EU's bioethanol potential from wheat straw and maize stover and the environmental footprint of residue-based bioethanol

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Abstract

To reduce greenhouse gas (GHG) emissions, the European Union (EU) have targets for utilizing energy from renewable sources. By 2030, a minimum of 3.5% of energy in the EU's transport sector should come from renewable biological sources, such as crop residue. This paper analyzes EU's 'advanced bioethanol' potential from wheat straw and maize stover and evaluates its environmental (land, water and carbon) footprint. We differentiate between gross and net bioethanol output, the latter by subtracting the energy inputs in production. Results suggest that the annual amount of the sustainably harvestable wheat straw and maize stover is 81.9 Megatonnes (Mt) at field moisture weight (65.3 Mt as dry weight), yielding 470 PJ as gross (404 PJ as net) advanced bioethanol output. Calculated gross advanced bioethanol can replace 3.44% of EU transport sector's energy consumption. EU's advanced bioethanol has a land footprint of 0.28 m^2 MJ^{-1} for wheat straw and 0.18 m^2 MJ^{-1} for maize stover. The average water footprint of advanced bioethanol is 173 L MJ^{-1} for wheat straw and 113 L MJ^{-1} for maize stover. The average carbon footprint per unit of advanced bioethanol is 19.4 and 19.6 g CO_2eq MJ^{-1} for wheat straw and maize stover, respectively. Using advanced bioethanol can lead to emission savings, but EU's advanced bioethanol production potential is insufficient to achieve EU's target of a minimum share of 3.5% of advanced biofuels in the transport sector by 2030 and the associated water and land footprints are not smaller than footprints of conventional bioethanol.

Keywords

Biofuel; Crop residue; Environmental footprint; EU energy policy; Lignocellulosic bioethanol; Sustainable development

Declarations

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Conflicts of Interest

None.

Availability of Data

Data is available from Zenodo Digital Repository (https://doi.10.5281/zenodo.3941862).

Code availability

Not applicable

1. Introduction

The climate of our planet is changing as a result of emissions of greenhouse gases (GHGs) from the consumption of fossil fuels (Edenhofer et al., 2011). Fossil fuels are mainly used as a source of energy across different sectors. By switching from fossil fuels to renewable energy sources, we may be able to reduce GHG emissions and limit the rate and magnitude of climate change.

Transport sector emissions constitute a quarter of global GHG emissions (IEA, 2018). The energy policy of the European Union (EU) requires a minimum of 14% of the final consumption in the transport sector to come from renewable sources by 2030 (European Commission, 2018), contributing to the EU's aim to be climate-neutral by 2050 (Council of the European Union, 2020). To achieve these goals, the energy policy specifies a minimum target of 3.5% of the final transport sector's energy consumption that shall originate from advanced biogas or biofuels (European Commission, 2018). Advanced biofuels are defined as liquid fuels produced from a specific type of feedstock, such as: algae, biowaste, agricultural residues, used cooking oil, animal fats, manure, etc. (for a complete list see EU Directive 2018, Annex IX), as opposed to conventional (first-generation) biofuels produced from crops. Advanced biofuels from agricultural residues are also called lignocellulosic biofuels.

Although we could theoretically produce a range of biofuel products using biomass feedstock, most forms of advanced biofuel production are still in a research or demonstration stage (IRENA, 2016). Some of the available technologies, such as thermochemical conversion of biomass to syngas or pyrolysis oils don't yield transport-ready biofuels but intermediate products that need further processing and input of hydrogen to become transport-ready fuels (Karatzos et al., 2014). Present-day advanced biofuel plants operating at the commercial scale mainly produce bioethanol using plant residues (IEA, 2019a). Considering the EU's current energy policy, it would be good to know how much advanced biofuel can be produced using available crop residues. In addition, it would be good to know natural resource appropriation and GHG emissions in the production of advanced biofuels in order to compare them to conventional biofuels.

Various studies have assessed the agricultural residue potential of the EU in terms of weight (Searle and Malins, 2016) or energy equivalents using the heat content of residues (EEA, 2006; Ericsson and Nilsson, 2006; Scarlat et al., 2010). Scarlat et al. (2010), for example, estimated the EU's bioenergy potential in terms of heat content from crop residues, when using the portion of agricultural residues remaining after environmental considerations and current uses. Heat content of biomass, however, is not the same as energy in the form of biofuel. Fischer et al. (2007) estimate EU's advanced biofuel potential at 8 Exa-joules by 2030, but they considered woody plants (i.e., poplar, willow, eucalypt) and herbaceous lignocellulosic plants (i.e., miscanthus, switchgrass, and reed canary grass). No study has assessed the sustainable advanced bioethanol potential of the EU from crop residues.

To fill this gap, this study estimates the EU's advanced bioethanol potential from wheat straw and maize stover, as residues of currently grown crops potentially available for bioethanol production. Cereals are the main crops grown in the EU with wheat and maize making up 48% and 19% of the cereals production, respectively (Eurostat, 2017). In addition, the study quantifies the environmental footprint of advanced bioethanol, more specifically the land, water and carbon footprints, which are part of the footprint family (Vanham et al., 2019a). Footprint assessment has been applied previously to analyze resource appropriation and emissions in the production of biofuels (Gerbens-Leenes et al., 2014; Gerbens-Leenes and Hoekstra, 2012; Holmatov et al., 2019; Holmatov et al., 2021; Mathioudakis et al., 2017), electricity (de Wild-Scholten, 2013; Mekonnen et al., 2015; Mekonnen et al., 2016; Mekonnen and Hoekstra, 2012; Zhang and Xu, 2015), and the consumptive water footprint of the EU energy sector (Vanham et al., 2019b) but to date, no study has specifically assessed the land, water and carbon footprints of advanced bioethanol in the EU and its member states from crop residues.

