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Potentials, Subsidies and Tradeoffs of Cellulosic Ethanol in the European Union

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Abstract

The EU's revised Renewable Energy Directive (RED2) sets high mandates for advanced biofuels like cellulosic bioethanol from agricultural residues. However, many residues are used for ecological and economic purposes such as soil organic carbon regulation and livestock bedding and fodder. We use the global CGE model DART-BIO with a detailed representation of the bioeconomy to simulate the RED2 cellulosic bioethanol mandates and run sensitivity analyses regarding processing technology, straw and oil prices. We implement a latent cellulosic ethanol technology and develop new sectors for agricultural residues. We find that the RED2 cellulosic ethanol mandates will require enormous amounts of residues that could exceed the sustainable available potential in the EU. Agricultural residue utilization changes substantially and the cellulosic ethanol industry becomes the main residue consumer. Results show that output and price impacts of advanced biofuel targets are small, but there is reallocation of land towards cereals that enter the agricultural residue sector away from other crops in the EU. Moreover, the size of necessary cellulosic ethanol subsidies and the abatement costs per tonCO₂eq are very sensitive to actual straw and oil prices.

Keywords: Agricultural residues; Advanced biofuels; Cellulosic ethanol; Bioeconomy; CGE model

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The EU's revised Renewable Energy Directive (RED2) sets high mandates for advanced biofuels like cellulosic bioethanol from agricultural residues. However, many residues are used for ecological and economic purposes such as soil organic carbon regulation and livestock bedding and fodder. We use the global CGE model DART-BIO with a detailed representation of the bioeconomy to simulate the RED2 cellulosic bioethanol mandates and run sensitivity analyses regarding processing technology, straw and oil prices. We implement a latent cellulosic ethanol technology and develop new sectors for agricultural residues. We find that the RED2 cellulosic ethanol mandates will require enormous amounts of residues that could exceed the sustainable available potential in the EU. Agricultural residue utilization changes substantially and the cellulosic ethanol industry becomes the main residue consumer. Results show that output and price impacts of advanced biofuel targets are small, but there is reallocation of land towards cereals that enter the agricultural residue sector away from other crops in the EU. Moreover, the size of necessary cellulosic ethanol subsidies and the abatement costs per tonCO₂eq are very sensitive to actual straw and oil prices.

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1. Introduction

Biofuels are a key industry of the bioeconomy to ease the transition towards a post-fossil and bio-based economy (Scarlat et al., 2015). The recently revised Renewable Energy Directive (RED2) of the European Union (EU) once again assigns biofuels an instrumental role to reach the target of 14% renewable energy use in the transport sector until 2030 (Directive (EU) 2018/2001). As biofuels are assumed to yield lower greenhouse gas (GHG) emissions than their fossil counterparts, they play a vital role for climate change mitigation, although detailed life cycle assessments are necessary to ensure actual emission savings (Hanaki and Portugal-Pereira, 2018). Due to the competition over limited land however tradeoffs with respect to food security and biodiversity have become apparent. The first generation biofuels produced from sugar, starch and oil crops were partly blamed for the 2007 food price crisis, and there is a continuing debate on how increased biofuel production contributes to indirect land use change and deforestation (Arima et al., 2011; Broch et al., 2013; Klein et al., 2017; Zilberman 2016).

To avoid these tradeoffs, advanced biofuels, especially those produced from lignocellulosic¹, biomass have become the hope of future growth in sustainable biofuels. If cellulosic biomass is derived from either agricultural or forestry residues, competition with food production for arable land will be minimized and land expansion unnecessary. While the conversion of cellulosic biomass into ethanol is straightforward in theory, it has been difficult to develop cost efficient technologies that can be profitably applied outside of pilot plants (Slupska and Bushong, 2019). Urgency to produce cellulosic ethanol commercially is high, because the

¹ Hereafter cellulosic biomass since the lignin part of lignocellulosic biomass cannot be processed into fuel.

RED2 postulates a minimum share of 3.5% for advanced biofuels in the transport sector by 2030. Given that production costs remain the major issue to make cellulosic ethanol economically viable, the quick phasing in of cellulosic ethanol is likely to require additional public subsidies. Economic viability of conversion technologies has dominated research about cellulosic ethanol so far, whereas potential feedback effects and tradeoffs between different sectors in the bioeconomy have received considerably less attention (Wyman, 2007; Lynd et al., 2017).

Although the use of agricultural residues for biofuel production could reduce the pressure on global agricultural markets on the one hand, it could also lead to increased competition over residues by already existing types of utilization. Firstly, utilization of residues will likely affect soil quality and GHG emissions, since a considerable amount of residues must remain in the field to regulate the organic carbon in the soil (Zeller et al., 2012). Residue removal could thus lead to both economic and climate change mitigation tradeoffs, since soil organic carbon (SOC) functions as organic fertilizer and as storage for carbon from the atmosphere (Kumar and Goh, 1999; Lal and Pimentel, 2009; Smith et al., 2019). Secondly, some residues are directly used or sold by farmers and thus have economic value, even if they are not traded at markets. Cereal straw for example is typically used as bedding and fodder for livestock as well as for horticultural activities (Panoutsou et al., 2017; LfL, 2020). This competition for residues from different sectors could lead to increased demand for dedicated livestock feed and thus affect agricultural markets, prices and land use. So far, none of the previous economic studies on the impacts of cellulosic ethanol from residues considered feedback effects with other uses of residues (e.g. Robertson et al., 2017; Taheripour et al., 2011b; Taheripour et al., 2017, Philippidis et al., 2018a and 2018b).

To the best of our knowledge our study is the first to comprehensively analyze the use of agricultural residues for cellulosic ethanol as postulated by the EU in the RED2 mandate by taking potential feedback effects with other uses into account and analyzing the actual magnitude of residue demand. Moreover, we investigate the size of potential subsidies per liter of cellulosic ethanol and the sensitivity to residue and oil prices. Based on these, we calculate the implicit CO₂eq abatement cost of cellulosic ethanol as a climate change mitigation instrument. We use an extended version of the DART-BIO model, a computable general equilibrium model of the world economy based on the GTAP9 database (Aguiar et al. 2016) with a detailed representation of the bioeconomy. We explicitly model the production of agricultural residues from different crops based on the production technology in Zeller et al. (2012) and include a latent cellulosic ethanol sector that processes residues using both hexose and pentose sugars for fermentation. We first simulate the introduction of the RED2 with its different targets for conventional and advanced biofuels until 2030. In a second step, we run several sensitivity analysis scenarios to understand how the price of agricultural residues, crude oil prices as well as the actual cellulosic ethanol processing technology affect the results.

The paper is structured as follows. Section 2 gives an overview of the challenges facing cellulosic ethanol production and the findings of previous studies. Section three examines our modelling strategy and our scenarios. Section 4 discusses our results and section 5 concludes.

2. Background on cellulosic biofuels

2.1 Available feedstock and potential

Biofuels produced from cellulosic biomass are seen as a sustainable alternative to conventional biofuels, because their residue feedstock, especially straw from agriculture, is often assumed to be available in large quantities at low cost and without major tradeoffs. Comprehensive studies however show that the global availability of agricultural residues varies a lot depending on which estimation technique is used and whether already existing uses of residues are considered (see Daioglou et al. (2016) for a review). This is because major uncertainties exist firstly with regard to the residue-to-product ratio, which denotes the theoretical potential of how much residues can be actually produced per crop. Given that crops have been grown with the goal of increasing yields and reducing other crop biomass, the relationship between crop yield and residue yield is likely to be negative (Scarlat et al., 2010). Secondly, estimations on how much agricultural residues can be sustainably removed from the field without negatively affecting SOC and soil erosion differ widely depending on the crop and the agricultural management practice from 15 to 60% (Kätterer et al., 2004; Ericsson and Nielsen, 2006; Daioglou et al., 2016). Lal (2005) cautions that even the removal of 30-40% of crop residues could severely deplete SOC stocks and lead to the release of CO₂ emissions from the soil. Finally, there is little data on the amount of residues that already serve economic purposes, such as livestock breeding, horticulture and traditional bioenergy, the latter mainly in developing countries. In the EU a lot of the used straw is not traded at markets and either directly sold or directly used by the farmer for animal bedding and fodder (Searle and Malins, 2013). Scarlat et al. (2010) for example estimate the straw used in the livestock sector in the EU with an assumed average consumption per head of cattle per day which they multiply with a fourth of the European livestock herd. They find that about 11% of residues produced (about 28 of 258 million tons produced) are already used for economic purposes in the EU, whereas Daioglou et al. (2016) estimate this value to be 20-30% on a global level. Krausmann et al. (2008) estimate that as much as 172 million tons of residues are harvested in Western Europe, more than half of their estimated production (326 million tons).

