biofuels can compete with fossil fuels only due to governments' regulation and subsidies. The hypothesis of this study is that medium and long term biofuel demand will become decreasingly based on governmental regulations and more and more on cost competitiveness compared to fossil fuels. If biofuels can be produced cheaper than fossil fuels, demand will be high enough during the next years to absorb all the produced biofuel quantities. Therefore, biofuel production costs will be responsible for the market share of biofuels.

In this model it was assumed that biofuel demand in Europe will be met by biofuel production in Europe and the option of biofuel production at other locations and import of biofuels was neglected. European production sites may benefit from a more developed production infrastructure, economies of scope to other production activities and greater proximity to end users. The production cost input data are focused on the situation in Europe but the model could easily be applied to other regions if the input data are changed accordingly.

2. Related literature

2.1. Calculation models for energy production costs

Various calculation models have been developed to give a better insight into the complexities of energy production systems under a range of policy objectives. Many authors describe the entire energy system either through the use of a technical bottom–up approach or a macro-economic top–down approach (Junginger et al., 2006). There are also a number of studies evaluating whole supply chains for biobased products (Stephen et al., 2010; Kim et al., 2011), biorefinery concepts (Fernando et al., 2006; Clark, 2007; Francesco, 2010) or the potential of biofuels for individual countries (Martinsen et al., 2010). For example, Kim et al. (2011) use a mixed integer linear programming model that enables the selection of fuel conversion technologies, capacities, biomass locations, and the logistics of transportation from the raw material locations to the conversion sites and then to the final markets.

Furthermore, there are numerous specific evaluations of biofuels, like biodiesel (Zhang et al., 2003; van Kasteren and Nisworo, 2007; Araujo et al., 2010) and simulations of biofuel processes with specialised software, like Aspen HYSYS (West et al., 2008). Despite the fact that production costs of biofuels compared to fossil fuels are an important driver for biofuel demand, there are only a few approaches to compare different biofuel production processes with each other and with the established production of fossil fuels considering scale and learning curve effects in the production process. Whereas some studies focus on individual process steps, like production costs for enzymes (Tufvesson et al., 2011; Klein-Marcuschamer et al., 2012), other studies compare different biofuels based on a production cost analysis (Bridgewater and Double, 1994; Giampietro and Ulgiati, 2005; de Wit et al., 2010; NREL, 2011). The analysis by de Wit et al. (2010), for example, shows that biodiesel is the most cost competitive fuel, dominating the early market of 1st generation biofuels. The better cost performance of biodiesel compared to 1st generation bioethanol can be explained by lower feedstock costs for oil crops compared to sugar or starch crops together with lower capital and operational expenses for transesterification of oil to biodiesel compared to the hydrolysis and fermentation of sugar or starch crops to bioethanol (de Wit et al., 2010).

Feedstock production costs can decrease over time, mainly by scale economies and by gaining technological experience with its production. Analyses performed for sugarcane in Brazil (van den Wall Bake et al., 2009), for corn in the US (Hettinga et al., 2009) and for rapeseed in Germany (Berghout, 2008) demonstrated that indeed cost reductions of (food) crops do follow an experience (or learning) curve pattern. In addition, other research papers investigated the economic dependency of fossil fuels and the potential replacement of crude oil by biomass (Dixon et al., 2007). The expanded use of biofuels competes with the energetic use of biomass in residential applications and heat/power generation in the conversion sector as well as food production, animal feed and industrial production. So, due to the utilisation of certain feedstocks, there are also negative spill over effects from the production of biofuels on global food prices. Owing to arbitrage effects, the positive correlation between biofuel production scale and global food prices becomes particularly evident when crude oil prices rise (Chen et al., 2010). For example, the growth of corn-based ethanol production and soybean-based bio-diesel production, following the increase in the oil price, has significantly affected the world agricultural grain productions and its prices. As biomass can also be used as raw material for chemicals and numerous other applications, biomass prices are not only driven by the fuel industry (Swinnen and Tollens, 1991; Hermann and Patel, 2007).

2.2. Scale and learning effects on production costs

The combination of economies of scale and cost reductions through technological learning is an essential element for the analysis of production costs (de Wit et al., 2010). A concept to measure and quantify the aggregated effect of technological learning is the experience curve approach. This commonly used approach states that costs decline with a fixed percentage amount over each doubling in cumulative production (Hettinga et al., 2009). Although learning curve effects have increasingly been incorporated in many energy models, only a few authors, like de Wit et al. (2010), specified corresponding models with a particular focus on biofuels. In line with studies on biomass integrated gasification/combined cycle (BIG/CC) plants for electricity production (Faaij et al., 1998; Uyterlinde et al., 2007), learning curve effects can be considered by estimating progress ratios for distinct process steps of biofuel production processes.

For the investigation of production costs, a distinction between two effects on efficiency must be made, depending on whether their impact on cost projections is driven by the production scale size (scale effects) or by technological process improvements (learning effects). Whereas learning effects are dynamic in nature and will accumulate over time (typically with a decreasing pace), scale effects are static, though they may also have a dynamic component if production capacities expand over time. Over the past decades, various researchers have attempted to distinguish between static scale economies and dynamic learning effects (Stobaugh and Townsend, 1975; Sultan, 1975; Hollander, 1965; Preston and Keachie, 1964). In summary, these studies have discovered static scale effects to be statistically significant but small in magnitude relative to learning-based effects (Lieberman, 1984).

The scale effect is based on a scale law describing the inverse correlation between increases in plant scale and the associated decrease in production costs (Blok, 2006; Haldi and Whitcomb, 1967). On the one hand, up to a certain point, larger production scales are associated with marginal costs per output unit that are increasing but still below the average costs per unit, which leads to decreasing average costs per unit of biofuel outcome. On the other hand, overcapacities at any stage along the value chain are to be minimised and transport costs have to be considered, which leads to an optimal production scale for each production facility. Furthermore, for the determination of the optimum plant size the specific characteristics of each type of biofuel should be taken into account. Exemplary for bioethanol production, Nguyen and Prince (1996) showed that through other measures, such as the use of mixed crops to extend the processing season, the capital costs per unit of bioethanol outcome can be reduced. Thus, total production costs decrease which, in turn, results in a lower optimum plant size.

Beyond scale-dependant potentials to improve cost efficiency, there are scale-independent potentials for further cost reductions from technological advancements and other learning benefits related to the production process. As examples for these scale-independent cost effects, de Wit et al. (2010) mention more efficient organisation of production and transportation processes, the use of advanced materials and lifetime prolongation of catalysts. In total, the significance of the scale-independent learning component becomes evident in various studies. These demonstrate that the related cost reduction potentials for ethanol production from corn (Hettinga et al., 2009) and sugarcane (van den Wall Bake et al., 2009; Hamelinck et al., 2005) range from 25% to 50%.

