INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

The Carbon and Food Opportunity Costs of Biofuels in the EU27 plus the UK

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1 Background and objectives

The European Renewable Energy Directive (RED) was introduced in 2010, setting a 10% renewable energy target for transport by 2020 for each member state. Its main effect has been to promote the use of crop-based biofuels across Europe (primarily rapeseed, palm and soy oil for biodiesel; and corn, wheat and sugar beet and sugar cane for bioethanol). With the promotion policy for biofuels, the environmental impacts and sustainability conflicts also became clearly apparent. The previous niche market for domestic rapeseed diesel became global. For the fulfilment of blending quotas, biodiesel from palm oil and ethanol from sugar cane are blended into the fuels.

As a consequence, vast areas of land across the world were occupied to grow the crops for these fuels. The issue of land use change became the key question about the pros and cons of crop-based biofuels. While direct deforestation through new plantations and fields could be excluded from the certification required by the RED, the issue of indirect land use change (iLUC) was far more complex, as it cannot be attributed to a single producer. However, the GHG balances including iLUC indicate in most cases that a net saving of greenhouse gases (GHG) emissions by biofuels compared to fossil fuels can hardly be accounted for any more.

The iLUC Directive in 2015 and finally RED II in 2018 addressed the issue by capping biofuels from food and feed crops. Provided that these caps are adhered to, hardly any additional production areas can be attributed to biofuels consumed in Europe. However, the existing areas for biofuel cropping are very extensive worldwide, and Europe is one of the largest producers and largest markets for biodiesel globally.

But what does the large-scale presence of agricultural land for biofuel production mean in an overall balance for climate change? An alternative to the production of substitutes for fossil fuels would be to reallocate these areas to build up biogenic carbon stocks, e.g. by allowing natural forest growth. Both are not achievable on the same area – even though efforts are being made to increase carbon in agricultural land through improved methods. Thus, the cultivation of fuel crops misses out on the opportunity of actually storing large amounts of carbon – the carbon opportunity costs of crop-based biofuels.

The goal of this study is to determine the carbon and food opportunity costs of crop biofuels, incl. biomethane, that are produced and consumed in the EU27 and the UK (henceforth 'Europe'). This study provides new analyses on biofuels and integrates existing analyses on biomethane (see the note below).

To do this, we present an approach to quantify the carbon and food opportunity costs and in a qualitative rather than quantitative way and also the ecological opportunity costs of crop biofuels which are both produced and consumed in Europe, including biofuels or biofuel feedstock produced outside, i.e. imported from third countries.

Thus, the targeted outcome is an estimate of how much carbon could be sequestered and stored if the large land areas currently reserved for either crop biofuels or biomethane (both within Europe and abroad for imported crop biofuels) were restored to or allowed to revert to their (near) natural state of forest, wetland, grassland or other natural vegetation. These forgone carbon savings will then be compared to the CO_2 reductions reported by the EU for the use of crop biofuels and biomethane.

Moreover, the study gives an estimate of the amount of food that could be freed up or grown on these lands, if those were not dedicated to the production of biofuels and biomethane.

The aim of our modelling is to move the public and political discourse around crop biofuels beyond the pros/cons of specific feedstocks and towards a better understanding of land as a scarce and precious resource. It should help to provide a positive vision of how we can shift to better land use practices which truly address the climate, food and biodiversity crises.

Note:

The scope of this study focusses primarily on transport fuels, including biomethane, where it is accounted for as a transport fuel. Furthermore, the study also considers biomethane produced in Europe for other energy applications and used directly or injected into the gas grid in total, because technically the same biomethane could also be used as transport fuel.

2 Methodology and data

2.1 Research questions

The focus of this study is to compare the officially reported emission savings from blending biofuels with fossil fuels on the one hand, and the carbon opportunity costs arising from the land requirements of biofuel production on the other. This requires a step-by-step analysis, which is divided into several sub-questions.

1. What quantities of crop biofuels and biomethane are produced and consumed in Europe?
2. How much land is occupied for the production of these crop biofuels and biomethane?
3. How much of this land would have to be set aside for solar power generation in order to supply an equivalent number of electric cars with electricity as is the case today with crop biofuels and biomethane?
4. Which (near) natural vegetation/ ecosystems could potentially cover the respective cropland and how much carbon could be stored by regrowth of such vegetation?
5. What are the carbon opportunity costs (COC) of crop biofuels and biomethane consumed in the EU and how do these COC compare to the reported GHG emission intensities and GHG savings from crop biofuels and biomethane?
6. How much food could be produced on the land currently occupied for biofuels and biomethane consumed in Europe?
7. Which additional ecological benefits, in particular with regard to biodiversity, would result from using the land areas in question for rewilding/ ecosystem restoration instead of crop biofuel and biomethane production

2.2 Approach, workflow and data

From a spatial perspective, this study covers the volume of biofuels produced and consumed in Europe. The data basis refers to the year 2020, because this is the most recent year for which data is available from the EU member states' and UK's responsible authorities. The data for 2021 have not yet been published in full. The study also reflects on development trends in recent years with regard to the type of biofuels consumed in individual states and Europe as a whole.

With regard to the fourth research point, the potential rewilding of biofuel cultivation areas is a dynamic process whose development must be considered over a longer period of time. With a view to 2050, as the central target year of climate policy, the consideration period for carbon storage in the course of natural vegetation development is set at 30 years. The annual saving of GHG emissions (represented by the data situation in 2020) is compared to a 30-year average value of annual storage of CO_2 in natural growth.

Figure 1 provides an overview of the individual steps within the workflow. These are described in more detail below and the data sources used in each case are stated.

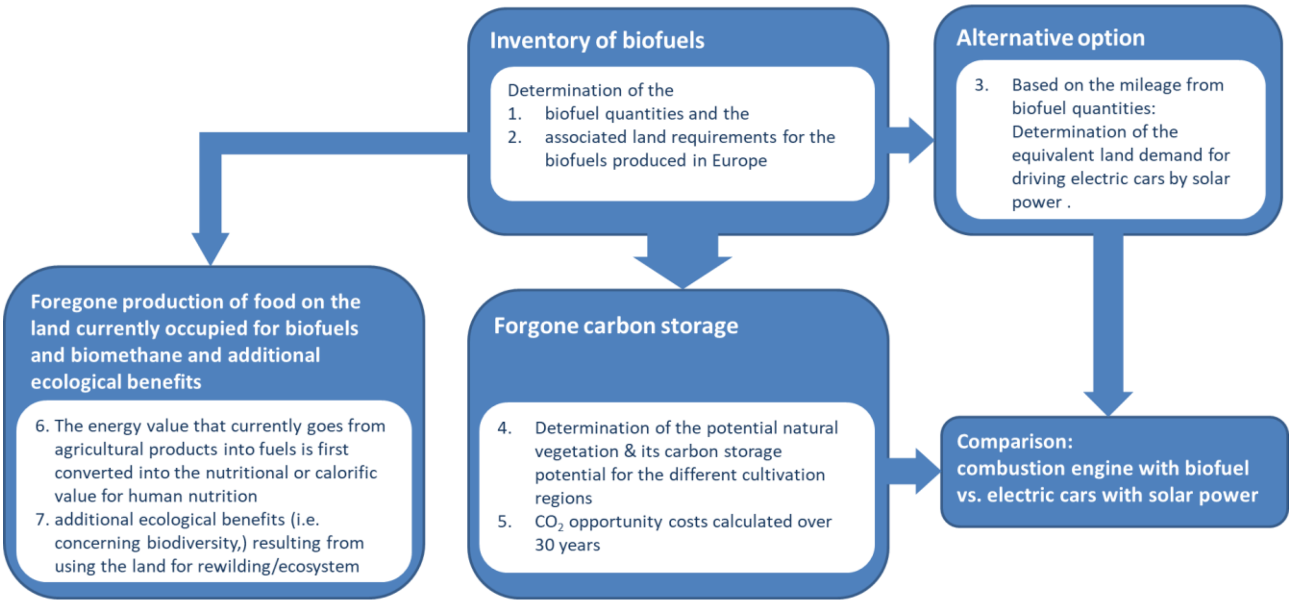

Figure 1: Workflow of tasks following the research questions 1 to 7; Source: ifeu

1. About quantities of crop biofuels and biomethane

The questions are:

a. What quantities are **produced** annually in Europe, broken down by types of fuels (biodiesel, hydrogenated vegetable oils (HVO), ethanol, biomethane etc.) and by type of crops (maize, wheat, rapeseed, palm oil etc.).

b. What quantities are **consumed** annually in Europe? Again, this will be broken down by feedstock and in this case also by country of origin – including volumes produced in and imported into Europe, minus those exported.

While the focus is on the issue of consumption (i.e. the amount of biofuel refuelled in Europe and accounted for the fulfilment of the RED mandates), the analysis of production only intends to give an estimation of the amount based on cultivation within Europe.

Data sources:

For quantities **produced** annually in Europe, the available national sources are collected, analysed and aggregated as well as data already prepared for the complete EU and UK; in particular, the GAIN reports by the Foreign Agriculture Service of the USDA (Flach et al. 2021). Two points should be noted about this data source. First of all, the production data include volumes exported from European countries. However, according to the current state of knowledge, exports of biofuels from European countries generally remain within the EU and are rarely exported beyond EU borders. This perception will be tested for plausibility.

Secondly, it should be noted that the GAIN report mainly shows the production volumes and capacities of biofuel production plants. If such plants process imported feedstocks, this is not evident from this data basis. In other words, the GAIN reports give no clear indication about the volume of crops grown for biofuel within Europe. The GAIN report therefore does not provide any information on the origin of the feedstocks and there is also no information on the type of crops.

Another data source is the EurOberserv'ER, in particular the RES in Transport barometer 2021 (EurObserv'ER 2021).

In order to explore this in more detail, reports of individual member states were analysed – which was necessary above all to obtain a sufficient data basis for **consumption**. Within the scope of this study, it was not possible to do this for each country. However, an extensive amount of country data was collected, which made it possible to establish a sufficiently good basis for this study. Another overarching data source for individual national information on the biofuel consumption situation is the EEA's EIONET database (EEA 2022a).[1] Unfortunately, however, access to the national reports is obstructed for many member states. Therefore, it turned out to be all the more important to research and analyse directly national reports. However, within the scope of this study, it was not possible to analyse the production and consumption situation for each individual member state.

Therefore, the focus is on the largest biofuel users, gaining a coverage of nearly 80 %. The total biofuel consumption in the EU27 plus UK is completed by plausible estimates.

Table 1: Explored member states' data for biofuels consumed at national level in the transport sector

Member state	Biofuel volume (2020) (PJ)	Share of crop-based biofuel	Report/ source
Germany	168	72.4%	(BLE 2021)
France	134	87.0%	(MTE 2021)
Sweden	72	35.2%	(STEM 2021)
UK	71	19.7%	(EEA 2022a)
Spain	64	66.1%	(MITECO 2021)
Italy	36	29.6%	(GSE 2021) (EEA 2022a)
The Netherlands	36	18.6%	(NEA 2021)
Austria	18	97.7%	(EEA 2022a)
Portugal	11	43.6%	(ESG and LNEG 2021)
Denmark	9	86.6%	(EEA 2022a)
Luxembourg	5	61.1%	(EEA 2022a)
Slovenia	3	18.8%	(EEA 2022a)
Total selected countries	**627**	**371 PJ** / 59.1%	
Total Europe GAIN report	**722**	no data	(Flach et al. 2021)
Total share covered by selected MS data	**79.4%**		
Total Europe EurObserv'ER [a)]	***661***	*475 PJ / 72%*	(EurObserv'ER 2021)

a) Data from EurObserv'ER here only for additional information, since in a number of cases the data do not comply with reports from member states; moreover, EurObserv'ER does not include UK data any more since 2020.

[1] https://cdr.eionet.europa.eu/ReportekEngine/searchdataflow

2. Land occupied for the production of these crop biofuels and biomethane

Based on the quantification of biofuels consumed, the land occupied by these quantities will be assessed by distinguishing between land

a. in Europe

b. abroad, for export to Europe

Data sources:

Data representing average yield by crop and region will be applied.

Average yield per hectare for each feedstock used to calculate the land area used per feedstock grown in Europe are taken from (Baruth et al. 2022). Yield data for crops grown outside Europe are taken from BioGrace (ifeu 2015).

If co-products are produced in biofuel production, the land for the crops is allocated according to the energetic shares of the co-products. This method thus follows exactly the rules of RED II for the **allocation of co-products**, which is used to calculate GHG emission savings (see Figure 2). The allocation is proceeded by applying also the BioGrace tool.

In a parallel additional analysis, the allocation of co-products is disregarded to see how much additional food could be produced if feed production for livestock farming were reduced at the same time.

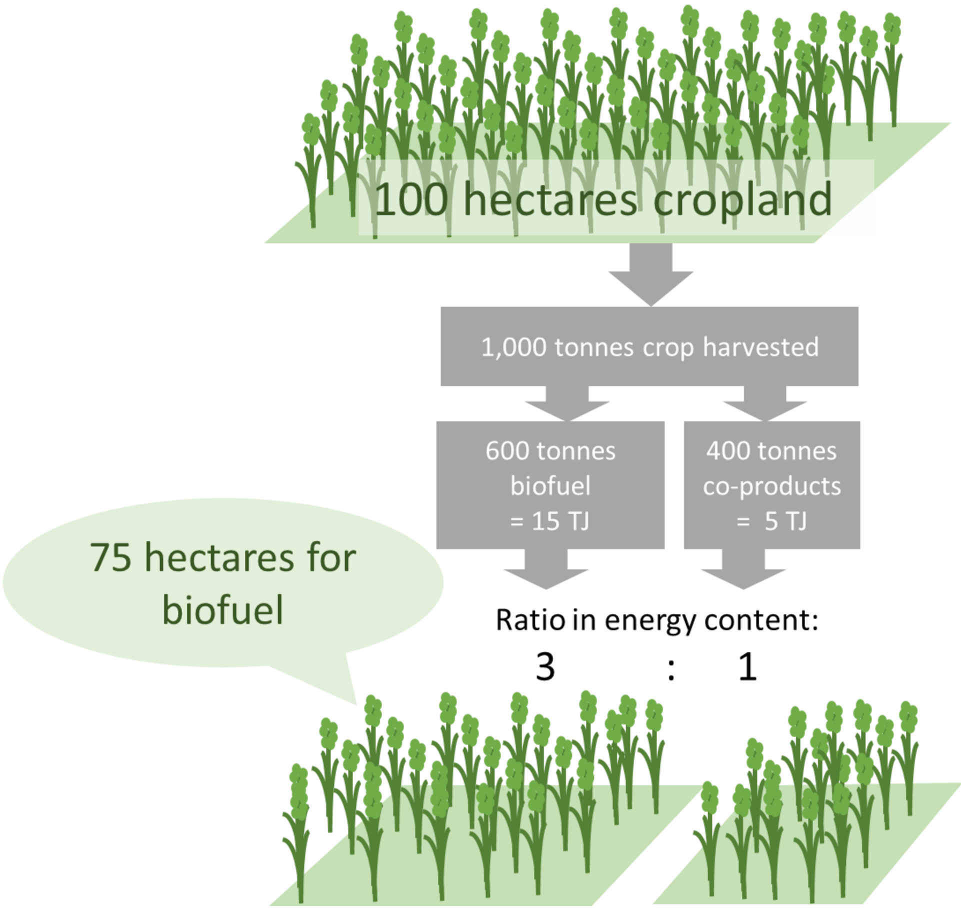

Figure 2: Spatial scope of land occupation considering the allocation to biofuel and co-products in line with the rules of the RED II by exemplary numbers; illustration ifeu

3. Comparing the land required for biofuel production with the equivalent land required to power electric cars using solar energy

The volume of biofuel consumed in Europe is connected with a certain mileage. At this point, the area which is needed to achieve the same mileage with an electric car is estimated. The most land-intensive renewable sources of electricity (RES-E) after biofuel – ground-mounted PV – is used.