Most recent studies estimate some kind of sustainable and available potential of agricultural residues that subtracts alternative uses in terms of ecological functions and economic utilization of residues (e.g. Scarlat et al., 2010; Searle and Malins, 2013; Daioglou et al., 2015). Scarlat et al. (2010) arrive at 83 million tons straw sustainably available each year on average in the EU. Searle and Malins (2013), who assume much lower residue retention in the field but higher shares of competing uses estimate 122 million tons sustainable potential in the EU. Finally, Zeller et al. (2012) estimate the sustainable straw potential in Germany between 8 and 13 million ton per year.

These large uncertainties regarding estimations of straw availability require an ex-ante assessment of the potential tradeoffs of upscaling cellulosic ethanol for competing uses of straw, as the competition for straw residues is likely to increase quickly with growing demand for residues from the bioeconomy (Scarlat et al., 2010; Searle and Malins, 2013). A detailed analysis of feedback effects of cellulosic ethanol policies on residue removal and its impact on SOC is beyond the scope of our study and will require a coupling of economic and biophysical models (such as process based crop models). Yet, we are the first to assess the actual magnitude

of cellulosic ethanol mandates in the EU with respect to residue utilization and thus determine how large the competition for residues among different users is going to be.

2.2 Production of cellulosic biofuels

Even if the availability of residue feedstock would be without tradeoffs, the processing of this feedstock has proven challenging. The standard approach to convert cellulosic biomass into transport fuels involves the fermentation of sugars similar to conventional ethanol production, but is much more complicated and costly. The first step is a thermochemical pretreatment to separate the ligno-cellulosic biomass into its three parts cellulose, hemicellulose and lignin (Liu et al., 2019). This is followed by enzymatic hydrolysis to extract the different sugars and then conversion of the sugar through fermentation into ethanol. The pretreatment process has proven especially difficult to master and considerably slowed down commercialization, while enzymes remain expensive and other process steps also involved further research (Passoth and Sandgren, 2019). This is because the cellulose contains the typical 6-carbon-atom-sugars like glucose that is also found in sugar and starch crops, but the hemicellulose consists of pentose with 5-carbon-atom-sugars. Whereas fermentation of glucose is straightforward with common yeast, fermentation of pentose requires the development of genetically modified yeast varieties (Liu et al., 2019). Most studies estimate the current production costs around at least double the costs as for conventional ethanol (e.g. Busic et al., 2017; Zhang, 2019). Apart from two factories producing cellulosic ethanol from sugarcane in Brazil, large-scale commercial production of cellulosic ethanol in the EU or the United States (US) has been difficult to achieve so far (Biofuelwatch, 2018). “Beta Renewables” opened the EU’s first large-scale commercial cellulosic ethanol plant in 2013, but shut down in 2017 due to problems with the pre-treatment process and the bankruptcy of its parent company (Pavlenko, 2018). In addition, two plants in Scandinavia (Norway and Sweden) produce cellulosic ethanol commercially but only as a by-product of lignin-processing (E4Tech, 2017). Ironically, the US produces some cellulosic ethanol on paper because the Environmental Protection Agency reclassified fuels from landfill gas and the starch in corn kernel fiber as cellulosic ethanol (Ernsting, 2016).

Public support for cellulosic ethanol has remained high over the years and several new technologies have been developed and are now built into large-scale commercial plants (Corvo, 2018; Slupska and Bushong, 2019). A promising technology was developed by the chemical company Clariant and successfully applied on pilot plant level, supposedly being cost-efficient, competitive with conventional biofuels and an average yield of 300 liter per ton residues (Clariant, 2014). It uses both hexose and pentose sugars from straw for ethanol production and the EU supported with 40 million € the construction of a large commercial factory with an annual capacity of 50,000 tons ethanol in Romania (Clariant, 2019). This factory was completed and started production in the fall of 2021 as the first large-scale commercial cellulosic ethanol plant (Clariant, 2021). If this factory will have commercial success eventually, the increased demand for agricultural residues will likely have feedback effects on agricultural markets in the EU and increase the competition over straw.

It is important to note that in our study, we exclusively simulate cellulosic ethanol production from agricultural residues and not from other types of cellulosic waste such as forest residues or grape lees and wine marcs from wine production that are mentioned in the RED2. Although

both could be very well used, their high lignin content makes their processing more expensive than agricultural residues (Davila et al., 2017; Yu et al., 2021). Cellulosic feedstock that grows well on marginal lands such as miscanthus is also a very promising avenue, but is still in the demonstration phase (GRACE, 2022). Most commercial efforts have therefore concentrated on developing processing technologies for agricultural residues (E4Tech, 2017). The processing of cellulosic ethanol is very sensitive to the actual feedstock in terms of pre-treatment and enzymes, so that the Clariant plant or those commercial biorefineries that are currently built could not simply change their feedstock. Until 2030, agricultural residues are thus the most likely feedstock in large-scale commercial plants.

2.3 Previous analyses of cellulosic ethanol

Comprehensive analyses of the economic impacts of cellulosic ethanol from agricultural residues are rare. Detailed case studies often show that is not feasible due to high costs and political barriers. Most assessments used simulation models like computable general (CGE) or partial equilibrium models to understand how the introduction of cellulosic ethanol will affect agricultural markets and land use. Taheripour et al. (2011a) were the first to introduce cellulosic feedstock into a global social accounting matrix for CGE modeling by splitting corn stover and miscanthus from existing sectors for some regions. The major limitation of this study is that residues enter ethanol processing only, so that competition for residues between different uses was not assessed. This dataset was used to analyze the impact of the US Cellulosic Biofuel Programme on global land use change without finding any significant effect from corn stover ethanol (Taheripour et al., 2011b, Taheripour 2017). Smeets et al. (2015) implement agricultural residues into a CGE model where farmers receive an output subsidy for selling agricultural residues and analyze land use change and food security effects of the estimated global sustainable potential of residues by Daioglou et al. (2016). They find that the subsidy increases the production of crops that simultaneously produce residues. Similarly, Thompson and Meyer (2013) show that the use of wheat straw and corn stover for ethanol in the US can lead to the increased production of either wheat or corn.

In a case study for the Netherlands, the MAGNET CGE model is linked to an energy market model to analyze macroeconomic impacts of a growing bioeconomy (van Meijl et al., 2018). The authors add a dedicated residue sector that includes both forest and agricultural residues from different forest and agricultural activities. The residues are then used as an input in several bioeconomy activities including cellulosic ethanol. Both Philippidis et al. (2018a) and Philippidis et al. (2018b) use this framework to analyze a range of bioeconomy policies in the EU. Philippidis et al. (2018a) also include one scenario with a 3.6% cellulosic biofuel mandate, and estimate very high required public subsidies to achieve this mandate until 2030 of more than €8 billion. However, their assumptions on the cellulosic ethanol processing technology and input prices remain unclear, even though they write that their results are very sensitive to these factors. Moreover, the authors do not consider feedbacks with alternative uses of residues.

