BIKE

BIOFUELS PRODUCTION
AT LOW - ILUC RISK
FOR EUROPEAN SUSTAINABLE
BIOECONOMY

D 3.3
Replication potential of case studies examined in BIKE

Dissemination level:
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Executive summary

In this task, RECORD, with the support of BIKE partners, assessed the possibility of replicating the four BIKE case studies, at European level. The assessment study has been performed considering two main criteria for the application of the proposed solutions: the low-ILUC risk feedstock and climate positive farming options, identified in WP2, and the technologies adopted in the existing biofuels production plants, identified in WP3. The replicability potential has been evaluated considering an application in the short/mid-term, thus based on existing infrastructure, technologies, and biofuels production facilities. The assessment has also been performed in strict relationship with WP6 activities, where open labs on real experiences have been organised. After a description of the adopted methodology, a theoretical estimation of Low ILUC biofuels production potential has been performed for each of the four case studies, which are: (i) perennial crops cultivation in unused lands for lignocellulosic bioethanol production; (ii) castor cultivation in arid or unused lands for oil extraction and renewable diesel production; (iii) brassica carinata cultivation as cover crop for oil extraction and renewable diesel production; (iv) biogas done right model (BDR) application for biomethane injection into the grid and conversion into liquid biofuels. The determination of the replicability potential enabled to identify and select the most promising areas for each case study, thus allowing for development of a preliminary outline in which real opportunities for biofuels in Europe are exhibited.

1 Introduction

Conventional biofuels obtained from crops that could be used in the production of food and/or feed have raised concerns about their impact on food prices, and on the use of land for agricultural and forest products. These issues could be mitigated using advanced biofuels, which are promoted by the European Renewable Energy Directive (REDII) [1] entered into force in December 2018. The latter aims to establish a framework for the development of renewable energy over the next decade, setting an overall binding target for Renewable Energy Sources consumption of at least 32% by 2030, which Member States must achieve together. Within the same year, the REDII mandates that Member States must require fuel suppliers to ensure that at least 14% of the transport sector's energy consumption comes from renewable sources. The REDII also contains several measures to limit the risks of indirect land-use change (ILUC):

- The REDII defines low ILUC-risk biofuels and the Commission published a Delegated Regulation (EU) 2019/807 which defines high ILUC-risk fuels and sets out criteria to identify low ILUC-risk biofuels.
- The Directive allows those biofuels certified as low ILUC-risk to continue contributing to the 14% renewable energy target.

According to the Delegated Regulation, the concept of low Indirect Land Use Change (ILUC) risk biofuels relies on *producing additional biomass*, either through additional yields in existing crop systems, or through new crop production on formerly unused land, abandoned agricultural land or severely degraded land. In this context, a detailed assessment of both low ILUC-risk pathways (i.e., unused land and increased productivity) and their potential of replicability in Europe will add value to the policy discussion and provide some foundation to analyses of EU renewables targets and its future energy mix.

1.1 Low ILUC risk feedstock potential availability in EU regions

The activities of BIKE are organised around two ILUC-risk pathways that match the definition for additionality. In the following paragraph, the two value chains will be presented, together with a preliminary overview of their potential of replicability in European regions.

Cultivation in unused, abandoned or severely degraded lands

This value chain involves biomass feedstock options that can be cultivated on unused, abandoned or severely degraded lands. To avoid fuel versus food debate, in this work we only considered lands that have not been used in the past five years, which we will refer to as *underutilized lands*. The area of underutilized croplands in Europe is estimated to be approximately 5.3 million hectares (Hirschmugl et al., 2021) and is distributed throughout the continent, with significant clusters in central and eastern regions (Figure 1).

[1] https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

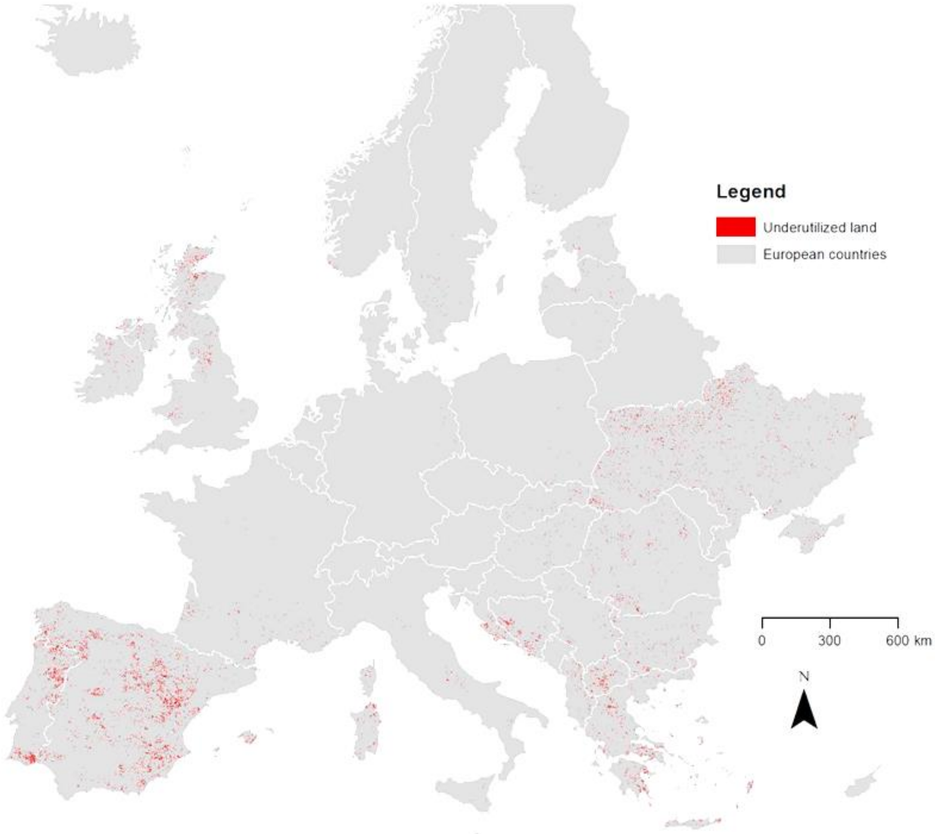

Figure 1. Map of underutilized lands in Europe. Source: Hirschmugl et al., 2021.

The BIKE project has identified two case studies that might potentially be developed in the underutilized lands: perennial grasses, which can be grown throughout the EU for the production of bioethanol, and castor beans, which can be grown in the Mediterranean agroclimatic regions for the production of renewable diesel.

Switchgrass and miscanthus are two perennial grasses which have received particular interest during the last decade as bioenergy crops. Switchgrass is a warm-season grass that is native to North America and has a lifespan of 10-20 years. It is adaptable to different soils, even marginal lands, and has low pest and disease incidence, minimal soil erosion, and low water and nutrient demands. The annual yield of switchgrass in Europe varies depending on location, with the highest yields recorded in southern Europe of around 23 tons/ha (Lasorella et al., 2011). Miscanthus is a perennial grass from East Asia that can produce biomass for up to 15 years after establishment. It has high survival percentages, even in marginal lands, and breeding efforts are underway to develop new genotypes that can achieve even higher yields. Miscanthus can be grown successfully across Europe, with yields ranging from 10 to 36 tons/ha depending on circumstances.

Castor (*Ricinus communis L.*), a valuable oilseed crop that can be either annual or perennial, is indigenous in the south-eastern Mediterranean Basin, Eastern Africa, and India, but it can grow well in a wide range of ecosystems (from temperate to tropical and subtropical regions). Castor bean has a very high percentage of seed oil content (40-55%), higher than other normally used oil crops such as soybean (15-20%), sunflower (25-35%), or rapeseed (38-46%). The crop can cope with several constraints such as drought, heat, saline soil conditions and previous field studies demonstrate its suitability to grow it in South Europe (Anastasi et al., 2015; Zanetti et al., 2017). Annual seeds yield in the Mediterranean region varies from 2 to 5 tons/ha.

Productivity increases from improved agricultural practices

This value chain will analyze biomass feedstock options that can be grown with a sequential cropping practice. Sequential cropping (also referred to as multicropping, double cropping or growing a "harvestable cover crop") is the cultivation of a second crop before or after the harvest of the main food or feed crop on the same agricultural land during an otherwise fallow period. According to a recent study (Fendrich et al., 2023), which represents a first effort to obtain a cover crop map at European scale (Figure 2), the use of cover crops still represents a small percentage of the total EU cropland area (8.9% in 2016). Despite cover crops (CC) playing a pivotal role in maintaining soil health, their adoption is currently an underused farming practice which is likely to increase in the EU in the future.

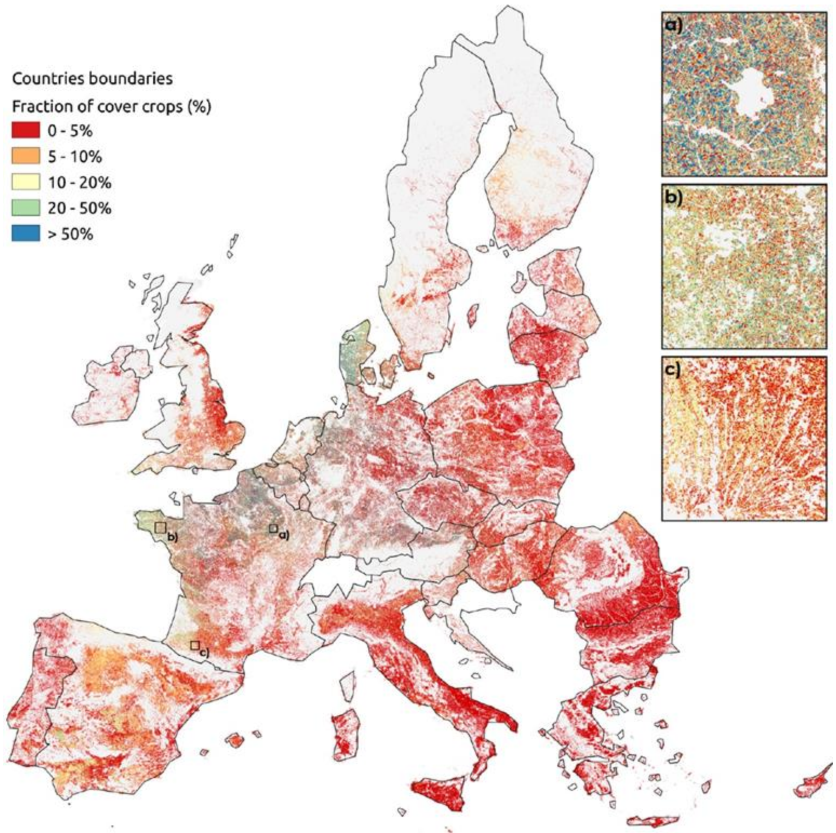

Figure 2. Left: model predictions of the occurrence of winter cover crops (CCs) in Europe (season 2016 – 2017). Right: Three zooms: Predictions on the East, West and South of France (a, b and c, respectively).