Data sources:

For comparability, a similar technical status is assumed for the combustion engine and the electric vehicle. The applied data refer to (Helms et al. 2019), (EU Commission et al. 2020) and (Fehrenbach and Bürck 2022).

4. Determining the (near) natural vegetation/ ecosystems potentially covering the respective cropland and estimating the carbon stored by regrowth of such vegetation

The land areas occupied for producing the biofuel consumed in Europe will be assigned to vegetations zones. In Europe (and also most other climate zones), forest ecosystems will generally be the natural climax vegetation.

We will consider the time period from 2020 until 2050 and apply typical/ average carbon sequestration and storage values for the different climate zones and natural ecosystems according to the assignment of sequestration rates in (Fehrenbach and Bürck 2022).

The derivation of the storage rates is as follows:

1.) The primary production region (large climatic regions) of the energy crops is identified

2) The vegetation type corresponding to this production region is determined from public sources (EU Commission 2010).

3) To calculate the storage rate, the difference in carbon content between the managed area and the natural vegetation form is determined and divided by 30, given the assumption that the natural vegetation form develops within 30 years.

More detailed information about the approach is given in chapter 3.4.1.

Data sources:

The Assessment refers to official data from (IPCC 2006) and from the EU decision on carbon stocks (EU Commission 2010). From further recent science we will determine factors representing the removal of CO_2 by the (re-)growth of the natural vegetation.

5. Calculating the carbon opportunity costs of crop biofuels and biomethane consumed in the EU

The GHG emission savings from crop-based biofuel consumption in Europe (= GHG emissions from biofuel production minus the GHG emission from production and use of substituted fossil fuels) will be compared to the forgone C-storage on the land occupied for biofuel production. The latter describe the carbon opportunity costs of the crop-based biofuels.

Data sources:

First, the GHG emissions from biofuel production have to be estimated based on the quantities of crop biofuels and biomethane figured out under task 1 (chapter 3.1) and combined with emission factors taken from literature. Two major sources will be applied: one is a generic data base: the TREMOD data base (Allekotte et al. 2020); the other represents a detailed analysis but also an optimistic situation: the report for biofuel use in Germany by (BLE 2021). The latter may be justified since the German share of European biofuel is rather high. The authors consider the official German data to be optimistic, since they include relevant minus-emissions from carbon capture and replacements (see also chapter 3.5.1).

The calculation of COC is already an output of the previous task.

6. Foregone production of food on the land currently occupied for biofuels and biomethane

Instead of allowing the natural vegetation to rebuild, the land could be also used for other purposes, e.g. food production or extension of organic farming. This step is primarily intended to make clear the dimensions of possible alternative use options.

The energy value that is currently converted from agricultural products into fuels is first converted into the nutritional or calorific value for human nutrition: for how many people can this cover the calorie requirement.

Data sources:

The yield data applied under task 2 will also be applied for this task. A comparison is also made using the EU Shares data[1] which shows the area occupied by renewable energy for all member states.

7. Estimating additional ecological benefits, in particular with regard to biodiversity

The study focuses on the GHG balance. However, there are also other ecological advantages to be gained by not cultivating biofuel feedstocks. Agriculture is known to be a key driver of biodiversity loss. Rewilding also leads to further ecological opportunity costs of crop biofuels, which are analysed here on a qualitative to semi-quantitative basis. Metrics for "measuring" such ecological costs related to biodiversity loss can be taken from LCA methods.

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[1] https://ec.europa.eu/eurostat/web/energy/data/shares

3 Results

3.1 Quantities of crop biofuels and biomethane in Europe's transport sector

3.1.1 Stocktaking of biofuel production in Europe

The overall volumes of biofuel **produced** in Europe in the year 2020 can be taken from the GAIN report (Flach et al. 2021):

- 4,747 million litres of bioethanol – equalling **101 PJ** referring to the lower heating value of ethanol
- 15,334 million litres of biodiesel and hydrotreated vegetable oil (HVO) – equalling **535 PJ** referring to the lower heating value of biodiesel and HVO

The GAIN report does not include biomethane production in total.

Most relevant crops grown in Europe for **bioethanol** are maize (corn), wheat and sugar beet. Triticale, rye and barley are of lesser importance. Ethanol from residues (ligno-cellulose) accounts for less than 1 %.

Biodiesel from crops grown in the EU is largely based on rapeseed. Only a few percent are based on sunflower. The GAIN data also include biodiesel processed in Europe and HVO based on imported palm and soybean oil. Besides, Europe imports rapeseed from outside the EU to be processed into biodiesel in the EU.

The GAIN report (Flach et al. 2021) does not really investigate the production of **biomethane** for transport. They just mention one plant in Germany processing straw, which is considered a residue and not a crop and is therefore counted as an advanced biofuel.

In chapter 3.1.2, the biomethane volume consumed in 2020 in the transport sector was calculated to 8.6 PJ. Just 0.6 PJ are produced from crops.

As shown in chapter 3.1.3, the total production of biomethane in Europe in 2020 has reached 115 PJ, steadily growing since 2011 (European Biogas Association 2022a).

3.1.2 Stocktaking of biofuel consumption in Europe

The overall volumes of biofuel **consumed** in Europe in the year 2020 again can be taken from the GAIN report (Flach et al. 2021):

- 5,495 million litres of bioethanol – equalling **117 PJ,** referring to the lower heating value of ethanol;

- 18,195 million litres of biodiesel and hydrotreated vegetable oil – equalling **605 PJ,** referring to the lower heating value of biodiesel and HVO[1]

Major consumers are Germany, France, Spain, the UK, Sweden, Italy, Poland and the Netherlands.

As explained in chapter 2.2, the information given by the GAIN report is not detailed enough to disclose the crop base and the origin of crops for biofuel consumed in Europe. Thus, reports or data sets of 11 individual member states plus the UK were intensively analysed. This selection covers the European biofuel consumption by approx. 80 %. The result from this investigation is aggregated in Table 2, showing:

- 82.0 PJ ethanol, of which 75.0 PJ are crop-based (91.5 %)
- 518 PJ biodiesel and HVO, of which 284 PJ are crop-based (55 %)
- 8.6 PJ biomethane, of which 0.6 PJ are crop-based (7 %)

Table 2: Biofuel consumption in Europe's transport sector; aggregation of reports from 11 EU member states including the UK

	Fuel type and feedstock	Total	Origin: Domestic	EU 3rd countries	Non EU Europe	SE Asia	Centr./S. America	Australia	Others
			all figures in PJ/a						
Biodiesel/ HVO	**Biodiesel/ HVO total**	**517.9**	57.8	155.3	11.1	197.0	47.5	9.8	39.6
	rapeseedME	135.1	39.8	61.2	3.6	0.0	0.0	8.7	21.8
	sunflowerME	7.8	0.2	7.6	0.0	0.0	0.0	0.0	0.0
	palm oil ME	42.1	0.0	0.1	0.1	36.2	5.7	0.0	0.0
	palm oilHVO	55.7	0.0	0.0	0.0	55.7	0.0	0.0	0.0
	palm oil CP HVO	1.4	0.0	0.0	0.0	1.4	0.0	0.0	0.0
	soybeanME	42.2	0.0	0.4	0.3	0.0	38.2	0.0	3.3
	UCOME & HVO	157.6	10.7	28.1	0.0	104.7	0.8	1.1	12.4
	tallowME &HVO	56.9	3.9	42.3	7.1	1.6	0.0	0.0	1.9
	other waste	16.1	0.3	15.7	0.0	0.0	0.0	0.0	0.1
Bioethanol	**Bioethanol total**	**82.0**	19.3	27.9	23.5	0.0	5.4	0.0	5.8
	maize EtOH	41.6	5.4	10.7	20.0	0.0	0.0	0.0	5.4
	wheat EtOH	15.8	5.1	8.4	2.2	0.0	0.0	0.0	0.1
	other cereal EtOH	5.8	2.1	3.5	0.0	0.0	0.0	0.0	0.2
	sugarbeet EtOH	6.5	2.8	2.3	1.4	0.0	0.0	0.0	0.0
	sugarcane EtOH	5.4	0.0	0.0	0.0	0.0	5.4	0.0	0.0
	residues	6.9	3.9	3.0	0.0	0.0	0.0	0.0	0.1
Biomethane	**Biomethane**	**8.6**	8.0	0.6	0.0	0.0	0.0	0.0	0.0
	residues	8.0	7.4	0.6	0.0	0.0	0.0	0.0	0.0
	maize methane	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL SUM		**608.4**	85.0	183.8	34.6	197.0	52.9	9.8	45.4
SUM CROP-BASED		**360.0**	56.0	94.2	27.5	93.3	49.4	8.7	30.9

[1] Assuming the same ration between biodiesel (77 %) and HVO (23 %) as given by production in Europe with lower heating values of 33 MJ/litre Biodiesel and 34 MJ/litre HVO according to RED II annex III.

In order to complete the picture of biofuels in Europe, the inventory of countries missing in the aggregation in Table 2 has to be derived by assumptions. Taking the GAIN report as reference, this missing volume is:

- 35.0 PJ bioethanol (30 % of the total)
- 86.8 PJ biodiesel and HVO (14 % of the total)

The major countries missing in the aggregation are given in Table 3, attributed by further data from the GAIN report and the (EurObserv'ER 2021). As mentioned above, the different data sources are not completely consistent, but they can serve to sort the missing information and to allow an approximation for the complete picture.

This approximation is done as follows: According to the data in Table 3 for Biodiesel/ HVO based on EurObserv'ER, the share of crop-based biodiesel/ HVO of the listed number of countries is 75 %, for bioethanol it is 78 %. Thus, 75 % of the remaining biodiesel/ HVO (i.e. 65.1 PJ) will be assigned to crop-based biofuel, as the major countries Poland or Romania are likely to focus on domestic crops such as rapeseed and sunflower seed.

For ethanol, 78 % of 35 PJ (i.e. 27.4 PJ) will be assigned to crop-based biofuel, most likely based on wheat or corn.

Table 3: Biofuel consumption in Europe's transport sector; aggregation of reports from 11 EU member states including the UK

Fuel type	Member state	GAIN report (PJ) (Flach et al. 2021)	EurObserv'ER (PJ) Total	Waste/residue based	Crop-based
		all figures in PJ/a			
BIODIESEL/ HVO	Poland	32	36.2	0	36.2
	Finland	15	12.7	12.7	0
	Romania	13	13.2	0	13.2
	Belgium	10	23.8	1.6	20.2
	Hungary	9	6.5	4.9	1.6
	Czech Rep.	n.n.	12.9	2.2	12.7
	Greece	n.n.	5.7	0.8	4.9
	Ireland	n.n.	6.5	6.5	0
	Slovakia	n.n.	5.7	1.3	4.4
	Bulgaria	n.n.	4.5	1.9	2.6
	SUM	**88**	**128**	**31.9** **25%**	**95.8** **75%**
BIOETHANOL	Poland	7.6	3.8	0	3.8
	Belgium	n.n.	4.1	0.7	3.4
	Romania	n.n	4.1	0	4.1
	Finland	n.n.	3.9	3.9	0
	Hungary	n.n.	2.3	0	2.3
	Czech Rep.	n.n.	2.7	0	2.7
	Greece	n.n.	2.6	0	2.6
	Ireland	n.n.	0.8	0.8	0
	Slovakia	n.n.	1	0	1.0
	Bulgaria	n.n.	1.1	0.3	0.8
	SUM	**7.6**	**26.4**	**5.7** **21.6%**	**20.7** **78.4%**

The resulting complete inventory of crop-based biofuels is given in Table 3, Table 5 and illustrated in Figure 3, while Table 4 gives a step-by-step explanation of the approach applied to complete the figures.

Table 4: Step-by-step explanation of the approach to complete the picture of crop-based biofuel consumed in the Europe's transport sector

PJ	Biofuel 11 MS (incl. UK)			GAIN report	Gap	EurObserv'ER	Gap	Final total
	Total A	Crop-based share B	Crop-based C	Total consumption D	GAIN minus 11 MS incl.UK E	Share crop-based F	Crop-based G	Crop-based H
Bioethanol	82.0	92%	75.0	117	35.0	78.4%	27.4	102.5
Biodiesel (HVO)	517.9	55%	284	604.7	86.8	75.0%	65.1	349.4
Biomethane	8.6	7%	0.6	-	-			0.6
Total	608.4		360.0	721.7	121.8		92.5	452.5
Formula			C = A x B		E = D – A		G = E x F	H = C + G

Table 5: Crop-based biofuel consumption in Europe's transport sector; aggregation of national reports and estimations by ifeu.

	Fuel type and feedstock	Total	Origin: Domestic	EU 3rd countries	Non EU Europe	SE Asia	Centr./S. America	Australia	Others
			all figures in PJ/a						
Biodiesel/ HVO	**Total**	**349.5**	105.2	69.2	4.0	93.3	44.0	8.7	25.1
	rapeseedME	200.2	105.0	61.2	3.6	0.0	0.0	8.7	21.8
	sunflowerME	7.8	0.2	7.6	0.0	0.0	0.0	0.0	0.0
	palm oil ME	42.1	0.0	0.1	0.1	36.2	5.7	0.0	0.0
	palm oilHVO	55.7	0.0	0.0	0.0	55.7	0.0	0.0	0.0
	palm oil CP HVO	1.4	0.0	0.0	0.0	1.4	0.0	0.0	0.0
	soybeanME	42.2	0.0	0.4	0.3	0.0	38.2	0.0	3.3
Bioethanol	**Total**	**102.5**	42.8	25.0	23.5	0.0	5.4	0.0	5.7
	maize EtOH	55.3	19.2	10.7	20.0	0.0	0.0	0.0	5.4
	wheat EtOH	29.5	18.8	8.4	2.2	0.0	0.0	0.0	0.1
	other cereal EtOH	5.8	2.1	3.5	0.0	0.0	0.0	0.0	0.2
	sugarbeet EtOH	6.5	2.8	2.3	1.4	0.0	0.0	0.0	0.0
	sugarcane EtOH	5.4	0.0	0.0	0.0	0.0	5.4	0.0	0.0
Biomethane	**Total**	**0.6**	0.6	0.0	0.0	0.0	0.0	0.0	0.0
	maize methane	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0
SUM CROP-BASED		**452.6**	148.6	94.8	27.5	93.3	49.4	8.7	30.9

Note: The estimation in this chapter based on the analysis of the country report leads to 243 PJ biofuels produced from crops cultivated within the EU27 & UK. This value does not match exactly with the data from the GAIN report (Flach et al. 2021) when adding crop-based bioethanol. This is because the Gain report refers to biofuel production within Europe including biofuels produced within Europe but is based on imported crops.