None of the previous studies have considered feedback effects of cellulosic ethanol with competing users of agricultural residues. In addition, no attempt has been made to analyze the impact of the cellulosic ethanol mandates in the RED2 on EU agricultural markets and necessary subsidies to guarantee a phasing in of cellulosic ethanol considering current state-of-

the-art cellulosic ethanol processing technologies and the sensitivity to input and oil prices. Our study will close these research gaps by extending the previous CGE approaches as explained in the next section.

3. Methodology

3.1 Model and data

CGE models have widely been used to understand the impact of policy measures on agricultural markets, land use and subsidies. Based on Walrasian general equilibrium theory, they simulate the functioning of a market economy by capturing production and consumption linkages through factor and product markets. The aim of general equilibrium theory is to explain the operation of the whole economy with a micro-founded approach, where the individual welfare maximization behavior of rational producers and households determines the aggregated (macroeconomic) market outcome (Sadoulet and De Janvry, 1995). A general equilibrium is only given through a balance of supply and demand at all factor and product markets, which is ensured through the price mechanism: at equilibrium prices, the decisions taken by all individual households and producers are compatible with each other, so that all commodity and factor markets clear and the allocations of commodities and resources are both optimal and pareto-efficient (Hahn, 1980).

Our global CGE model DART-BIO is a multi-regional and multi-sectoral model of the world economy and is calibrated to an extended version of the Global Trade Analysis Project (GTAP) 9 database (Aguiar et al., 2016). In our current aggregation, our model includes 21 aggregated regions with special attention to the EU and major global players at agricultural markets as shown in Table 1. The focus of our model is on the bioeconomy both in terms of the production of agricultural and other biological resources as well as the processing of these goods into food, fodder, bioenergy and other products made from biomass. Of the 51 sectors in our model as shown in Table 2, 40 sectors are involved in bioeconomy activities. In addition, our 21 factors of production include 18 land types based on the GTAP-AEZs (agro-ecological zones) that cover six different lengths of growing period and three different climatic zones.

Each region features a representative consumer that interacts with producers at product and factor markets where flexible prices and market balance conditions ensure general equilibrium on all markets (see Delzeit et al. (2021) for a technical description of the model). Consumers maximize their utility subject to a Stone-Geary utility function and producers maximize profits under zero profit conditions. Production is governed by multi-nested constant elasticity of substitution (CES) functions that allow for imperfect substitution between the production factors capital, labor, and land as well as energy inputs. Both capital and labor are completely mobile between sectors and within regions, whereas the mobility of land within and between the agricultural and forestry sectors is determined by constant elasticity of transformation (CET) functions. Fixed input-output coefficients in Leontief functions define the combination of the composite production factors with intermediates. Imperfect substitution between domestic and foreign goods under the Armington assumption is governed by CES functions for imports and CET functions for exports. In terms of macroeconomic closures, regional investment is savings driven by fixed regional household savings. Each region's current account balance is fixed except for the United States, which balances trade as the numeraire region. We run our recursive dynamic model over a period of 19 years between 2011 and 2030, where it is solved annually and each year builds on the previous year. To capture the long-term dynamics of the world

economy, essential parameters including capital stocks, total factor productivity as well as labor force and population growth are updated between each year.

Central and South America		Europe	
BRA	Brazil	FSU	Rest of former Soviet Union
PAC	Paraguay, Argentina, Uruguay, Chile	CEU*	Central European Union with Belgium, France, Luxembourg, Netherlands
LAM	Rest of Latin America	DEU*	Germany
Middle East and Northern Africa		MED*	Mediterranean with Cyprus, Greece, Italy, Malta, Portugal, Spain
		MEE*	Eastern European Union with Austria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Romania, Bulgaria, Croatia
MEA	Middle East and Northern Africa	NWE*	North-Western European Union with Denmark, Finland, Ireland, Sweden, United Kingdom
AFR	Sub-Saharan Africa	RNE	Rest of Northern Europe: Switzerland, Norway, Lichtenstein, Iceland
Asia		Northern America	
CHN	China, Hong Kong	CAN	Canada
IND	India	USA	United States of America
EAS	Eastern Asia with Japan, South Korea, Taiwan, Singapore	Oceania	
MAI	Malaysia, Indonesia		
ROA	Rest of Asia		
RUS	Russia		
		ANC	Australia, New Zealand, Rest of Oceania

Table 1: Regional aggregation in DART-BIO

*Members of the European Union

Since the original GTAP 9 database only includes biofuels as part of aggregated industries, we substantially disaggregated the social accounting matrices of the GTAP 9 database to include the conventional biofuel feedstock, processing and by-product sectors. This was done by collecting numerous secondary data for example from FAOSTAT, F.O. Licht and UN Comtrade on production, consumption and trade of crops and biofuels to generate weights, which were then entered in the data splitting software splitcom to disaggregate the original GTAP 9 sectors. A detailed technical description of the database construction process can be found in Delzeit et al. (2021). So far however, our standard DART-BIO database does neither contain cellulosic ethanol production nor the residue feedstock. Therefore, we added a new residue sector as well as enter a latent technology in our model as explained in the next section.

Agricultural related products (29)		Energy products (14)	
<u>Crops</u>		COL	Coal
PDR	Paddy rice	CRU	Oil
WHT	Wheat	GAS	Gas
<i>MZE</i>	<i>Maize</i>	<i>MGAS</i>	<i>Motor gasoline</i>
GRON	Other cereal grains	<i>MDIE</i>	<i>Motor diesel</i>
<i>PLM</i>	<i>Oil Palm fruit</i>	OIL	Petroleum and coal products
<i>RSD</i>	<i>Rapeseed</i>	ELY	Electricity
<i>SOY</i>	<i>Soy bean</i>	<i>ETHW*</i>	<i>Bioethanol from wheat</i>
OSDN	Other oil seeds	<i>ETHM*</i>	<i>Bioethanol from maize</i>
C_B	Sugar cane and sugar beet	<i>ETHG*</i>	<i>Bioethanol from other grains</i>
AGR	Rest of crops	<i>ETHS</i>	<i>Bioethanol from sugar cane</i>
<i>STR</i>	<i>Agricultural residues</i>	<i>ETHC</i>	<i>Cellulosic Bioethanol from agricultural residues</i>
<u>Processed agricultural products</u>		<u>Biofuels</u>	
VOLN	Other vegetable oils	<i>BETH</i>	<i>Bioethanol</i>
SGR	Sugar	<i>BDIE</i>	<i>Biodiesel from all other oilseeds</i>
FOD	Rest of food	<i>BDIE_PLM</i>	<i>Biodiesel from Palmoil</i>
<i>PLMoil*</i>	<i>Palm oil</i>	<i>UCOME</i>	<i>Biodiesel from used cooking oil</i>
<i>RSDoil*</i>	<i>Rapeseed oil</i>	<u>Non-energy products (3)</u>	
<i>SOYoil*</i>	<i>Soy bean oil</i>	CRPN	Other chemical rubber plastic products
<i>OSDNoil*</i>	<i>Oil from other oil seeds</i>	ETS	Paper, minerals and metals
<i>SOYmeal*</i>	<i>Soy bean meal</i>	OTH	Other goods and services
<i>OSDNmeal*</i>	<i>Meal from other oil seeds</i>	<u>Forest and forest products (2)</u>	
<i>PLMmeal*</i>	<i>Palm meal</i>	FRS	Forestry
<i>RSDmeal*</i>	<i>Rapeseed meal</i>	FRI	Forest related industry
<i>DDGSw*</i>	<i>DDGS from wheat</i>		
<i>DDGSm*</i>	<i>DDGS from maize</i>		
<i>DDGSg*</i>	<i>DDGS from other cereal grains</i>		
<i>UCO</i>	<i>Used cooking oil</i>		
<u>Meat and dairy products</u>			
OLVS	Outdoor livestock and related animal products (cattle and other grazing animals, raw milk and wool)		
ILVS	Indoor livestock (swine, poultry and other animal products from indoor livestock)		
PCM	Processed animal products		

Table 2: Sectors in the extended DART-BIO database

Note: New products are in cursive. All goods are produced by an analogous industry, except were indicated by an asterisk (*), which indicates jointly produced goods. Bioethanol and DDGS are jointly produced by the bioethanol industry (3 types of industries); and oilseeds oil and meal are jointly produced by the vegetable oil industry (4 types of industries).