The two case studies identified for this value chain are: (i) brassica carinata for renewable diesel production in the Mediterranean regions and (ii) Biogas Done Right model (BDR) for biomethane-to-liquid fuels in all European territory.

Ethiopian mustard (*Brassica carinata A. Braun*) is an annual crop closely related to rapeseed (*Brassica Napus*). Compared to rapeseed, it presents several advantages, including greater resilience, higher resistance to water stress conditions, a reduction in nutrient requirements that results in a significant reduction in nitrogen supply, greater tolerance to some parasites (Basili & Rossi, 2018; Del Gatto et al., 2015). The species can be cultivated in the Mediterranean region as a spring or winter crop, even though it is crucial to notice that it cannot cope with frost. Always referring to Mediterranean regions, the average yields range from 1.5 to 3.0 tons/ha and the oil content is around 40%. The oil is rich in erucic and linoleic acid and well suited for biofuel production.

The Biogas Done Right Model (BDR) is based on the production of biomethane from sequential cropping methods, further biomethane injection into the grid, and processing in centralized biomethane-to-liquid conversion plants. Fisher-Tropsch and MeOH plants currently represent the most promising types of centralized plants at commercial scale. In the present work, estimation of biomethane potential production is based on the findings of a previous study (Schellenbach, 2022) that took into account the regional average yields of the most prevalent cover crops in Europe, represented by triticale, barley, green rye, and ryegrass. In the Methodology chapter, more detailed information about this case study will be provided.

1.2 Overview of conversion technologies

In the present work, three main types of biofuels have been considered: cellulosic ethanol, renewable diesel (HVO and biodiesel) and biomethane.

Cellulosic ethanol (also referred to as “second-generation” ethanol) is a biofuel made by hydrolysis and fermentation of lignocellulosic biomass. In 2022, Europe accounted for a total lignocellulosic ethanol capacity of 50 million liters. On the other side, first-generation ethanol, produced via fermentation of plant sugars and starches and obtained from crops such as wheat and corn, is considered as “non-advanced” but accounted for the 99% of the total bioethanol production, with 3.3 billion liters of total capacity. In the present work, both type of refineries has been considered in the assessment, assuming that for first-generation plants an upgrading to second-generation would be possible by 2040.

Hydrotreated Vegetable Oil (HVO) is a biofuel made by the hydrocracking or hydrogenation of vegetable oil. Hydrocracking breaks big molecules into smaller ones using hydrogen while hydrogenation adds hydrogen to molecules. In 2022, Europe accounted for 3.5 billion liters of HVO total capacity. In this report, the conversion of castor and brassica carinata vegetable oils into green diesel using the Hydrotreated Vegetable Oil (HVO) conversion system has been evaluated. Alongside with HVO conversion technology, the replicability potential of castor and brassica carinata case studies has also been evaluated considering the more established transesterification conversion technology for the production of FAME. In 2022, Europe accounted for a total production capacity of 12 billion liters of FAME. These types of plants have been considered for the assessment only in those areas and countries (e.g., Greece) in which HVO technology is not yet established at a commercial scale.

Biomethane is the CH_4 obtained from any biomass stream processed by the integration of anaerobic digestion and biogas purification (i.e., separation of CH_4 and CO_2) processes. The biomethane is fully equivalent to the fossil methane currently adopted for light vehicles transport, household, and industrial thermal energy supply. In 2020, biogas production in Europe was of 15.8 billion cubic meters, while biomethane production was of 2.4 billion cubic meters. The majority of the produced gas (85%) has been used for electricity, while only the 15% left has been used for the transport sector. In this study, both biomethane and biogas plants have been considered in the assessment, assuming that for the biogas plants an upgrading would be feasible by 2030.

2 Methodology

The methodology employed involved the overlay and elaboration of available, open access data from different sources (e.g., WebGIS, satellite monitoring services, open modelling platforms, databases, literature). Collected data were processed within a Geographical Information System (GIS) framework in order to:

1) Simulate the potential attainable yield of the target crops for cultivation in European underutilized lands or as cover crops.
2) Identify the suitable biorefineries in the case study areas.
3) Evaluate the potential biomass production that could be achieved within a given distance from biorefineries.
4) Select the most promising case studies for the two value chains.

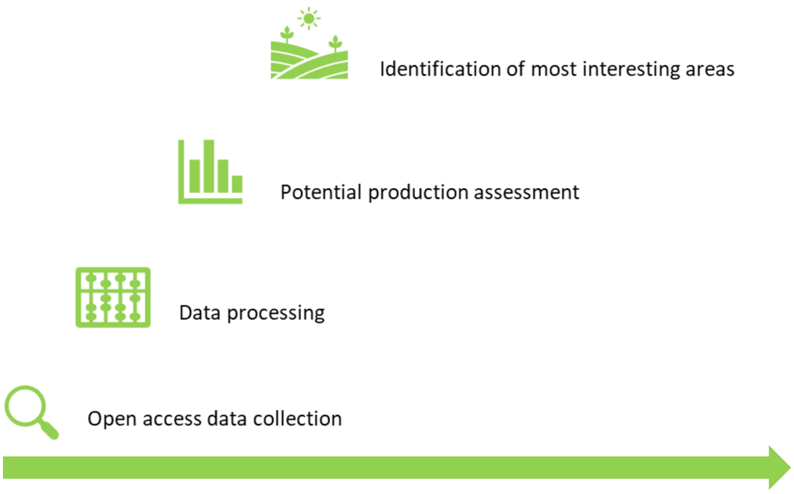

Figure 3. Summary of the adopted methodology

The approach utilised to identify location and characteristics of biorefineries and evaluate the potential for replication of the two value chains is explained in detail in the following sections.

2.1 Location and characteristics of biorefineries

The identification of refineries that could produce bioethanol, HVO, biodiesel relies on combined information gathered from different databases (Table 1).

Table 1. List of databases for determination of biorefineries location in Europe.

Biorefinery type	Source
First-generation bioethanol	BIOPLAT[2], ePure[3]
Second-generation bioethanol	BIOPLAT, IEA[4]
HVO	BIOPLAT, IEA
Biodiesel	BIOPLAT, EBB[5]

The process of integrating data from multiple sources led to the creation of a layer in which existing and planned biorefineries are displayed (Figure 4). A total of 19 HVO plants (10 operational, 8 planned and 1 under construction), 79 operational biodiesel plants, 25 second-generation bioethanol plants (13 operational and 12 planned), and 118 first-generation bioethanol plants were identified.

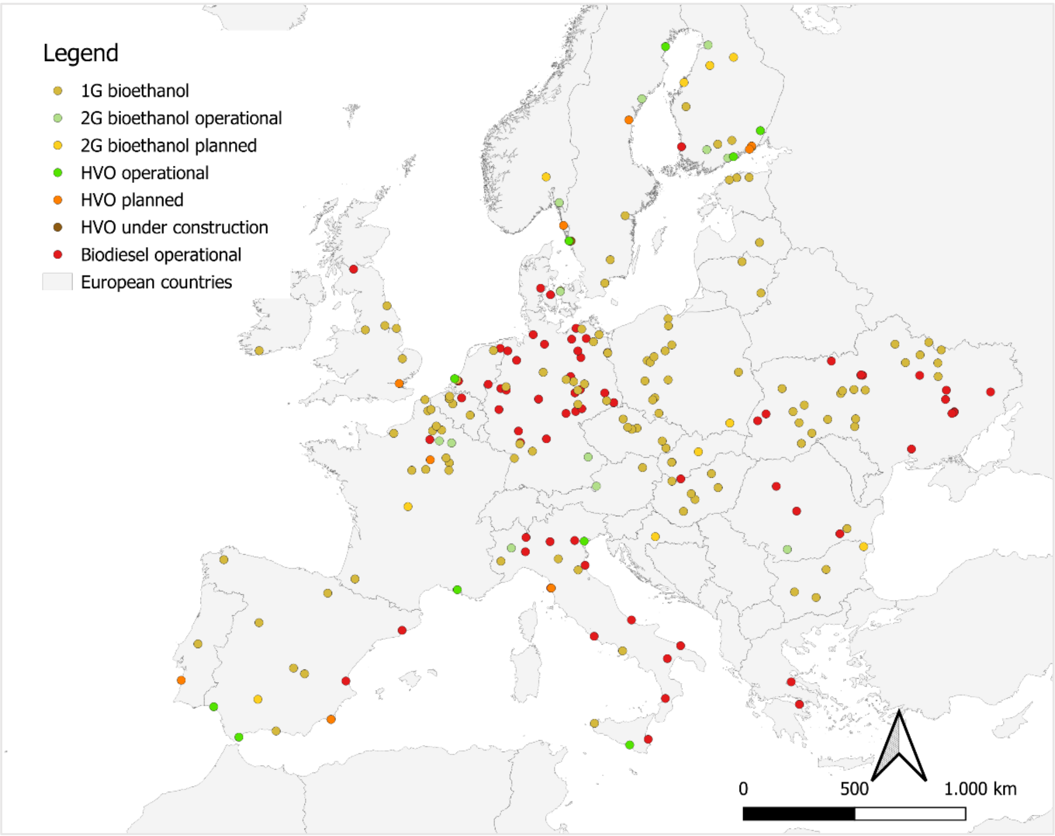

Figure 4. Map of existing and planned biorefineries in Europe.

[2] https://bioplat.eu/, Horizon 2020 project, Grant Agreement N° 818083
[3] https://www.epure.org/about-epure/who-we-are/, Eu Ethanol plants – ePure, 2022
[4] https://demoplants.best-research.eu/, IEA Bioenergy, Task 39
[5] https://ebb-eu.org/our-members/, European Biodiesel Board

First-generation ethanol plants have undergone an additional screening process aimed at identification of all those plants that could be upgraded to second generation by 2040. This operation was based on the inclusion of those plants only dedicated to biofuels production and the exclusion of all bioethanol plants associated to sugar refineries, distilleries, wine, and vinegar industries. Following this screening, 47 first generation ethanol plants that could potentially be upgraded were found.

In addition to geographical data, the attribute table of the created layer also includes collected data on plants' capacity and input feedstocks (Figure 5).