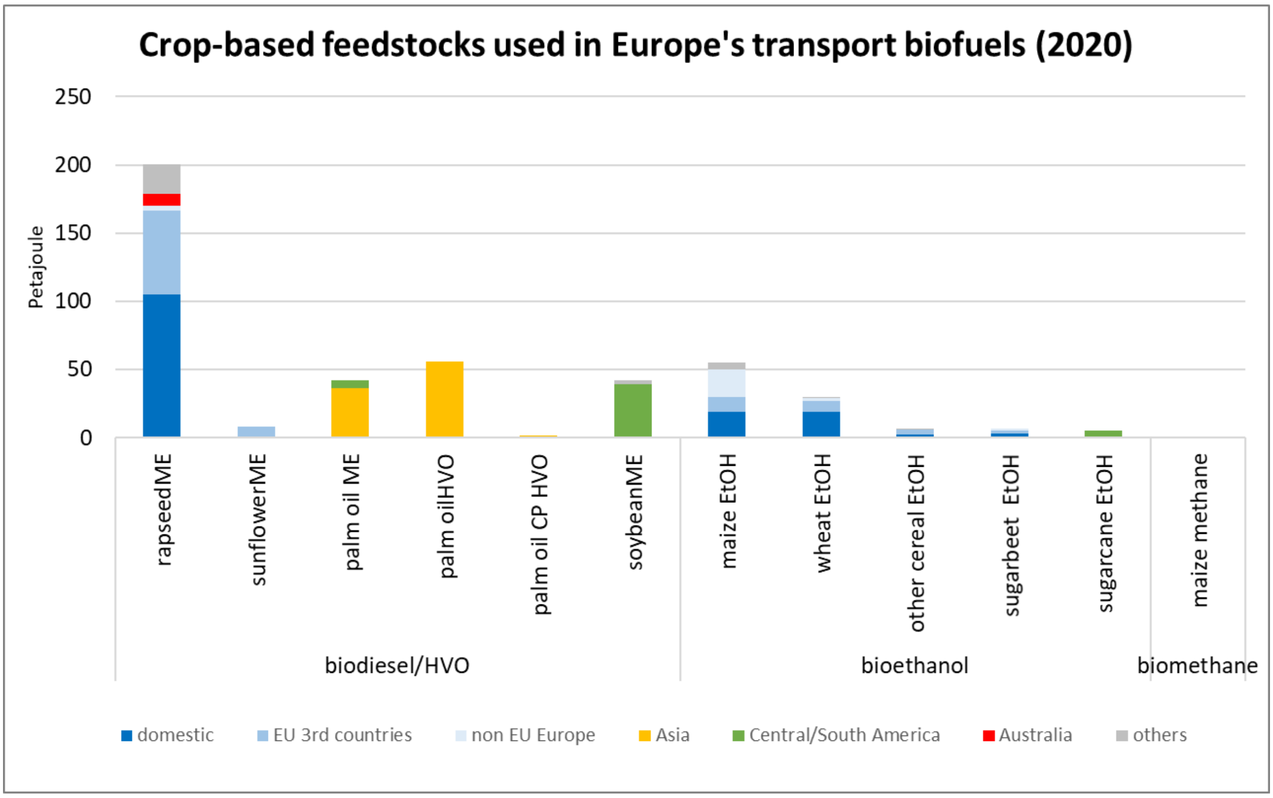

Figure 3: Biofuel consumed in Europe's transport sector in 2020; aggregation of national reports and estimations by ifeu

3.1.3 Stocktaking of biomethane production and consumption in Europe

The chapters above included the biomethane production and consumption in Europe for the transport sector, amounting to 8.6 PJ in 2020. Major producing countries are Sweden and Germany. Just 0.6 PJ are produced from crops, mainly maize, in Germany.

Despite the rather small volumes of biomethane used in the transport sector, biomethane is produced in larger volumes in Europe for electricity and heat purposes. Even greater are the volumes of biogas produced, which can be upgraded to biomethane wherever the technique and infrastructure are available.

The combined biogas and biomethane production in 2020 were approx. 18 bcm (natural gas equivalent, equalling 115 PJ), of which 83% was directly used to produce local power or heat. Only 3 bcm were upgraded to biomethane (European Biogas Association 2022a). Germany is the largest producer of biogas and biomethane (nearly one third of the total volume in Europe), followed by the UK, the Netherlands, Denmark, Sweden, France and Italy (Abdalla et al. 2022), as shown in Figure 4.

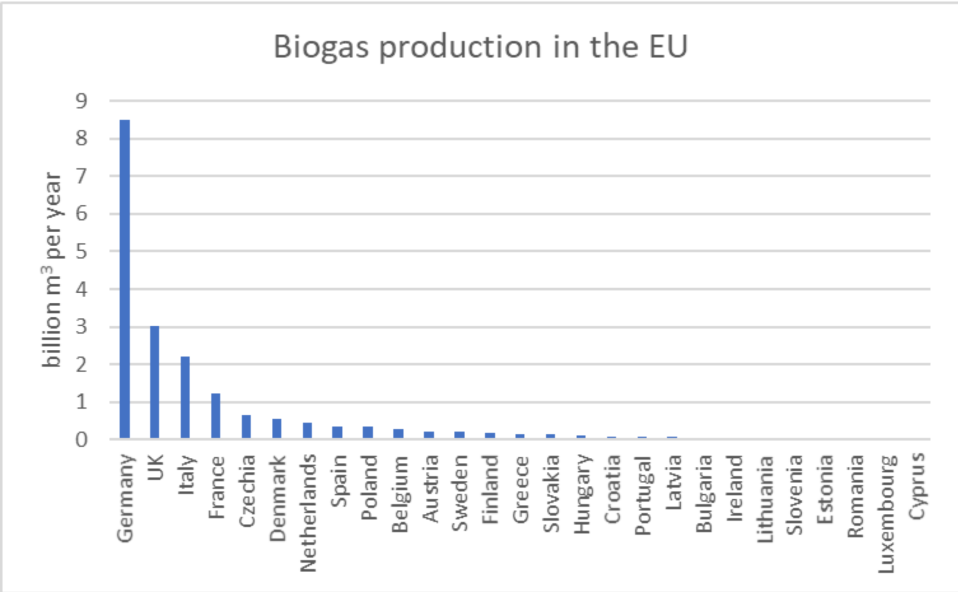

Figure 4: Total biogas production in European countries, in 2018; source: (REGATRACE 2020); illustration (Abdalla et al. 2022)

The composition of the substrates of biogas plants differs significantly among European countries. While the production of sewage and landfill gas has reached a plateau since more than a decade, agricultural material (crops and manure) and biowaste (municipal and industrial) have accounted for the overall increase in biogas production since 2005. In Germany – the largest producer of biogas – the use of energy crops (silage maize, etc.) developed to be the most relevant feedstock, due to high biogas yields and favourable support schemes. In terms of mass input, crops account for slightly more than 50% of the feedstock in German biogas plants. In terms of energy output, 78% are attributed to crops (Daniel-Gromke et al. 2017). Also, in Austria, Italy and Poland, biogas production is based on crops by rather high shares. The utilisation of agricultural residues such as manure is particularly important in countries like Denmark, France, Italy and Germany. In Belgium, the use of industrial organic waste from the food and beverage industry is most relevant, while in Estonia, Poland and Sweden sewage sludge still dominates the biogas market (European Biogas Association 2022a).

Based on data from the (European Biogas Association 2022b) and various evaluations, e.g. (Wouters et al. 2020), it can be seen that the largest feedstock contribution for biogas production in Europe is based on crops, at around 42% in terms of energy (see Figure 5).

The second most important substrate in terms of quantity – agricultural waste, i.e. predominantly wet manure – has a significantly lower gas formation rate. It therefore contributes less than 24% to the total biogas.

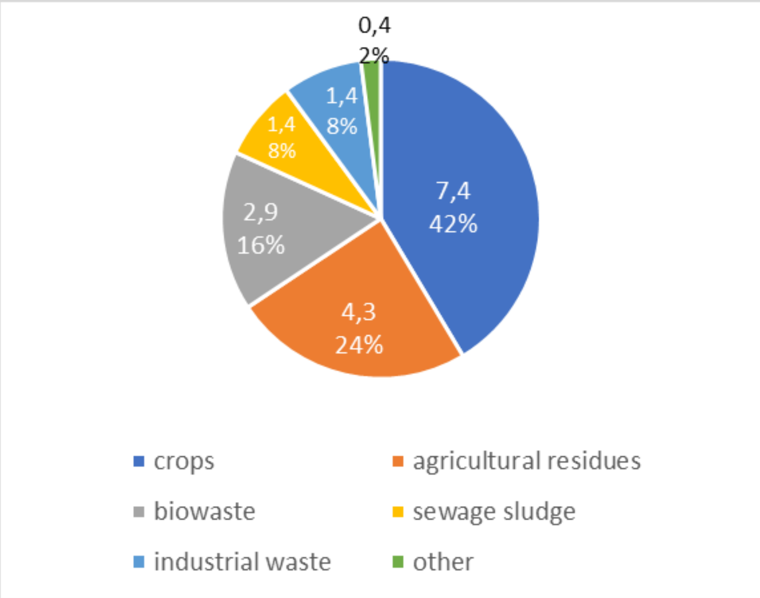

Figure 5: Feedstocks applied for biogas production in the EU in billion cubic meter (bcm) and percent; source: (Wouters et al. 2020); illustration (Abdalla et al. 2022)

3.1.4 Comparison with EU Shares data

The data above are compiled by the authors based on diverse sources, mostly national reports and the EIONET data repository (EEA 2022a).

In this chapter, the results presented above will be compared to data from another European data base: the SHARES (renewables) by (Eurostat 2022a), which samples and provides information on the shares of renewable energy used in Europe and each member state. The data are originally in kilotons oil equivalents (ktoe) and distinguish between energy for electricity, transport, heat and cooling. For transport fuel, those based on waste and residues are also separately identified. Thus, the remaining volume can be assumed to be crop-based.

Regarding biofuel for transport, the SHARES repository provides the data shown in Table 6. These data do not exactly match with the biofuel volumes assessed within this study. Limited to the EU27, the SHARES data are higher overall, especially in relation to crop-based biofuel and also for “other compliant biofuels”, where it is unclear what they specifically represent. On the other hand, waste and residue-based biofuels are represented to a greater extent in the present analysis than in the SHARES repository. Consequently, the data used in this study should be regarded as the more conservative estimate for crop-based biofuels used in Europe.

Table 6: Biofuels accounted for renewable energy in the EU27, according to the SHARES (renewable) data base (Eurostat 2022a)

	SHARES (EU27)		This study	
	ktoe	PJ [b)]	(EU27) PJ	(EU27 & UK) PJ
Compliant biofuels	16,257	681	630	701
Annex IX	4,285	179	192	249
Article 3(4)d first paragraph [a)]	10,808	453	439	453
Other compliant biofuels	1,163	49	n.a.	n.a.
Non-compliant biofuels	66	3	n.a.	n.a.

a) This refers to crop based biofuels
b) Conversion factor: 1 ktoe = 41.868 TJ or 0.041868 PJ

3.2 Land occupied for crop-based biofuels and biomethane

3.2.1 Land area occupied for the production of crop-based biofuels and biomethane consumed by the transport sector in Europe

The task here is to estimate the land occupied in Europe for the production and consumption of the biofuels quantified in chapter 3.1. As for yield factors at European level, the JRC MARS Bulletin - Crop monitoring in Europe (Baruth et al. 2022) is used as a data basis for this purpose. For crops grown outside Europe (oil palm, soybean, sugarcane), yield factors are taken from BioGrace as a proxy, as well as conversion and allocation factors. Table 7 displays the basic data.

Table 7: Estimation of land occupied within the EU27 & UK for the production of crop-based biofuels

Crop	Yield factors (tonne per hectare and year)	Allocation factors [c)]
Wheat	5.84 [b)]	59.5%
Corn/ maize	7.87 [b)]	59.5%
Other cereals	4.5 [b)]	59.5%
Sugar beet	17.2 [a) b)]	71.3%
Rapeseed oil	1.21 [b)]	58.6%
Sunflower oil	1.02 [b)]	62.9%
Sugarcane	22.7 [c)]	100%
Palm oil	4.22 [c)]	91%
Soybean oil	0.52 [c)]	33.4%

a) Dry matter
b) (Baruth et al. 2022)
c) (BioGrace)

The volumes of crop-based biofuels **consumed** in Europe is taken from chapter 3.1.2.

Based on all these data the **total sum of occupied land is 9.64 million hectares - without allocation of co-products.**[1]

Table 8 gives the results **considering allocation of co-products, whereas the total sum of occupied land is 5.27 million hectares.**

Table 8: Estimation of land occupied for the production of crop-based biofuels consumed in the EU27 & UK in 2020 – allocated to biofuels by considering co-products

	Fuel type and feedstock	**Total**	**Origin:** Domestic	EU 3rd countries	Non EU Europe	SE Asia	Centr./S. America	Austra-lia	others
			million hectares						
Biodiesel/ HVO	**Total**	**3.876**	1.441	0.975	0.052	0.570	0.389	0.119	0.329
	rapeseedME	2.742	1.437	0.837	0.049	0.000	0.000	0.119	0.299
	sunflowerME	0.137	0.003	0.133	0.000	0.000	0.000	0.000	0.000
	palm oil ME	0.257	0.000	0.000	0.000	0.221	0.035	0.000	0.000
	palm oilHVO	0.340	0.000	0.000	0.000	0.340	0.000	0.000	0.000
	palm oil CP HVO	0.009	0.000	0.000	0.000	0.009	0.000	0.000	0.000
	soybeanME	0.391	0.000	0.003	0.003	0.000	0.355	0.000	0.030
Bioethanol	**Total**	**1.396**	0.599	0.342	0.330	0.000	0.041	0.000	0.084
	maize EtOH	0.809	0.280	0.157	0.292	0.000	0.000	0.000	0.080
	wheat EtOH	0.432	0.275	0.123	0.031	0.000	0.000	0.000	0.002
	other cereal EtOH	0.084	0.030	0.051	0.000	0.000	0.000	0.000	0.003
	sugarbeet EtOH	0.030	0.013	0.011	0.007	0.000	0.000	0.000	0.000
	sugarcane EtOH	0.041	0.000	0.000	0.000	0.000	0.041	0.000	0.000
Biomethane	**Total**	**0.005**	0.005	0.000	0.000	0.000	0.000	0.000	0.000
	maize methane	0.005	0.005	0.000	0.000	0.000	0.000	0.000	0.000
SUM CROP-BASED BIOFUELS		**5.271**	**2.040**	**1.317**	**0.383**	**0.570**	**0.430**	**0.119**	**0.413**

[1] Extraction meals and glycerine from rapeseed, sunflower seeds, soybean, palm kernels and glycerine from palm oil fruits, dried distiller's grains and solids (DDGS) from ethanol made from cereals, sugar beet slices from sugar beets.

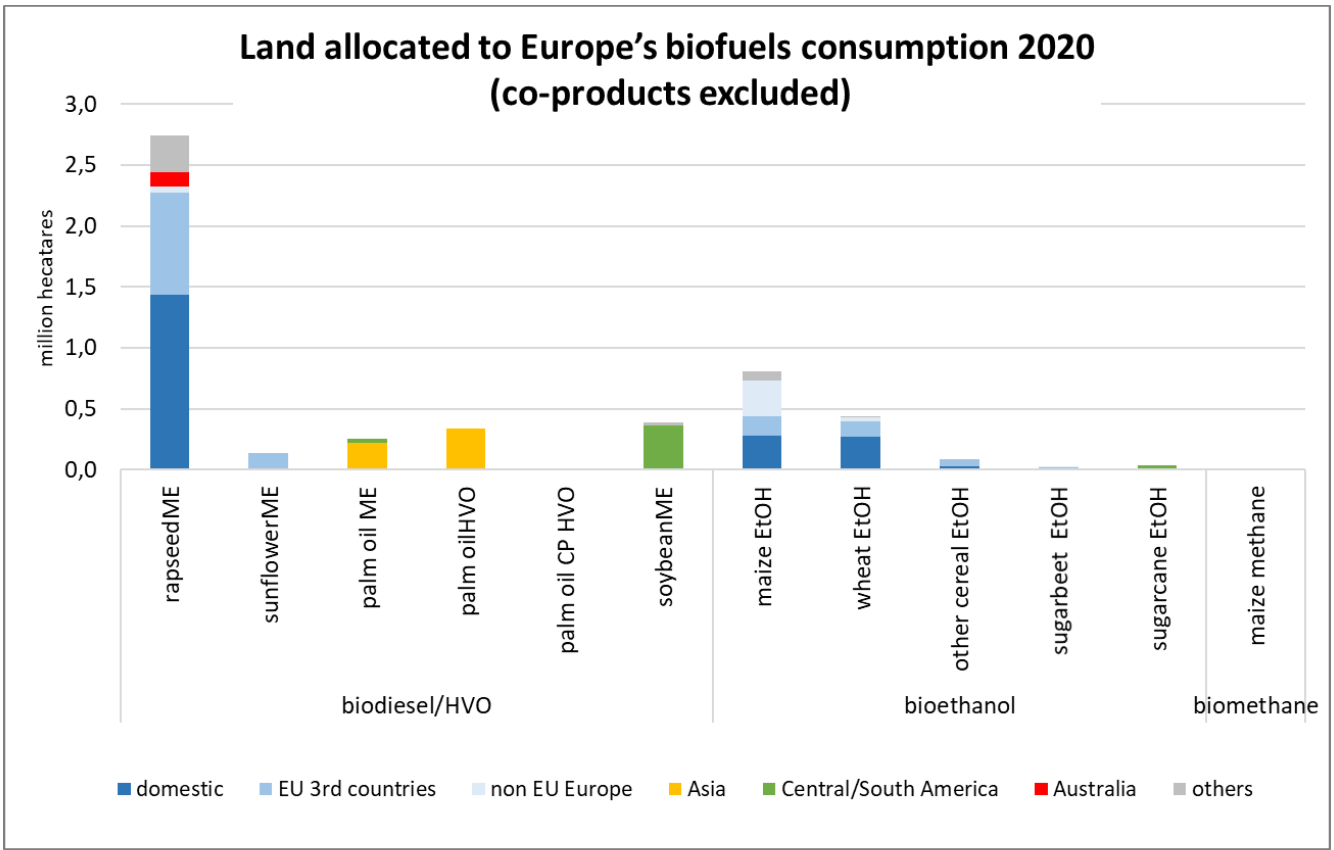

Figure 6: Estimation of land occupied globally for the production of crop-based biofuels consumed in the EU27 & UK in 2020 – considering the share of land allocated to co-products (such as rapeseed meal); calculations and illustration by ifeu

There is a clear predominance of biodiesel from rapeseed, followed by palm oil, bioethanol from maize and wheat, and biodiesel from soybean oil. Just under a third of the crops come from the country where the biofuel produced from them is used. 40% of the crops are imported from other continents. Southeast Asia dominates for palm oil, South and Central America for soy and sugar cane, Australia for rapeseed. The other countries are mainly Canada and the USA.