3.2 Modelling cellulosic ethanol production

In the original GTAP database, (priced) agricultural residues are part of a large aggregated crop sector that gets input from all cereal crop sectors. We disaggregate the “straw” industry from this sector using information on agricultural residues production in Germany from Zeller et al. (2012). Table 3 shows the cost of inputs per ton and per 1 US\$ produced output of agricultural residues. Since the cost shares in the right column add up to 1, they can be interpreted as percentages and then represent the input-output vector of production or the production technology of agricultural residues. More than 30% of input costs are paid to capital, making

the German production technology relatively capital intensive, since the residues are collected by a baling press that simultaneously forms the straw into bales. Since we will only look at cellulosic ethanol production in the EU for now and given that industrialized agriculture is very similar in most industrialized and emerging regions, we implement the German technology for all regions. Agricultural residues are mainly produced from cereal straw such as wheat, maize and other grains. If demand for agricultural residues is increasing, this could thus affect production of these crops.

Sectoral input	Per ton	Shares per US\$
Feedstock (straw)	22.80	0.34
Transport and trade	3.35	0.05
Machinery	1.68	0.025
Diesel	1.68	0.025
Labor	15.44	0.23
Capital	22.11	0.33
Total	67.06 US\$	1 US\$

Table 3: Cost of inputs per ton and per 1 US\$ output of agricultural residues

Source: Agricultural residue production technology calculated based on Zeller et al. (2012).

Due to its low cost and heavy weight, straw is rarely traded outside a certain region even within a particular country, e.g. in Germany each state has its own particular straw price (Zeller et al., 2012). Schaub and Finger (2020) for example show that due to its low market integration, droughts affect prices of hay, another bulky and low protein feed, much more than prices of other livestock feed in Southern Germany. Therefore, we do not include global nor intra-EU trade of agricultural residues in our model for now.

While agricultural residues are already produced and at least partly traded at markets, cellulosic ethanol is so far mostly produced in pilot plants apart from the Clariant plant that was just completed. For this reason, we include a latent cellulosic ethanol sector in our model that produces effectively zero at the beginning and then gradually grows once the RED2 policy kicks in. The technology we choose to process residues into cellulosic ethanol is based on Johnson (2016) for wheat straw. The technology integrates enzyme production that convert both hexose and pentose sugars into single sugar molecules which can then be fermented. This integrated production is key in lowering costs and is also at the center of the Clariant production technology. Without explicitly stating, the integrated production technology from Johnson (2016) should thus be very similar to the technology that is used in the first large-scale plant by Clariant. One difference is the yield, as Johnson arrives at an ethanol yield per ton of residues of 285 liters which is a bit lower than the 316 claimed by Clariant (Clariant, 2014). Table 4 shows the cost shares of inputs per liter and per US\$ output of ethanol. Johnson (2016) calculates a production cost of around 0.62 US\$ per liter of cellulosic ethanol, which is on the lower range of current production costs estimates but not as low as the cellulosic ethanol costs of 0.57 USD/liter in Brazil from sugarcane straw (Zhang, 2019). Note that Johnson assumes rather low costs for agricultural residues of 38.5 US\$ per ton. With the 67 US\$ per ton straw from Zeller et al. (2016), production cost per liter of ethanol amount to 0.66 US\$. Even though

we are implementing a relatively advanced technology, conventional bioethanol costs in the US and Brazil are much cheaper around 0.30 - 0.40 USD/liter (Zhang, 2019).

Sectoral input	Johnson (2016)		APEC (2010)	
	Per liter	Shares per US\$	Per liter	Shares per US\$
Feedstock (straw)	0.22	0.36	0.14	0.24
Chemical and enzymes	0.13	0.20	0.17	0.28
Utilities	0.02	0.03	0.02	0.03
Labor	0.03	0.05	0.07	0.11
Capital	0.23	0.37	0.21	0.35
Total	0.62 US\$	1 US\$	0.60 US\$	1 US\$

Table 4: Cost shares of inputs per liter and per 1 USD of cellulosic ethanol

Source: Cellulosic ethanol production technologies calculated based on Sassner et al. (2008) and APEC (2010).

3.3 Scenarios

The following section describes our scenarios which can be found in Table 5.

Name	Description
Base	RED2 without cellulosic ethanol
RED2	RED2 with cellulosic ethanol quota and Johnson (2016) production technology
MUP	RED2 with price markup for straw
APEC	RED2 with APEC technology
OIL	RED2 with positive oil supply shock
NEG_OIL	RED2 with negative oil supply shock

Table 5: Scenarios

Source: own compilations using DART-BIO

Baseline scenario (“Base”)

Our baseline scenario tracks the development of the world economy from 2011 to 2030 based on GDP growth and population growth projections by the OECD (OECD, 2018). In addition, we calibrated conventional biofuel production to match actual biofuel output until 2018 based on data from Eurostat for the EU (Eurostat, 2020) and from the USDA Global Agricultural Information Network (GAIN) reports for the other regions. From 2019 on, we implemented the biofuel mandates for conventional biofuels in the RED2 (Directive (EU) 2018/2001). This

means that biofuels produced from food or feed crops (essentially all biofuels in our model except for UCOME²) are not allowed to exceed 7% of the market share in the transport sector. For UCOME the RED2 postulates a maximum share of 1.7% that is counted towards the mandate. Finally, biodiesel from palm oil is phased out until 2030. Detailed impacts of the RED2 for conventional biofuels on agricultural markets are discussed in Delzeit et al. (2019) and will not be subject of this study. Here the baseline scenario is just a “status quo” and is used to compare the impacts of the advanced biofuel mandate in the RED2 to a world without these additional mandates.

RED2 with cellulosic ethanol mandate (“RED2”)

In our major scenario, we implement the advanced biofuel mandates postulated by the RED2. From 2022 on, advanced biofuels need to have a share of 0.2% in the transport sector, which increases to 3.5% until 2030. We implement the mandate with a quota on Armington consumption, but since we do not allow for trade in cellulosic ethanol for now, the quota pertains effectively only to consumption of domestic cellulosic ethanol. Given that cellulosic ethanol is much more expensive than the fossil fuels with which it competes in the market, we introduce a negative endogenous tax on consumption. This endogenous tax is allowed to vary to ensure consumption equals the specified quota or higher and as such decreases the price consumers need to pay for cellulosic ethanol. The endogenous tax can be interpreted as the public subsidy required to phase in cellulosic ethanol and we can recalculate the tax into an implicit subsidy per liter of cellulosic ethanol. During the expansion of the cellulosic ethanol sector, demand for inputs such as straw, capital and labor will increase, which could lead to tradeoffs with other sectors. Since the profitable production of cellulosic ethanol is subject to many uncertainties, the following scenarios can be seen as sensitivity analyses with respect to the main RED2 scenario.

Increase in the price of agricultural residues (“MUP”)

CGE models assume perfect competition and therefore function under the zero profit condition. In our baseline the price of straw thus equals its production cost based on the production technology we are using, i.e. 67.06 US\$ per ton (Zeller et al., 2012). This straw price is very close to 70 \$/ton dry basis estimated by APEC (2010) for the cellulosic biofuel production in the US, so we feel confident that this is a first best assumption. Yet, the price of straw can rapidly change depending on demand and supply. Due to a dry spring and then rainy summer in 2011, the national average price in Germany amounted to 155 \$/ton (Proplanta, 2011). In addition, transport costs for agricultural residues can increase substantially depending on the distance to the biorefineries. Therefore, we run a scenario where we increase the price of residues to 100 US\$/ton. This is a simplifying assumption as a drought is a covariate shock that could also affect crop prices and prices of other feed such as hay. However, Schaub and Finder (2020) have shown that grain feed prices are not much affected by regional or national droughts

² UCOME stands for “used cooking oil methyl ester” and denotes biodiesel produced from used cooking oil.

due to their high market integration. Moreover, our residue sector also encompasses hay and other types of fodder as far as these are included in our database³.