2. Data collection and analysis

2.1 Resource inputs

2.1.1 Overview of production phases and output products

As feedstock for the production of lignocellulosic bioethanol, we assume wheat straw and maize stover produced in member states of the EU in 2017. We distinguish between resource inputs in the agriculture phase and the conversion phase (Fig. 1). The outputs from the agriculture phase are crop grains and residues while the outputs from the conversion phase are bioethanol and electricity. Considering the bulkiness of crop residues, a suggested distance of 50 km on average is assumed between the agricultural field and biorefinery (Spöttle M., 2013).

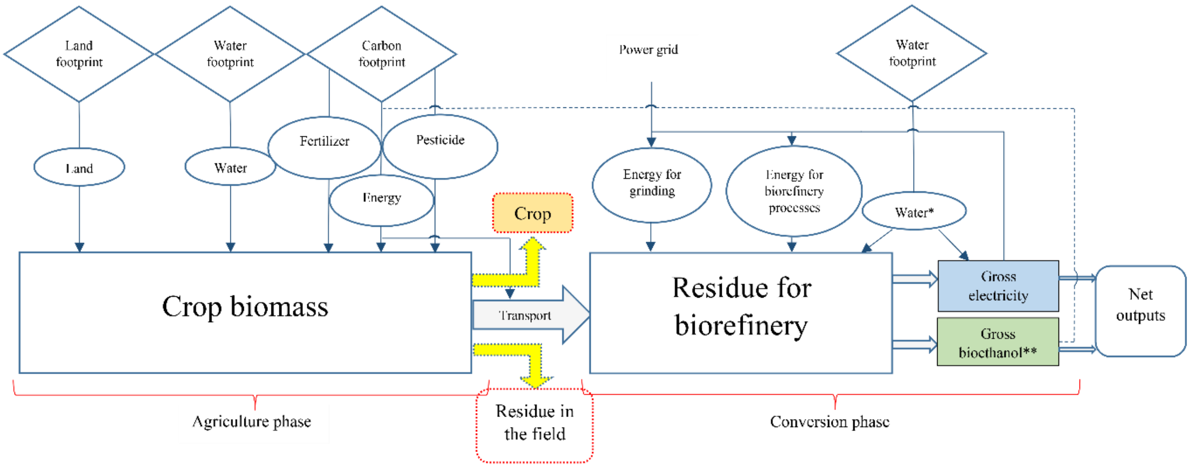

Fig. 1. Schematic representation of resource inputs in the production of advanced bioethanol. Notes: *Water is mainly lost due to evaporation; **Distinction between gross and net bioethanol is applied to show the difference in energy balance but does not affect the carbon footprint calculation. The carbon footprint in the agriculture phase is calculated assuming diesel input.

2.1.2 Inputs during the agriculture phase

Crop production, harvested area and yield data for individual EU countries are obtained from Eurostat for 2017 (Eurostat, 2019d). No data were available for Malta, which is therefore excluded from this study. Maize production refers to maize harvested for grain and excludes green maize used for fodder, maize grown for producing first-generation biofuel and sweet corn used for human consumption (Eurostat, 2019a). Maize production data were not available for Cyprus, Estonia, Finland, Ireland and Latvia, and thus, our estimation of bioethanol production potential from maize residues excludes these countries. Wheat yield data for 2017 were not available for Italy, the Netherlands and the United Kingdom; the latest available data from 2016 were used instead. Maize and wheat yields are converted to straw and stover yields using crop residue-to-yield correlations proposed by Scarlat et al. (2010).

Resource inputs during the agriculture phase are land, water, fertilizer, pesticide and fuel energy (Table 1). For technical and environmental reasons, only part of the residue can be collected to generate bioethanol. Removing even part of the residues (30-40%) can lead to a number of side-effects, including soil erosion, additional emission of GHGs, depletion of the soil organic carbon pool, etc. (Lal, 2005). Consistent with Scarlat et al. (2010) we assume that maximally 50% of maize stover and 40% of the wheat straw can be sustainably removed from fields in European conditions. Harvested wheat straw moisture is assumed to be 15% and maize stover moisture is assumed to be 30% (Scarlat et al., 2010). Moreover, the least dry matter loss of 6% is assumed during bale storage in the field (POET-DSM, ND). Throughout this work, dry weight is converted to harvested moisture weights through:

$$HW(r) = \frac{DW(r)}{dmc(r)} \quad (1)$$

where $HW(r)$ is the harvested moisture weight of residue feedstock r (in mass units); $DW(r)$ is the dry weight of the residue feedstock (mass units); and $dmc(r)$ is the dry matter content of the harvested residue feedstock (expressed as a fraction).

Table 1. Resource inputs during the agriculture phase of the bioethanol production.

Resource input	**Process**	**Value**		**Units**	**Source**
		Wheat straw	Maize stover		
Water	Crop cultivation	Varies by country	Varies by country	m^3 $tonne^{-1}$ (crop)	Mekonnen and Hoekstra (2010)
Fertilizers (N&P)	Crop cultivation	N: 180 (201.8) P: 90 (100.9)	N: 80 (89.7) P: 40 (44.8)	lb ac^{-1} (kg ha^{-1})	Kissel (ND)
Pesticide related energy	Crop cultivation	571	1681	MJ ha^{-1}	Audsley et al. (2009)
Diesel (energy)	Crop cultivation (field activities)	35.5*	37.5**	L ha	Šarauskis et al. (2014) Dalgaard et al. (2001)
	Residue harvest (mowing)	5	5	L ha^{-1}	Dalgaard et al. (2001)
	Residue harvest (bailing & handling)	2	2	L $tonne^{-1}$	Dalgaard et al. (2001)
	Residue transport†	0.2	0.2	L $tonne^{-1}$ km^{-1}	Dalgaard et al. (2001)

Notes: *Refers to the sum of the following field activities: stubble cultivation; shallow ploughing, pre-sowing, fertilization, conventional drilling and spraying; **Refers to the sum of the following field activities: stubble cultivation; ploughing (21 cm); seedbed harrowing; fertilization; sowing and spraying; †same as the energy requirement of fodder transport.