These examples show that, given the complex interactions between fossil fuels and the various biofuels, top–down models to easily understand the production costs for fossil fuels and biofuels without too many technical details can be a useful tool for producers, investors and policy makers. This paper attempts to contribute to this discussion by developing a simple top–down calculation model for biofuel production in Europe based on different raw materials and conversion technologies compared to fossil fuels for the years 2015 and 2020.

3. Types of biofuels

This section describes the different types of biofuels examined in this study and explains the calculation model to determine production costs. The analysed biofuels were defined as a combination of raw materials and conversion technologies following Fig. 1: 1st generation and 2nd generation bioethanol as well as biodiesel, hydrated vegetable oil (HVO) and BTL fuel.

Bioethanol is produced by the fermentation of sugar and starch containing organic materials. Whereas sugar containing plants can be directly fermented, starch containing plants have to first be converted to sugars using enzymes. During the fermentation process microorganisms, such as yeast, convert sugars into ethanol. Bioethanol yields can be increased significantly should lignocellulose be processed to bioethanol. In comparison to using sugar and starch containing raw materials this process is more complex due to the conversion of lignocellulose to sugar. As yet, no large scale production of bioethanol from lignocellulose exists, although researchers (Kim and Dale, 2004) estimated that lignocellulosic biomass could produce up to 442 billion litres per year of bioethanol.

Biodiesel is won from plant oils (most commonly used is rapeseed oil with an oil content of 40–45%) or animal fats and transesterification with methanol. The largest disadvantage of biodiesel is that it acts aggressively against some rubbers and plastic, and rubber parts in the fuel system may corrode in time. It also could clog filters inside the tank or cause leaking seals. As outlined by Antoni et al. (2007), most diesel cars have been licensed to use a blend of diesel with biodiesel of up to 5%. In Germany, for example, the conversion of a conventional diesel engine for pure biodiesel use is offered by many companies for up to €1500 per car. At the same time, however, the modified engine requires more frequent engine oil changes.

Like biodiesel, HVO can be produced from oil-containing raw materials. Hydrotreating of vegetable oils or animal fats is an alternative process to esterification for producing bio-based diesel fuels (Mikkonen, 2008; Hodge, 2008). The first commercial scale HVO plant with a capacity of 170 000 tonnes per year was started up in 2007 in Finland. Several HVO units with a scale of up to 800 000 tonnes per year per unit are under consideration by many oil companies and process technology suppliers around the world.

The production of BTL fuel comprises of a number of different process steps. First, the biomass is broken down into coke and a gas

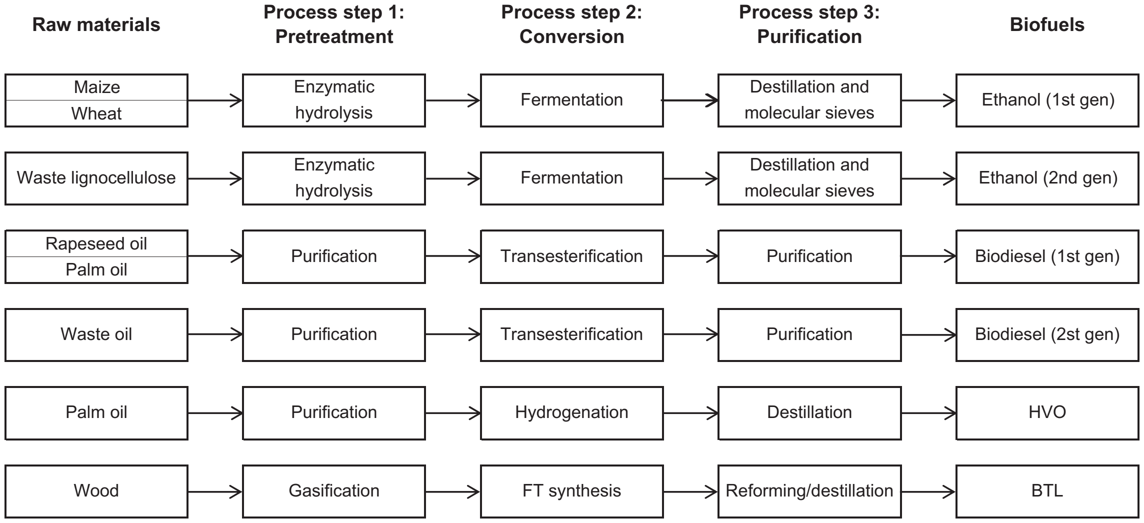


Fig. 1. Investigated biofuels with standardised production process steps.

containing tar by means of a low temperature gasifier. In a gasification reactor, a tar-free synthesis gas is produced which is then liquefied in a Fischer–Tropsch reaction to fuel. BTL fuels can be used, depending on the octane number, in conventional petrol or diesel powered cars without requiring any modification to the engine. Fischer–Tropsch plants for producing BTL fuels from biomass, like wood and residues, are estimated to be in commercial scale within the next decade.

As maturity of the technology has a decisive impact on production costs and some technologies are not expected to leave pilot or demonstration stage in the foreseeable future, the first step in the analysis is the projection of the production scale for each technology in the future. Thus, based on the maturity of each biofuel technology, a comparable reference scenarios related to biofuel production for the years 2015 (scenario 2015) and 2020 (scenario 2020) (Fig. 2) was defined. For each scenario the (projected) status (pilot scale, demonstration scale or production scale) of each technology for the corresponding year was compared. Through this procedure, the analysis takes into account that the more mature technologies have larger scales than technologies under development, thus more mature technologies offer a significant cost advantage.

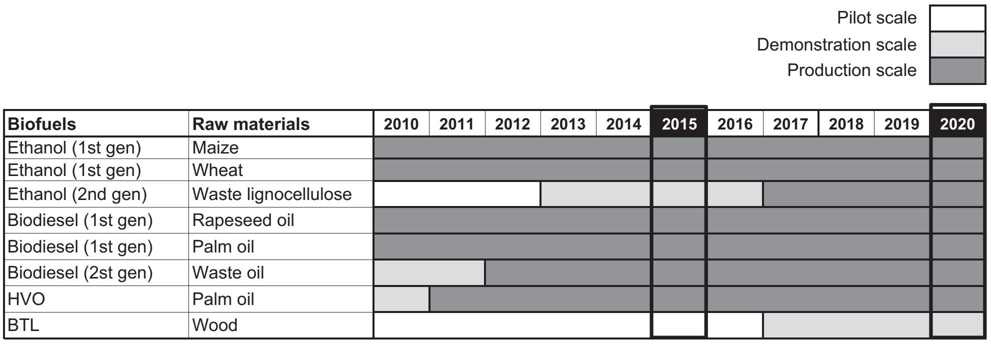
4. Scenarios for future raw material prices

Raw material prices are critical for the economic viability of biofuel production. Profitability of biofuels depends on prices for biofuel raw materials and the price for crude oil as key competitor product. This section presents the method used to derive scenarios for future development of raw material prices for each type of fuel.