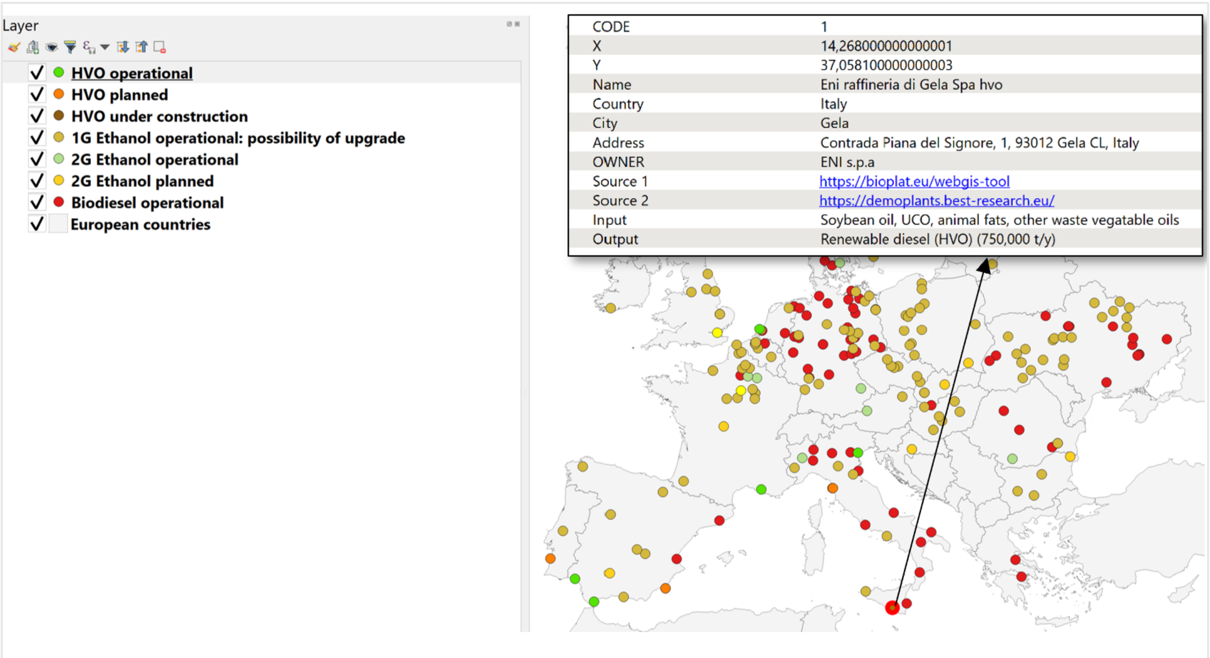

Figure 5.Example of information related to an Italian HVO plant stored in the attribute table.

2.2 Value chain 1 – Cultivation in unused, abandoned or severely degraded lands

The first task of assessing replicability potential of value chain one involved the identification of underutilized lands in Europe, which relies on BIOPLAT[2], a web-based platform that helps identify abandoned croplands in Europe. The platform is designed to support sustainable use of underutilized lands for bioenergy production and serves as a source of information and decision-making tool for stakeholders. It includes maps generated from high-resolution data, such as Copernicus high resolution layers (HRLs), and time series data from Sentinels and other satellites. In particular, the pan-European layer of potentially underutilized land shows all land that has not been used in the previous five years and was created using a customized methodology based on Landsat 8 and Sentinel-2 satellite imagery from 2015-2019 (Figure 6).

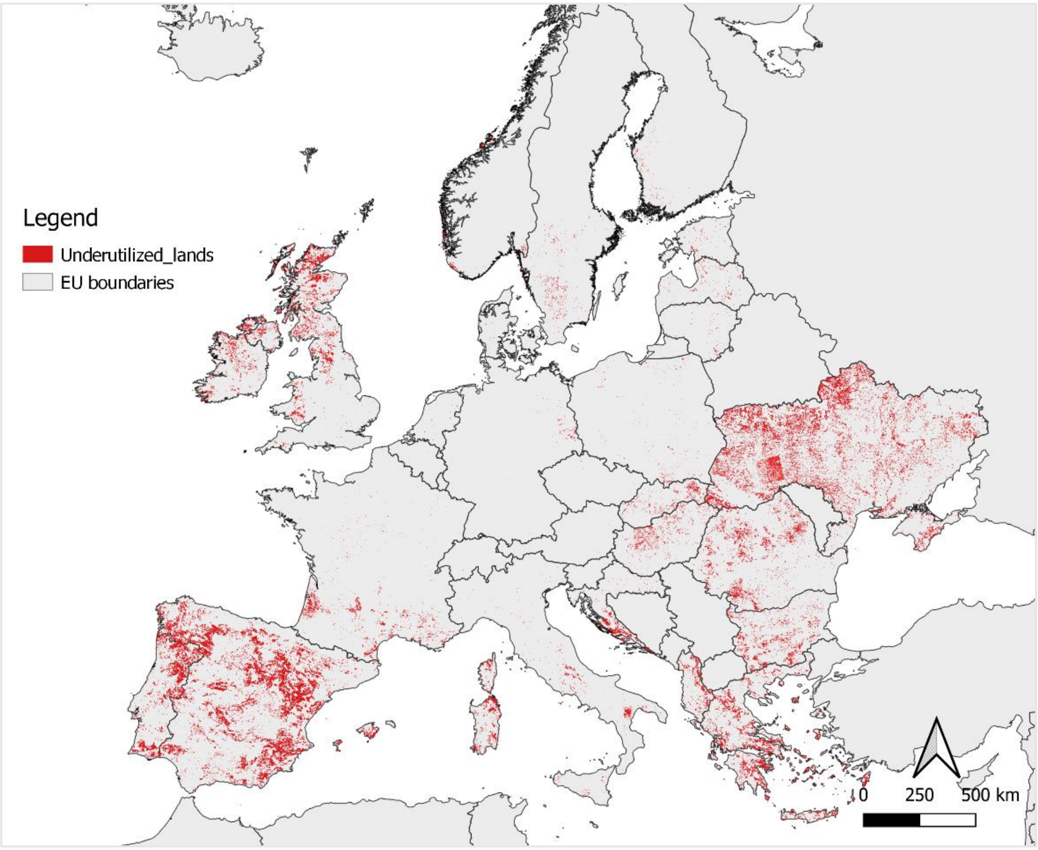

Figure 6. Underutilized lands in Europe. Source: BIOPLAT.

The two sections below provide more detailed information on the methodology employed to assess the replicability of each of the two case studies of the first value chain.

Case study 1 – Perennial crops for bioethanol

Yield modelling

The study has been performed on the whole EU territory. Attainable yields of the target crops – switchgrass and miscanthus – have been simulated using GAEZ v4[6] (Global Agro-Ecological Zones), a modeling system co-developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The information provided by GAEZ is organized into six categories: (1) land and water resources, (2) agro-climatic resources, (3) agro-climatic potential yield, (4) suitability and attainable yield, (5) actual yields and production, and (6) yield and production gaps.

To model the potential biomass production of the selected crops, data from the fourth category (suitability and attainable yield) of GAEZ layers was utilized. This section presents the results of the GAEZ crop suitability and productivity assessment, which combines agro-climatic potential yields with soil/terrain evaluation results, including yield reduction factors caused by soil limitations and prevailing terrain-slope conditions. Specifically, each land unit is individually assessed and assigned a suitability rating (Figure 7), as well as a simulated attainable yield (i.e., the highest yield which could be obtained in practice).

[6] https://gaez.fao.org/pages/data-viewer

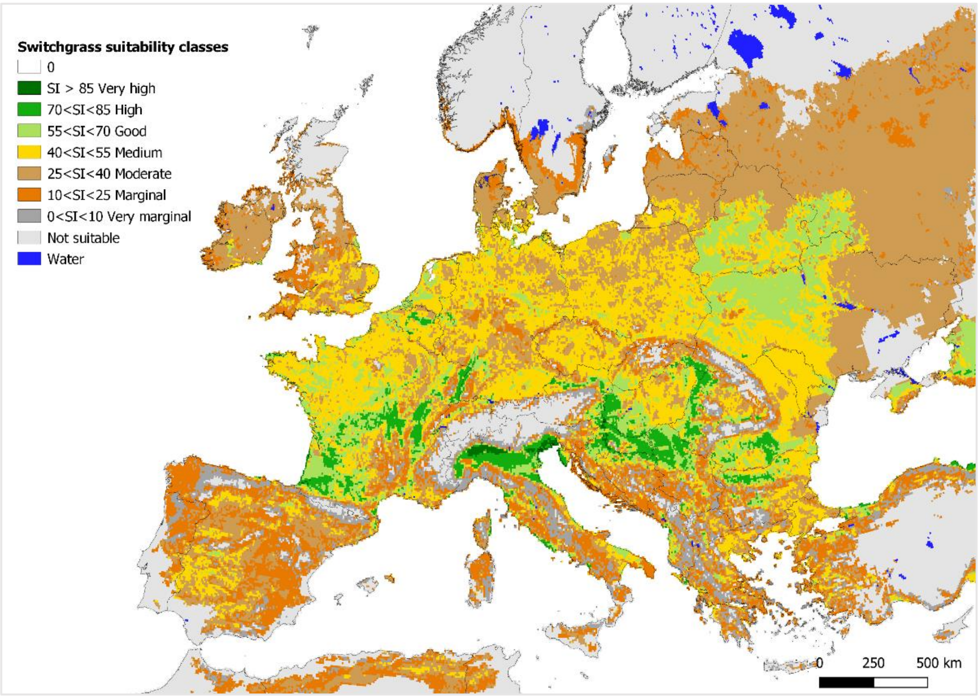

Figure 7. Agro-ecological suitability of Switchgrass under high level inputs and rain-fed condition (climate of 1981–2010).

Yield estimates are available in GAEZ for different soil management scenarios and for different time periods. In this work, attainable yields were modeled based on the following variables:

- Management scenario: high input
- Time period: 2011-2040
- Water supply: rainfed

According to GAEZ, the "high input scenario" implies that the farming system is primarily market-oriented with the aim of commercial production; based on this definition, the high input scenario was chosen considering that most agricultural systems in Europe fall under this category. As regards the 2011-2040 time period, multiple forecasts are available in GAEZ based on different climate models and different Representative Concentration Pathways (RCPs). Attainable yields were first downloaded for all climate models and all RCPs available. Afterwards, the average attainable yield was computed by averaging first over the RCPs and then over the different climate models. Table 2 provides an example of the list of data layers downloaded for modelling of switchgrass attainable yield.

Table 2. Example of the data layers for attainable yield obtained from GAEZ for future climates for Switchgrass. Each row represents a unique combination of time-period, climate model and RCP.