3.2.2 Land occupied for the production and consumption of crop-based biomethane in Europe in total

Despite the relatively small volume of biomethane in the transport sector, 3 bcm (= 115 PJ) of biogas was upgraded to biomethane in Europe in 2020, as explained in chapter 3.1.3. Based on data from the (European Biogas Association 2022b) and other studies, e.g. (Wouters et al. 2020), the largest feedstock contribution for biogas production in Europe, at around 42% referring to energy, is based on crops (see Figure 5 in chapter 3.1.3). Various crops are used for biogas production, mainly maize, but also whole plants from other cereals or grass cuttings.

Maize is the dominant substrate, mainly because it achieves the highest biogas yields. It is therefore a conservative view if we use the biogas yield of maize for all biogas crops and estimate the land requirements on this basis. The land occupation is figured out by following steps:

- For silage maize as feedstock, BioGrace provides a yield factor of **131 GJ** biomethane per hectare and year (equals 3,430 m^3 per hectare and year);

- Taking 45% of 115 PJ total biomethane production in 2020 results in **60 PJ** crop based biomethane;
- 60 PJ divided by the yield factor results in: **456,000 hectares**.

This value is close to the land occupied in Europe for the production of bioethanol from grain maize (see Table 8).

3.3 Land requirements for crop-based biofuels vs. e-mobility

In the following, the land use for crop-based biofuels is compared to an alternative drive option, which is electromobility based on solar power. Figure 7 demonstrates how the land requirements would change if the driving distance currently travelled with biofuels was instead covered with solar power for electric cars.

For the calculation, the biofuel volume (349.5 PJ of biodiesel and 102.5 PJ of bioethanol, see chapter 3.1.2) is converted to litres,[1] and then multiplied by the fuel consumption of an average medium-sized passenger car of 4.7 l/100 km (Helms et al. 2019). With this amount, a mileage of 329,152 million km can be achieved.

In order to reach the same mileage with electromobility based on solar power, 60.5 TWh of electricity are required, assuming the average electricity demand of an equivalent medium-sized e-car of 18.4 kWh/100 km[2] (Helms et al. 2019). Based on land-use data for ground-mounted photovoltaics (PV) of 22 m^2*a/MWh (Fehrenbach et al. 2021a), the electricity demand is converted into area, assuming efficiency factors typical for Central Europe. Following this calculation, a total of 0.133 million ha will be occupied by PV.

Thus, the area for PV constitutes 2.5% of the entire area occupied for the cultivation of energy crops for biofuels. Consequently, 97.5% of the cultivation area (5.1 million ha) would become available for other options, whether rewilding or cultivation of crops for human nutrition.

[1] in line with the factors in RED II Annex III
[2] the electricity demand of 18.4 kWh is based on the electricity demand of 16 kWh + 15% charging losses from Helms et al. (2019)

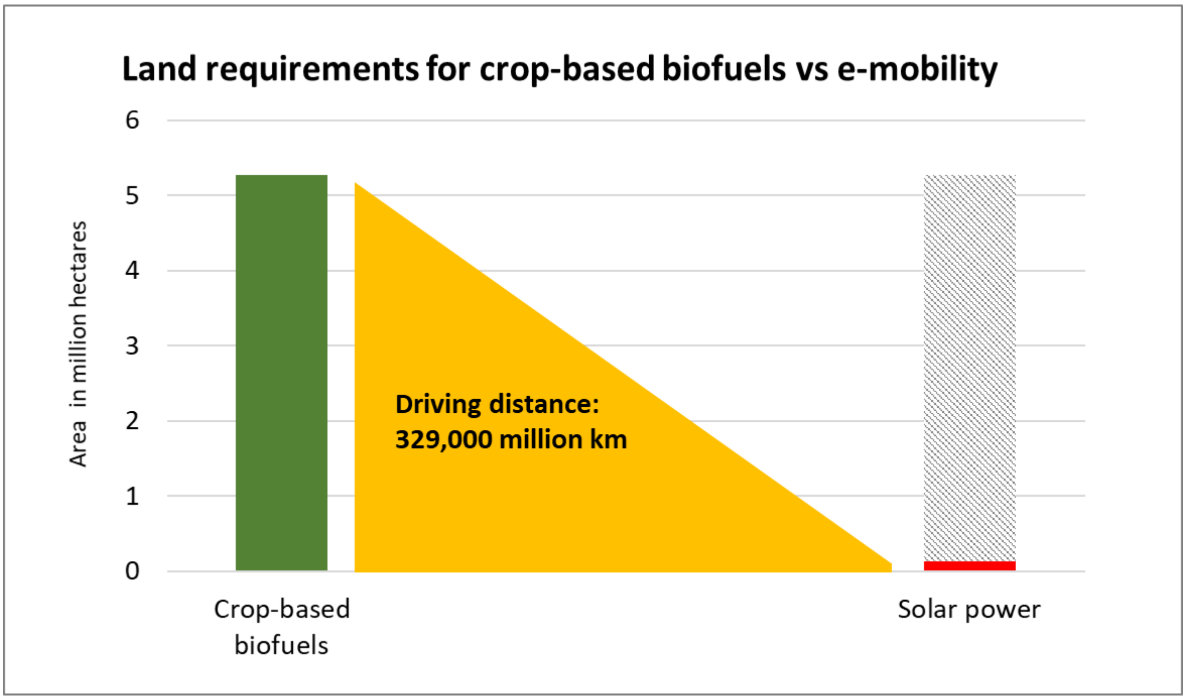

Figure 7: Land occupation of biofuels (consumed in Europe) and the alternative ground-mounted photovoltaics for the provision of the same driving distance; data and calculations see text; illustration by ifeu

3.4 Determining the natural vegetation potentially covering the respective cropland and its carbon storage

3.4.1 Approach

Considering the option of rewilding, which means that the cultivation of energy crops for the European biofuel consumption is not carried out anymore, a total of 5.27 million ha would be available for rewilding. Within this study, the term rewilding refers to the natural regrowth of vegetation on former cultivated land.

Assuming that the option of driving is maintained and that the driving distance is provided with electromobility based on PV (see chapter 3.3), this area would be slightly reduced to 5.1 million ha.

In Central Europe, especially in Germany, primarily forest communities of beech forests would develop if the land was left to itself according to the concept of potential natural vegetation (Suck et al. 2013, 2014a; b). Consequently, it can be assumed that forest communities with beech dominance would develop in Central Europe in the long term on the agricultural land which is currently occupied by energy crop cultivation.

However, as can be seen in chapter 3.2, the cultivation areas are globally distributed. Accordingly, the natural vegetation types that would develop vary geographically.

Table 9 provides an overview of the production regions of the biofuels consumed in Europe differentiated by crop. In addition, Table 9 contains information on vegetation types potentially developing there, based on an assignment of the regions and their corresponding production countries to the ecozones in (EU Commission 2010). According to this, forest systems would develop on the majority of the agricultural areas (mainly for rapeseed and cereals) in Europe, comprising the cultivation regions called "domestic", "EU 3rd countries" and "non-EU Europe". The corresponding potential natural vegetation system from (EU Commission 2010) is called "*Temperate-continental forest, Asia, Europe (> 20 years)*". In line with the procedure presented in 2.2, a carbon sequestration rate of 2.9 t C per hectare and year (t C/ha x a) can be assigned to this vegetation type.

In Asia, where oil palms are cultivated for palm oil, "*Tropical rainforest, Asia (islands)"* with an annual C sequestration rate of 5.67 t C/(ha x a) develops. In South America, where soy and sugar cane are cultivated, "*Tropical rainforest, North and South America"* (6.6 t C/(ha x a)) and "*Scrubland, tropical, North and South America"* (1.6 t C/(ha x a)) develops. For agricultural areas in Australia, which currently are occupied by rapeseed cultivation, a carbon sequestration rate of 1.53 t C/(ha x a) can be assigned – assuming the development of "*Scrubland, tropical, Australia"*. With an annual sequestration rate of 3.1 t C/(ha x a), a mixture of "*Temperate-continental forest, North and South America" (> 20 years)* and Bushland develops on agricultural fields for soy production in North America.

Table 9: Overview of potential vegetation development and associated sequestration rates

Crop	Region	Potential natural vegetation system	C storage rate Rewilding in t C/(ha • a)
Rapeseed	domestic	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Rapeseed	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Rapeseed	non EU Europe	Temperate-continental forest, Asia, Europe (>20 years)	2.90·
Rapeseed	Australia	Scrubland, tropical, Australia	1.53
Rapeseed	others	Temperate-continental forest, North and South America (>20 years)	3.10
Sunflower	domestic	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Sunflower	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Soybean	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Soybean	non EU Europe	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Soybean	Centr./S-America	Tropical rainforest, North and South America	6.60
Soybean	others	Temperate-continental forest, North and South America (>20 years)	0,2-3,1[1]
Palm oil (all)	Asia	Tropical rainforest, Asia (islands)	5.67
Palm oil (all)	Centr./S-America	Tropical rainforest, North and South America	4.60
Maize	domestic	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Maize	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Maize	non EU Europe	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Maize	others	Temperate-continental forest, North and South America (>20 years)	3.10
Wheat	domestic	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Wheat	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Wheat	non EU Europe	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Wheat	others	Temperate-continental forest, North and South America (>20 years)	3.10
Other cereals	domestic	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Other cereals	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Other cereal	others	Temperate-continental forest, North and South America (>20 years)	3.10
Sugar beet	domestic	Temperate-continental forest, Asia, Europe (>20 years)	2.90

[1] As Soy is mostly cultivated in central US, we assume that prairies would develop on these areas. However, the data from EC does not contain such a vegetation type. Therefore, it is assumed that on half of the area forest would develop (3,1 t C/ha x a) and that on the other half bushland (0,2 t C/ha x a) would develop.

Sugar beet	EU 3rd countries	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Sugar beet	non EU Europe	Temperate-continental forest, Asia, Europe (>20 years)	2.90
Sugar cane	Centr./S-America	Scrubland, tropical, North and South America	1.60

3.4.2 Potential carbon storage on the land cultivated for the European biofuel consumption

Considering the entire area which is currently used for the cultivation of biofuel crops for the European biofuel consumption, an **annual carbon sequestration of 66.3 million t CO_2** could take place. These are the carbon opportunity costs (COC) of the crop-based biofuels consumed in Europe.

Figure 8 shows the COC differentiated by region. Especially in Europe, where the main part of the cultivation area is situated, more than half of the carbon storage potential could be realized through rewilding. Besides this, in Asia and South America large carbon storages could develop.

In 2050, a total of nearly 2 billion t CO_2 could be stored, assuming continuous annual carbon sequestration of 66.3 million t CO_2.

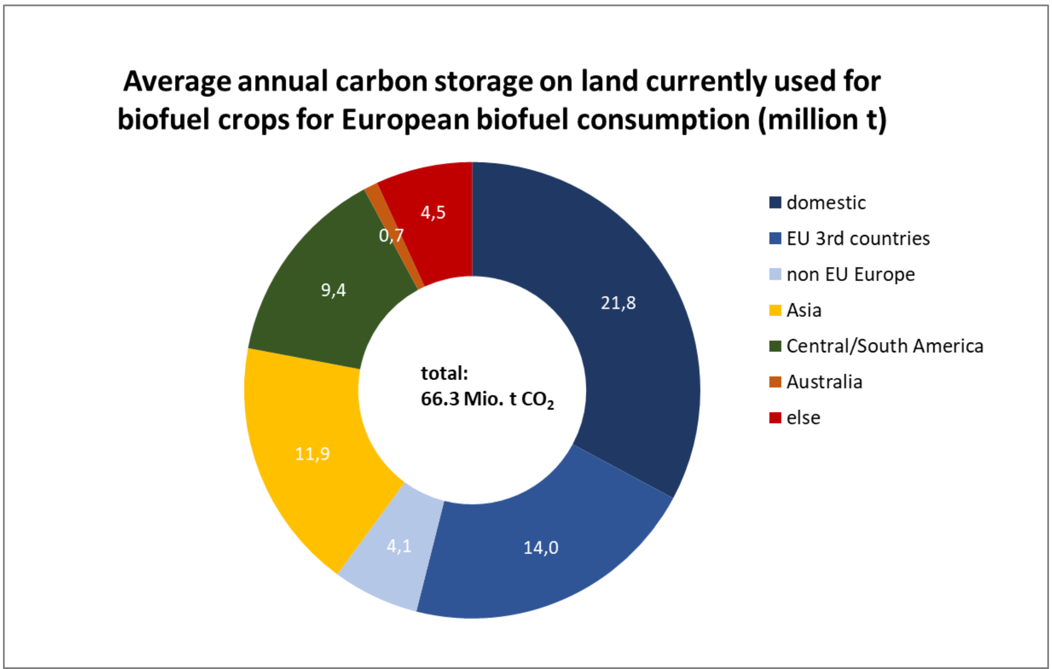

Figure 8: Mean annual CO_2 storage by natural vegetation growth on current cropland for the production of biofuels consumed in Europe; calculations and illustration by ifeu

For information: if the allocation of co-products is disregarded and the total actual acreage for biofuel crops is accounted for, the storage potential increases to 120 million t CO_2. This would be a feasible approach if demand for feed for the industrial livestock farming were reduced as well – a measure that should be considered by policy makers for many reasons.

3.5 Calculating the carbon opportunity costs of crop biofuels and biomethane consumed in the EU

3.5.1 Estimating the GHG emissions and savings of crop-based biofuels and biomethane consumed in Europe

Crop-based biofuels

A number of member states provide national reports about GHG emissions and emission savings due to the consumption of crop-based biofuels. However, there is no official summary of the data in Europe. Thus, an estimation based on reliable sources has to be performed within this study.

The transport emission model TREMOD (Allekotte et al. 2020) provides estimated emission factors (e-factors) based on the assessment of technological potential. These values are clearly below the typical values of the RED II annex V part A. Anyway, they may be considered to be rather conservative.