A three step approach is used to project raw material prices for biofuels:

- First, the impact of main determinants of prices for biofuels for each type of fuel is identified, including the likely impact of the crude oil price. For this purpose, a multivariate auto-regression model is used based on data of biofuels prices for the period 1981–2011. The model is described in detail below.
- Secondly, scenarios are developed for future values of all model determinants for the years 2015 and 2020. Since the impact of different levels of crude oil prices is of interest, all other determinants are kept constant while considering three different oil price developments until 2020.
- Thirdly, the estimation results (i.e. the effects of the various determinants on the prices of different types of biofuels) are used and the estimated coefficients are multiplied with the values of the scenarios to obtain the projected biofuel prices for 2015 and 2020.

In the first step, the relation between the price of biofuel raw materials (pB) of type *k* (maize, wheat, rapes oil, palm oil, wood) and past crude oil prices (pO) are analysed while also considering a number of other major drivers of raw material prices, including a price index for agricultural products (pA), global population (POP) and growth in wealth (per capita income: GDP/POP) as proxies for global demand, energy consumption per capita (EN/POP) and



Pilot scale □
Demonstration scale ░
Production scale ▓

Biofuels	Raw materials	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ethanol (1st gen)	Maize	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
Ethanol (1st gen)	Wheat	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
Ethanol (2nd gen)	Waste lignocellulose	□	□	□	░	░	░	░	▓	▓	▓	▓
Biodiesel (1st gen)	Rapeseed oil	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
Biodiesel (1st gen)	Palm oil	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
Biodiesel (2st gen)	Waste oil	░	░	▓	▓	▓	▓	▓	▓	▓	▓	▓
HVO	Palm oil	░	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
BTL	Wood	□	□	□	□	□	□	□	░	░	░	░

Fig. 2. Biofuel production scenarios for 2010, 2015 and 2020.

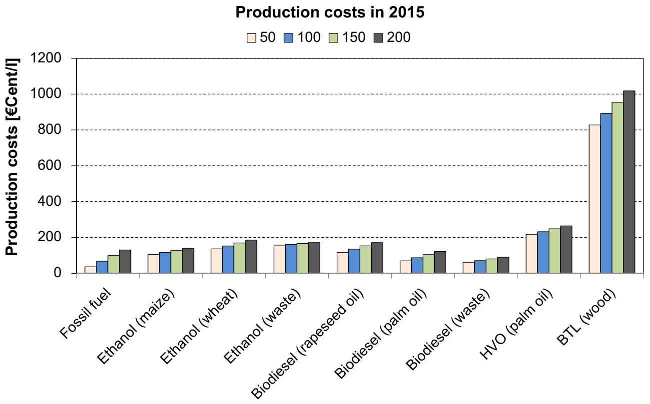


Fig. 3. Production costs in the year 2015 based on crude oil price scenarios of €50, €100, €150 and €200 per barrel.

global inflation (pGDP). The linear regression model to be estimated reads as follows:

$$\begin{aligned} \mathrm{pB}_{k,t} = {} & \alpha + \beta_{1,k}\mathrm{pO}_{t-1} + \beta_{2,k}\mathrm{pA}_{t-1} + \beta_{3,k}\mathrm{pGDP}_{t-1} + \chi_{1,k}\mathrm{POP}_{t-1} \\ & + \chi_{2,k}\mathrm{GDP/POP}_{t-1} + \chi_{3,k}\mathrm{EN/POP}_{t-1} + \varepsilon_{k,t}, \end{aligned} \tag{1}$$

with t being a time index for months, α being a constant, β and χ being parameters to be estimated and ε being a time and k-specific error term. The following monthly price data for five different biofuel raw materials k are taken.

Table 1
Raw material prices from 1982 to 2010 (annual averages).

Year	Crude oil		Maize	Wheat	Rapeseed oil	Palm oil	Wood	
	[€/barrel]	[€/t]	[€/t]	[€/t]	[€/t]	[€/t]	[€/m³]	[€/t]
1982	29	362	98	146	380	333	172	286
1983	31	217	141	163	525	435	179	298
1984	34	239	159	179	807	704	228	380
1985	34	243	141	170	683	524	198	331
1986	14	98	86	111	350	206	176	294
1987	15	107	62	93	286	233	219	364
1988	12	84	86	117	431	290	214	356
1989	15	109	95	144	406	247	278	464
1990	17	120	81	101	319	178	269	449
1991	15	106	83	99	320	215	285	474
1992	14	99	76	111	296	238	308	513
1993	14	99	85	117	385	260	433	722
1994	13	94	90	125	517	362	467	779
1995	13	93	94	135	482	410	396	661
1996	16	112	127	161	436	362	407	678
1997	17	120	103	140	495	431	419	699
1998	12	84	92	114	568	541	344	573
1999	17	121	84	105	399	350	422	703
2000	31	218	95	123	373	280	476	793
2001	27	193	100	141	437	266	430	717
2002	27	189	106	157	509	379	421	701
2003	26	183	94	130	537	365	372	619
2004	30	217	90	127	576	351	366	610
2005	43	306	79	122	578	295	392	654
2006	51	365	97	153	678	332	433	721
2007	52	369	120	186	737	524	412	686
2008	65	463	151	220	961	578	406	676
2009	44	314	119	161	614	462	394	657
2010	59	423	140	168	760	646	426	709

All prices are average prices per year.
1 barrel (used as an oil industry unit) = 159 litres (l).
The conversion from volume to mass unit is based on density factors of 0.883 l/kg for crude oil and 600 kg/m³ for wood.

- Maize: U.S. No.2 Yellow, FOB Gulf of Mexico ($/ton)
- Wheat: No.1 Hard Red Winter, ordinary protein, FOB Gulf of Mexico ($/ton)
- Rapes oil: Crude, FOB Rotterdam ($/ton)
- Palm oil: Malaysia Palm Oil Futures (first contract forward) 4–5 percent FFA ($/ton)
- Wood: average price ($/m^3) for softwood (average export price of Douglas Fir, U.S. Price) and hardwood (Dark Red Meranti, select and better quality, C&F U.K port)

For crude oil prices, the average of Dated Brent, West Texas Intermediate and Dubai Fateh (€/barrel) is used. Monthly raw material prices run from April 1981 to April 2011 and were taken from www.indexmundi.com. Table 1 shows the annual average prices for the five biofuel raw materials and for crude oil based on monthly data from April 1982 to April 2010. As this historical price overview reveals, there are significant differences in price developments of each type of raw material. For example, whereas the market prices for wood remained almost stable between 1993 and 2010, the price for palm oil was more than doubling during the same time period. In this 17 year period the price of crude oil rose from 14€ to 50€ per barrel.

Annual data on population, GDP, energy consumption, inflation and agricultural prices were taken from the World Development and transferred to monthly data using linear interpolation. All price data as well as GDP and energy consumption were measured in US$ and converted into € using average monthly exchange rates.