Time Period	Climate Model	RCP	Crop	Water Supply	Input level
2011-2040	NorESM1-M	RCP8.5	Switchgrass	Rainfed	High
2011-2040	NorESM1-M	RCP6.0	Switchgrass	Rainfed	High
2011-2040	NorESM1-M	RCP4.5	Switchgrass	Rainfed	High
2011-2040	NorESM1-M	RCP2.6	Switchgrass	Rainfed	High
2011-2040	MIROC-ESM-CHEM	RCP8.5	Switchgrass	Rainfed	High
2011-2040	MIROC-ESM-CHEM	RCP6.0	Switchgrass	Rainfed	High
2011-2040	MIROC-ESM-CHEM	RCP4.5	Switchgrass	Rainfed	High
2011-2040	MIROC-ESM-CHEM	RCP2.6	Switchgrass	Rainfed	High
2011-2040	IPSL-CM5A-LR	RCP8.5	Switchgrass	Rainfed	High
2011-2040	IPSL-CM5A-LR	RCP6.0	Switchgrass	Rainfed	High
2011-2040	IPSL-CM5A-LR	RCP4.5	Switchgrass	Rainfed	High
2011-2040	IPSL-CM5A-LR	RCP2.6	Switchgrass	Rainfed	High
2011-2040	GFDL-ESM2M	RCP8.5	Switchgrass	Rainfed	High
2011-2040	GFDL-ESM2M	RCP6.0	Switchgrass	Rainfed	High
2011-2040	GFDL-ESM2M	RCP4.5	Switchgrass	Rainfed	High
2011-2040	GFDL-ESM2M	RCP2.6	Switchgrass	Rainfed	High

Geospatial data obtained from GAEZ and BIOPLAT databases were then integrated. The attainable yield map obtained from GAEZ was overlaid onto the map of underutilized lands obtained from BIOPLAT, thereby allowing the assessment of potential biomass production in those lands classified as underutilized and also suitable for selected crops' cultivation. An example of this integration is reported in Figure 8.

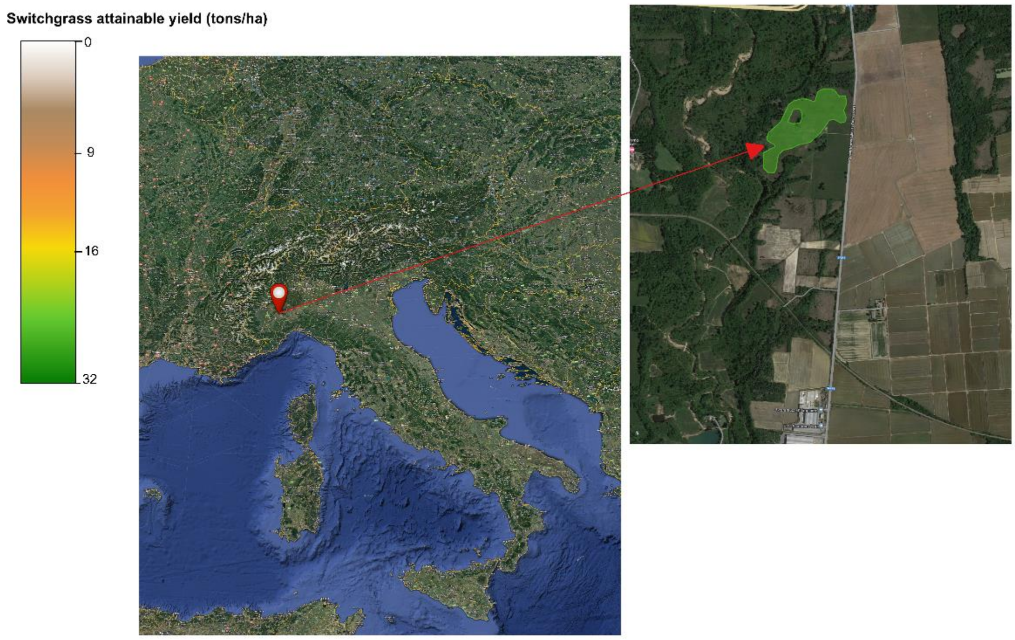

Figure 8. Detail of Switchgrass attainable yield (26 dry tons/hectare) in an underutilized piece of land in Northern Italy.

Selection of biorefineries

Figure 9 displays all bioethanol facility that is now active, planned, or under construction in the European Union, using both first- and second-generation conversion technology. Specifically, the replicability potential assessment has been conducted including:

- 13 operational second-generation ethanol plants;
- 12 planned second-generation ethanol plants;
- 47 first-generation ethanol plants with possibility of upgrade.

Further information related to operational second-generation ethanol plants can be found in Table 3. Further information related to planned second-generation ethanol plants and operational first-generation ethanol plants are available in Supplementary Data section.

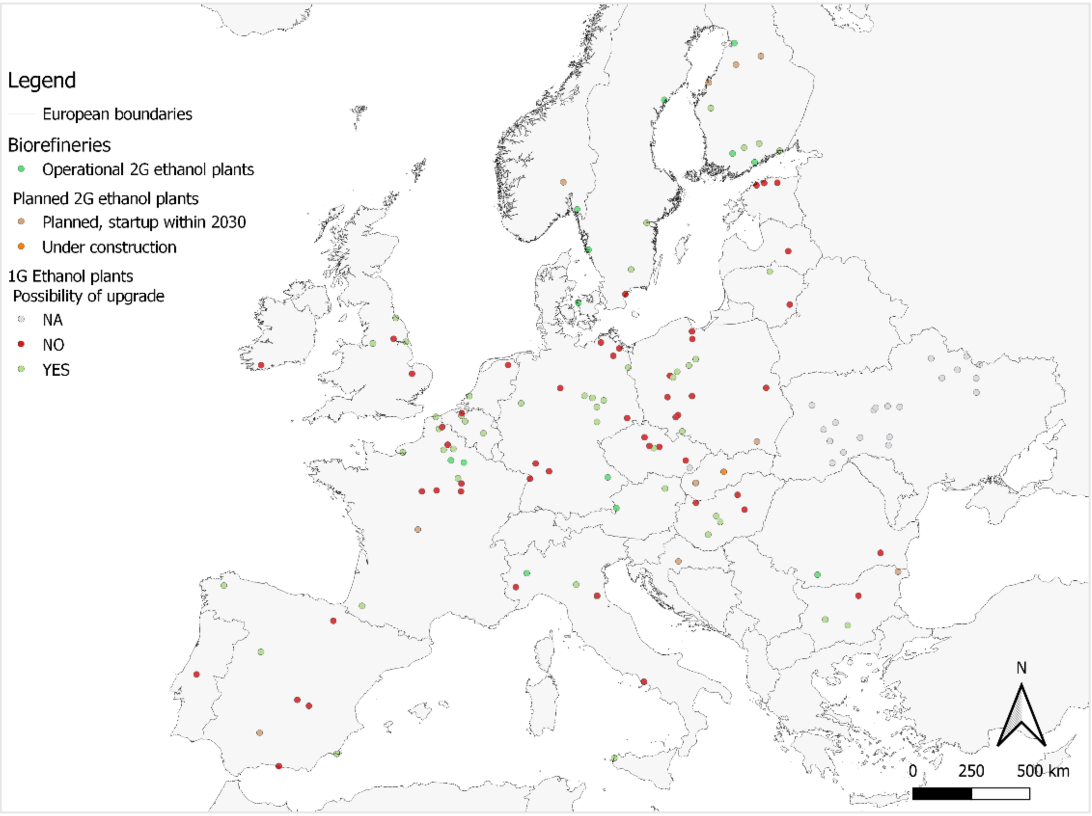

Figure 9. Map of bioethanol plants in Europe.

Table 3. List of operational second-generation bioethanol refineries in Europe.

Name	Country	City	Production capacity (t/y)	Notes
Crescentino Bioethanol Plant	Italy	Crescentino	25,000	Commercial plant
AustroCel Hallein	Austria	Oberlam	30,000	Commercial plant
Futurol ARD	France	Bazancourt	100	Pilot plant
Futurol IFP	France	Bucy-le-Long	8,000	Demo plant
Clariant AG	Germany	Straubing	1,000	Demo plamt
Clariant Products RO	Romania	Podari	50,000	Commercial plant
Inibicon Biomass Refinery	Denmark	Kalundborg	N.A.	Commercial plant
Gothenburg Ethanol Plant	Sweden	Goteborg	5,000	Demo plant
Borregaard Industries AS	Norway	Sarpsborg	15,800	Commercial plant
Ornskoldsvik SEKAB Biorefinery	Sweden	Ornskoldsvik	160	Demo plant
St 1 Bionolix Hammeenlinna	Finland	Jokioinen	800	Demo plant
Chemopolis Oy	Finland	Oulu	5,000	Demo plant
Etanolix Vantaa	Finland	Vantaa	1,000	Commercial plant

Identification of supply radius from biorefineries

The following step consisted in the identification of a sustainable distance from biorefineries for biomass supply. Deliverable 2.2 from the FORBIO project[7] – which analyses different options for the development of a sustainable value chain for lignocellulosic ethanol production in underutilized lands of Sulcis region, Sardinia – has been used as a reference for this evaluation (Barsali et al., 2016).

In the considered supply chain, the material is chipped during the harvesting (forage harvester) and loaded into agricultural trailers that follow the machine in the field and deliver the biomass to a field storage or a middle storage (due to high volumes of biomass needed to produce lignocellulosic bioethanol, industrial plants typically do not have the storage capacity to store the entire seasonal production). Subsequently, transportation of material to bioethanol plant is done by vehicle with higher load capacity – such as road tractor (plus trailers) or semitrailers – and a transportation volume that ranges between 80 and 150 m^3.

The assessment of replicability potential was conducted using two different scenarios: one with a supply radius of 70 km from biorefineries – identified in FORBIO Deliverable 2.2 – and one with a supply radius of 150 km from biorefineries, chosen to compare the potential biomass production when the distance from the plant is doubled.

[7] https://forbio-project.eu/, Horizon 2020 project, Grant Agreement N°691846

Case study 2 – Castor oil for HVO

The study has been performed considering only mediterranean regions of Europe. In accordance with the methodology employed for the case study on perennial crops, the castor bean case study involved integrating geospatial data regarding underutilized lands and corresponding target crop attainable yield, subsequently calculating the potential oil production within a certain supply radius from suitable biorefineries.

Castor yield estimation in Mediterranean regions

Castor bean was not included in the GAEZ dataset or any other open modelling tools or platforms, therefore yield of this target crop in Mediterranean countries was retreived from available literature and compared with data produced from activities of the BIKE project. The screening of online literature databases led to the selection of seven experiences regarding experimental trials of castor cultivation, of which three set in Italy, two in Greece and two in Spain. Information about castor mean seed yield and mean oil content of the trials was collected and reported in Table 4.

Table 4. Selection of papers regarding experimental trials of castor bean cultivation.

Nr.	Country	Area of experiment	Mean seed yield (t/ha)	Mean oil content (%)	Source
1	Italy	Ragusa	3.4	47	(Anastasi et al., 2015)
2	Italy	Sassari	1.8	47	(Laureti et al., 1998)
3	Italy	Pozzallo	3.1	N.R.*	(Patanè et al., 2019)
4	Greece	Tessaloniki	3.3	51	(Koutroubas et al., 1999)
5	Greece	Aliartos	2.2	55	(Zanetti et al., 2017)
6	Spain	Gerona	1.3	N.R.*	(Capuano, 2008)
7	Spain	Cordoba	2.8	47	(Cabrales et al., 2014)

**Not Reported*

The locations of the experiments listed in the above table are displayed in Figure 10.