Alternative and more optimistic data can be taken from (BLE 2021). These data represent the emission intensities as reported by the economic operators via certification systems to the national registry NaBiSy[1] in Germany. They are significantly lower than the TREMOD e-factors. Despite the official acceptance of the BLE data, the authors have some doubt about the real savings connected with some of the reported fuel data. In particular, this concerns the bioethanol production from cereals, where negative emissions are allegedly achieved through carbon capture and substitution (e_{ccr}).

Indeed, the *Note on the conducting and verifying actual calculations of GHG emission savings* (EU Commission 2017) suggests that such credits presuppose that the use of the CO_2 demonstrably replaces fossil CO_2 emissions. However, it is unclear exactly how this proof is to be provided. This raises the question of whether the use of CO_2 as a fermentation by-product from bioethanol production in greenhouses really makes the otherwise deliberate production of CO_2 (beyond the exhaust gases of targeted heating) obsolete.

Table 10: Emission intensities for crop-based biofuels

Emission intensities in g CO_2eq/MJ	TREMOD	(BLE 2021)
Rapeseed oil ME	45	27.6
Sunflower ME	40	24.7
Palm oil ME	41	20.0
Palm oil HVO	36	20.0
Soybean oil ME	40	27.5
Maize/ corn EtOH	25	7.3
Wheat EtOH	25	7.3
Other cereal EtOH	25	7.3
Sugarbeet EtOH	25	14.5
Sugarcane EtOH	10	10.7
Maize biomethane	30	8.9

[1] https://nabisy.ble.de/app/locale;jsessionid=890857DB8012C96C74E177250375FFD5?set=en

Note: These emission intensities are calculated in line with the rules given by the RED II Annex V part C. They don't include emissions from indirect land-use change (iLUC), because according to the RED II rules, these may not be counted towards the emission intensity of biofuels. Direct LUC, on the other hand, would be have to be included. However, it is very unlikely that biofuels with direct LUC will be used in the EU to meet the quota, as this would make it almost impossible to achieve the minimum savings to be fulfilled by each consignment.

The overall GHG emission saving is calculated as follows:

1. The total GHG emission due to crop-based biofuels production for the European consumption in 2020 is
   - 17.3 million tonnes CO_2eq based on the **conservative** emission factors (TREMOD)
   - 9.7 million tonnes CO_2eq based on the **optimistic** emission factors (BLE 2021)
2. The substitution of 452.6 PJ fossil fuel (equivalent to the energetic volume of the crop-base biofuels) corresponds to 42.5 million tonnes CO_2eq.[1]
3. Thus, the total GHG saving due to the substitution of fossil fuel by crop-based biofuels is according to the
   - **Conservative** approach: 25.2 million tonnes CO_2eq. (= 59%)
   - **Optimistic** approach: 32.9 million tonnes CO_2eq. (= 73%)

Biomethane

For biomethane from maize, there are default values according to RED II, resulting from the calculations of the Well-to-Wheels study (Prussi, Yugo, De, et al. 2020). Other sources are (ICCT 2021), BioGrace, or BioEm (Fehrenbach et al. 2016). It is difficult to capture the diversity of possible crops for biomethane production. All the more so because there is no knowledge of the exact composition across Europe.

Since silage maize is considered particularly efficient both in terms of crop yields and biogas formation, it is most favourable for biomethane to use only the emission factor for maize biomethane for the GHG balance. Moreover, the best case is taken from RED II annex VI: typical value, close digestate and off-gas combustion. The resulting emission intensity is 29.7 g CO_2eq/MJ.

According to chapter 3.2.2, the volume of crop-based biomethane in Europe in 2020 is 60 PJ in total. Multiplied with the emission intensity, the GHG emission of crop-based biomethane is **1.78** million tonnes of CO_2eq.

The overall GHG emission saving is calculated as follows with reference to the GHG intensity of EU natural gas. This is 67 g CO_2e/MJ with reference to (Giuntoli et al. 2017) and (Prussi, Yugo, de Prada, et al. 2020). The gross saving therefore is 4.02 million tonnes of CO_2eq. and the net saving **2.24** million tonnes of CO_2-eq. (= 56% saving).

[1] referring to the comparator of 94 g CO_2/MJ according to RED II Annex V part C, point 19

3.5.2 Complementing the GHG savings of crop-based biofuels consumed in Europe with carbon opportunity costs

According to chapter 3.5.1, the consumption of biofuels in Europe in 2021 saved a total of **25.2** (conservative) to **32.9** (optimistic) million tonnes CO_2eq. This figure is calculated from the emissions of 17.3 (conservative) to 9.3 (optimistic) million t CO_2eq. caused by the provision of biofuels and the emissions of 42.5 million t CO_2eq. saved by substituting the corresponding quantity of fossil fuels.

The authors emphasise that these only refer to crop-based biofuels. However, an additional share is accounted for by waste-based biofuels (e.g. used cooking oil).

In Figure 9, the COC of crop-based biofuels presented in chapter 3.4 are compared with the GHG emission savings of the optimistic and conservative view. Whereas a total of 25.2 - 32.9 million t CO_2-eq. are assumed to be saved annually with the production and use of crop-based biofuels according to official figures, a total of 66.3 million t CO_2-eq. could be stored annually on the same area (5.27 million ha in 2021) if natural vegetation were allowed to grow up. Consequently, the COC of crop-based biofuels significantly exceed the official CO_2 savings from their use.

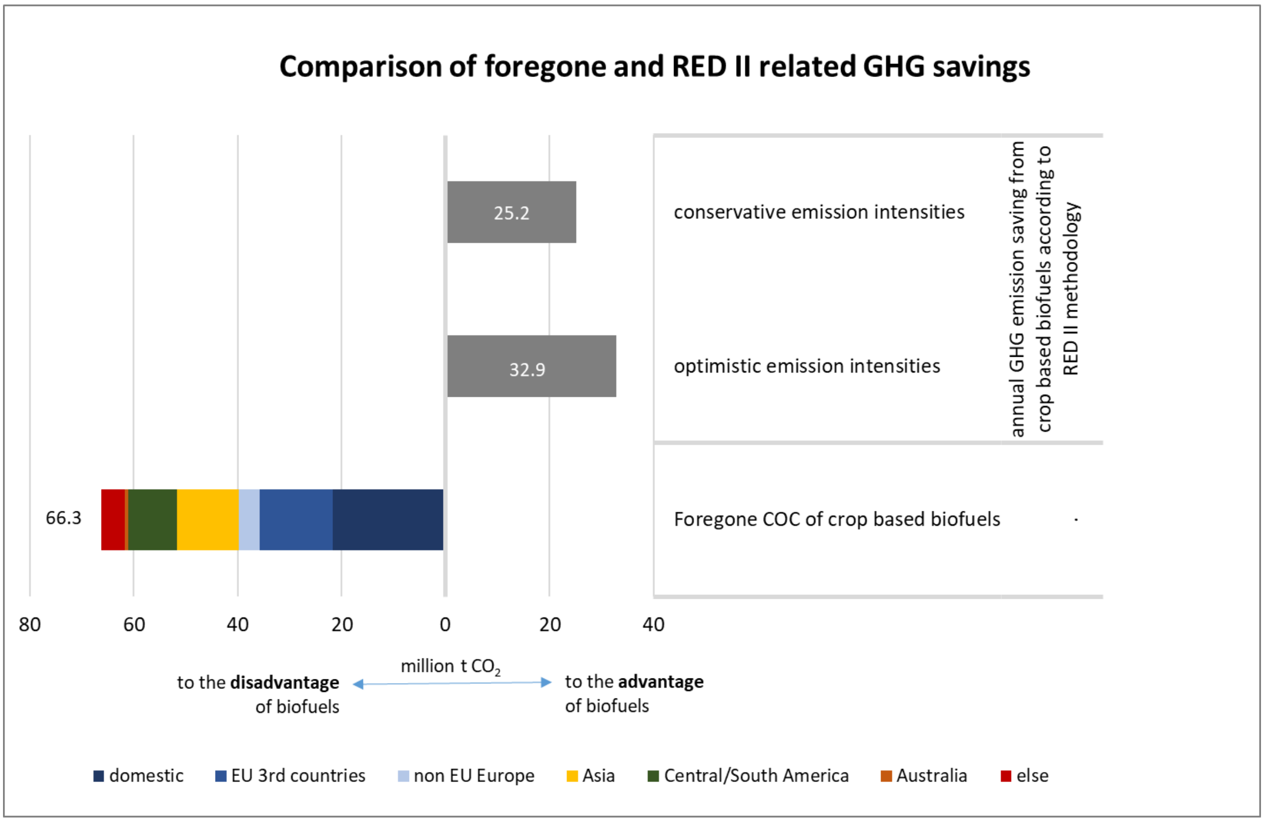

Figure 9: Comparison of GHG emission savings in Europe (conservative and optimistic view) through crop-based biofuels with the carbon opportunity costs of crop-based biofuels; calculations and illustration by ifeu

3.5.3 Comparing the GHG balance of biofuels including carbon opportunity costs with the balance of e-mobility through solar power

Here the two options are compared in terms of their GHG balances:

1. The status quo of crop-based biofuel use (occupying 5.27 million ha)
2. Alternatively, e-mobility by solar power by equivalent mileage (occupying 0.133 million ha).

For option 1, the COC for the excess land use (5.12 million ha) is considered. Consequently, the annual carbon sequestration as shown in Figure 9 is reduced from 66.3 million tonnes of CO_2 to 64.7 million tonnes of CO_2. For this comparison, the optimistic GHG reduction rate for biofuel due to fossil fuel substitution of 32.9 million tonnes of CO_2eq is applied.

It should be emphasised that the comparisons in the GHG balances are only limited to the area requirements and emissions from the generation of propulsion energy. A comprehensive system comparison which also includes the production of infrastructure or vehicles is not made here.

Figure 10 gives a schematic overview of the net savings of both options at the same mileage, including the areas occupied. The figure of 0 million t CO_2-eq. for the production emissions of solar electricity is justified by the setting that no emissions from the production of plants are considered here.[1]

The following picture becomes apparent: if the areas for the cultivation of biofuels and their sink potential are included in the calculation, e-mobility achieves a net saving of 107 million t CO_2-eq. and biofuel only 33 million t CO_2-eq. The e-mobility option with ground-mounted PV can thus save over 70 million t CO_2-eq. more than crop-based biofuel, which is more than 9% of total GHG emissions in Germany.

[1] This is also in line with in RED II calculation rules given in Annex V, part C, point 1a

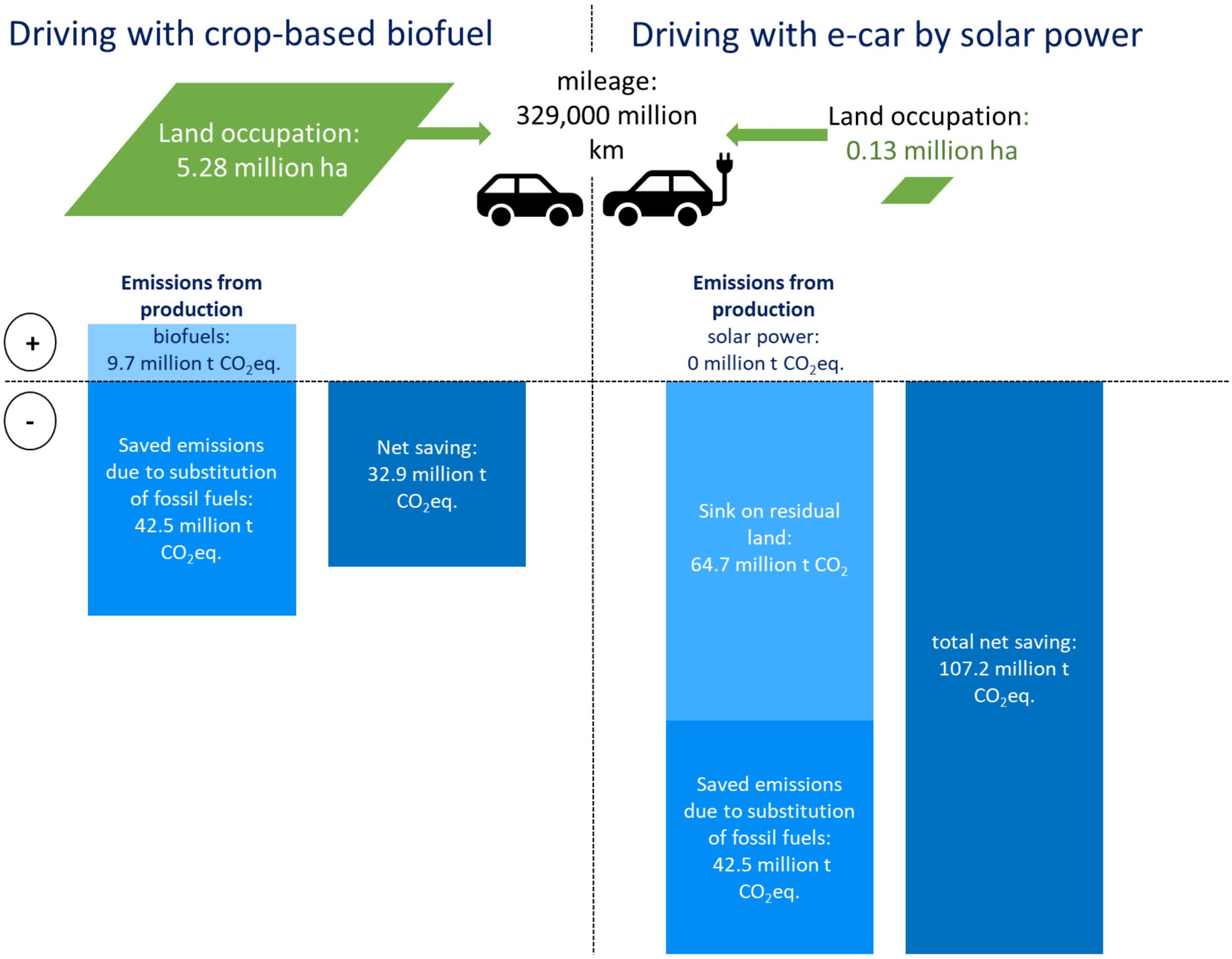

Figure 10: Schematic illustration of the annual net emission savings of the option use of biofuels (left) and substitution of biofuels by e-mobility with PV (right) (Source: ifeu calculations based on data described in the text; see also chapter 3.3).

3.5.4 Complementing the GHG savings of crop-based biomethane consumed in Europe with carbon opportunity costs

The net saving of GHG emission from 60 PJ crop-based biomethane has been figured to 2.24 million tonnes of CO_2eq. The land occupied for cropping is 456,000 hectares (see chapter 3.2.2).

With reference to (Abdalla et al. 2022), an average annual increment of about 2 t carbon per hectare (equals 7.33 t CO_2e) is assumed conservatively for the initial phase of a temperate-continental forest in Europe. Maize acreage for biomethane would have an annual storage capacity of about **3.34 million tonnes CO_2.**

Thus, this forgone climate benefit is clearly higher than the saving by substituting fossil natural by maize-based biomethane.

3.6 Foregone production of food on the land currently occupied for biofuels and biomethane

For the estimation of COC, chapter 3.5 focuses on the foregone option of accumulating carbon on the land by allowing natural vegetation to grow up. In this chapter, alternative uses are highlighted.

Firstly, the logical alternative would be **food production**. One question could be:

- What would be the equivalent calorific value for human nutrition of the biofuel crops if they were not used for biofuel consumption in Europe?

Another question could be:

- To what amount can food be produced on the area of 5.27 million hectares which are occupied for biofuel crops for biofuel consumption in Europe?

Both questions are answered by assessing the size of the population that could be fed using the alternative approach.

Table 11 shows basic data for calorific value and other nutritional value of biofuel crops consumed in Europe.