Different technology (“APEC”)

Given the problems in the different processing steps of cellulosic ethanol as explained in section two, the final commercial technologies that will be used for the production of cellulosic ethanol are subject to debate. In this scenario, we thus implement a different technology based on APEC (2011) for cellulosic ethanol production in the US that can be found in the second column of Table 4. APEC (2011) assume higher yields than Johnson (2016) of 325 liter/ton of feedstock as well as higher production costs with 0.72 US\$/liter. Compared to Johnson (2016), APEC (2011)’s technology is more labor intensive and has a higher cost share for chemicals and lower cost share for feedstock. These differences will determine the size of the subsidy and the impact of increased cellulosic ethanol on product and factor markets compared to the other technology.

Oil supply shocks (“OIL” and “NEG_OIL”)

Crude oil prices are a decisive factor in the feasibility of biofuel production and determine whether biofuels can be competitive in the transport sector (Reboredo et al., 2016). In our base year 2011, global crude oil prices were rather high around 100 US\$/barrel due to high demand and political conflicts in oil producing countries and thus made biofuels very competitive (Baumeister and Kilian, 2016). Since then however, they have fallen to around 70 US\$/barrel due to a large increase in US oil production among other reasons. This means that our previous scenarios might underestimate the subsidies that need to be paid by EU governments to increase cellulosic ethanol in the market. On the other hand, global climate action or conflicts in the Middle East could lead to higher crude oil prices that would render potential subsidies unnecessary. Therefore, we run two oil price scenarios: a positive crude oil price shock where we increase the price of crude oil by 10% (“OIL”) and a negative crude oil price shock where we decrease the price of crude oil by 20% compared to the baseline (“NEG_OIL”). We refrain from simulating the price crash of crude oil to below 50 US\$/barrel in 2020 due to the Covid-19 crises as this is a complex shock to the world economy and for now unrelated to the introduction of advanced biofuels.

4. Results and Discussion

We start reporting the results for the RED2 scenario compared to our baseline in 2030. All our sensitivity analysis scenarios will then be compared to the original RED2 scenario.

4.1 Output, price and land use effects from cellulosic ethanol

In the RED2 scenario, we increase the share of cellulosic ethanol in the transport sector to 3.5% until 2030. The left part of Figure 1 shows that this leads to a production of between 2.2 and 3.8 billion liters cellulosic ethanol depending on the EU region. Note that the amount of liter produced is dependent on the size of the transport sector in each region. At the same time, this

³ Like straw markets hay markets are very regional and characterized by informal market exchanges (Schaub and Finger, 2020).

requires between 7.7 and 13.5 million tons agricultural residues (left part of Figure 2), which is a large shock to the agricultural sectors in the EU compared to the sustainably available amount of residues as discussed in section 2. In fact, the 10.5 million metric tons needed for cellulosic ethanol production in Germany are in the mid-range of the sustainable residue potential estimates by Zeller et al. (2012). The EU as a whole requires almost 50 million metric ton of residues to achieve the 3.5% mandate, which is more than half of the 83 million tons sustainable straw potential given by Scarlat et al. (2010). These results show that the 3.5% cellulosic ethanol mandate alone would require up to the complete amount of sustainably available agricultural residues in regions like Germany. If all sustainably available residues are used up for ethanol, none would be left for other economic purposes unless more residues are harvested than would be sustainable. These numbers indicate that the EU's advanced biofuel policy is unlikely to succeed without major tradeoffs for the environment and existing uses of agricultural residues.

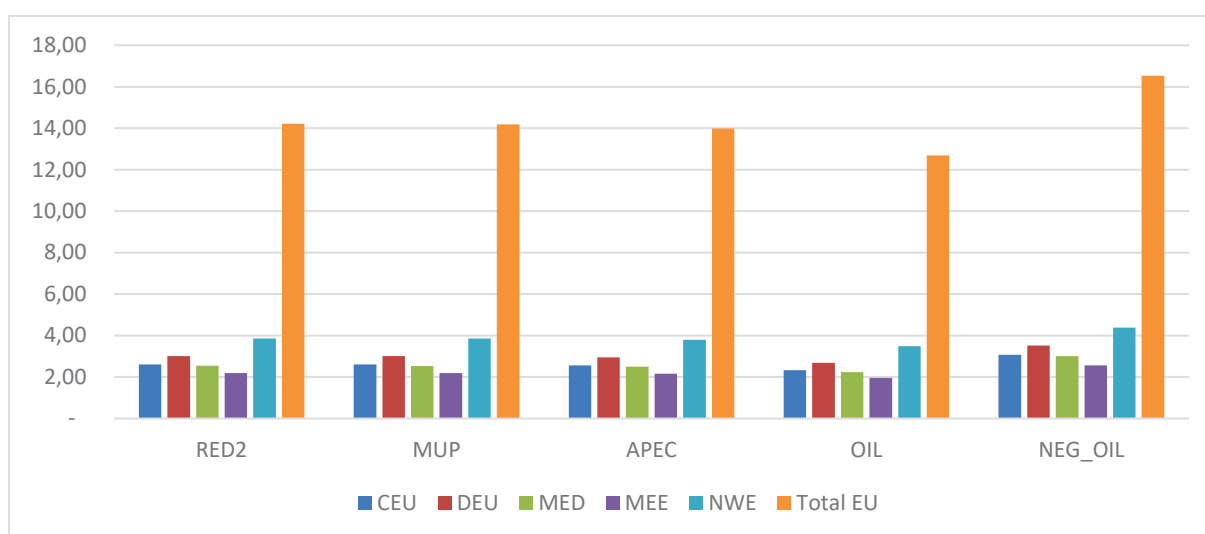


Figure 1: Cellulosic ethanol production in billion liters in each scenario and region

Source: Results from cellulosic ethanol scenarios in DART-BIO.

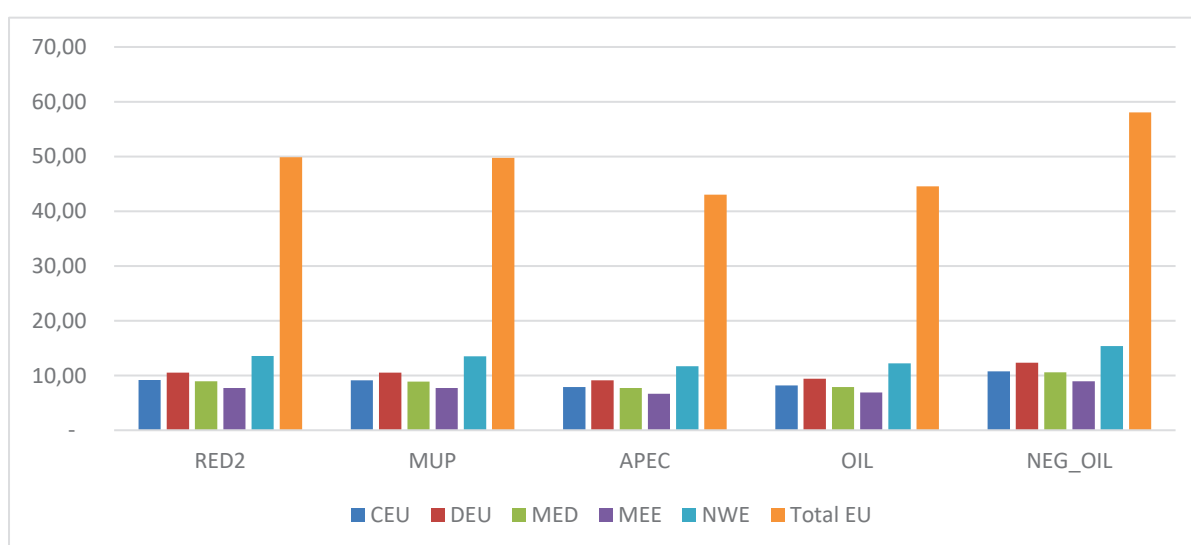


Figure 2: Use of agricultural residues in million metric tons in each scenario and region

Source: Results from cellulosic ethanol scenarios in DART-BIO.