All inputs during the agriculture phase are partly allocated to bioethanol, based on the value of the bioethanol output compared to the summed value of all final outputs (crop, bioethanol, and electricity output). This value fraction is calculated as:

$$f_v(BE) = \frac{price(BE) \times w(BE)}{\sum_{p=1}^{3}((price(p) \times w(p))} \quad (2)$$

where $f_v(BE)$ is the value fraction of bioethanol, $price(BE)$ the price of bioethanol, and $w(BE)$ the quantity of gross bioethanol. The denominator is the sum of the total values of the three output products (crop yield, gross bioethanol and gross electricity), whereby total values follow from price time quantity. In the case of diesel inputs for residue mowing, bailing and handling, and for residue transport, the footprints of that diesel are allocated to two output products (bioethanol and electricity).

Crop prices for 2017 are taken from the Eurostat database (Eurostat, 2019c). Wheat prices were not available for 12 countries: Belgium, Cyprus, Denmark, Estonia, Ireland, France, Latvia, Finland, Spain, Sweden, the Netherlands and the UK. For Spain and France, the latest available wheat prices were for 2016 and were utilized in this study. For all other countries, the wheat price is assumed at the average wheat price in the 15 EU countries with available data. The latest available maize price data for Spain and France were from 2016 and were utilized in this study. For the price of bioethanol we took the price of European duty paid ethanol in July 2017 from ICIS (2017). The price of electricity for household consumption per country in 2017 is calculated using the bi-annual electricity price data from Eurostat (2019b).

2.1.3. Inputs during the conversion phase

Resource inputs during the conversion phase are energy, water and residues (Table 2). The electricity requirement for grinding biomass to the size of 0.5 mm is taken from German and Bauen (2018). The water input in the biorefinery is allocated to bioethanol as in equation 2 (with two output products: bioethanol and electricity).

Table 2. Resource inputs per liter of bioethanol output during the conversion phase.

Resource input	**Value**	**Units**	**Source**
Electricity (biorefinery's use)	1.03	kWh L^{-1}	Humbird et al. (2011)
Consumptive water use	5.4	L L^{-1}	
Electricity (grinding) wheat straw	0.138*	kWh L^{-1}	German and Bauen (2018)
Electricity (grinding) maize stover	0.174*		
Wheat straw	2.922**	kg(dry) L^{-1}	Saha et al. (2015)
Corn stover	3.039	kg(dry) L^{-1}	O'Connor (2013)

Notes: *Calculated from a reported requirement of 40 kWh per tonne of feedstock; **Calculated from a yield of 0.27 gram of bioethanol per gram of wheat straw after 76 hours.

To calculate bioethanol yield from crop residues (kg of dry residue L^{-1} of bioethanol), we used data from Saha et al. (2015) for wheat straw and O'Connor (2013) for corn stover. Co-production of electricity in a biorefinery is calculated using data from Humbird et al. (2011). In addition to the electricity for the plant's own use, an excess of 1.8 kWh per gallon of bioethanol (0.48 kWh L^{-1}) can be generated using lignin and post-processed insoluble solids. Electricity generation from wheat straw processing is assumed similar to maize stover processing because of similar lignin composition in wheat straw and corn stover (Jia et al., 2013).

2.2 Energy balance

The net energy yield in terms of bioethanol is calculated as the gross bioethanol output minus the energy inputs during production (see Fig. 1). During the agriculture phase, energy inputs are associated with the direct input of diesel and with the embedded energy in the pesticides and fertilizers applied. Energy equivalent units for these inputs are subtracted from the gross bioethanol output. The lower heating value (LHV) of bioethanol is obtained from USDOE (2014), i.e., 76330 btu $gallon^{-1}$ or approximately 21.27 MJ L^{-1} (26.96 MJ kg^{-1}) [1]. LHV of diesel is calculated from IEA and OECD (2010). The energy used in fertilizer (ammonium nitrate and triple superphosphate) production

[1] Converting btu to MJ, gallons to liters and liters of ethanol to kg of ethanol: 76330 btu/gallon * 0.00105506 MJ/btu * (1/3.7854 liters/gallon) * (1/0.789 liters/kg). Conversion factor for btu to MJ is obtained from IEA, OECD (2010) Energy Statistics Manual. https://www.iea.org/training/toolsandresources/energystatisticsmanual. June 26, 2019. Density of ethanol is obtained from Haynes, W.M. (2014) CRC handbook of chemistry and physics. CRC press.

(expressed per weight of product) is obtained from Fertilizers Europe (2019). The energy used in pesticide production is taken from Audsley et al. (2009).

During the conversion phase, electricity is used for grinding and biorefinery. This electricity input is subtracted from the gross electricity output to get net electricity output.

2.3 Land footprint

The land footprint of bioethanol production is associated with the agriculture phase only. It is calculated as the inverse of the net bioethanol output per hectare (which gives the total area used per unit of net bioethanol produced) multiplied by the value fraction for bioethanol (which allocates only a part of the total area to the bioethanol output).

2.4 Water footprint

The water footprint of bioethanol consists of (1) agricultural water requirements for crop cultivation and (2) processing water requirements at the biorefinery. The water footprint of the agriculture phase is composed of blue, green and grey components while the water footprint of conversion phase is only blue water. The blue water footprint refers to consumptive use of irrigation water; the green water footprint refers to consumption of rainwater; and the grey water footprint refers to water pollution (although in this study we only consider water pollution through nitrogen, which is applied on the cropland as fertilizer). Country-average data on the water footprint of crops per weight is taken from Mekonnen and Hoekstra (2010). The water footprint per weight of crop is first converted to water footprint per hectare using the country-specific crop yields and then allocated to bioethanol based on the value fraction of gross bioethanol (see Section 2.1.2).