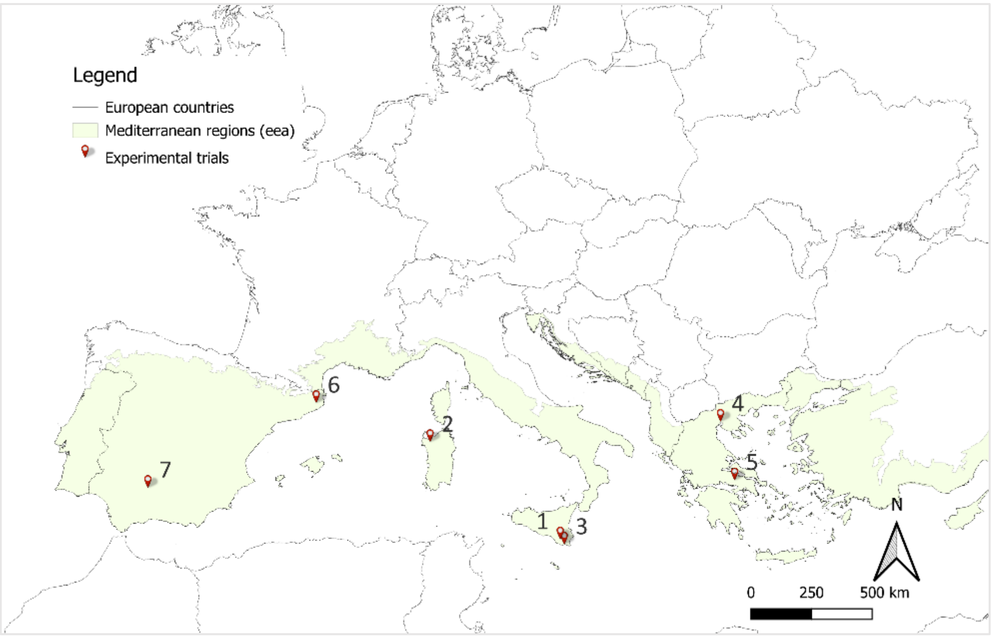

Figure 10. Experimental trials' locations of castor bean cultivation in Mediterranean regions of Europe.

The replicability potential of castor oil production from cultivation on underutilized lands was therefore evaluated in Italy, Greece, and Spain, using for each country the lowest yield value given in literature. Specifically, Castor attainable yield was set at 1.8 tons seeds/hectare in all of the underutilized lands in Italy, at 2.2 tons seeds/hectare in all of the underutilized lands in Greece, and at 1.3 tons seeds/hectare in all of the underutilized lands in Spain.

Selection of biorefineries

Figure 11 shows the position of the biorefineries considered for determining the replicability potential of castor oil production. The assessment took into account five HVO plants, of which three located in Spain and two in Italy, and three biodiesel plants, located in those areas in which HVO technology is not established yet (i.e., Greece, Eastern Spain, South-eastern Italy). Additional information related to the HVO and biodiesel facilities included in this case study is listed in Table 5. Additional information related to all the HVO facilities in Europe is listed in Supplementary Data section.

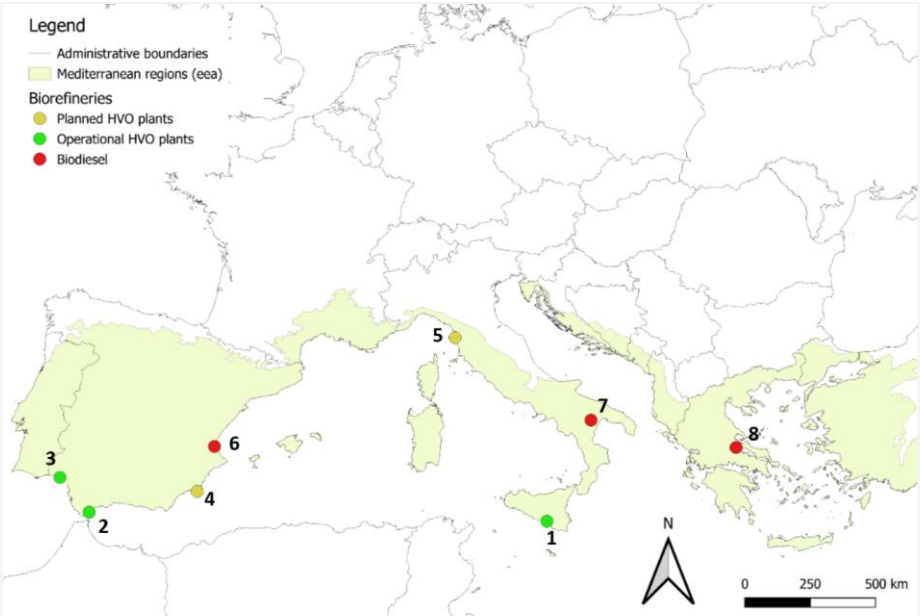

Figure 11. Map of renewable diesel plants in Mediterranean regions of Europe included in the assessment.

Table 5. List of biorefineries considered for the analysis of the Castor bean case study.

Nr.	Name	Country	City	Status	Input	Output	Capacity (t/y)
1	Eni raffineria di Gela	Italy	Gela	Operational	Soybean oil, UCO, animal fats	HVO	750,000
2	Abengoa Biofuel plant	Spain	San Roque	Operational	Organic residues and waste streams	HVO	50,000
3	La Rabida Energy Park	Spain	Palos de la Frontera	Operational	N.A.	HVO	50,000
4	Complejo Industrial de Repsol	Spain	Cartagena	Planned	Organic residues and waste streams	HVO	250,000
5	Eni raffineria di Livorno	Italy	Livorno	Planned	Oilcrops, oils and fats	HVO	500,000
6	Biocom energia	Spain	Algemesì	Operational	UCO, oleins, second-use animal fats.	FAME	120,000
7	Greenswitch	Italy	Ferrandina	Operational	Oilcrops, UCO, animal fats	FAME	120,000
8	Agroinvest	Greece	Achladi	Operational	Oilcrops, UCO, animal fats	FAME	200,000

Identification of supply radius from biorefineries

In the considered value chain, it was supposed that castor oil is extracted from seeds directly at the farm, then stored and transported to the existing HVO or to conventional oil refineries currently operating. Transportation from farm to refinery is done by tanker truck with load capacity of 37,500 L. Sustainable distance from the plants for biomass supply was identified starting from the two scenarios assessed for perennial grasses case study. In particular, energy density of castor was compared to that of lignocellulosic crops (i.e., switchgrass and miscanthus) in order to establish two equivalent scenarios. A calculated indicator of 5.98 GJ per kilometer (Table 6) related to the transport of biomass served as the basis for comparison.

Table 6. Summary table for calculation of an indicator based on distance and lignocellulosic crops energy density.

Parameter	Lignocellulosic crops	U.M.	Source
Values retreived from literature			
Supply radius	70	km	(Barsali et al., 2016)
Transportation volume	115	m^3	(Barsali et al., 2016)
Material type	chipped with forage harvester and then stored in square bales		(Barsali et al., 2016)
Biomass bulk density	182	kg/m3	(Lu et al., 2015)
Calorific value	20	MJ/kg	
Values calculated			
Biomass weight per transport	20,930	kg	
Calorific value per transport	419	GJ	
GJ per kilometer	**5.98**	**GJ/km**	

Table 7. Summary table for calculation of supply radius for castor bean case study.

Parameter	Castor bean	U.M.	Source
Values retreived from literature			
Calorific value	38.2	MJ/kg	(Ismail et al., 2014)
Transportation volumes	37,500	L	
Castor oil density	0.95	kg/L	(Patel et al., 2016)
Values calculated			
Biomass weight per transport	35,630	kg	
Calorific value per transport	1361	GJ	
GJ per kilometer	5.98	GJ/km	
Supply radius	**230**	**km**	

Staring from the calculated indicator of 5.98 GJ/km, a first scenario of 230 km supply radius was determined for castor bean case study (Table 7).

The same methodology was then applied starting from the 150 km scenario of lignocellulosic crops case study, resulting in a second scenario of 500 km supply radius for castor bean case study.

2.3 Value chain 2 – Productivity increases from improved agricultural practices

In this value chain, two distinct approaches were used for the case studies involved, described in the following sections.

Case study 3 – Brassica Carinata for renewable diesel

The investigation was conducted in European Mediterranean areas. The first step consisted in the identification of the most common sequential crop calendars adopted in these areas and into which brassica carinata could be incorporated. Next, the amount of arable land involved in the selected cultivation schemes has been determined. The yield of brassica on these lands has subsequently been modelled in order to determine the possible annual oil production, thus the potential of replicability of this case study.

Identification of sequential crop calendars

Multiple studies have demonstrated the ability of Brassicaceae to provide the soil with many advantages, such as suppression of weed populations, reduction of soil erosion and nutrient losses, increase of soil organic matter (Alcantara et al., 2009; Basili & Rossi, 2018). However, the successful establishment of Brassica Carinata in Mediterranean regions depends on its rotational fit into current cropping system. Brassica carinata can be grown either as a winter cover crop or as a summer cover crop (Seepaul et al., 2021). In this work, both varieties have been considered, representing two different scenarios of the assessment. The primary crops considered for developing the crop rotation calendars are winter cereals, cotton, and corn. Further information about primary crop type, land use and corresponding scenario is listed in Table 8.

Table 8. List of primary crops adopted in the study and corresponding land use and scenario.

Crop species	Crop type	Land use	Scenario
Common wheat	Winter cereal	Non irrigated arable land	Brassica summer crop
Durum wheat	Winter cereal	Non irrigated arable land	Brassica summer crop
Barley	Winter cereal	Non irrigated arable land	Brassica summer crop
Rye	Winter cereal	Non irrigated arable land	Brassica summer crop
Oats	Winter cereal	Non irrigated arable land	Brassica summer crop
Cotton	Industrial spring crop	Irrigated arable land	Brassica winter crop
Corn	Spring cereal	Irrigated arable land	Brassica winter crop

The crop calendars regularly adopted (Figure 12) were identified through multiple consultations with partners from other Work Packages of the BIKE project, in particular: partners of Imperial Collage and Wageningen University from WP2, partners of FAO from WP4, partners of CRES from WP6.