The model presented in Equation (1) is estimated using an ARMAX modelling approach (Harvey, 1993) with a one month autoregressive term of the structural model disturbance and additive annual effects. ARMAX models are a tool for analysing time series data when there is autoregression (i.e. the value in period t depends on the past values) and a longer term trend. ARMAX models consist of three elements, an autoregressive (AR) element, a moving average (MA) element and a vector of other exogenous variables (X). The AR element is modelled through the lagged dependent variable ($\mathrm{pB}_{k,t-1}$) and an error term ε, which is assumed to be independent, identically distributed random variables sampled from a normal distribution. The MA element is modelled through the lagged error term ($\varepsilon_{k,t-1}$) and also considers annual effects by including the error term lagged by 12 months ($\varepsilon_{k,t-12}$). The X element is presented in Equation (1). The ARMAX model is estimated employing a full maximum likelihood estimator which is implemented in the statistical software package STATA® 12.1.

Table 2 shows the estimation results. The price of crude oil has a statistically significant impact on the prices of biofuel raw materials. The strongest effects of crude oil prices are found for rape oil and palm oil, while wheat and maize are affected by oil price developments to a far lesser extent. Wood prices show an oil price impact between these two groups of raw materials. The results indicate that both rape and palm oil have been used as energy inputs to a significant degree in the past and are therefore more closely related to oil price changes than wheat and maize, which are still predominantly used as input for food production.

In a second step, projected values for all independent model variables (i.e. pO, pA, pGDP, gPOP, GDP/POP and EN/POP) for 2015 and 2020 are defined. For crude oil prices (pO), reference it made to oil price scenarios published by IEA (2007) and the International Energy Outlook and the effects of crude oil prices in 2020 of €50, €100, €150 and €200 per barrel investigated. Oil prices for 2015 are determined by linear interpolation of the 2011 prices and the scenario prices in 2020. For the other model variables, a 1% p.a. increase in world population (POP) is assumed, a 2.5% p.a. increase in GDP per capita (GDP/POP), a 1.25% p.a. increase in energy consumption per capita (EN/POP), a 5% p.a. increase in agricultural

Table 2
Results of ARMAX model estimations.

	Maize		Wheat		Rapes		Palm		Wood	
	Coeff.	Std.E.	Coeff.	Std.E.	Coeff.	Std.E.	Coeff.	Std.E.	Coeff.	Std.E.
pO	0.58	0.11***	0.78	0.17***	3.88	0.83***	3.65	0.66***	1.19	0.30***
pA	0.61	0.10***	0.56	0.15***	2.86	0.61***	1.79	0.45***		
pGDP	4.93	2.55*	9.51	2.52***	21.98	17.47	24.52	17.31	18.66	6.22***
POP	−0.02	0.06	−0.03	0.04	−0.10	0.33	0.21	0.31	0.42	0.12***
GDP/CAP	0.05	0.05	0.11	0.03***	0.40	0.29	−0.01	0.27	−0.21	0.11*
EN/CAP	−0.11	0.17	−0.29	0.11**	−0.89	1.10	−0.83	0.87	−0.48	0.36
Const	41	104	123	56**	78	503	192	419	−424	292
ar(L1)	0.01	171	0.02	38	0.01	110	0.02	37	1.00	0.00***
ma(L1)	0.31	0.16*	0.38	0.06**	−0.08	0.04**	0.52	0.04***	0.02	0.09
ma(L12)	−1.02	0.28***	−0.12	0.31	−0.67	0.17***	−0.03	0.46	−0.82	0.14***
Sigma	4.57	0.68***	8.86	0.46***	35.10	2.61***	30.27	0.90***	12.45	0.92***
LogLikelihood		−1225		−1333		−1890		−1791		−1545
No. observ.		361		361		361		361		361

Note: ***, **, * indicate that estimated coefficients are significant at the 1%-, 5%-, 10%-level, respectively.
Agricultural prices (pA) had to be omitted in the regression on wood prices due to multicollinearity issues.
Coeff.: estimated coefficient; Std.E.: standard error.

prices (pA) and a global inflation of 6% p.a. (pGDP). All these assumed values are close to the average rate of change for these variables over the period 1982 to 2010. For simplicity, no business cycle effects during the scenario period are considered.

Based on these assumptions, biofuel raw material prices for 2015 and 2020 for different crude oil price developments are calculated. The calculation uses the estimated coefficients for each determinant as shown in Table 2. For 2020 and the €50 crude oil price scenario, the calculation for the price for maize is as follows:

$$\begin{aligned} pB_{\text{maize},2020} &= 40.847 + 0.58054 \cdot 50 + 0.60792 \cdot 184.68 \\ &\quad + 0.04907 \cdot 7809 + -0.01642 \cdot 7582 \\ &\quad + 4.9345 \cdot 6.0 + -0.11149 \cdot 2136 \end{aligned} \tag{2}$$

For the other five types of biofuels, calculations are made according to Equation (2), but using the respective estimated coefficients. For alternative crude oil price scenarios, the value for crude oil price is altered.

Table 3 shows projected prices for 2015 and 2020 as well as actual and predicted prices in 2010. As production cost scenarios use tonne units for all material inputs, prices need to be expressed in € per tonne. For crude oil a mass density factor of 0.883 kg/l is assumed. For wood a mass density factor of 0.6 kg/dm^3 is applied. Predicted prices for 2010 are higher for most raw materials than the actual ones (except for palm oil). This result indicates that the price level in 2010 was lower than would be expected if prices had followed the typical development of the past three decades. A main reason for this deviation may be a calming effect of the economic crisis on commodity prices or unstable prices caused by financial speculation in commodities. The 2010 price level for all raw materials, except palm oil, was below the peak of the pre-crisis level in 2006 and 2008, while crude oil prices in 2010 were close to the pre-crisis peak. For the projections, focus was on longer term trends in raw material prices whereby any type of business cycle effects on prices is not considered. For this reason, projected prices for 2015 and 2020 are not adjusted to the 'prediction error' in 2010 but do take into account the higher predicted prices for 2010 (and consequently for 2015 and 2020) as reflecting an upcoming upwards trends of commodity prices in case the world economy recovers.

Under this assumption, prices for rapes oil, wheat and maize are expected to increase strongest until 2020. Based on the €50 scenario for crude oil price per barrel, prices for wheat, rapes oil and maize will increase by 89%, 85% and 66%, respectively, as compared with the actual (rather low) prices in 2010. For the €200 scenario, price advances will be significantly higher, at rates of 106%, 118% and 101%, respectively. For palm oil, prices will remain stable in the €50 scenario but will increase substantially in the €200 scenario, reflecting the stronger link between crude oil prices and palm oil prices. For wood, falling prices are expected for all scenarios except the €200. Wood prices are likely to remain constant between 2010 and 2020.

For one relevant group of raw materials for biofuels, waste material, no world market prices are available since waste is rarely traded internationally due to high transport costs per unit and small unit values. For the scenario analysis, it was assumed that the price for waste lignocellulosic material is constantly 1/4 of the price of maize, and the price for waste oil is 1/2 of the price of palm oil. Here, like for all other types of raw materials examined in this analysis, it was assumed that each producer is a price taker without any influence on the market price and that production functions are linear homogeneous.