Processing water requirement at the biorefinery is reported as consumptive water usage, mainly due to evaporative losses (Humbird et al., 2011). Water input in the biorefinery is also allocated to bioethanol based on the value fraction of bioethanol. The water footprint per unit of net bioethanol output is calculated by dividing total water inputs for bioethanol production by the total net bioethanol output.

2.5 Carbon footprint

The carbon footprint of bioethanol production is associated with the agriculture phase only. It is the sum of the GHG emissions from diesel combustion and the GHG emissions related to fertilizer and pesticide production and use. The CO_2eq emission factor of diesel combustion is obtained from Zijlema (2018). Fertilizer production and use emissions are calculated by multiplying fertilizers applied to the field (Table 1) by their respective total CO_2eq emissions during production and use (soil effects) from Fertilizers Europe (2019). Pesticide production and use related emissions are calculated by multiplying pesticide applied to the field (Table 1) by the CO_2eq emission factor suggested by Audsley et al. (2009). CO_2eq emissions associated with the production of enzymes is not included in the carbon footprint calculation due to its large uncertainty, although enzyme production and use in hydrolysis was identified as possibly one of the major contributors to the carbon footprint of bioethanol (Gilpin and Andrae, 2017; Zhao et al., 2019) and is discussed in section 4.3. The carbon footprint per unit of net bioethanol output is calculated by allocating the CO_2eq emissions per hectare to bioethanol based on the value fraction of gross bioethanol and dividing by the net bioethanol output per hectare.

3. Results

3.1 Residue availability in the EU

The total amount of residue from wheat and maize available for biorefineries is estimated at 81.9 Megatonnes (Mt) at field moisture weight, which is equivalent to 65.3 Mt as dry weight. The latter figure is very similar to the amount reported by Scarlat et al. (2010), who estimated that maize and wheat together contribute 60% (i.e., 66.6 Mt) to the total of 111 Mt dry residue weight that can be sustainably collected in the EU (without counting the 6% bailing loss considered in this study).

Wheat straw at field moisture contributes 65% to the total residue calculated in this study, with the remaining 35% being maize stover. In terms of dry weight, wheat straw contributes 69% and maize stover 31% to the total combined residue. The largest producers of total combined residue calculated in this study are France, Germany, and Romania. France produces 22.9%, Germany 12.3% and Romania 12.1% of the total residues.

France produces the largest amount (23.7%) of wheat straw in the EU, followed by Germany (14.8%) (Fig. 2). The United Kingdom, Poland and Romania are the other big contributors, producing 8.4%, 8.3% and 7.2% of EU's wheat straw, respectively.

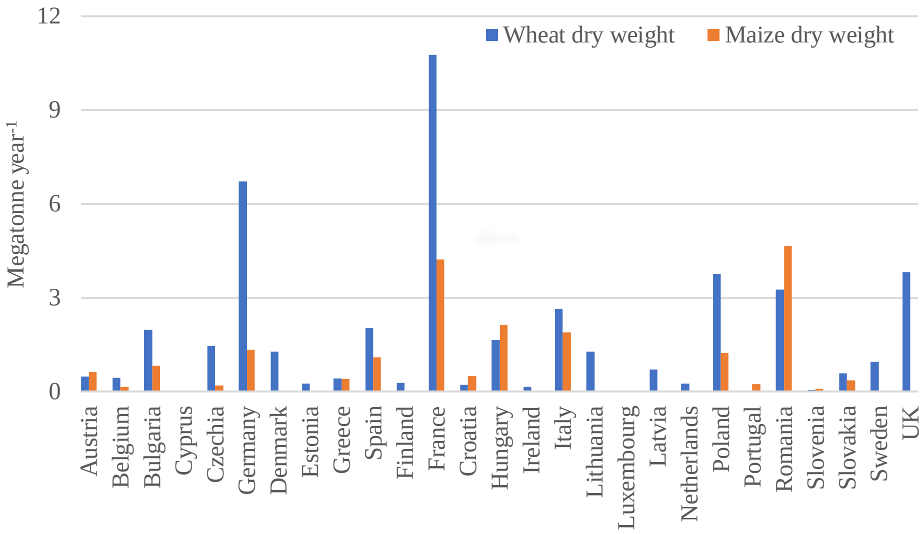

Fig. 2. Wheat straw and maize stover availability for bioethanol production per EU country.

The largest producer of maize stover is Romania, which contributes 23.3% to the EU's total maize stover production, followed by France (21.2%). Next in line are Hungary (10.7%), and Italy (9.4%).

3.2 Advanced bioethanol production potential in the EU

Total bioethanol production potential from wheat and maize residue in the EU is 470 PJ as gross output or 404 PJ as net output. The potentially largest producer of advanced bioethanol from wheat straw and maize stover in the EU is France, which could produce 23.6% of the total European potential (Fig. 3). Germany and Romania can produce 12.9% and 11.6% of the total potential net bioethanol from wheat and maize residues, respectively.