Region	Percentage change	
	Price	Output
CEU	-0.04	894.60
DEU	-0.05	2,208.06
MED	1.75	1,048.52
MEE	0.15	195.50
NWE	0.07	1,973.48

Table 6: Change in prices and output of agricultural residues % in the RED2 scenario relative to the baseline in 2030

Source: Results from base and RED2 scenarios in DART-BIO

As cellulosic ethanol production is expanded in the EU, this increases the demand for straw from the cereal crop sectors. While straw output grows substantially, straw price increases remain relatively small and even decrease slightly in two regions (Table 6). This is because prices of cereal crops do not change compared to the baseline except for paddy rice production in Mediterranean countries (MED) as shown in the first column of Table 7. Prices of crops are determined on the world market and not influenced by production changes in the EU. As agricultural residues in MED also contain straw from paddy rice, the price for residues increases by almost 2%. Even though prices change little between the scenarios, there is some movement in terms of output quantities (second column of Table 7). Especially wheat, whose straw is an essential input into the agricultural residue sector, increases by almost 1% in Germany, by 1.1% in MEE and by 1.3% in NWE. Maize and other cereal output is even 2.6% and 1.9% higher, respectively, under the RED2 scenario in NWE. In CEU, wheat, maize and other cereals also exhibit some output increases. Overall, the effects on crop output differ across the EU due to the slightly different composition of straw from different crops that enter the agricultural residue sector in each region. Conversely production of certain crops like soybeans and other crops slightly contracts in all regions. This is because there is some reallocation of land towards crops that enter the agricultural residue sector like wheat, maize, and other cereals away from the just mentioned soybeans and other crops as shown in Figure 3.

Region	Sector	Δ Price	Δ Output
CEU	Wheat	0.0	0.2
	Maize	0.0	0.7
	Other cereals	0.0	0.5
	Rapeseed	0.0	0.2
	Soybeans	0.0	-0.2
	Other crops	0.0	-0.1
	Outdoor livestock	-0.1	-0.1
	Indoor livestock	-0.1	-0.1
	Processed livestock products	-0.1	-0.1
DEU	Wheat	0.0	0.9
	Maize	0.0	0.2
	Other cereals	0.0	0.2
	Rapeseed	0.0	0.0
	Other crops	0.0	-0.2
	Outdoor livestock	-0.1	-0.1
	Indoor livestock	-0.1	-0.1
	Processed livestock products	-0.1	-0.1
MED	Paddy rice	4.8	3.0
	Wheat	0.0	0.7
	Maize	0.0	0.1
	Other cereals	0.0	0.1
	Rapeseed	0.0	0.0
	Other crops	0.0	-0.1
	Outdoor livestock	0.0	-0.1
	Indoor livestock	-0.1	-0.1
	Processed livestock products	-0.1	-0.1
MEE	Paddy rice	2.9	1.1
	Wheat	0.1	1.4
	Maize	0.1	0.0
	Other cereals	0.1	0.0
	Rapeseed	0.1	-0.1
	Soybeans	0.1	-0.3
	Other crops	0.1	-0.2
	Outdoor livestock	0.0	-0.1
	Indoor livestock	0.0	-0.1
	Processed livestock products	-0.1	-0.1
NWE	Wheat	0.2	1.3
	Maize	0.3	2.6
	Other cereals	0.2	1.9
	Rapeseed	0.2	-0.1
	Other crops	0.2	-0.5
	Outdoor livestock	-0.1	-0.1
	Indoor livestock	0.0	-0.1
	Processed livestock products	-0.1	-0.1

Table 7: Changes in output and prices of agricultural commodities in % in the RED2 scenario relative to the baseline in 2030

Source: Results from base and RED2 scenarios in DART-BIO

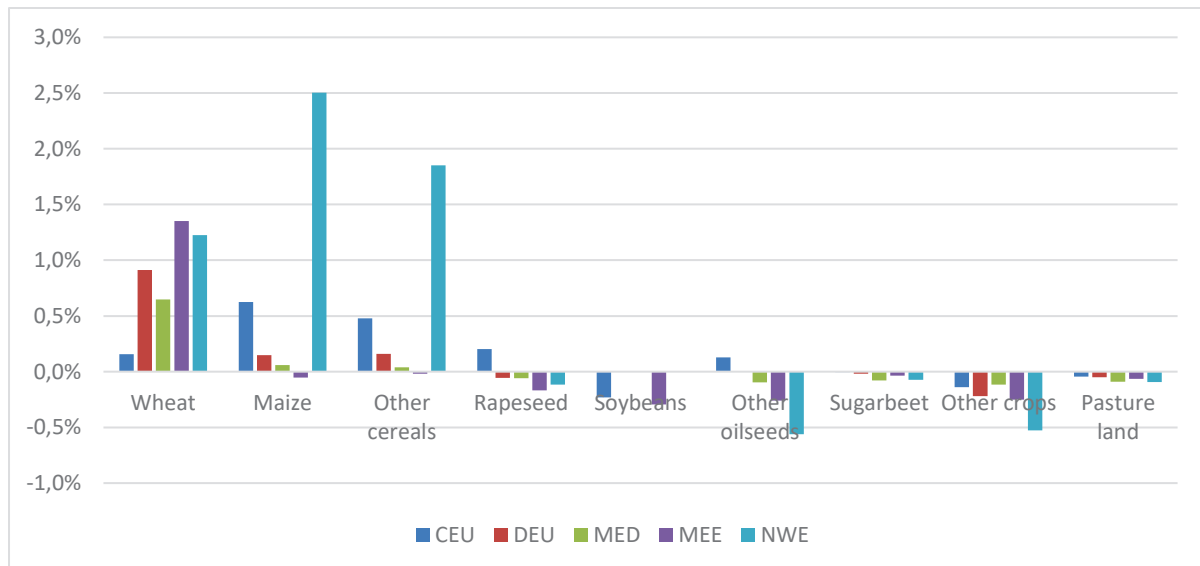


Figure 3: Change in land use in % in the RED2 scenario relative to the baseline in 2030

Source: Results from base and RED2 scenarios in DART-BIO

The livestock sectors seem to be only slightly affected by increased competition over agricultural residues at the first glance at Table 7, which makes sense because straw prices do not change a lot between the scenarios (Table 6). However, a closer look at the intermediate utilization of agricultural residues in Figure 4 shows that in the RED2 scenario in 2030, almost 90% of all residues in the EU enter cellulosic ethanol processing compared to 6% in the baseline. While the large intermediate use share from the cellulosic ethanol sector can be relatively easily compensated for by the higher output of residues from the crop sectors in the RED2 scenario, this is only possible because of the reallocation of land away from crops such as soybeans that are an important input into the livestock feed industry. Although actual negative economic impacts of cellulosic production under the RED2 mandates have not become apparent in our scenario, one must keep in mind that a lot of the residues already in use are not included in our market-based data and model. As mentioned above, most of the utilized straw is not traded at the market and directly used by the farmer for livestock and other purposes (Searle and Marlins, 2013), so that we very likely underestimate the actual competition for agricultural residues between different types of utilization. As the demand for agricultural residues from different sectors in the bioeconomy will increase, so will the competition between the livestock sector and industrial uses of biomass. Figure 4 gives thus a glance how large this competition is going to be.