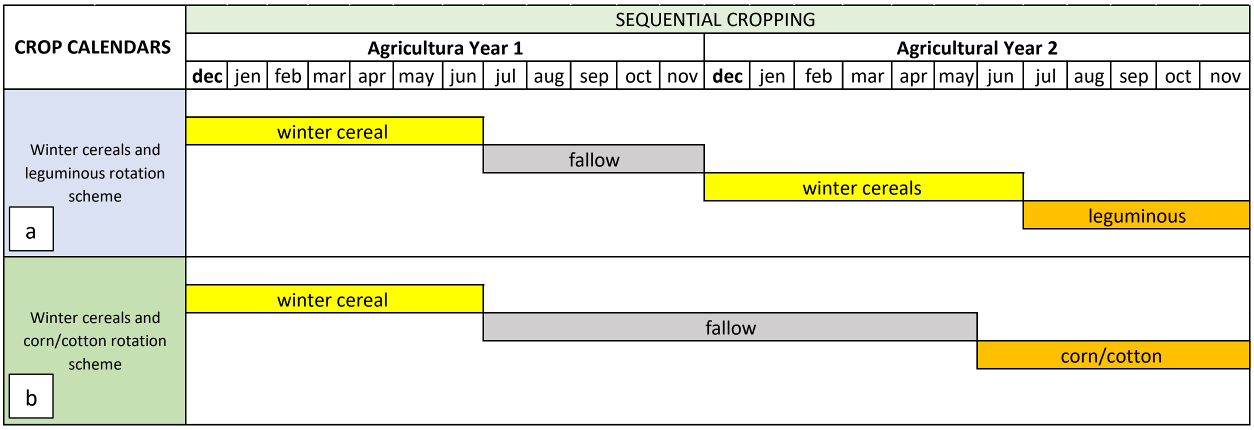

Figure 12. Sequential cropping calendars for winter cereals (a) and corn/cotton (b).

In Mediterranean regions, the most established rotation scheme for winter cereals involves sowing in the months of November/December and harvesting in the months of June/July. Between two cycles of sowing and harvesting, usually a fallow period or a leguminous cultivation – for N availability improvement – is expected (Figure 12a). Winter cereals cultivation in Southern Europe is typically non irrigated. On the contrary, the spring cultivation of corn and cotton, which require a high demand of water, is typically conducted with an irrigated rotation (Figure 12b). Sowing of corn and cotton usually takes place in the months of May/June and harvesting in the months of October/November. The growing cycle of these crops usually alternate with a long fallow period (July – May) and cultivation of fodder or winter cereals (Dec – June).

Figure 13 and Figure 14 display the solutions identified for incorporating brassica carinata in the rotation schemes described above. It is important to underline that the arrangement of the cropping calendars is very complex and dynamic throughout the year. As a result, the sequential cropping rotations developed can be interpreted as a general scheme whose boundaries can be adjusted according to local environmental and economic conditions.

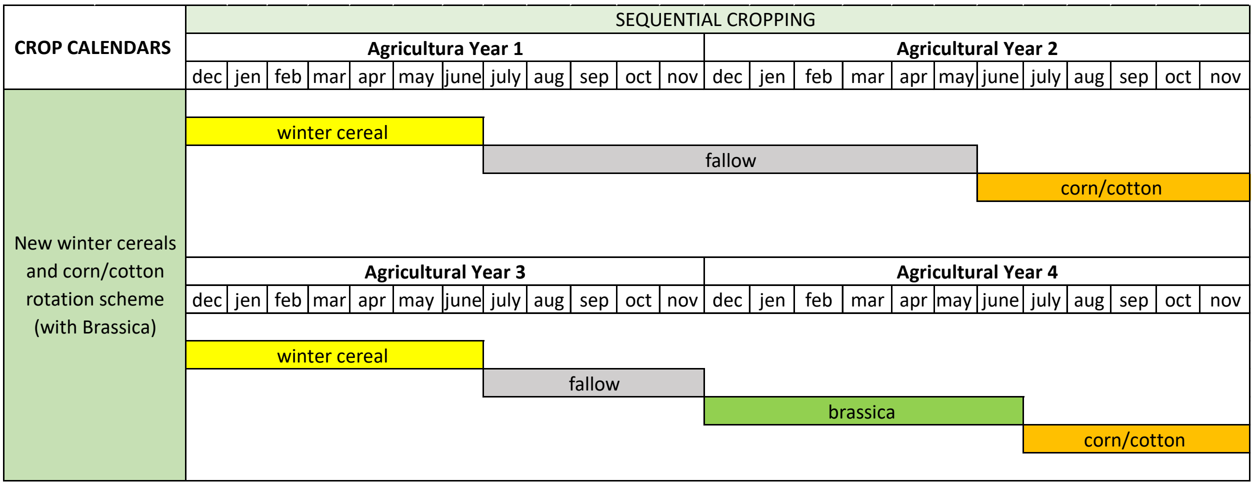

Figure 13. New crop calendar for corn/cotton cultivation (Brassica winter cover crop)

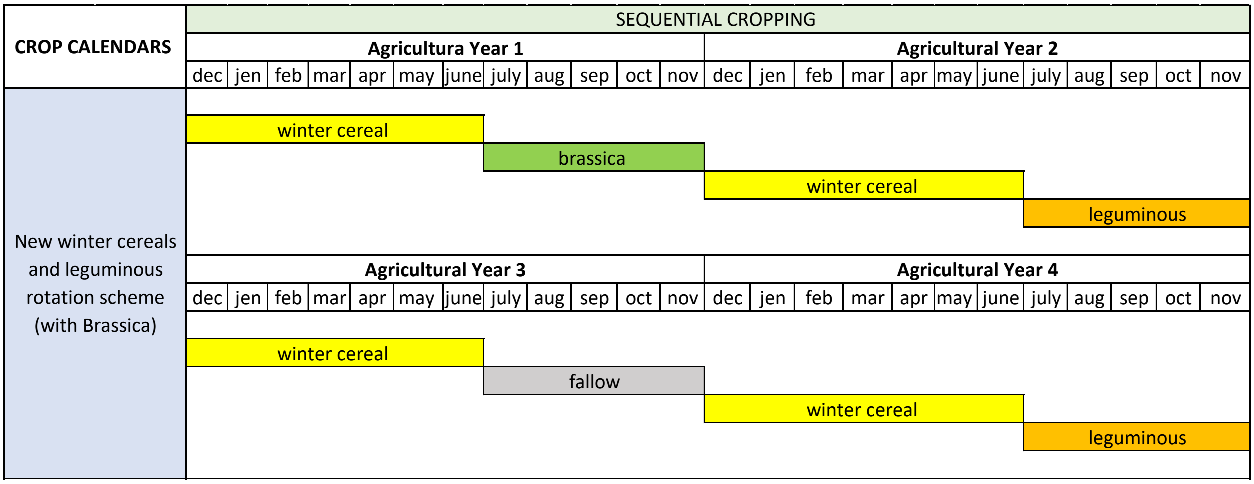

Figure 14. New crop calendar for winter cereals (Brassica summer cover crop).

The developed rotation calendars consist of four agricultural years; this ensures a fallow period once every four years that allows for recovery and storage of soil organic matter as well as replenishment of nutrients in the soil.

In accordance with previous studies and consultations with BIKE partners, a growing cycle of 6 – 7 months has been considered for brassica winter variety (Dec – June). Consequently, the scheme proposed for brassica carinata as a winter cover crop (Figure 13), involves replacing of a part of the fallow period (Dec – May) and a delay of the sowing of corn or cotton, which is considered as feasible due to the short-cycle varieties available on the market. When defining the calendar for brassica as a summer cover crop, a growing cycle of five months has been considered on the assumption that the crop would perform a shorter cycle during the summer months. The scheme proposed involves replacing of the fallow period (Jul – Nov) once every four years (Figure 14).

At this point, it is important to highlight that the extended growing cycle of this crop – particularly of the winter variety – may result in an obstacle for farmers to include it into their rotation plans.

The development of new genotypes with shorter cycle may represent a solution to facilitate incorporation of brassica in European agricultural system.

As already mentioned, the selected rotational calendars of four agricultural years involve one fallow period every four years and one harvest of brassica every four years. To account for this assumption when calculating potential oil production, we considered 25% of identified arable lands as available every year for brassica cultivation.

Hectares of land available for sequential cropping

The Mediterranean areas included in the study are represented by Spain, Italy, Southern France, and Greece. The identification of the total hectares of arable land dedicated to winter cereals and corn/cotton cultivation was conducted at a NUTS 3 level, which is the administrative level that identifies sub-regions (Figure 15). Information have been collected from different, country-specific databases, listed in Table 9. Table 10 presents an example of collected data for the Greek sub-regions. The same approach has been adopted for the other target countries.

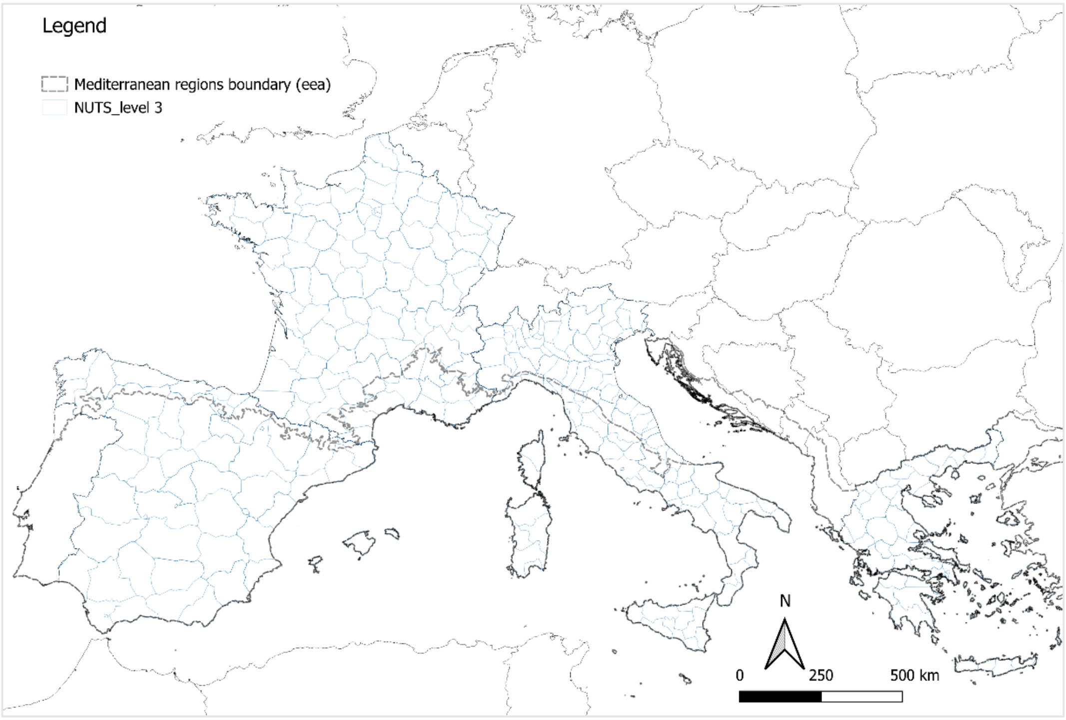

Figure 15. Administrative subdivision at NUTS 3 level of Spain, France, Italy, and Greece.

Table 9. List of online databases that store information about hectares of arable land dedicated to crop cultivation.