5. Production cost modelling and results

The total production costs for each type of fuel are given by the sum of its raw material price and its conversion costs. Whereas the former summand has already been projected in Table 3, the conversion costs have to be projected under consideration of the expected technical status for the years 2015 and 2020. Production cost analyses for fuels are based on reference scenarios of crude oil prices of €50, €100, €150 and €200 per barrel.

Whereas Table 5 represents the core element of the scenario analysis, the next section describes how this table is derived and its relationship to the input parameters contained in other tables and figures. In the subsequent Sections 6.2 and 6.3 the results of Table 5 are discussed and supported by illustrating figures. In the analysis, all monetary amounts are related to the Euro (€) as the basic currency unless specified differently. In the cases where monetary amounts are related to a literature reference and is available in US$ only, the corresponding Euro amount is added in brackets using a foreign exchange rate for € per US$ of 0.69768 per 31 December 2009 for the conversion.

5.1. Production costs model

Given the specific conversion technology, the raw material prices are exogenous variables in the here presented model and independent from the production scale. This is a rough assumption as transport costs are a main driver for biomass prices and the

Table 3
Actual raw material prices for 2010 and estimated raw material prices for 2015 and 2020 (annual averages).

Year		Crude oil		Maize	Wheat	Rapeseed oil	Palm oil	Wood	
		€/barrel	€/t	€/t	€/t	€/t	€/t	€/m^3	€/t
2010	Actual	59	423	140	168	760	646	426	709
	Predicted	59	423	159	211	910	591	468	780
2015		50	356	184	245	1079	548	381	635
		100	712	213	284	1273	731	441	734
		150	1068	242	323	1467	913	500	834
		200	1425	271	362	1661	1095	560	933
2020		50	356	232	317	1405	582	286	476
		100	712	261	356	1599	764	345	576
		150	1068	290	395	1793	947	405	675
		200	1425	319	434	1987	1129	465	775
2020		Rate of change (%) over actual level in 2010							
		50	−16	66	89	85	−10	−33	−33
		100	68	87	112	110	18	−19	−19
		150	153	108	135	136	46	−5	−5
		200	237	129	159	161	75	9	9

All prices are average prices per year.

transport costs per unit increase with scale as transport routes are becoming longer. The rationale behind this assumption is that each company aims to operate at the optimal production scale in light of the tension between scale benefits on the one hand and increasing cost of capital associated with transportation costs on the other, which is in line with the results of Nguyen and Prince (1996). Unlike for raw material costs, cost advantages driven by scale size and learning effects related to experience are significant endogenous parameters and therefore main determinants in this calculation model.

Exemplary for 2nd generation ethanol, Table 4 shows the determination of the conversion costs. For each specific scale size, the required investment volume as well as the operational costs in million Euros (m €) are estimated based on industrial experience by the authors and supported by interviews with practical experts. With regard to the initial investment volume, the average depreciation period is assumed to be 20 years. To account for technical learning potential on production costs until 2020, learning curve coefficients are estimated and applied to all process steps as defined in Fig. 1. Depending on the type of fuel, these learning curve coefficients are specifically estimated and are assumed to show diminishing effects over time. As exemplary demonstrated in Table 4 for 2nd generation bioethanol, the estimated cost reduction potential from learning curve effects are: 40% for the time period 2005–2010, 30% for time period 2010–2015 and 20% for the time period 2015–2020, which in turn leads to corresponding learning curve factors for the specific time periods of 60%, 70% and 80%, respectively. In an autoregressive time series model, these learning curve factors are sequentially multiplied with the previous values to derive the operational and total production costs for the specified points in time. The effect of economies of scale from the size of the production facility is also reflected in Table 4 and specified for biofuel output scales of 10, 50, 100, 250 and 500 kilo tonnes (kt). Based on the accumulated costs over each step in the production process, the total conversion costs for each type of biofuel were derived for 2015 and 2020. The relevant amounts representing the production costs for each type of biofuel are determined under consideration of the estimated scale size as illustrated in Fig. 2. So for 2nd generation bioethanol, the relevant total conversion costs are derived by considering the expected scale sizes of 50 kt for 2015 and 250 kt for 2020. This results in conversion costs of €Cent 80/l and €Cent 28/l for the respective reference years.

These amounts are then used for all further calculations and Table 5 also shows these assumed conversion costs in Euro cent per litre (€Cent/l) of fuel output for the forecasted years 2015 and 2020. These amounts are added to the corresponding raw material costs to determine the total production costs. Furthermore, to ensure the comparability of the total costs for each type of biofuel, the energy density factor in Millijoule per litre (MJ/l) has to be taken into consideration. By this measure, the total production costs for each type of biofuel are normalised on the average energy density of fossil fuel, to account for variations in the energy density of the biofuels. Particularly the total costs for ethanol fuels have to be revised upwards, due to the low energy density factor of 21.14 MJ/l, which is about 37% lower than the energy density factor of 33.65 MJ/l for fossil fuel.

In consequence, this led to some significant adjustments in the production costs based on the specific energy density of biofuels. With these data, the production costs for the reference scenarios of all relevant biofuels in 2010, 2015 and 2020 are calculated. This model enables the calculation for different production scales in place and planned or hypothetical scales (e.g. simulation of not yet realised production scales).

5.2. Estimations of biofuel production costs in 2015

As presented in Table 5 and illustrated in Fig. 4, for 2015 the results obtained from modelling the production costs for various biofuels indicate that there is no biofuel that can be produced at competitive costs compared to fossil fuel (€Cent 68/l) under the assumption of a crude oil price of €100/barrel. However, with total production costs of €Cent 71/l and €Cent 87/l for biodiesel from waste oil and from palm oil, the gap towards fossil fuel is relatively small for these two types of biofuel.

Similarly, in the case of a crude oil price of €200/barrel, the production costs for most types of biofuels exceed those for fossil fuel (€Cent 131/l). Even under this extremely negative crude oil price scenario, the only biofuels that are most likely to be competitive are biodiesel from waste oil (€Cent 90/l) and biodiesel from palm oil (€Cent 122/l). Compared to these types of biodiesels, the production costs for bioethanol from lignocellulosic waste material are higher in all crude oil price scenarios, e.g. €Cent 171/l given a crude oil price of €200/barrel. Furthermore, unlike for other biofuels, the simulation of different crude oil price scenarios in Fig. 3 indicates that production costs for bioethanol from lignocellulosic waste is largely independent of the crude oil price levels. Besides this, the simulation in Fig. 3 reveals that production costs of HVO and BTL are significantly above all fuels and for

Table 4
Modelling of conversion costs for ethanol 2nd generation.