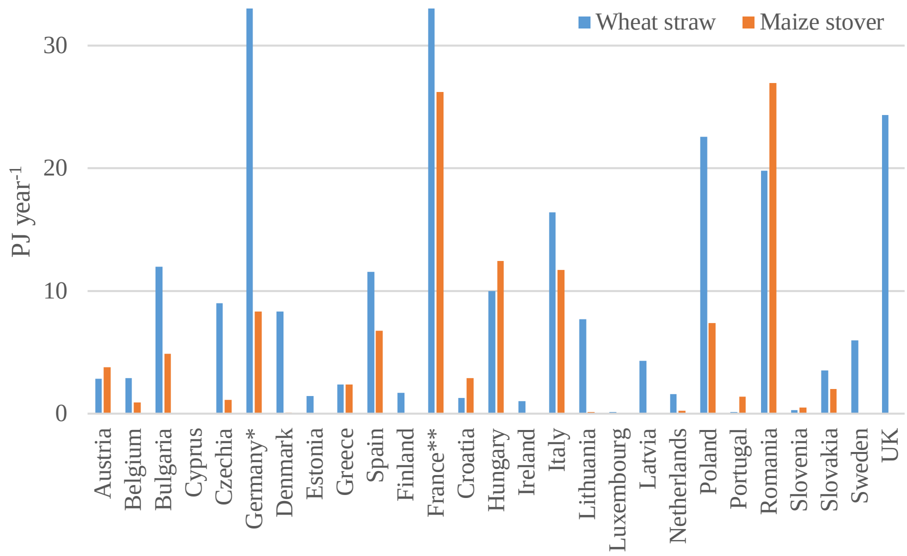

Fig. 3. Net bioethanol production potential from wheat straw and maize stover per EU country. Note: * net bioethanol production potential from wheat straw in Germany is 43.7 PJ $year^{-1}$; ** net bioethanol production potential from wheat straw in France is 69.3 PJ $year^{-1}$.

Net bioethanol production from wheat straw is 284 PJ (70% of the total), while net bioethanol production from maize stover is 120 PJ (30%). Total potential net bioethanol production from wheat and maize in the EU is slightly over 19 billion liters. Total EU produced advanced bioethanol can replace 3.44% (using gross bioethanol output) or 2.95% (using net bioethanol output) of the EU's final energy consumption in the transport sector (326.872 Mtoe or 13685 PJ in 2017) (Eurostat, 2019). Separately, gross bioethanol from wheat straw can replace 2.41% and gross bioethanol from maize stover 1.02% of EU's final energy consumption in the transport sector.

Net bioethanol production from residues per hectare is higher for the case of maize than for the case of wheat (Fig. 4). The average net bioethanol yield from wheat straw in the EU is 10.3 GJ ha^{-1} while the average net bioethanol yield from maize stover is 14.7 GJ ha^{-1}. These values are lower than net first-generation bioethanol yields, which are 29.1 GJ ha^{-1} for maize, 139.6 GJ ha^{-1} for sugar beet and 142 GJ ha^{-1} for sugarcane (Holmatov et al., 2019). Yields of advanced bioethanol vary between countries and between the two types of feedstock. For example, net bioethanol yield from wheat straw in the UK (13.6 GJ ha^{-1}) is higher than the EU's average and higher than net bioethanol yield from maize stover in the UK (9.1 GJ ha^{-1}). The highest net bioethanol yield from wheat straw is in Ireland (15.4 GJ ha^{-1}) and the lowest in Cyprus (4.4 GJ ha^{-1}). The highest net bioethanol yield from maize stover is in Spain (20.3 GJ ha^{-1}) and the lowest in the UK (9.1 GJ ha^{-1}).

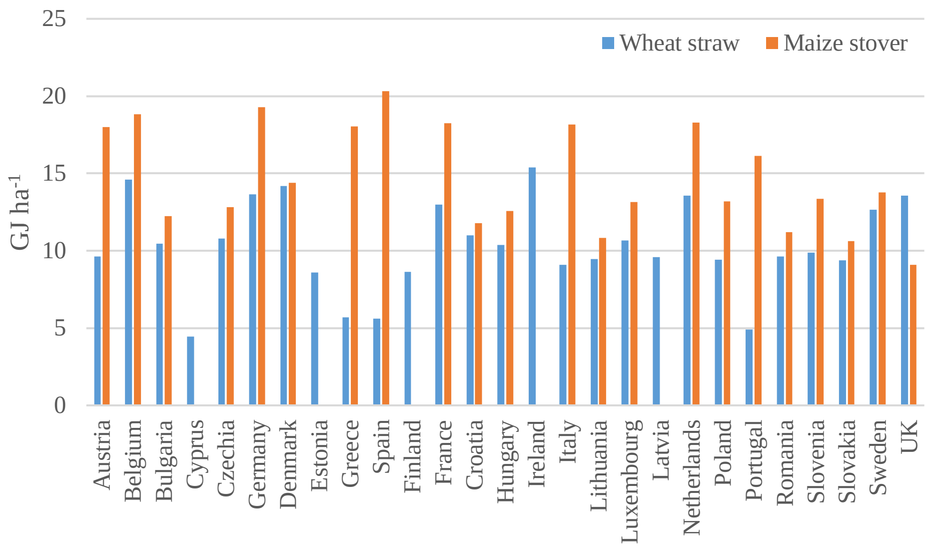

Fig. 4. Net bioethanol yield from wheat straw and maize stover per hectare across EU countries.

The average difference between net and gross bioethanol output from wheat straw is 15%. In Cyprus, this loss is 28% (4.4 GJ ha^{-1} as net vs 6.2 GJ ha^{-1} as gross) while in Belgium the loss is only 10% (14.6 vs 16.3). The average difference between net and gross bioethanol output from maize stover is 13.6%. The largest difference is found for the UK, namely 17.7% (9.1 vs 11), while the smallest difference is in Germany, namely 10.3% (19.3 vs 21.5).

3.3 Bioelectricity co-generation potential in the EU

The bioelectricity co-generation potential in the EU related to the production of advanced bioethanol from wheat straw and maize stover is 7232 GWh or 26 PJ. Using wheat straw can co-produce 5250 GWh or 73% of the total co-generated bioelectricity. France alone can co-generate 1245 GWh of bioelectricity from post-processed wheat straws (Fig. 5). In terms of energy, total co-generated bioelectricity is equivalent to 6.4% of the total net bioethanol's energy (26 PJ vs 404 PJ).