Country	Database	Year
Spain	Anuario dè Estadistica (Ministerio de Agricoltura, Pesca y Alimentaciòn)	2020
Italy	Coltivazioni in Italia (ISTAT)	2021
Greece	Annual Agricultural Statistical survey (ELSTAT)	2019
France	Statistique agricole annuelle	2021

Table 10. Example of collected data: number of hectares in Greece used for corn, cotton, and winter cereals cultivation (2019).

	SPRING CROPS			WINTER CEREALS				
Regional (NUTS 2) and sub-regional (NUTS 3) units	Corn [ha]	Cotton [ha]		Common wheat [ha]	Durum wheat [ha]	Barley [ha]	Oats [ha]	Rye [ha]
		Irrigated	Non irrigated					
Eastern Macedonia								
Rodopi	1156	26701	8826	3299	5582	2734	118	68
Drama	7694	4594	7	4721	5051	2802	805	113
Evros	1148	17110	17656	4882	17462	2023	38	229
Thasos, Kavala	9357	153	4	1067	298	626	20	17
Xanthi	5644	4060	146	7225	581	1300	141	134
Central Macedonia								
Thessaloniki	4122	12496	1720	10795	20767	10039	892	283
Imathia	1657	15334	0	1279	1490	487	22	1
Kilkis	1199	5780	2256	12796	22836	4635	563	470
Pella	5554	13263	0	3291	4814	2438	153	265
Pieria	1201	3841	14	5326	8901	3276	828	33
Serres	15614	28933	428	4931	21808	6845	196	355
Chalkidiki	125	330	53	1226	0	3913	1565	42
Western Macedonia								
Kozani, Gravena	2718	16	0	17486	21651	12047	903	1556
Kastoria	697	10	18	2211	3727	607	28	771
Florina	3709	56	0	3034	1770	2740	310	2842
Region of Epirus								
Ionnina	1105	0	0	260	13	186	93	272
Thesprotia	369	0	0	8	1	12	240	1
Arta, Preveza	1145	96	1	93	53	33	809	2
Region of Thessally								
Larissa	9873	31814	214	5669	54805	25243	3578	360
Karditsa, Trikala	12647	53322	0	5619	15786	3419	1904	63
Magnesia, Sporades Islandes	1065	4988	26	798	8640	8327	1064	1
Central Greece								
Viotia	2117	17080	654	99	17557	6099	2241	8
Evia	738	585	0	1040	2711	2806	1841	3
Evritania	17	0	0	1	6	2	2	0
Fokida, Pthiotida	2588	14523	270	1466	17801	5446	2202	39
Ionian Islands								
Corfu	6	0	0	0	0	0	2	0
Zakynthos	0	0	0	32	14	78	1795	4
Kefallonia, Ithaka	0	0	0	47	135	56	158	0
Lefkada	0	0	0	4	0	3	22	3
Western Greece								
Achaia	690	0	0	354	2326	1342	3426	1
Etolia and Akarnania	10225	2704	0	455	1164	921	6914	0
Ilia	5011	768	0	327	37	938	8273	1
Peloponnese	0							
Korinthia	93	0	0	661	1398	413	1181	3
Arkadia, Argolida	220	0	0	1165	842	1782	2414	4
Lakonia, Mesinia	163	0	0	129	58	356	987	13
Region of Attica								
Athens Central Section	0	0	0	0	0	0	0	0
Athens North Section	0	0	0	0	0	0	0	0
Athens West Section	0	0	0	0	0	0	0	0
Athens South Section	0	0	0	0	0	0	0	0
Athens East Section	12	0	0	103	716	355	250	0
West Attica	1	17	846	11	1554	299	243	0
Pireaus, Attica Islands	0	0	0	3	11	0	0	0
Northern Aegean								
Samos, Ikaria	0	0	0	45	33	1	39	0
Chios	1	0	0	1	96	65	18	0
Lesbos, Limnos	12	0	0	488	453	6205	515	19
Southern Aegean								
Syros, Andros, Thira, Kea, Milos, Mykonos, Naxos, Paros, Tinos	0	0	0	128	2	2117	41	3
Kalimnos, Karpathos, Kos, Rodhes	0	0	0	409	1642	560	613	9
Region of Crete								
Heraklion	8	0	0	204	134	3149	317	279
Lasithi	1	0	0	35	13	253	213	19
Rethymno	3	0	0	5	8	17	278	0
Chania	17	0	0	5	1	0	114	0

Yield modelling and climate suitability

The yield of Brassica Carinata was modelled following the same methodology used for perennial grasses and explained in Chapter 2.1. Brassica Carinata was assimilated to rapeseed (*Brassica Napus*) , which, unlike Carinata, was accessible in the GAEZ dataset. The two crops present similar responses to growing conditions of Mediterranean climates, as emerged from literature (Del Gatto et al., 2015) and from results of BIKE activities and open labs. Furthermore, two supplementary layers showing suitability of the Brassica Carinata winter variety (Figure 16) and summer variety (Figure 17) in Europe were overlayed during data elaboration.

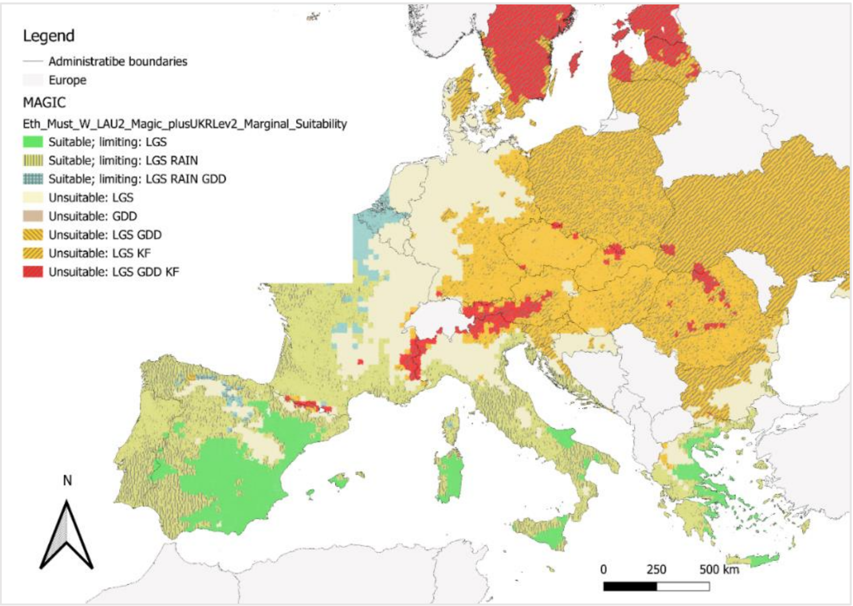

Figure 16. Climate suitability of Winter Brassica Carinata in Europe.

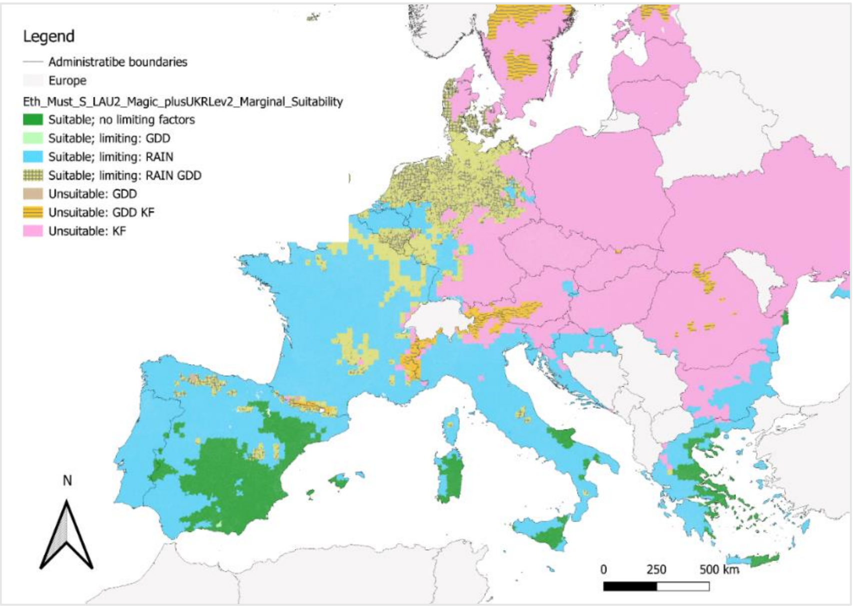

Figure 17. Climate suitability of Summer Brassica Carinata in Europe.

The two layers were retrieved from the MAGIC project[8], which carefully mapped the climatic suitability of the various crops in order to understand which crops can be grown most successfully in the different AEZs and which natural constraints are most frequently present (Elbersen et al., 2022).

The climate suitability is mapped according to the following factors:

1) Minimum length of growth season (days), linked to base temperature.
2) Minimum length of growing degree days (GDD), linked to base temperature.
3) Level to which the crop (above and below ground biomass) can survive different levels of killing frost (KF), assuming this frost occurring for at least 5 days in a row.
4) Minimum level of precipitation the crop needs during the growing season.

In the present work, only those areas defined as suitable with no limiting factors or suitable with only one limiting factor have been considered for the assessment. Consequently, only a few locations in eastern Greece, southeastern Spain, and southern Italy (shown in light green on the map) can be regarded ideal for the winter variety (Figure 16). On the contrary, the summer variety has a significantly wider range of suitability (shown in green and blue on the map) and is applicable for all Mediterranean areas (Figure 17).

Identification of biorefineries and supply radius

Replicability potential of brassica carinata case study was determined using the same biorefineries as those used for the Castor bean case study, with the addition of one HVO operational facility in Chateauneuf-les-Martigues, Southern France (Figure 18). The latter is owned by TOTAL and has an annual capacity of 500,000 tons of renewable diesel, with input feedstocks that include oilcrops, UCO and animal fats. As regards biomass supply, distances of 230 km and 500 km from biorefineries have been considered.

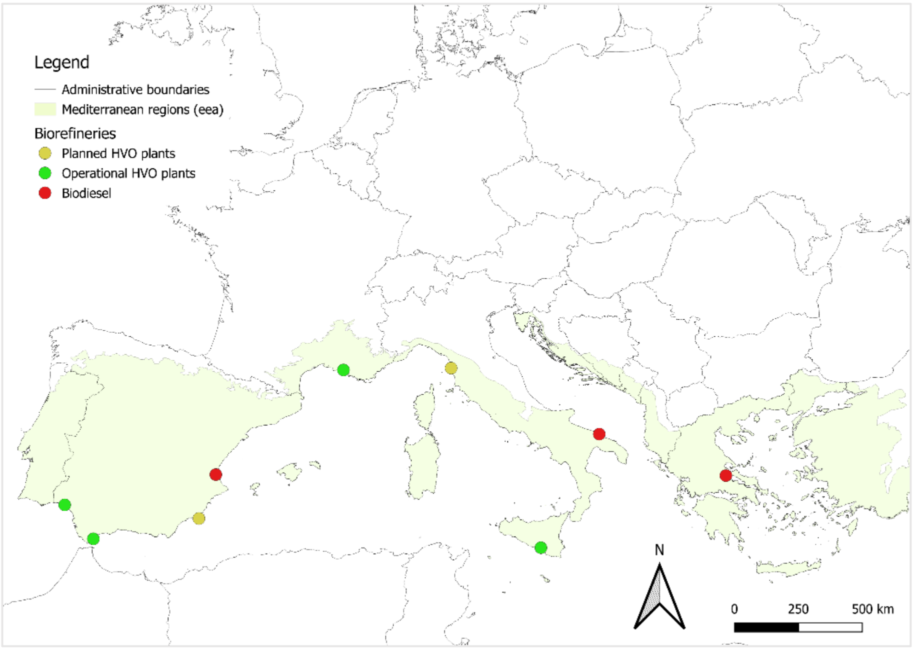

Figure 18. Biorefineries considered for Brassica Carinata case study.