Conversion costs – Ethanol 2nd gen																				
Learning curve effect 2005–2010					0.60															
Learning curve effect 2010–2015					0.70															
Learning curve effect 2015–2020					0.80															
Scale		Investment	Depreciation		Operational costs								Total costs = operational expenses plus depreciation							
					2005		2010		2015		2020		2005		2010		2015		2020	
[kt]	[m l]	[m €]	[m €/year]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]	[m €]	[€Cent/l]
Process step 1																				
10	13	20	1.00	7.90	12.00	94.80	7.20	56.88	5.04	39.82	4.03	31.85	13.00	102.70	8.20	64.78	6.04	47.72	5.03	39.75
50	63	70	3.50	5.53	24.00	37.92	14.40	22.75	10.08	15.93	8.06	12.74	27.50	43.45	17.90	28.28	13.58	21.46	11.56	18.27
100	127	100	5.00	3.95	36.00	28.44	21.60	17.06	15.12	11.94	12.10	9.56	41.00	32.39	26.60	21.01	20.12	15.89	17.10	13.51
250	316	150	7.50	2.37	48.00	15.17	28.80	9.10	20.16	6.37	16.13	5.10	55.50	17.54	36.30	11.47	27.66	8.74	23.63	7.47
500	633	200	10.00	1.58	60.00	9.48	36.00	5.69	25.20	3.98	20.16	3.19	70.00	11.06	46.00	7.27	35.20	5.56	30.16	4.77
Process step 2																				
10	13	30	1.50	11.85	18.00	142.20	10.80	85.32	7.56	59.72	6.05	47.78	19.50	154.05	12.30	97.17	9.06	71.57	7.55	59.63
50	63	105	5.25	8.30	36.00	56.88	21.60	34.13	15.12	23.89	12.10	19.11	41.25	65.18	26.85	42.42	20.37	32.18	17.35	27.41
100	127	150	7.50	5.93	54.00	42.66	32.40	25.60	22.68	17.92	18.14	14.33	61.50	48.59	39.90	31.52	30.18	23.84	25.64	20.26
250	316	225	11.25	3.56	72.00	22.75	43.20	13.65	30.24	9.56	24.19	7.64	83.25	26.31	54.45	17.21	41.49	13.11	35.44	11.20
500	633	300	15.00	2.37	90.00	14.22	54.00	8.53	37.80	5.97	30.24	4.78	105.00	16.59	69.00	10.90	52.80	8.34	45.24	7.15
Process step 3																				
10	13	25	1.25	9.88	15.00	118.50	9.00	71.10	6.30	49.77	5.04	39.82	16.25	128.38	10.25	80.98	7.55	59.65	6.29	49.69
50	63	88	4.38	6.91	30.00	47.40	18.00	28.44	12.60	19.91	10.08	15.93	34.38	54.31	22.38	35.35	16.98	26.82	14.46	22.84
100	127	125	6.25	4.94	45.00	35.55	27.00	21.33	18.90	14.93	15.12	11.94	51.25	40.49	33.25	26.27	25.15	19.87	21.37	16.88
250	316	188	9.38	2.96	60.00	18.96	36.00	11.38	25.20	7.96	20.16	6.37	69.38	21.92	45.38	14.34	34.58	10.93	29.54	9.33
500	633	250	12.50	1.98	75.00	11.85	45.00	7.11	31.50	4.98	25.20	3.98	87.50	13.83	57.50	9.09	44.00	6.95	37.70	5.96
Total process																				
10	13	75	3.75	29.63	45.00	355.50	27.00	213.30	18.90	149.31	15.12	119.45	48.75	385.13	30.75	242.93	22.65	178.94	18.87	149.07
50	63	263	13.13	20.74	90.00	142.20	54.00	85.32	37.80	59.72	30.24	47.78	103.13	162.94	67.13	106.06	50.93	80.46	43.37	68.52
100	127	375	18.75	14.81	135.00	106.65	81.00	63.99	56.70	44.79	45.36	35.83	153.75	121.46	99.75	78.80	75.45	59.61	64.11	50.65
250	316	563	28.13	8.89	180.00	56.88	108.00	34.13	75.60	23.89	60.48	19.11	208.13	65.77	136.13	43.02	103.73	32.78	88.61	28.00
500	633	750	37.50	5.93	225.00	35.55	135.00	21.33	94.50	14.93	75.60	11.94	262.50	41.48	172.50	27.26	132.00	20.86	113.10	17.87

Table 5
Production costs for all scenarios. Interpretation example: Based on the expected production scale for Ethanol from lignocellulosic wast of 50 kt in 2015 and 250 kt in 2020, the relevant conversion costs are €Cent 80,46/l and €Cent 28,00/l, respectively (see Tables 4 and 5).

(Bio-) fuel	Raw material	Conversion factor [l/t]	Crude oil price [€/barrel]	Raw material costs [€Cent/l]		Conversion costs [€Cent/l]		Total costs [€Cent/l]		Energy density [MJ/l]	Total costs [€Cent/l]	
				2015	2020	2015	2020	2015	2020		2015	2020
Fossil fuel	Crude oil	–	50	31.45	31.45	5.00	5.00	36.45	36.45	33.65	36.45	36.45
			100	62.89	62.89	5.00	5.00	67.89	67.89		67.89	67.89
			150	94.34	94.34	5.00	5.00	99.34	99.34		99.34	99.34
			200	125.79	125.79	5.00	5.00	130.79	130.79		130.79	130.79
Ethanol (maize)	Maize	400	50	45.96	58.06	20.37	11.42	66.33	69.49	21.14	105.58	110.61
			100	53.21	65.32	20.37	11.42	73.58	76.74		117.13	122.16
			150	60.47	72.58	20.37	11.42	80.84	84.00		128.68	133.71
			200	67.73	79.83	20.37	11.42	88.10	91.26		140.23	145.26
Ethanol (wheat)	Wheat	375	50	65.32	84.63	20.37	11.42	85.69	96.06	21.14	136.40	152.90
			100	75.73	95.04	20.37	11.42	96.10	106.46		152.96	169.46
			150	86.13	105.44	20.37	11.42	106.50	116.87		169.53	186.02
			200	96.54	115.85	20.37	11.42	116.91	127.27		186.09	202.59
Ethanol (waste)	Ligno-cellulosic waste material	250	50	18.38	23.22	80.46	28.00	98.84	51.22	21.14	157.34	81.54
			100	21.29	26.13	80.46	28.00	101.75	54.13		161.96	86.16
			150	24.19	29.03	80.46	28.00	104.65	57.03		166.58	90.78
			200	27.09	31.93	80.46	28.00	107.55	59.93		171.20	95.40
Biodiesel (rapeseed oil)	Rape seed oil	1100	50	98.07	127.77	17.26	8.10	115.33	135.86	33.03	117.49	138.41
			100	115.70	145.40	17.26	8.10	132.96	153.50		135.46	156.38
			150	133.34	163.04	17.26	8.10	150.60	171.14		153.43	174.35
			200	150.97	180.68	17.26	8.10	168.24	188.77		171.39	192.32
Biodiesel (palm oil)	Palm oil	1100	50	49.84	52.93	17.26	8.10	67.11	61.03	32.26	70.00	63.66
			100	66.41	69.50	17.26	8.10	83.68	77.60		87.28	80.94
			150	82.98	86.07	17.26	8.10	100.24	94.16		104.56	98.22
			200	99.55	102.64	17.26	8.10	116.81	110.73		121.85	115.50
Biodiesel (waste)	Waste oil	1000	50	27.41	29.11	32.59	15.02	60.00	44.13	32.68	61.78	45.44
			100	36.53	38.22	32.59	15.02	69.12	53.25		71.17	54.83
			150	45.64	47.34	32.59	15.02	78.23	62.36		80.55	64.21
			200	54.75	56.45	32.59	15.02	87.34	71.47		89.93	73.59
HVO (palm oil)	Palm oil	1100	50	49.84	52.93	170.51	77.32	220.36	130.25	34.3	216.18	127.78
			100	66.41	69.50	170.51	77.32	236.93	146.82		232.44	144.04
			150	82.98	86.07	170.51	77.32	253.50	163.39		248.69	160.29
			200	99.55	102.64	170.51	77.32	270.07	179.96		264.95	176.55
BTL (wood)	Wood	158	50	401.72	301.46	421.31	114.74	823.03	416.21	33.45	827.95	418.69
			100	464.69	364.43	421.31	114.74	885.99	479.17		891.29	482.03
			150	527.65	427.39	421.31	114.74	948.96	542.13		954.63	545.37
			200	590.61	490.35	421.31	114.74	1011.92	605.10		1017.97	608.72