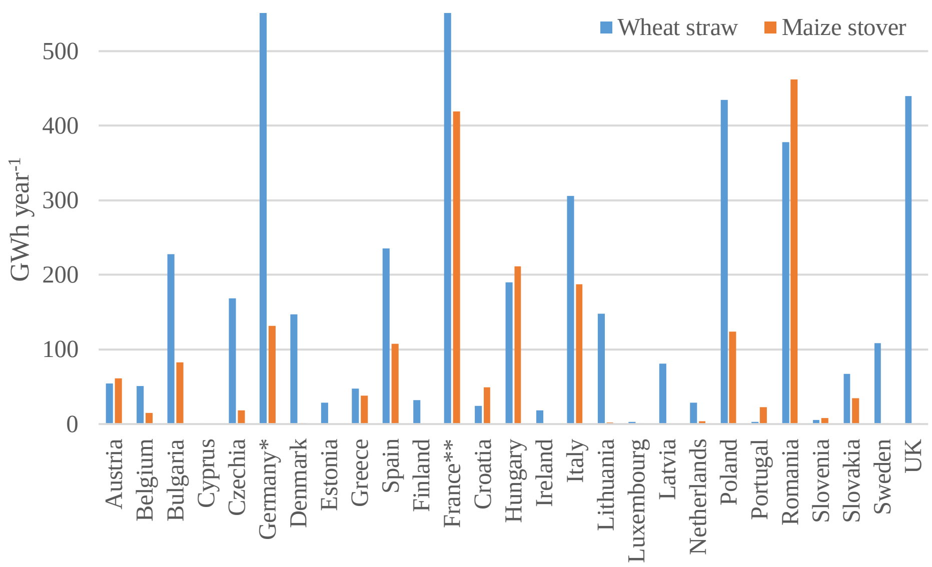

Fig. 5. Bioelectricity co-generation with advanced bioethanol from wheat straw and maize stover per EU country. Note: * bioelectricity co-generation from wheat straw in Germany is 776 GWh year^{-1}; ** bioelectricity co-generation from wheat straw in France is 1245 GWh year^{-1}.

3.4. Land footprint of advanced bioethanol

EU's average land footprint per unit of net advanced bioethanol from wheat straw is 0.28 m^2 MJ^{-1}; for advanced bioethanol from maize stover this is 0.18 m^2 MJ^{-1} (Fig. 6). The difference is explained by the higher bioethanol yield from maize stover per ha. Ireland has the smallest land footprint per unit of net bioethanol from wheat straw (0.14 m^2 MJ^{-1}), while Cyprus has the largest (0.69 m^2 MJ^{-1}). For bioethanol from maize stover, the largest land footprint is in the UK (0.27 m^2 MJ^{-1}), and the smallest in France (0.11 m^2 MJ^{-1}). The land footprint of advanced bioethanol is larger than the land footprint of first-generation bioethanol from sugar beet or sugarcane (0.07 m^2 MJ^{-1}), but smaller than the land footprint of first-generation bioethanol from maize (0.34 m^2 MJ^{-1}) (Holmatov et al., 2019).

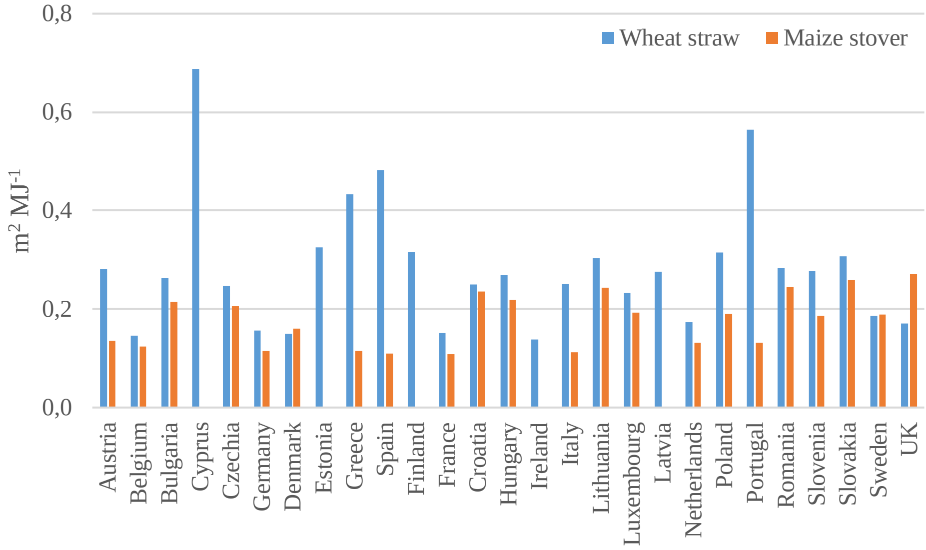

Fig. 6. Land footprint per MJ of net advanced bioethanol from wheat straw and maize stover per EU country.

3.5 Water footprint of advanced bioethanol

The average total water footprint per unit of net bioethanol output in the EU is 173 L MJ^{-1} for bioethanol from wheat straw and 113 L MJ^{-1} for bioethanol from maize stover. Most of the total water footprint is made up of green water. Across EU, blue water on average contributes less than 1% to the total water footprint for bioethanol from wheat straw (median 0.22%) and 8.9% for bioethanol from maize stover (median 0.64%). Maize is mostly irrigated in the Southern European countries and the share of blue water footprint in Greece and Spain reaches 44 - 45% and in the case of Portugal 55%. In contrast, wheat is mostly rainfed, with the highest share of blue water footprint in Cyprus, reaching 6.3%.

The average water footprint of net advanced bioethanol from maize stover is almost half the water footprint of first-generation bioethanol from maize (113 vs 235 L MJ^{-1}) (Holmatov et al., 2019). However, there is a large variation of the water footprint of advanced bioethanol between countries (Fig. 7), where the water footprint of advanced bioethanol exceeds the water footprint of conventional bioethanol in some countries. For example, the largest water footprint per unit of bioethanol from wheat straw is in Portugal (488 L MJ^{-1}), that is mostly (84%) green water. The largest water footprint per unit of bioethanol from maize stover is in Lithuania (462 L MJ^{-1}), mostly (50%) composed of grey water.