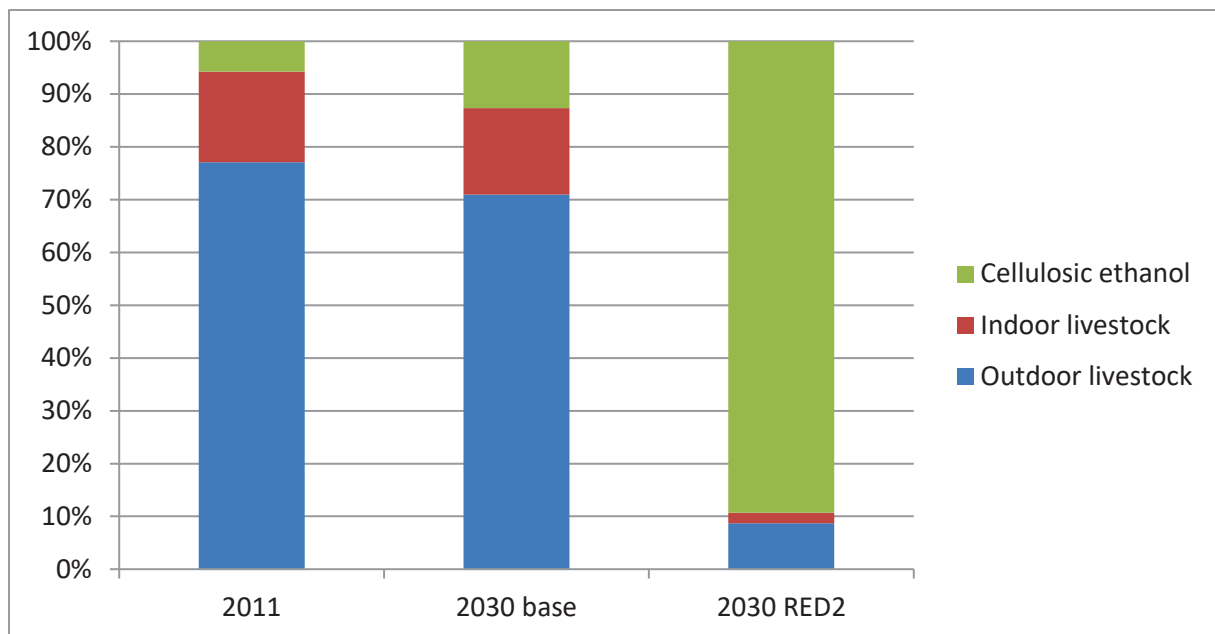


Figure 4: Composition of agricultural residue utilization in the baseline and RED2 scenarios

Source: Results from base and RED2 scenarios in DART-BIO

A look at the transport sector in Table 8 illustrates that impacts are small but as desired by the EU RED2 mandates. Output of gasoline as shown in the second column of Table 8 decreases between 1 and 1.4% in all EU regions as gasoline is substituted by cellulosic ethanol. As fossil fuel prices are determined on the world market, there are only very small prices decreases within the EU. Conventional bioethanol remains mostly unaffected since the renewable energy mandates of the RED2 that apply to conventional biofuels are still in place.

Other economy-wide impacts are negligible given the relatively small intervention. Factor markets are barely affected and since agricultural residues are not traded internationally, changes in trade flows are minimal. The latter is likely to change if the value of straw increases and trade becomes profitable.

Region	Sector	Δ Price	Δ Output
CEU	Gasoline	-0.2	-1.1
	Diesel	-0.2	0.0
	Bioethanol (conventional)	0.0	0.0
	Biodiesel	-0.1	0.0
DEU	Gasoline	-0.2	-1.4
	Diesel	-0.2	0.0
	Bioethanol (conventional)	0.0	0.0
	Biodiesel	0.0	0.0
MED	Gasoline	-0.2	-1.0
	Diesel	-0.2	0.0
	Bioethanol (conventional)	0.0	0.0
	Biodiesel	-0.1	0.0
MEE	Gasoline	-0.2	-1.4
	Diesel	-0.2	0.0
	Bioethanol (conventional)	0.1	-0.1
	Biodiesel	0.0	0.0
NWE	Gasoline	-0.2	-1.0
	Diesel	-0.2	0.1
	Bioethanol (conventional)	0.1	-0.2
	Biodiesel	0.0	-0.2

Table 8: Changes in output and prices in the transport sector in % in the RED2 scenario relative to the baseline in 2030

Source: Results from base and RED2 scenarios in DART-BIO

4.2 Changes through prices and technologies

As a second step, we run different sensitivity analyses scenarios to understand how straw and crude oil prices and a different technology affect the results. For the MUP scenario where we increase the price of straw, the impacts on agricultural markets are very similar to the original RED2 scenario and therefore not reported here. This makes sense because effectively the same amount of liters of cellulosic ethanol are produced and thus the same amount of agricultural residues are used as shown in Figures 1 and 2. Impacts on crop output is slightly different in the APEC scenario where we implemented a cellulosic ethanol processing technology that requires less residues and has higher output per ton of residues. Here, the crops that enter the residue sector such as wheat and other cereals have slightly lower output in the EU compared to the original RED2 scenario, but the numbers are below 1% (not shown here). Looking at Figure 2 the more efficient APEC technology requires about 15% less agricultural residues to produce the same amount of ethanol.

In the two crude oil price scenarios, impacts on agricultural markets are very large. This is because crude oil is an important input in basically all sectors of the economy and thus any crude oil price shock leads to substantial general equilibrium effects on both product and factor markets. Since these are of marginal interest in the current study, we refrain from analyzing them here. What we are more interested in is how the change in crude oil prices affects the economic viability of cellulosic ethanol as discussed in the next section.

4.3 Subsidies and CO₂ abatement costs

So far, cellulosic ethanol is not market ready as production is difficult and costly. In our scenarios, we have implemented modern technologies for cellulosic ethanol that have a relatively small price markup compared to conventional ethanol. Until 2030 this price markup decreases further in all our scenarios due to cost reductions in the inputs in cellulosic ethanol production especially with regard to chemicals and capital. Therefore, the subsidies per liter of ethanol as shown in Table 9 cannot be interpreted in absolute terms and rather serve to compare how the size of the subsidy changes in the different scenarios.

Region	Scenarios				
	RED2	MUP	APEC	OIL	NEG_OIL
Subsidy per liter of cellulosic ethanol in 2030 in US\$					
CEU	0.2	0.31	0.18	0.14	0.27
DEU	0.17	0.31	0.16	0.12	0.25
MED	0.22	0.31	0.2	0.16	0.3
MEE	0.19	0.27	0.16	0.13	0.26
NWE	0.22	0.32	0.2	0.17	0.3
Total EU subsidies in billion US\$	2.86	4.35	2.54	1.85	4.59
Total EU emission reduction in million ton CO ₂ eq	42.21	42.11	41.51	37.69	49.10
Abatement cost in US\$ per ton CO ₂ eq	67.58	103.25	60.79	48.69	93.26

Table 9: Subsidies, emission reductions and abatement costs in 2030

Source: Results from cellulosic ethanol scenarios in DART-BIO.

In the RED2 scenario, we have a relatively high subsidy per liter of ethanol in the EU of around 0.2 US\$ despite our efficient technology assumption and the just mentioned price reductions for inputs. However, in the RED2 scenario straw prices are very moderate with 67.06 US\$/ton and crude oil prices are high with 100 US\$ per barrel. Once straw prices increase to 100 US\$/ton as in the MUP scenario, the necessary subsidy per liter increases substantially in all regions and is for example 45% higher in Germany compared to the original RED2 scenario (second column of Table 9). Prices of 100 US\$/ton or more for agricultural residues are frequently found during drought years. As the occurrence of extreme weather events is increasing, the MUP scenario might be the more likely reality in terms of straw prices. This would not only mean high public costs for phasing in cellulosic ethanol, but will likely increase the competition between the cellulosic ethanol industry and other sectors using agricultural residues. The third to last row of Table 9 shows the cumulative subsidies paid by EU countries for the 3.5% advanced biofuel mandate. Governments pay 2.86 billion US\$ to achieve the mandate in the RED2 scenario, but more than 4 billion in case of high straw prices. Interestingly, this is much lower than the

estimate from Philippidis et al. (2018) of 8 billion € (about 11 billion US\$) and shows the influence of technology and input assumptions that are not clear in previous work.