economic reasons they do not appear as a reasonable alternative. As it becomes obvious by the comparison in Table 5, the uncompetitive total costs for HVO and BTL are mainly due to the excessive conversion costs in 2015 of €Cent 421/l and €Cent 171/l, respectively. This reflects that the scale and learning effects have not yet generated their full impact on the conversion costs by 2015.

5.3. Estimations of biofuel production costs in 2020

Even when taking into account the scale and learning effects on the conversion costs for the time period until 2020, no biofuel can be produced competitively to fossil fuel at crude oil prices €50 per barrel (Table 5 and Fig. 4). Given a crude oil price of €100 per barrel, according the here presented model, the most promising biofuel is biodiesel from waste oil (€Cent 55/l) with even lower costs than fossil fuel (€Cent 68/l), followed by biodiesel from palm oil (€Cent 81/l) and bioethanol from lignocellulosic waste (€Cent 86/l). Assuming a market price for crude oil of €150/barrel in 2020 (Fig. 5), ethanol from lignocellulosic waste (€Cent 91/l) and biodiesel from both, waste oil (€Cent 64/l) and palm oil (€Cent 98/l) can be produced at competitive costs, below those for fossil fuel (€Cent 99/l). Whereas the first two types of biofuels can be produced even cheaper than fossil fuel, the production costs for the latter are almost the same as those for fossil fuel from crude oil. Similarly, in the scenario of a market price for crude oil of €200/barrel there are three types of biofuels that can be produced at lower costs compared to fossil fuel (€Cent 131/l): biodiesel from waste oil (€Cent 74/l), ethanol from lignocellulosic waste (€Cent 95/l) as well as biodiesel from palm oil (€Cent 116/l).

6. Discussion

6.1. Implications from the 2015 and 2020 scenarios

As the results in Table 5 demonstrate, the total production costs for each type of fuel are primarily driven by the market price of the underlying raw materials. In contrast, the conversion costs only play a subordinate role, particularly the more the projection goes further into the future and towards larger production scales. With regard to the drivers of the conversion costs, the results indicate that the total conversion costs can be primarily reduced by scale effects, given the assumptions specified for the learning curve coefficients and production scale size level (the initial investment as well as operational costs). Exemplary for all types of biofuels covered in this study, Table 4 shows that the total conversion costs can be reduced to roughly one tenth solely through scale economies associated with an upscaling of the production plant size from 10 kt to 500 kt, e.g. from €Cent 149/l to €Cent 18/l in the 2020 scenario. In contrast, between 2005 and 2020 the expected reduction of the conversion costs attributable to learning effects is approximately half, resulting from the combination of the learning curve coefficients during this time period.

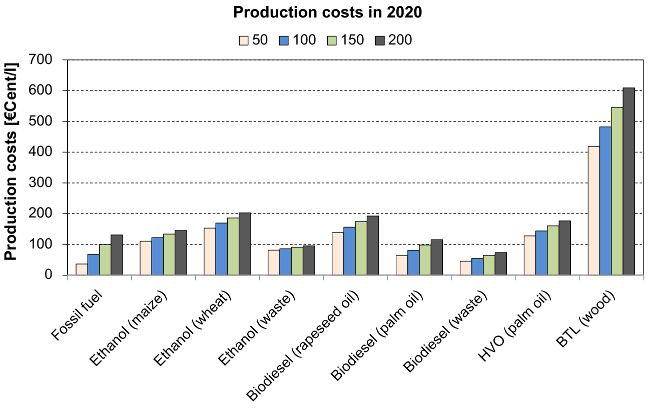


Fig. 4. Production costs in the year 2020 based on crude oil price scenarios of €50, €100, €150 and €200 per barrel.

In total, despite positive learning and scale effects, 1st generation bioethanol as well as 1st generation biodiesel show increasing total production costs between 2015 and 2020, which is due to the high level of raw material prices. This increase in total production costs pertains to all 1st generation biofuels except biodiesel from palm oil, where the advancements in production processes overcompensate rising feedstock prices.

Similarly, HVO, and particularly BTL, are uncompetitive because of relatively high raw material costs combined with high conversion costs. Although HVO, and especially BTL, are associated with considerable lower conversion costs due to learning effects in 2020 compared to 2015, the related cost saving potentials are not sufficient to compensate the high raw material costs. Consequently, HVO and BTL are not expected to be produced at competitive costs even though both have a higher energy density compared to other biofuels, in particular to bioethanol.

Taking into account positive effects from learning and scale size in all crude oil price scenarios, 2nd generation biofuels show the highest cost saving potentials until 2020. Biodiesel from waste oil and bioethanol produced on a large scale from lignocellulose containing raw materials are the most promising with regard to total production costs.

The results obtained from modelling the total production costs of (bio-) fuels demonstrate that 2nd generation biodiesel from waste oil is the most cost competitive fuel followed by bioethanol from lignocellulosic waste material. This is in line with the research results from de Wit et al. (2010), who explain this order between those two types of biofuels by lower feedstock, capital and operational costs. Unlike bioethanol, the production of biodiesel is associated with lower feedstock costs for oil crops compared to sugar and starch crops. Furthermore, biodiesel requires relatively lower capital and operational expenses for transesterification of oil to biodiesel compared to hydrolysis and fermentation of sugar and starch crops to bioethanol. This initial advantage of biodiesel over bioethanol, however, may impede the exploitation of positive effects associated with learning and a larger scope and, in consequence, may prevent the use of related cost saving potentials for bioethanol.