Table 11: Calorific value and content of protein, fat/oil and carbohydrates of biofuel crops or crude products

Crop	Calorific value	Protein content	Oil/fat content	Carbohydrates content
	kcal/kg	kg/kg	kg/kg	kg/kg
Rapeseed (seeds)	6243[1]	0.00	0.50[2]	n.d.
Sunflower (seeds)	4800	0.26	0.26	0.35
Palm oil (oil)	8720	0.00	0.99	0.00
Soybean (fresh beans)	1430	0.12	0.06	0.10
Maize	3310	0.09	0.04	0.65
Wheat (full grain)	3130	0.12	0.02	0.61
Other cereals[3]	3130	0.12	0.02	0.61
Sugar	4050	0.00	0.00	1.00

Data source: https://www.naehrwertrechner.de/naehrwerttabelle/;

[1] The values from the data source refer to rapeseed oil. To obtain the energy content for rapeseed, the value for rapeseed oil was converted using the lower heating value from Biograce (*26,4/37).

[2] Because the data source refers to rapeseed oil, data from FNR has been used here to refer to rapeseed: https://pflanzen.fnr.de/industriepflanzen/oelpflanzen/raps

[3] Values have been taken from Wheat (full grain)

3.6.1 Calorific value for human nutrition of the crops used for biofuel consumption in Europe

Table 12 compiles the results for the crop production for European biofuel **consumption** (chapter 3.1.2) multiplied with the factors in Table 11. It shows that total biofuel consumption equals a nutritional value of 178 trillion kcal per year. Expressed in nutriments, the biofuel crops contain 2.04 million tonnes of protein, 8.03 million tonnes of oil or fat and

11.77 million tonnes of starch or sugars. Parts of these end as co-products by processing biofuel out of the crops (see also below).

Table 12: Calorific value and other nutritional value of the crops produced for the biofuel consumption in Europe (co-products included)

Crop	Calorific value	Protein content	Oil/ fat content	Carbonhydrates cont.
	trillion kcal	million tonnes	million tonnes	million tonnes
Rapeseed	89.69	0.00	7.18	0.00
Sunflower	2.44	0.13	0.13	0.18
Palm oil	24.51	0.00	0.00	0.00
Soybean	5.03	0.42	0.21	0.35
Maize	35.41	0.91	0.41	6.95
Wheat	13.26	0.51	0.08	2.58
Other cereals	1.86	0.07	0.01	0.36
Sugar (beet)	2.97	0.0	0.0	0.73
Sugar (cane)	2.46	0.0	0.0	0.61
Total	**177.62**	**2.04**	**8.03**	**11.77**

Source: own calculation based on Table 11

An average demand of 2200 kcal per capita and day[1] is assumed for calculating the number of people that could be fed with the crops produced for biofuels. Based on this demand factor, 178 trillion kcal per year would cover the daily calorie demand of **221 million people.**[2] This corresponds to 43 % of the population in the EU27 & UK (513.5 million in 2019).[3]

This calculation does not consider the co-products (extraction meal from rapeseed, soybean etc., distiller residues from ethanol fermentation etc.). These co-products are mostly used as animal feed since they contain the major shares of the crops' protein content. In the same way as the land use was allocated between biofuel and co-product in chapter 3.2, the nutritional value is also split at this point.

The allocation again is performed based on the energy content in line with the RED II rules. The allocation factors are displayed in Table 7 (chapter 3.2).

Figure 11 shows that due to allocation, the nutritional value attributed to the biofuel and subtracting the co-product value leads to 113 trillion kcal per year. This corresponds to the daily calorie demand of **140 million** people, being 27 **%** of the population of the EU27 plus UK.

[1] The actual food demand ranges widely considering age, sex and physical strain.
[2] 177,622,802,000,000 kcal/year / (2,200 kcal/(capita x day) x 365 days/year) = 221,199,006 capita
[3] https://ec.europa.eu/eurostat/documents/2995521/11081093/3-10072020-AP-EN.pdf/d2f799bf-4412-05cc-a357-7b49b93615f1

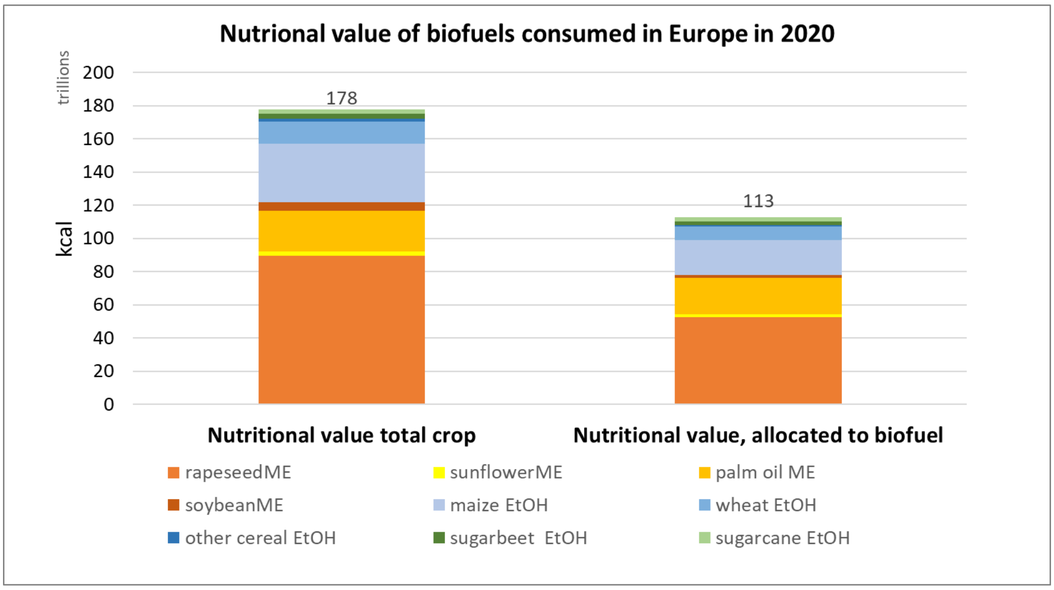

Figure 11: Allocation of the nutritional value of complete crop to the biofuel share; calculations and illustration by ifeu.

3.6.2 Amount of food potentially grown on cropland for biofuel consumption in Europe

In chapter 3.2.1, the land occupied for crops for biofuel consumption in Europe has been calculated to amount to 5.27 million hectares (considering the co-products by allocation). In this case consideration, the land can be used specifically for dedicated food production. Assuming wheat (yield: 5.48 t/(ha x a)), the harvest would be 31 million tonnes with a nutritional value of 96 trillion kcal. This would be lower than the mix of biofuel crops, since these include high yield oil crops (palm oil with high calorific values).

It still corresponds to the food for 120 million people.

Without considering allocation, a total of 56.3 million tons of wheat can be grown on 9.6 million ha, which would provide food with 176 trillion kcal for approximately 220 million people.

3.6.3 Further comparisons

Share of arable land in the EU & UK:

The arable land in the EU in 2016 amounts to 103.11 million ha (Eurostat 2023).

- The land occupied for biofuel crops (9.64 million ha) is equivalent to 9.35%
- The land allocated only to the biofuel share (5.27 million ha) is equivalent to 5.11 %
- Plus, the land for crops for biomethane production (0.46 million ha) is equivalent to 0.45% of the European arable land.

Harvests of other countries:

Taking the forgone wheat harvest of 31 million tonnes as figured out in chapter 3.6.2:

- This corresponds to 4.1% of the global wheat production (which is 761 million tonnes in 2020 according to (Destatis 2022))

- This is more than the wheat production of France (30.1 million tonnes), clearly more than the Ukrainian production (24.9 million tonnes) and more than one third of the wheat production in the Russian Federation (85.9 million tonnes) (Destatis 2022).

Share of organic farming in the EU:

The total area under organic farming in the EU covered 14.7 million hectares of agricultural land in 2020, which is 9.1% of total EU agricultural land (Eurostat 2022b). The area of organic **arable** land was 6.8 million hectares.

A conversion of the land attributed to biofuel production in Europe (5.27 million hectares) to organic farming would increase its extend in Europe by 77.5%.

3.7 Additional ecological aspects

The focus of this study is the carbon opportunity cost of biofuel, which is "merely" focused on the aspect of climate protection. However, when comparing agricultural land and naturally developing land, a number of other factors must be considered, in particular:

1. impacts of intensive agriculture on the biosphere, pedosphere, atmosphere, hydrosphere
   - Inputs of nitrogen and other fertilisers that can lead to undesirable inputs of nitrate into ground or surface waters or to air pollutant emissions effecting acidification and/or eutrophication.
     In Germany, where infringements of the EU Nitrates Directive are particularly frequent, excessive nutrient inputs are seen first and foremost as a threat to biodiversity - ahead of impacts on health (NO_X in the air and nitrate in drinking water) and climate protection (N_2O). (SRU 2015)
   - Input of pesticides, which can also be transferred to neighbouring ecosystems and thus have an impact on biodiversity.
     The issue of pesticides has received widespread attention, particularly in connection with the decline of insects and bee mortality. While in specific cases, such as neonicotinoids, the connections have been described relatively clearly (Hallmann et al. 2017), (Woodcock et al. 2017)), the multitude of insecticides, herbicides and fungicides in agriculture poses a problem in terms of quantity and also possible combination effects (BfN 2018).
2. Ecosystem services of semi-natural forests:
   The ecological quality of the habitat itself, i.e. the ecosystem quality and biodiversity between more or less intensively used agricultural land and a naturally developing system differs greatly and is decisive for the provision of ecosystem services. Near-natural forests provide a wide range of ecosystem services, such as climate change adaptation or regulation of the water balance (EU Commission 2021a).

The impact of agricultural production on biodiversity is considered a key problem of global dimension. According to the report of the World Biodiversity Council (IPBES 2019), the drivers of global biodiversity loss have accelerated over the last 50 years. Over one million animal and plant species – 25% of the world's known species – are at risk of extinction. According to (IPBES 2019), key drivers include land-use change and overexploitation.

Measuring human intervention in ecosystem

The degree of intensity or level of human intervention in the natural self-regulation of ecosystems can also be quantified within the framework of the life cycle assessment method. The term '*hemeroby*' has been established for this measure, which describes precisely this degree of human intervention in the sense of a distance from nature.

Using the methodology proposed by (Fehrenbach et al. 2022), the degree of remoteness of agricultural land from its natural state when used for the production of biofuels used in Germany is a factor of 0.39 (on a scale of 0 - natural to 1 - artificial).[1] This includes the areas for rapeseed, wheat, as well as palm oil and the other agricultural raw materials. Translating the factor to the European level and applying it to the biofuel crop area of 5.27 million ha thus corresponds to 2.06 million ha equivalent of artificial area. Instead, a naturally and undisturbed developing forest ecosystem would have no negative impact (factor 0 and thus 0 ha equivalent of artificial area). In this case, the ecological opportunity costs would be 2.06 million ha equivalent of artificial area. Measured in terms of the intensity of intervention, this would be equivalent to an additional 2.06 million ha of sealing. According to official data, the real sealed area in Europe (EU27 & UK) is 34.2 million ha (Eurostat 2022c). The ecological opportunity costs of biofuel cultivation measured in *hemeroby* would thus amount to 6% of the existing burdens due to sealing in Europe.

[1] Logarhytmic scale

4 Discussion

This study has analysed questions about the amount and extent of European biofuel consumption and production, alternative drive options and the question of foregone natural carbon sinks and food production. The discussion addresses the limitations and boundaries of these investigations.

Inventory

For the inventory, i.e. the presentation of biofuel quantities and land use occupation, the results represent the first comprehensive presentation of the current situation of biofuels according to latest available data. This inventory is based on the original data from national reports under the RED II framework, the EIONET data repository (EEA 2022a) and the GAIN report (Flach et al. 2021). The latter has been consulted mainly for the assessment of the biofuels produced within Europe and to determine the total sum of biofuels consumed in Europe.

In total, the national reports for eleven EU member states and the UK were analysed, covering approx. 80% of the production and consumption of biofuels in Europe. It was necessary to look at the national reports in order to determine the exact type of raw materials used and their origin. For the remaining quantities, plausible assumptions were made based on data from (EurObserv'ER 2021)*,* so that the identified inventory gives a good overall picture of the biofuel landscape in Europe for the year 2020. In the annex the biofuel consumption of the analysed member states is given in detail.

The analysis shows a number of remarkable results:

- **63% of the biofuels consumed in Europe are crop-based.**
  - 84% of the biofuel is biodiesel which is based by 58% on crops, while the remaining share is based on used cooking oil (UCO) and animal fat;
    rapeseed is the most important crop (57% of crop-based biodiesel), but palm oil (28%) and soybean (12%) are still represented.
  - bioethanol is predominantly based on maize and wheat.
  - Advanced biofuel and biomethane as transport fuel are only marginally represented.
- **The shares of biofuel types vary tremendously between individual member states**:
  - e.g. France relies nearly completely on biodiesel mostly from rapeseed oil, with import rates from other European countries as well as from abroad;
    Since 2020, there is no more palm oil biodiesel in France, whereas this was the predominant biofuel the years before.
  - e.g. Sweden's most relevant source is animal fat (tallow) imported from other European countries.
  - e.g. the Netherlands almost totally rely on Used Cooking Oil (UCO).
  - e.g. Germany's most relevant feedstock for biodiesel and HVO is palm oil, followed by UCO and rapeseed.

Note: From 2023, palm oil will not be accountable in Germany. At present, it looks as if soybean oil will fill the gaps in addition to more rapeseed, provided that the EU Commission will not classify soybean as a high iLUC risk feedstock.

- **It can be stated that biofuel and its feedstocks are rarely produced and used domestically, but are traded much more intensively within Europe and on a global scale.**

Occupied land

The study identified an area of 6.2 million hectares occupied for the production of biofuel within Europe. This equals 6% of the arable land in the EU27 plus UK. The total land area dedicated to the consumption of biofuel in Europe is 9.6 million hectares, including imported biofuels.

Biofuel production involves co-products (e.g. extraction meals and glycerine from oilseeds). In line with the RED II rules for the calculation of GHG emission, the allocation of co-products shall also be applied for the calculation of the land required for biofuel.

Taking co-products into account reduces the area for biofuels production in Europe to 3.7 million hectares and the area of biofuels consumption to 5.27 million hectares.

Critical consideration of the estimated emission savings from crop-based biofuels

A precise indication of the GHG emissions of the biofuels used in Europe does not exist. Individual country reports are available. It was therefore possible to estimate these total emissions within the scope of the study. Two approaches were followed: firstly, emission intensities based on TREMOD (Allekotte et al. 2020), which are significantly below the typical values of RED II Annex V, but are still considered conservative. Secondly, the emission intensities reported by the (BLE 2021) in Germany were used. These contain significantly lower values which are also critically questioned (Fehrenbach and Bürck 2022). Since Germany has a large share of biofuel consumption in Europe on the one hand and *actual* emission values are available with the data from BLE on the other, these values are assumed here to be representative for an optimistic approach for the EU as a whole.

Thus, the “conservative” emission from crop-based biofuels consumed in Europe is 17.3 million tonnes CO_2eq, corresponding to a net saving of 59% against fossil fuel comparators. The “optimistic” emission is 9.7 million tonnes CO_2eq, corresponding to a net saving of 73%. These two emission values represent the range into which the actual life cycle GHG emissions of crop-based biofuels are likely to fall. Please note: Indirect land use changes (iLUC) are not taken into account here, nor are other indirect effects, such as carbon opportunity costs (COC), as discussed below.

Rewilding potential

The first step in determining the COC is to estimate the rewilding potential. Again, this is done at two different levels: the biofuels produced and the ones consumed in Europe.

These respective area values, as given above, are considered to be potentials, as the specific areas on which energy crops are grown are not known in detail and as they might spatially vary among years. Therefore, the area values are considered general potentials.

Similarly, the potentially developing vegetation types are rather general in character and contain several simplifications.

The authors are aware of the fact that beside rewilding, several other options, such as agroforestry or organic farming could take place. However, the option of rewilding has been chosen explicitly, as this option is in line with current goals of climate and environment policy.