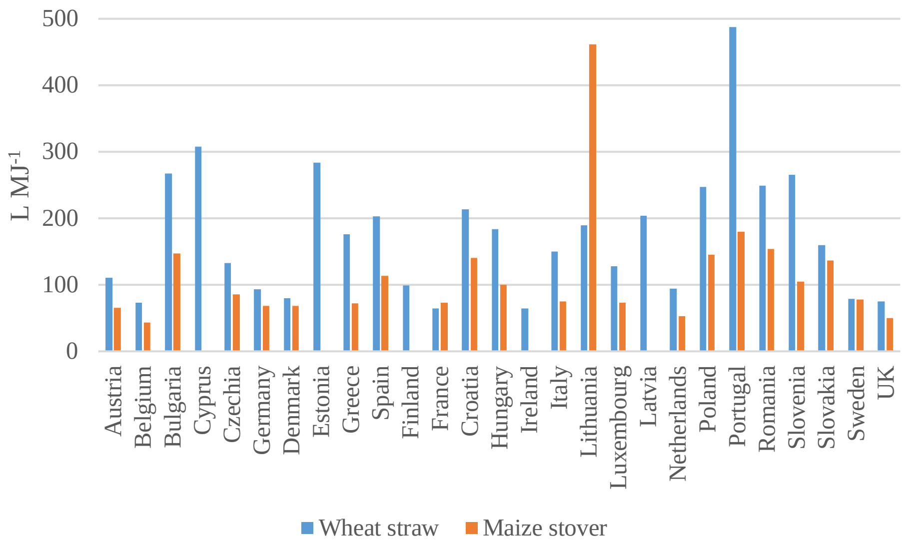

Fig. 7. Water footprint per MJ of net advanced bioethanol from wheat straw and maize stover per EU country.

3.6 Carbon footprint of advanced bioethanol

The average carbon footprints per unit of net advanced bioethanol from wheat straw and maize stover in the EU are 19.4 and 19.6 g CO_2eq MJ^{-1}, respectively. There are, however, large variations between countries (Fig. 8). For example, the carbon footprint of net bioethanol from wheat straw is highest in Cyprus (41.4 g CO_2eq MJ^{-1}) and lowest in Ireland (11 g CO_2eq MJ^{-1}). The carbon footprint of net bioethanol from maize stover is highest in the UK (27.4 g CO_2eq MJ^{-1}) and lowest in Germany (13.3 g CO_2eq MJ^{-1}).

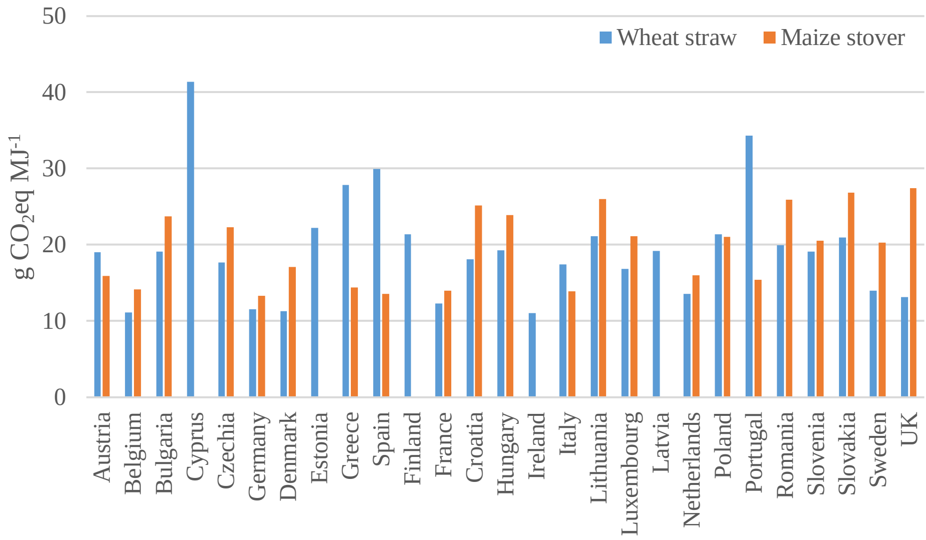

Fig. 8. Carbon footprint per MJ of net advanced bioethanol from wheat straw and maize stover per EU country.

Regardless of the country of production, the carbon footprint of advanced bioethanol is much lower than the carbon footprint of gasoline or diesel (72-73 g MJ^{-1}) (Zijlema, 2018). Compared to the carbon footprint per unit of net first-generation bioethanol, the carbon footprint of advanced bioethanol can be equal, higher or lower, depending on the feedstock used to produce conventional bioethanol (Table 3).

Table 3. Carbon footprint of conventional bioethanol per unit of net energy (g CO_2eq MJ^{-1}). Adopted from Holmatov et al. (2019)

Feedstock	Sugar beet	Sugarcane	Maize
Carbon footprint	19	14	82

4. Discussion

4.1 Advanced bioethanol can contribute to emission savings but may have adverse implications

The carbon footprints of advanced bioethanol from wheat straw and maize stover calculated in this study are much smaller than the carbon footprints of conventional gasoline or diesel. Thus, replacing conventional gasoline and diesel in the transport sector with advanced bioethanol can lead to large emission savings. Potential savings are achieved by using the maximum sustainable harvest of residues; this study assumes that 40% of wheat straw and 50% of maize stover can be sustainably harvested, which is probably optimistic. A 2010 study by the International Energy Agency assumed that the sustainable harvest rate of residues for biofuel production is in the range of 10-25% (Eisentraut, 2010). Factors that determine actual sustainable harvest rates depend on location (climate and soil), slope (Gregg and Izaurralde, 2010), management style, soil type, and yield (Andrews, 2006). Given the regional focus of this study, we felt justified in assuming an average share of residues that can be sustainably harvested from a given area. This approach is consistent with the assumptions used in other studies (Holmatov et al., 2021; Kadam and McMillan, 2003; Scarlat et al., 2010).