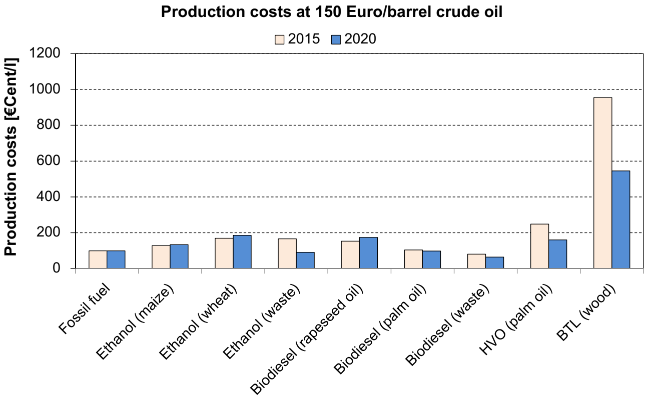


Fig. 5. Production costs at 150 Euro/barrel crude oil.

6.2. *Influence of economic policies on biofuels*

Owing to the continuously increasing demand in crude oil aligned with lagged increase in supply and thus rising crude oil prices, the attractiveness of alternative fuels is growing. Compared to conventional fuels, competitive production costs are essential to gain market share as the current tax advantages are only temporary.

Since 2002, the Brazilian government has launched several national programmes to enhance its technical, economic, and environmental competitiveness of biodiesel production in relation to fossil fuel and has achieved considerable progress, especially due to its richness in required raw materials (Ramos and Wilhelm, 2005; Nass et al., 2007). For bioethanol from Brazil, however, an import tariff of US$Cent 54 (€Cent 0.38) per gallon (de Gorter and Just, 2009; Lamers et al., 2011) that had been established due to economic and environmental reasons, impeded market access in the United States until 2012. With very competitive production costs in the range of approximately US$Cent 34/l (€Cent 0.24/l) in 2009 and an estimated range between US$Cent 20/l (€Cent 14/l) and US$Cent 26/l (€Cent 18/l) (van den Wall Bake et al., 2009), import tariffs are a decisive factor for the market acceptance of Brazilian biodiesel.

In the European Union, biofuel policies on national and international level enhanced the general demand for biofuels and simultaneously stimulated the production (Lamers et al., 2011). Primarily for 1st generation biofuels, the European Union itself is not able to domestically produce sufficient biofuel feedstock to fulfil these policies, so it is forced to import biofuel crops and run a higher agricultural trade deficit. Simultaneously, this leads to additionally increasing biofuel crop production in other countries with a comparative advantage, especially in South and Central American countries like Brazil (Banse et al., 2011).

The results of this study indicate that the total production costs for all types of fuels are mainly driven by the market price of the underlying raw materials and that a considerable reduction of the conversion costs can only be achieved by an extensive increase in the production scale. However, ignoring the market price for raw materials, the realisation of a corresponding increase in the production scale requires a volume of biomass feedstock that can hardly be generated, particularly when taking into account the demanded quantity and the European land size.

6.3. *Methodological limitations and recommendations for further research*

The most important limitation of this analysis is associated with the future development of the raw material prices. The study is based on the assumption that 1) the development of biofuel feedstock prices and market prices for crude oil can be extrapolated to future periods and that 2) the raw material prices are exogenous variables and not endogenously affected by the production of biofuels. As such, the study takes the perspective of a biofuel producer acting as a price taker, without influence on the market price of the raw materials. However, the market prices of related feedstock depend on numerous factors, some of which are interdependent, and therefore hard to anticipate. For 1st generation biofuels, various studies (Mitchell, 2008; Lipsky, 2008; Headey and Fan, 2008) investigating the future development and relevant impact factors have shown that biofuels are a main driver of increasing feedstock prices. The prices for lignocellulose biomass underlying 2nd generation biofuels have not been as thoroughly investigated as those for 1st generation biofuels, even though raw material costs are certainly the main driver for total production costs. In this regard, Gnansounou and Dauriat (2010) conclude that in the medium to long term, besides biofuels, lignocellulosic raw materials are increasingly being used also for chemicals and materials. As a result, there is rising demand and competition for these resources pertaining various technical applications including both energy and non-energy uses.

Another limitation in this analysis is that it does not distinguish between diesel and petrol substitute markets. This approach is in line with de Wit et al. (2010), who reference to the current European policy, which does not differentiate the biofuel targets, and note that a separation may lead to a suboptimal allocation of technological efforts and feedstock between the two fuel types.

7. Conclusions

As the price is the decisive factor for a fuel's market acceptance, competitive production costs are essential in order to establish biofuels as an alternative source to fossil sources. This research paper focuses on future production cost developments and follows three objectives: 1) projection of future biomass prices partly based on the change of crude oil prices, 2) simulation of not yet realised scale and learning effects in the production of biofuels; and 3) comparison of the competitiveness of different biofuels and fossil fuels. This study demonstrated that modelling biofuel production costs based on three standardised production process steps enables a better understanding of cost competitiveness. Furthermore, unlike many other studies in the field of biofuels, this paper provides a macro-economic driven bottom—up approach in order to compare different types of fuels and gives insights to future price developments that are useful for producers as well as consumers. In this context, as one of very few studies, the calculation model presented takes into account the effects from technological learning and production scale and enables a justified discussion about the future potential of certain types of fuels among academics as well as practitioners. As the most important model parameter, besides the crude oil price, the price development of the underlying biomass raw materials is endogenously projected by the price index for agricultural products, growth in world population, growth in wealth per capita income, and change in energy consumption per capita. The results show that the total production costs for each type of fuel is primarily driven by the market price of the underlying raw materials. In contrast, the conversion costs are only of minor importance, particularly the more the projection goes further into the future and towards larger production scales. With regard to the drivers of the conversion costs, the results indicate that the total conversion costs can be primarily reduced by scale effects and that the effect from technological learning has only a limited impact on the conversion costs and thus on the total production costs.

In general, 1st generation biofuels are produced from expensive feedstock with established and optimised technologies, while the 2nd generation are associated with relatively lower raw material costs and increasing efficiencies due to advanced conversion processes. Over the short and medium term, 2nd generation biodiesel from waste oil and from palm oil are the most promising with regard to production costs. Even given a crude oil price of €200/barrel in 2015, the only biofuels that are most likely to be competitive are biodiesel from waste oil and biodiesel from palm oil.

Particularly for 2nd generation biofuels, the competitiveness will additionally increase mid- to long-term due to economies of scale and learning curve effects. In this time horizon, bioethanol from lignocellulose biomass as well as biodiesel from waste oil and palm oil show high cost saving potentials which enable highest yields. So mid- to long-term, at all oil price scenarios, 2nd generation biofuels are most likely to be produced competitively. Except for biodiesel from palm oil, the production costs of 1st generation biofuels exceed those for fossil fuel and they are thus associated with a poor financial performance. In particular, this applies when additionally taking into account even increasing feedstock costs. As cost saving potentials from production scale have already been exploited to a large extend, any further competitive improvements of 1st generation biofuels can only be realised by experience-driven learning effects.

However, for all types of biofuels remains a serious doubt whether a sufficient amount of feedstock can be generated to satisfy the growing demand and to achieve the shift from fossil fuel to biofuels.

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