At European and international level, too, the demand for rewilding is becoming more and more important. For example, legal requirements on binding rewilding targets are currently expected at the EU level (EU Commission 2021b). At the international level (UNEP and FAO n.d.) have announced the Decade of Restoration. During the COP26 in Glasgow, the carbon storage of forests was also a central topic and a pact for the protection of forests was concluded. It can therefore be assumed that the role of carbon storage by natural vegetation will also become an increasingly important issue at the political level.

Carbon opportunity costs of biofuels

Within the framework of the study, an average annual increment of carbon stocks of 66.3 million t CO_2 has been estimated for the rewilding of the areas currently occupied for the production of biofuels consumed in Europe. This corresponds to approx. 2.1% of total GHG emissions of the EU (EEA 2022b). Thus, in principle, a not inconsiderable proportion of GHGs could be sequestered by implementing the rewilding option on current agricultural land for biofuels. There are various works on regional carbon sequestration rates in a global context, e.g. (Cook-Patton et al. 2020). The values of the applied annual storage rates are associated with some uncertainties. These refer, on the one hand, to the carbon stocks of agricultural land and forest or shrubland areas, and, on the other hand, to the assumption that the respective carbon stocks of the vegetation types develop within 30 years. However, the statements of the study are to be regarded as reliable due to the conservative approach. Deviations in the concrete figures do not lead to a change in the core statement.

It has to be pointed out that the area on which biofuel is cultivated is not determined as such. It can change spatially and temporally. Often, not even farmers know which market their crops will end up in, whether they will become food, animal feed or biofuels. It is therefore not a question of a specific acreage of biofuel crops being specifically converted to natural area, but of the entire amount of acreage. However, the conversion can occur when the political incentive for crop-based biofuel production is abandoned and, at the same time, effective incentives are set for augmenting carbon stocks on the land.

As far as the calculation of the COC is concerned, the authors are aware that carbon sequestration is not a constant process and is subject to certain fluctuations. Thus, the authors would like to emphasise that carbon stocks are seen as potential reservoirs. The assumption that the carbon stock of vegetation forms is to be reached within 30 years is a simplification. Against the backdrop of new findings on the regenerative capacity of tropical forests (Heinrich et al. 2021) this observation period seems plausible for tropical regions in any case. The authors note that carbon storage is far more dynamic and differentiated in space and time. For example, it can be assumed that within the first ten years, carbon sequestration is stronger in the tropics than in temperate latitudes. Thus, the data on carbon storage in the tropics tend to be an underestimate, while those for the temperate and boreal regions tend to be an overestimate.

Incidentally, it should be emphasised that the carbon stock determined in this study does not include soil carbon. Depending on the region, this can account for a considerable share of the total carbon stock in forest systems. Literature reveals that filling this gap in the balance sheet would ultimately only increase the effect of the COC (Neufeld 2022) (Cook-Patton et al. 2020). Thus, the applied figures even correspond to an underestimation.

GHG emission savings versus carbon opportunity costs

This study shows that a significant potential carbon sink is lost when land is occupied with the cultivation of energy crops for biofuels. The savings effects of biofuels compared to fossil fuels are even clearly exceeded. If the COC of 66.3 million tonnes CO_2eq is included in the balance, in the optimistic case a net saving of 32.9 million tonnes CO_2eq inverts to net emission of 33.4 million tonnes CO_2eq emissions. This result is in line with (Fehrenbach and Bürck 2022), (Righelato and Spracklen 2007) and (Evans et al. 2015).

The authors are aware of the fact that the calculations of COC contain several simplifications and that many other factors should be included in order to give a holistic view on biofuels. Such additional factors could be the aspect of impacts of biofuels on biodiversity, on energy and also food security. Russia's invasion of Ukraine and the following import ban of energy sources and a drop in food supplies shows how current and urgent the debate on energy and food security is in general. Another factor that might influence the outcomes of the study is the potential development in the agricultural sector which might result in higher yields. These might automatically have an impact on the amount of biofuels produced and the subsequent GHG emissions. However, the war in Ukraine also reduces the availability of artificial fertilizer from Russia as the main global exporter – future yields are all but guaranteed to grow or even be maintained.

However, the aim of the study was to extend the current view on the carbon balance of biofuels in line with RED II with the aspect of COC.

Better alternatives?

The message of this study is not to (continue to) use fossil fuels instead of crop-based biofuel. For this reason, an additional balance sheet was drawn up to show how e-mobility compares to biofuel when the COC is included.

For this purpose, it was investigated what area would be required if the mileage associated with the crop-based biofuels for the same vehicle class were to be provided by electromobility based on ground-mounted photovoltaic systems. The result shows that only 2.5% of the cropland is needed for the electric alternative. This is calculated based on data from (Fehrenbach et al. 2021b). With other renewable energy sources, such as wind energy, the land requirement would be even lower.

The savings effect of crop-based biofuels against fossil fuels applies in the same way to e-mobility. In terms of their climate impact, biofuels have clear disadvantages compared to the use of PV-based electromobility. This is due to the sum of the emissions associated with the production of biofuels (9.7 million tonnes CO_2eq) plus the COC (64.7 million tonnes CO_2eq). In other words: Based on the data for 2020, PV-based e-mobility is at an advantage over biofuels by 74.4 million tonnes CO_2eq.

Foregone food production

As mentioned earlier, forgone carbon storage by rewilding is not the only lost opportunity. The crops used for biofuels could also serve as food or the area could be converted to organic farming. Actually, the food value of the volume of biofuel crops is remarkable:

If the vegetable oil and the part of the grain and sugar from which bioethanol is produced were used as foodstuffs, the calorie needs of **140 million people** could be met – more than a quarter of the population of the EU27 plus UK. The total crop for biofuel – including the co-products – would even be sufficient for 221 million people, nearly half of the European population.

This is despite the fact that "only" 5.1 % - or 9.2% including co-products - of European arable land is taken up by these biofuel crops. The apparent disproportion of less than one tenth of the total arable land to one quarter of the EU population that could be fed by this land can be explained by the fact that most of the arable land is used for animal feed production.

Incidentally, the argument that biofuels in particular contribute valuable animal feed with their co-products can be countered by the fact that abandoning of cropping for biofuel would make even larger areas available for feed production. However, the land or the reduction in land pressure could also be used to increase the share of organic farmland. The current organic arable land could thus be almost doubled.

Biomethane

Currently, biomethane plays only a marginal role as a transport fuel. Much more is produced for electricity and heat production – in total an amount that corresponds energetically to the amount of bioethanol from maize. Biogas production is even many times higher. For this reason, biomethane production was also considered in this study.

5 Summary

In this study, the biofuels produced and consumed in Europe were compiled for the first time. The compilation of the data and their analyses makes it possible to determine the carbon and food opportunity costs of crop biofuels, incl. biomethane, that are produced and consumed in the EU27 and the UK. These investigations provide information for current political discussion in the context of biofuels and provide a better understanding of land as a scarce and precious resource.

Regarding the quantities of crop biofuels and biomethane in Europe, it could be shown that in 2020 about 99 PJ bioethanol and about 213 PJ biodiesel were produced in Europe from energy crops grown in Europe. About 102 PJ of bioethanol, 349 PJ of biodiesel and 0.6 PJ of biomethane based on cultivated biomass are consumed. These production volumes are accompanied by a land requirement of 3.7 million ha in the case of the produced biofuels and 5.27 million ha in the case of the consumed biofuels.

A comparison with an electric vehicle powered by electricity from ground-mounted photovoltaics shows that, for the same mileage, only 2.5% of the arable land used for biofuel production is required to provide electricity for the electric cars.

In this study we assume as one alternative use of land the national regrowth of region-specific vegetation types to develop on the globally distributed cultivation areas if no longer used for energy crops. This would mean that carbon storages in the natural vegetation would develop on these areas. In total, 66.3 million tonnes of CO_2 could be stored annually through so-called rewilding. This lost storage effect corresponds to the carbon opportunity costs (COC) of crop biofuels.

If the COC are put in relation to the GHG savings from replacing fossil fuels with biofuels in Europe, it becomes clear that so-called rewilding can save 30 Mt CO_2-eq. more compared to using the same land area for growing crops to replace fossil diesel and petrol. Consequently, the COC of crop-based biofuels significantly exceed the official CO_2 savings from their use. This does not mean that fossil fuels are to be preferred. Instead, the comparison with the land consumption for PV electricity shows that e-mobility can achieve even higher savings.

In addition, the study shows the calorific value of the energy crops currently dedicated to biofuel production. The energy crops for the biofuels provide a calorific value of 178 trillion kcal (without consideration of by-products) or 113 trillion kcal (with by-products). Approximately 27% (in the case of the 114 trillion kcal) and 43% (in the case of the 180 trillion kcal) of the EU27 & UK population can be supplied with these calories. Regarding the amount of food that can be grown on the entire cultivation area, the area could be used to grow 31 million tonnes of wheat corresponding to a nutritional value of 96 kcal. These are the food opportunity costs.

With regard to other ecological aspects, the study found out that 5.27 million hectares of agricultural land, which are currently occupied for biofuels in the European transport sector, are equivalent to 2.06 million hectares of sealed land. These ecological opportunity costs are similar to 6% of the existing burdens due to sealing in Europe. The study has shown that the use of biofuels does not contribute to climate protection and that other uses of the land are to be preferred from the perspective of climate protection, biodiversity protection and food security.

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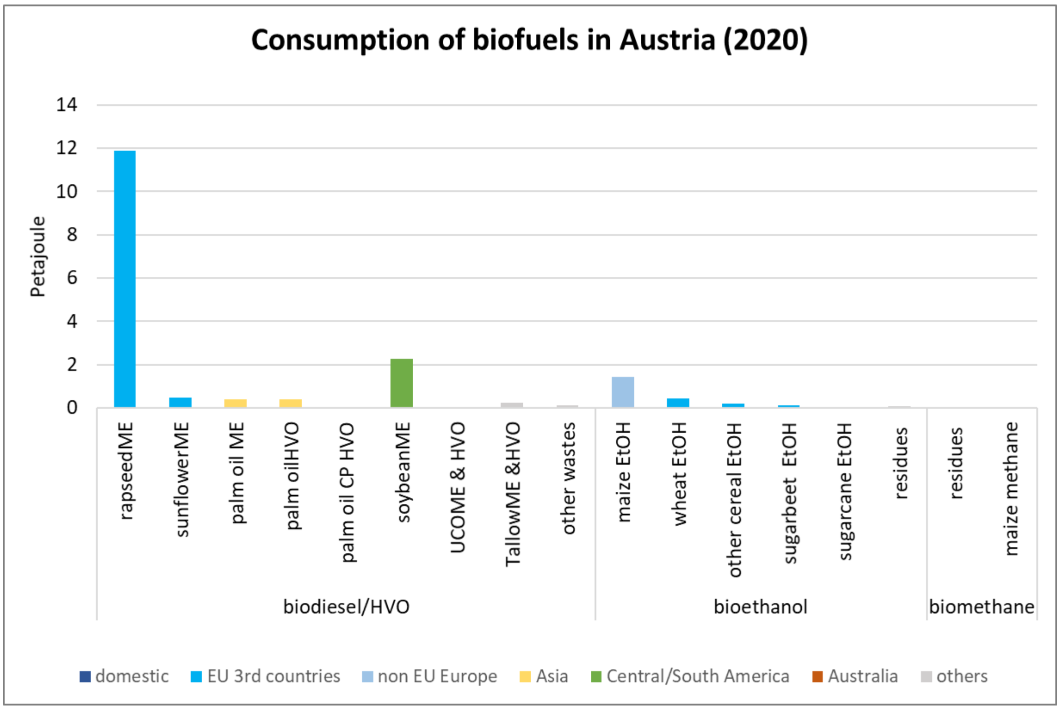
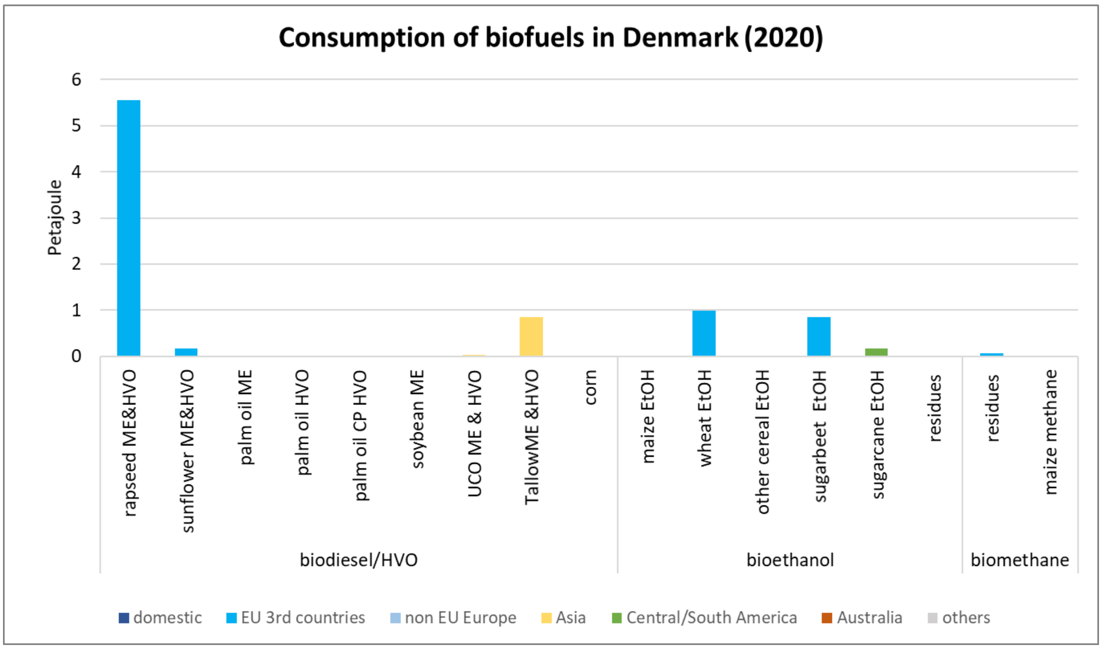
Annex: Biofuel consumed in selected member states

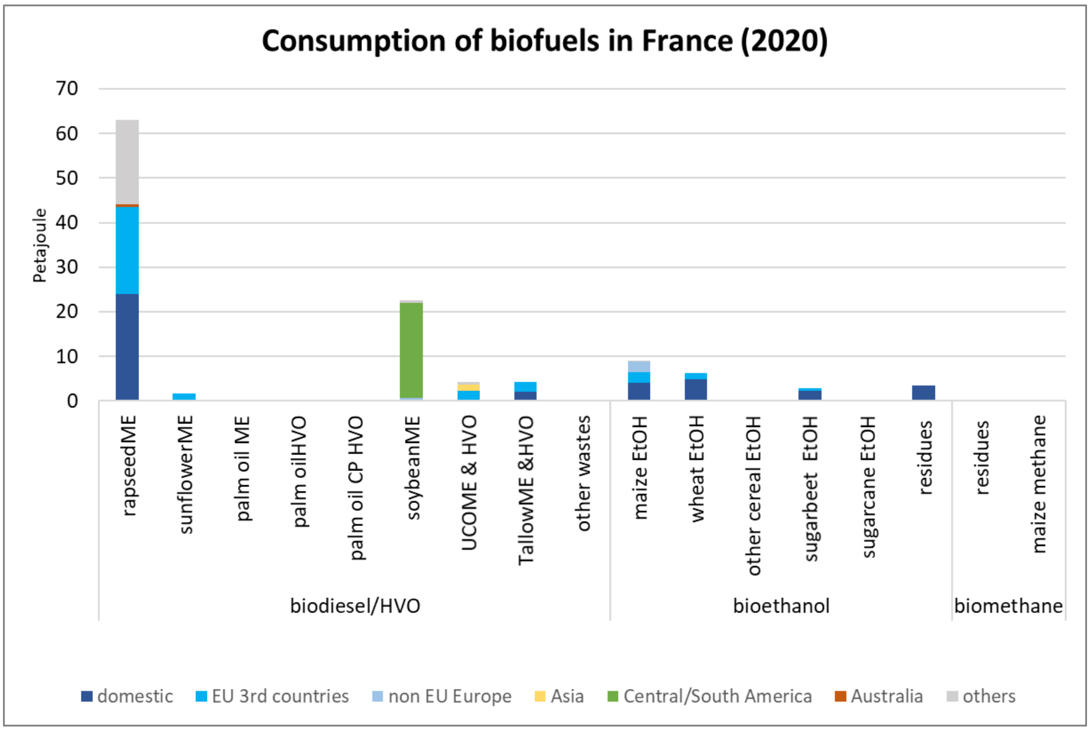
Austria: 18.1 PJ total biofuels; 17.6 PJ total crop-based biofuels (97% of total)