The subsidy per liter also increases in case of 30% lower oil prices (NEG_OIL, last column of Table 10), similar to the oil prices in 2018, and would amount to 0.25 US\$/liter in Germany, which is 32% higher than in the RED2 scenario. With the relatively low crude oil prices in the last 5 years around 60 US\$ per barrel and even lower prices due to COVID-19 crisis, phasing in cellulosic ethanol in the next 2 years will very likely require substantial public subsidies. Interestingly, in the high oil price scenario (OIL) once the crude oil price increases by 10% in 2030 as compared to the original RED2 scenario, the subsidy estimates per liter of cellulosic ethanol are around 40% lower (fourth column of Table 9). A consistent global climate policy that raises the price of crude oil would therefore also ease the phasing in of cellulosic ethanol by making cellulosic ethanol more competitive.

Finally, in the APEC scenario, the subsidy is on average 10% smaller in each region as the APEC technology benefits from lower input costs and does not require as much agricultural residues (third column of Table 9). The more efficient the cellulosic ethanol production technologies, the lower will be the additional public costs to ensure the RED2 mandates are fulfilled. The APEC technology however was only tested in laboratory environments and might thus not be achievable in a large-scale commercial context.

As a final step, we calculate the actual GHG emissions abated in the transport sector through the substitution of gasoline with cellulosic ethanol and then use the total subsidy costs to calculate the implicit CO₂eq abatement cost. Wang et al. (2007) calculated the life cycle well-to-wheel GHG emissions of cellulosic ethanol compared to gasoline and arrive at 0.33 kgCO₂eq/liter for cellulosic ethanol and 3.3 kgCO₂eq/liter for gasoline. This means that each liter cellulosic ethanol that substitutes for one liter of gasoline leads to a reduction of almost 3 kgCO₂eq in the transport sector. Rather than the production cost however, we use the cost faced by the consumer. We multiply this number with the amount of liters of cellulosic ethanol produced in each scenario and arrive at an emission reduction around 42 million tonCO₂eq for the EU for the first 3 scenarios as shown in Table 9. Interestingly, with a higher oil price the emission reduction is slightly smaller due to the smaller transport sector, but much larger (49 tonCO₂eq) in the case of lower oil prices with a higher transport sector and more cellulosic ethanol produced to fulfil the quota. Given that the EU transport sector emitted around 1000 million tonCO₂eq annually in the previous years (EEA, 2021), the emission reduction in our scenarios around 4% seems reasonable considering that we substitute 3.5% of fossil fuels with cellulosic ethanol.

To calculate the GHG abatement costs of cellulosic ethanol, we use the formula by Dwivedi et al. (2015) and divide the price difference between cellulosic ethanol and gasoline, i.e. the implicit subsidy, by the difference in their life cycle GHG emissions from Wang et al. (2007). In the RED2 scenario, this leads to a marginal abatement cost of 67\$ per tonCO₂eq on average for the EU. In the case of higher residue prices in the MUP scenario the abatement cost reaches even 103\$ per tonCO₂eq and varies depending on the oil price and the competitiveness of cellulosic ethanol in the other scenarios. These numbers are much lower compared to Dwivedi et al. (2015) who estimate abatement costs for cellulosic ethanol from corn stover around 200\$ per tonCO₂eq. The reason for our lower numbers is our modern (and cheap) cellulosic ethanol

processing technology, but our numbers fit well in the ball park of IEA abatement cost estimates for biofuels (0-121\$ per tonCO₂eq; IEA (2020)). Abating GHG emissions with cellulosic ethanol is clearly more expensive compared to wind and solar energy (around 30\$ per tonCO₂eq on average according to the IEA) and costs also vary with straw and oil prices, but producing cellulosic ethanol with a large-scale commercial processing technology as in our scenarios would be a cheaper climate change mitigation measure than many other options (e.g. coal production with carbon capture and storage still costs 130\$ per tonCO₂eq on average; IEA (2020)).

5. Conclusion

The revised Renewable Energy Directive (RED2) of the European Union (EU) again sets high mandates for biofuels to reach the target of 14% renewable energy use in the transport sector until 2030 (Directive (EU) 2018/2001). To reduce potential tradeoffs with respect to food security and biodiversity, cellulosic bioethanol produced from agricultural residues is supposed to replace conventional biofuels in the fuel mix. Due to the difficult and costly processing of cellulose into ethanol however, large scale production has failed so far and will likely require substantial subsidies. In addition, the utilization of agricultural residues for bioenergy is not without drawbacks, since residues are also needed in the field to regulate the organic carbon in the soil and are used as bedding and fodder for livestock as well as for horticultural activities.

To understand the impacts of the introduction of cellulosic ethanol in the EU according to the RED2 on residue use, agricultural markets and subsidies, we use an extended version of the global CGE model DART-BIO that includes a detailed representation of the bioeconomy. We explicitly model the production of agricultural residues from different cereals and include a latent cellulosic ethanol sector that processes residues using both hexose and pentose sugars for fermentation. We simulate the introduction of the RED2 mandates and run several sensitivity analyses with respect to processing technology, straw and oil prices.

We find that the EU advanced biofuel mandates will require an enormous amount of agricultural residues and could eat up to the complete amount of sustainably available agricultural residues in regions like Germany. Our numbers indicate that the EU's advanced biofuel policy is unlikely to succeed without major tradeoffs for the environment and existing uses of agricultural residues.

Given that crop prices are determined on the world market, impacts on crop prices are small but we find that the use of agricultural residues clearly leads to production and land use changes. In all EU regions there is a reallocation of land towards crops that enter the agricultural residue sector like wheat, maize, and other cereals away from soybeans and other crops. In addition, even though the livestock sector is not affected due to the small price changes, the composition of agricultural residue utilization changes substantially and the cellulosic ethanol industry becomes the main consumer of agricultural residues in the EU. These findings show how large the competition between the livestock sector and industrial uses of biomass is likely to become, as the demand for agricultural residues from different sectors in the bioeconomy will increase.

Moreover, we find that with current trends in prices of agricultural residues and crude oil, subsidies per liter are likely to be high. While we find relatively high subsidies already in our

original RED2 scenario despite an efficient technology assumption and price reductions for inputs until 2030, an increase in agricultural residue prices during drought years could increase the necessary subsidy per liter in Germany by 45%. As the occurrence of extreme weather events is increasing, a high residue price could be a likely reality. This would not only mean high public costs for phasing in cellulosic ethanol, but will likely increase the competition between the cellulosic ethanol industry and other sectors using agricultural residues. Similarly, current crude oil prices would lead to increases in subsidies per liter of cellulosic ethanol by 30%. On the other hand, a consistent global climate policy that raises the price of crude oil could lead to much lower subsidies and would ease the phasing in of cellulosic ethanol by making it more competitive. The more efficient the cellulosic ethanol production technologies, the lower will be the subsidy per liter and the additional public costs to ensure the RED2 mandates are reached.

Looking at the potential of cellulosic ethanol for climate change mitigation, we find that abatement costs range between 50 and 103 US\$ per tonCO₂eq depending on the scenario. Like for the subsidy, abatement costs are higher, the higher residue prices or the lower the oil prices. Since abatement costs are in the medium range compared to other mitigation options, producing cellulosic ethanol with the modern processing technology that we model could be an important contribution to climate change mitigation in the transport sector.

Eventually, the introduction of cellulosic ethanol to the European transport sector must be handled very carefully to avoid tradeoffs with competing users of agricultural residues. More research is needed to understand how many residues are actually used on farm and not traded at markets. Moreover, future studies need to consider global trade in agricultural residues once trade becomes profitable with higher demand for straw. While we put a first number on the actual magnitude of residues needed to fulfil the EU advanced biofuel mandates, a comprehensive analysis of the environmental tradeoffs arising from the increased demand for residues is vital. Given that the ecosystem is not a market player and cannot react to increased demand and price changes, the chances that the mandates will come at the cost of the environment and not the economy are high.

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