Choice of a feedstock can lead to tradeoffs between the different footprints. The results of this study show that using maize is relatively better from the water and land footprint perspectives. Using maize stover leads to higher net bioethanol yield per unit of land. However, the carbon footprint of bioethanol from maize stover is also larger than the carbon footprint of bioethanol from wheat straw.

Miscalculation of the sustainable harvest rate and excessive removal of crop residues can lead to adverse effects, from soil erosion and organic matter/nutrient removal (Andrews, 2006; Gregg and Izaurralde, 2010; Wilhelm et al., 2004) to heightening emission of GHGs (Lal, 2005). Moreover, removal of residues can compete with traditional uses of residues (i.e. fodder, bedding, etc.) and raise residue prices, which will affect current residue users (Eisentraut, 2010). Farmers may likely have to apply additional fertilizer due to nutrient losses that come along with residue removal.

4.2 Advanced bioethanol production has a long way to go to catch up with policy targets

Realistically, considering the net bioethanol output, the EU can replace 2.95% of the energy needs of EU’s transport sector with advanced bioethanol from wheat straw and maize stover. EU’s renewable energy policy sets a minimum target of 3.5% from advanced biofuel/biogas in the transport sector’s final energy use by 2030. Despite the growing use of biofuels in the transport sector, EU’s total bioethanol production (conventional and advanced) was only 5.84 billion liters in 2017 (0.91% of the EU’s transport sector needs), while the share of advanced bioethanol production in 2017 was 250 million liters (0.04%) (ePure, 2017). Considering that the transport biofuels are forecasted to grow by 0.5%/year between 2019-2024 (IEA, 2019b), some serious breakthrough in advanced biofuel production is required to reach the minimum target of 3.5% or approximately 22.5 billion liters (479 PJ) of gross bioethanol by 2030.

4.3 Limitations and uncertainties

We acknowledge that there is uncertainty associated with the data utilized in this study. Specifically, crop yields, harvested area and crop production data was obtained for a single year, while in reality there may be interannual variations. Also crop productivity improvements can result in higher bioethanol output and smaller footprints. For instance, increasing crops yields by 10% leads to a 7%

increase in bioethanol production per hectare for wheat straw and 9% for maize stover, and a 9% reduction in land and 7% reduction in carbon footprints for both feedstock while the water footprint stays essentially unchanged. We also assumed equal fertilizer, pesticide and diesel energy input for all EU countries. In reality, such inputs can vary between individual countries and affect the gross to net conversion as well as the carbon footprint of net bioethanol in individual countries. Given the large uncertainty regarding the GHG emissions associated with enzymes production, emissions from this process is not included in the carbon footprint calculation. Previous studies have reported different GHG emission ranges from enzymes production and use, from 3.3-3.6 g CO_2eq MJ^{-1} of lignocellulosic bioethanol (MacLean and Spatari, 2009) to 2-22 g CO_2eq MJ^{-1} (Gilpin and Andrae, 2017) and 18-30 g CO_2eq MJ^{-1} (Olofsson et al., 2015). Depending on the choice of enzyme related emission factor, the average carbon footprint of lignocellulosic bioethanol in the EU could increase from 10% for both feedstocks (when we assume enzyme related emission factor of 2 g CO_2eq MJ^{-1}) to 155% for wheat straw and 153% for maize stover (when we assume enzyme related emission factor of 30 g CO_2eq MJ^{-1}).

Moreover, the price of crops used in the allocation of footprints over crop and residue outputs were not available for all individual countries or for 2017 and by using prices from a different year or the average price of crops across countries that had the data, results of some countries may have been skewed. Finally, the bioethanol yield from a given feedstock depends on many factors such as the composition of feedstock (cellulose and hemicellulose), cellulose/hemicellulose conversion and recovery efficiency, fermentation efficiency, and ethanol stoichiometric yield (Badger, 2002), and the type of pretreatment. In this study, we used the simplifying assumption to associate a mass of wheat straw and maize stover with a stable bioethanol yield based on the crop-residue-specific values reported in literature.

5. Conclusion

This paper assessed the EU's advanced bioethanol production potential and evaluated the land, water and carbon footprint of this sort of bioethanol. The advanced bioethanol production potential in the EU was assessed per member state using country-specific wheat straw and maize stover production data. The findings of this study lead to two major conclusions. First, the environmental footprint of advanced bioethanol from wheat straw and maize stover is not necessarily smaller than the environmental footprint of conventional bioethanol. Second, current and forecasted advanced bioethanol production is not on track to provide a significant contribution towards achieving the minimum policy target of 3.5% by the year 2030.

The environmental footprints of advanced bioethanol calculated in this study vary greatly between EU countries. Since the environmental footprints of conventional bioethanol also vary depending on the feedstock used, it is difficult to compare the environmental footprints of conventional and advanced bioethanol without specifying the country of production for the advanced bioethanol and the feedstock for the conventional bioethanol. Average land, water and carbon footprints of EU's advanced bioethanol from maize stover are smaller than the respective footprints of conventional bioethanol from maize. In contrast, average land, water and carbon footprints of advanced bioethanol from wheat straw are larger than the respective footprints of conventional bioethanol from sugar beet or sugarcane.

At current rates, advanced bioethanol production from crop residue is not likely to provide a significant contribution towards achieving a minimum policy target of 3.5% by 2030. The best solution would be to reduce our energy use in the transport sector and utilize other renewable fuels and electricity to significantly lower transport-related emissions. Moreover, advanced bioethanol production can lead to emission savings but may also have adverse effects like increased soil erosion and degradation. Hasty decisions in promoting advanced bioethanol production without understanding and addressing different production-related challenges can leave us in a situation where we have more problems than we anticipated.

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