Denmark: 9.0 PJ total biofuels; 7.8 PJ total crop-based biofuels (87%)

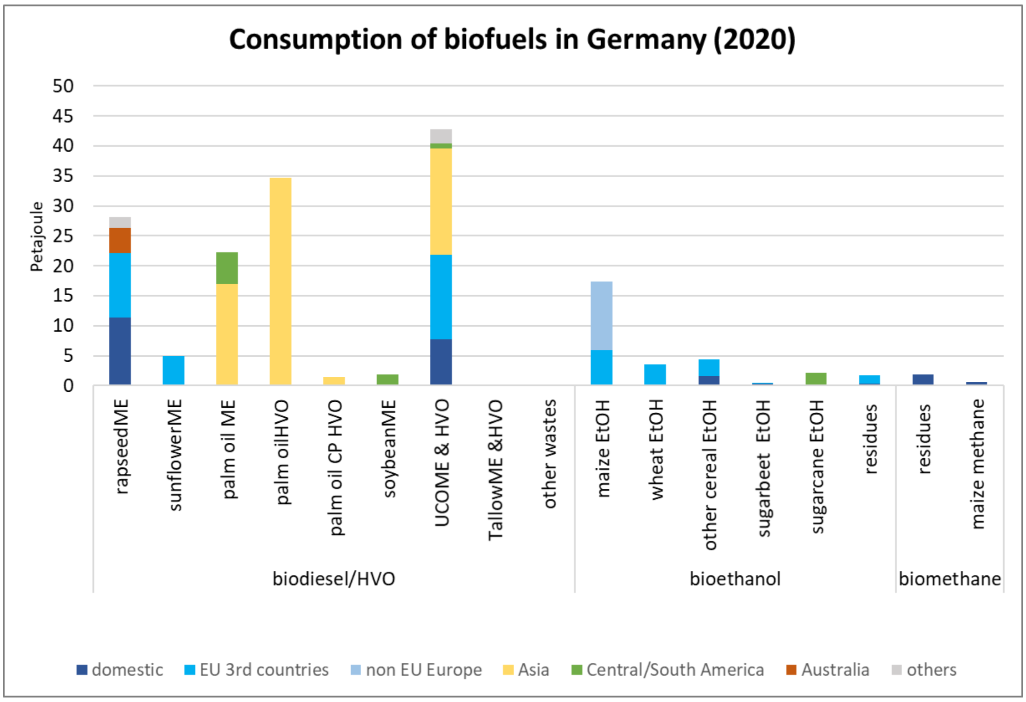


France: 118 PJ total biofuels; 106 PJ total crop-based biofuels (90%)

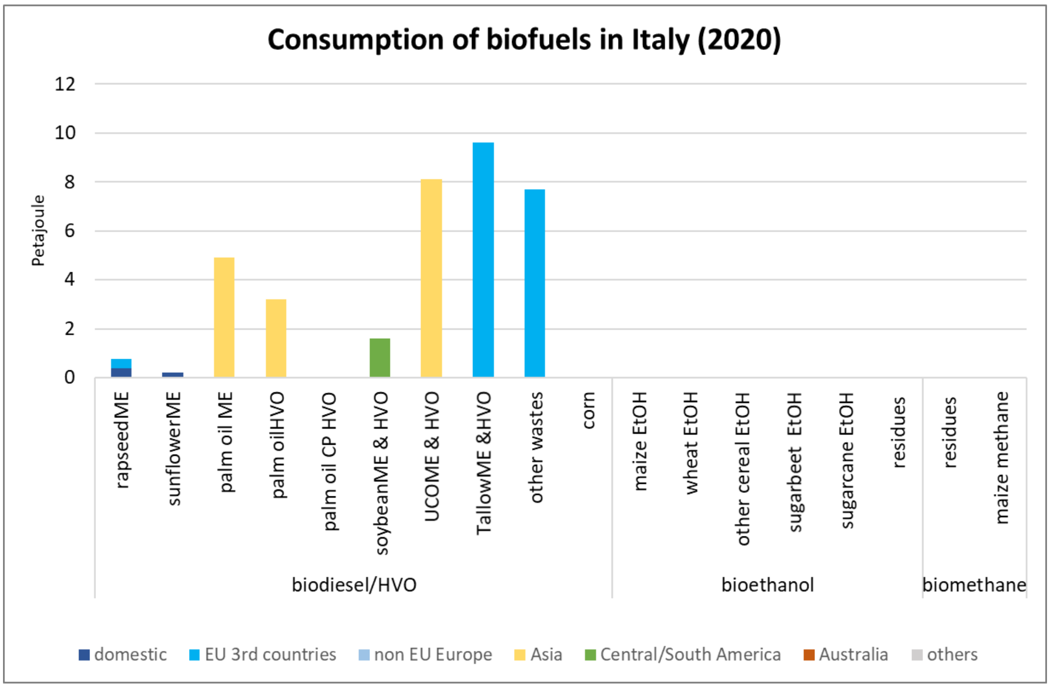


Note: The large rapeseedME share from "others" originates predominantly from Canada (canola)

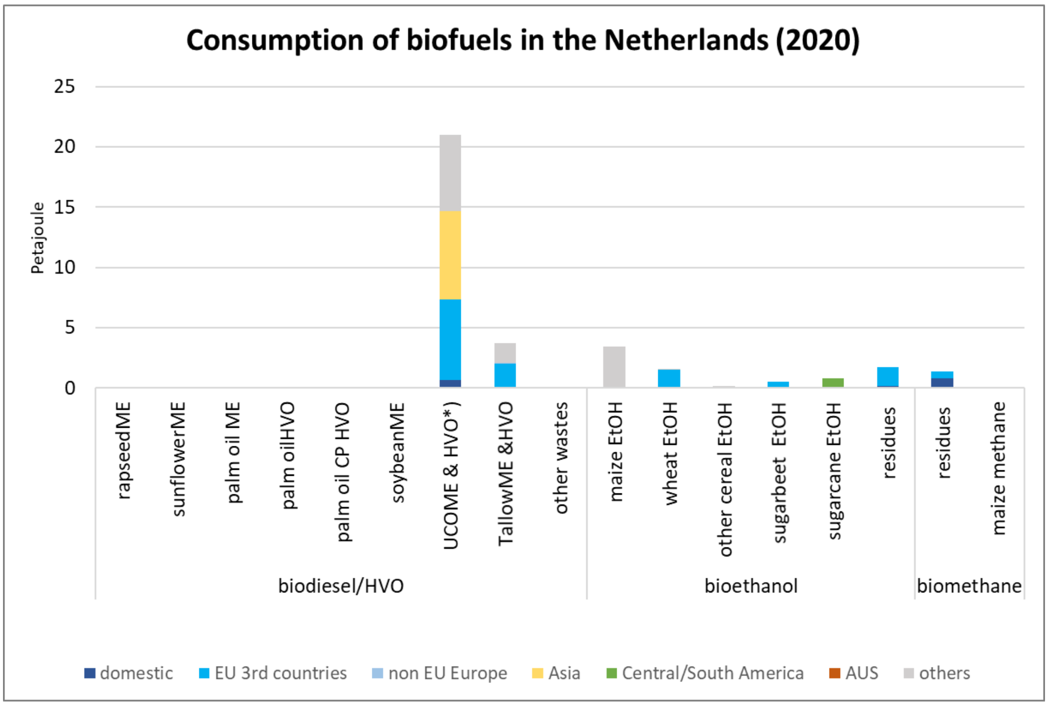
Germany: 168 PJ total biofuels; 122 PJ total crop-based biofuels (72,4%)



Italy: 36.1 PJ total biofuels; 10.7 PJ total crop-based biofuels (30%)[1]

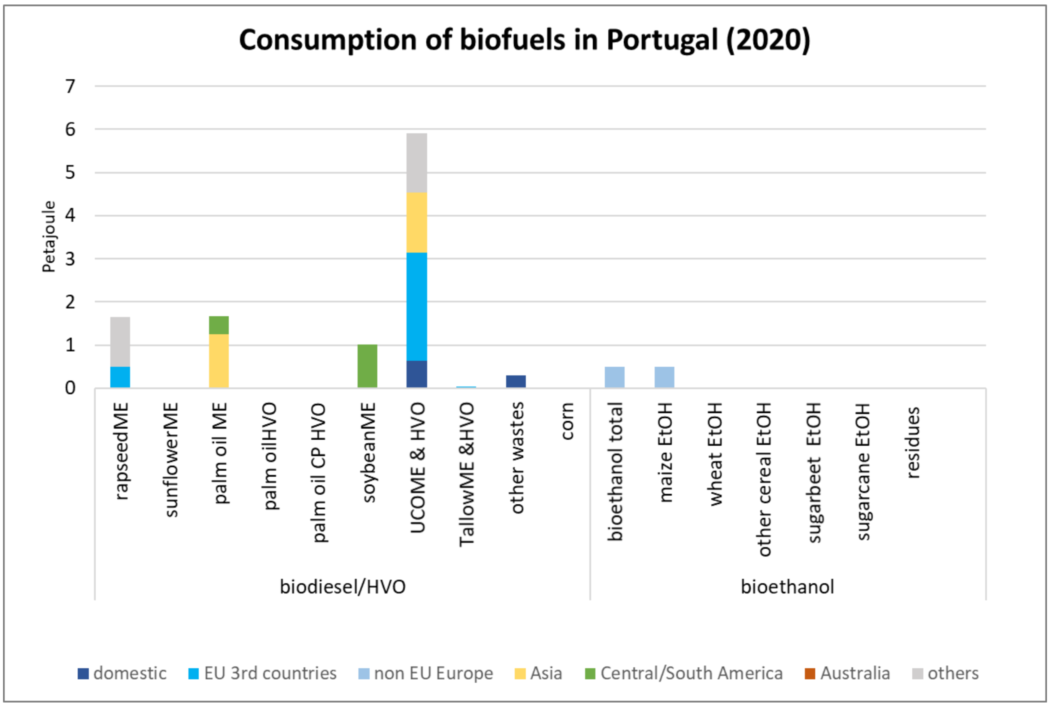


The Netherlands: 34.9 PJ total biofuels; 6.5 PJ total crop-based biofuels (19%)

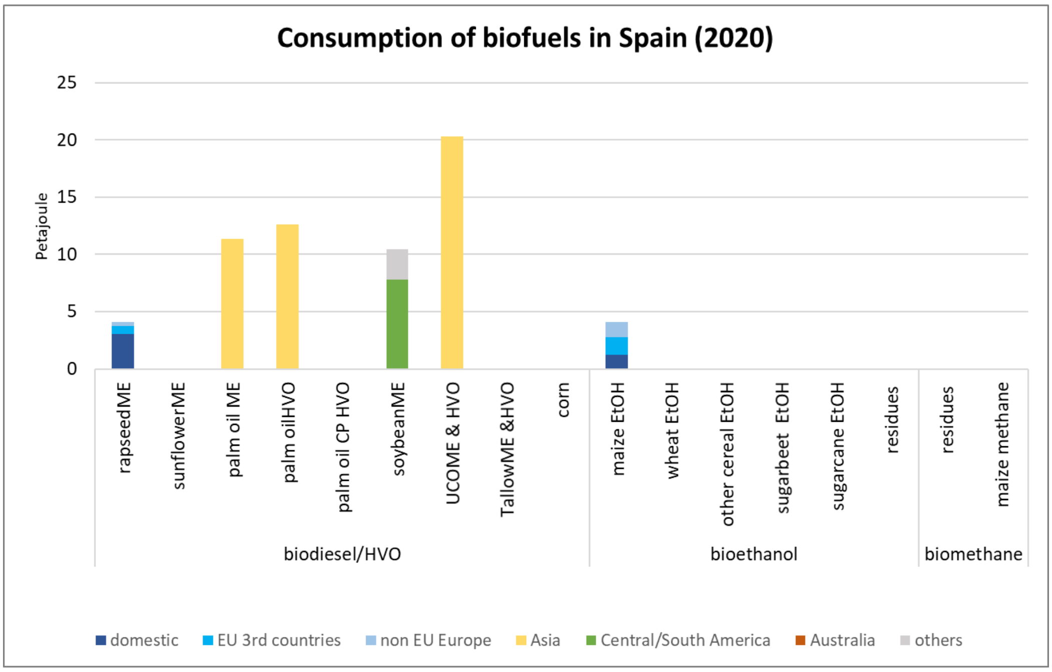


[1] In addition to biodiesel, 436 800 MJ of bioethanol are consumed in Italy. Since this share is very low and neither the feedstock of bioethanol nor its origin is known, the share of bioethanol is not included in the figure.

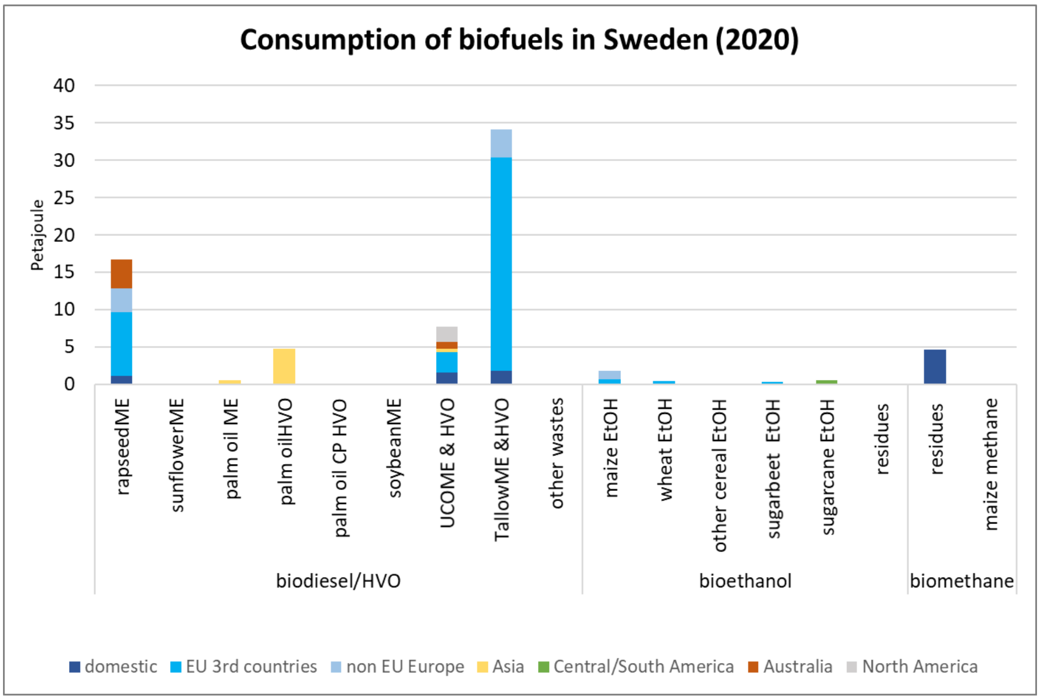
Portugal: 11.1 PJ total biofuels; 4.8 PJ total crop-based biofuels (44%)



Spain: 64.3 PJ total biofuels; 42.5 PJ total crop-based biofuels (66%)



Sweden: 71.8 PJ total biofuels; 25.2 PJ total crop-based biofuels (35%)



United Kingdom: 70.8 PJ total biofuels; 13.9 PJ total crop-based biofuels (20%)