[8] https://magic-h2020.eu/, Horizon 2020 project, Grant agreement n° 727698.

Case study 4 – Biogas done right model (BDR) for biomethane-to-liquid fuels

The BDR model case study involved the evaluation of biomethane potential production from cover cropping by 2030 in all European countries, as well as evaluation of EU countries level of development in terms of the number of biomethane/biogas plants and development of the natural gas network. All these information was retreived from literature and existing databases. The replicability potential of the case study was determined by identifying the most promising countries in terms of number of plants and development of the gas grid, and calculating:

- The potential biomethane production that could be achieved through an upgrading of 90% of the biogas plants by 2030.
- The potential liquid production that could be achieved through installation of a centralized Fisher-Tropsch or MeOH plant.

Results for biomethane potential production from upgrading of biogas plants were then compared to estimated biomethane potential production from cover cropping.

Evaluation of biomethane potential production from cover cropping (CC)

A Gas for Climate Report (Schellenbach, 2022) provided the information on the biomethane potential that sequential cropping strategies could produce by 2030. The report identifies the short- and long-term potential of biomethane production in each EU Member State (plus Norway, Switzerland, and the UK), through anaerobic digestion or thermal gasification.

The four biogeographical regions of the Atlantic, Continental, Mediterranean, and Other (which includes Boreal and Mountain) were used in the methodology of the study to first categorize the European countries. Next, data on hectares of arable land area of each Member State was gathered from Eurostat (three-year average from 2018 to 2020). Based on forecasts released by the European Commission, the arable land areas in 2030 were calculated. According to a conservative scenario, 20% of all arable land in each region was considered as suitable for sequential cropping. Different types of sequential crops were defined for each biogeographical region, along with the appropriate shares of each crop. For the Continental region, for instance, green rye (67%) and ryegrass (33%) were selected. The average yield for sequential cropping for each region was then estimated. Ultimately, the theoretical sequential cropping productivity was calculated using the average regional yields and the available land area (i.e., 20% of arable land) for each country. Another important assumption that is defined is how often a sequential crop could be harvested in cultivated land (e.g., annually or only every two to three years to account for years when the land is still fallow or to allow for the possibility that occasionally the second crop would not produce a yield that was worthwhile to harvest). Therefore, it was assumed that by 2030, 10% of the calculated theoretical potential may be realized. A higher share of 65% was applied to Italy, while a higher share of 20% was applied to France and Germany, in order to account for the significant results already achieved to date and determined focus to continue to develop this concept. The biomethane production ultimately was computed using the assumptions of a 0.57 m^3 biogas yield per kg of dry feedstock and a 57% methane content in the biogas. Results are shown in Figure 19 and summarized in Table 11.

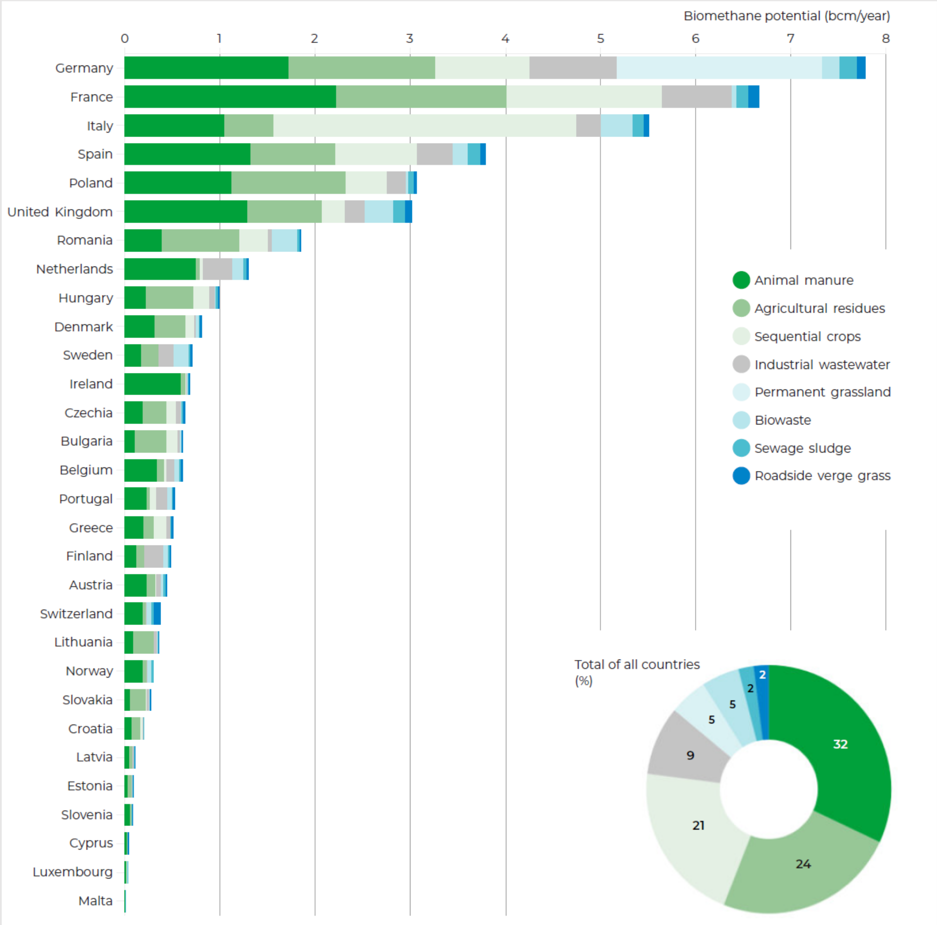

Figure 19. Anaerobic digestion potential in 2030 per feedstock per country. Source: A Gas For Climate report, 2022.

Table 11. Potential production from sequential cropping by 2030. Source: A Gas For Climate Report, 2022.

Nr.	**Country**	**Biomethane potential [bcm/year]**
1	Italy	3.2
2	France	1.65
3	Germany	1
4	Spain	0.85
5	Poland	0.45
6	Romania	0.25
7	UK	0.25
8	Hungrary	0.15
9	Greece	0.15

The top 5 countries identified for biomethane potential from sequential cropping include Italy, France, Germany, Spain, and Poland, with values ranging from 0.45 billion cubic meters per year (Poland) to 3.2 billion cubic meters per year (Italy).

Determination of the natural gas grid development in selected countries

The determination of natural gas grid level of development in European countries relies on the System Development Map realised from the European Network of Transmission System Operators for Gas (ENTSOG) in 2023 [9].

The System Development map (Figure 20), which was created in collaboration with GIE (Gas Infrastructure Europe), offers a clear and regular overview of the current state of gas infrastructure, projections for its growth, and the actual supply and demand situation at the national and European levels from the perspective of a particular year. It aims at establishing an accessible reference for such data and to map trends and their evolution through time.

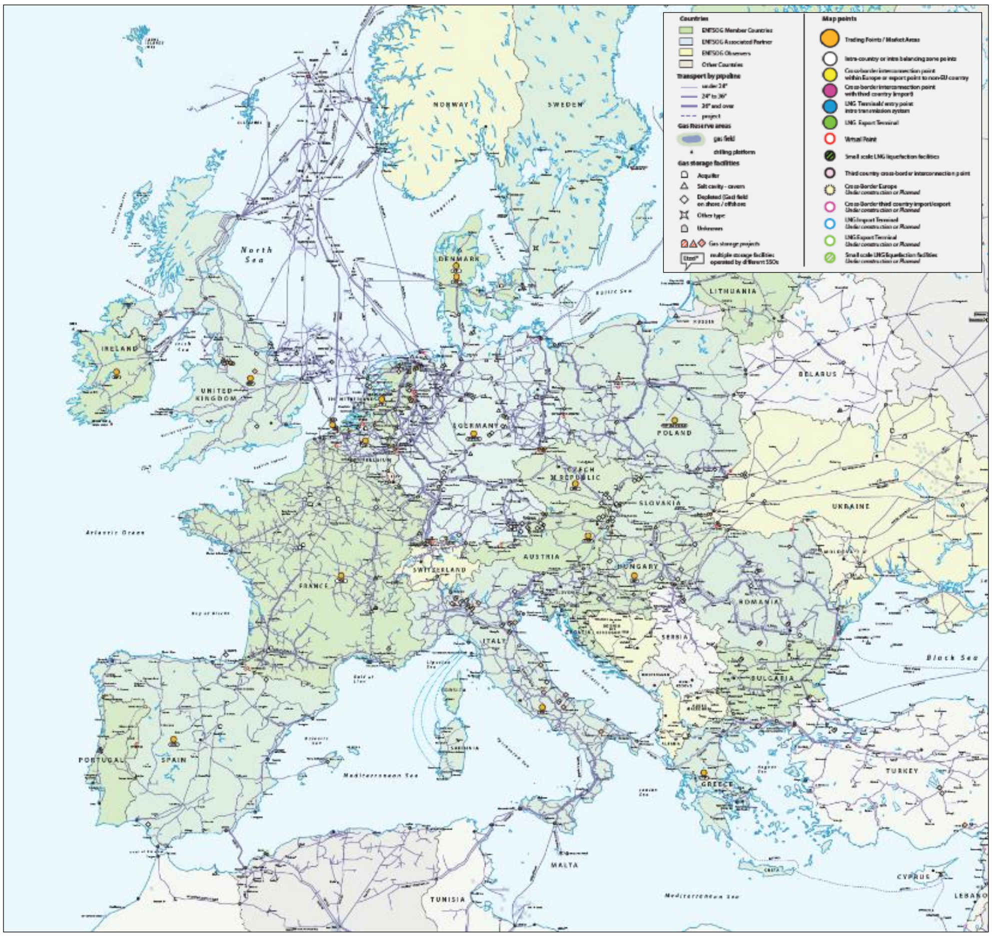

Figure 20. System Development Map. Source: ENTSOG,2023.

Values of mean storage capacity and total natural gas demand of European countries for the year 2020 were obtained from the map and are shown in Figure 21 and Figure 22.

[9] https://www.entsog.eu/maps

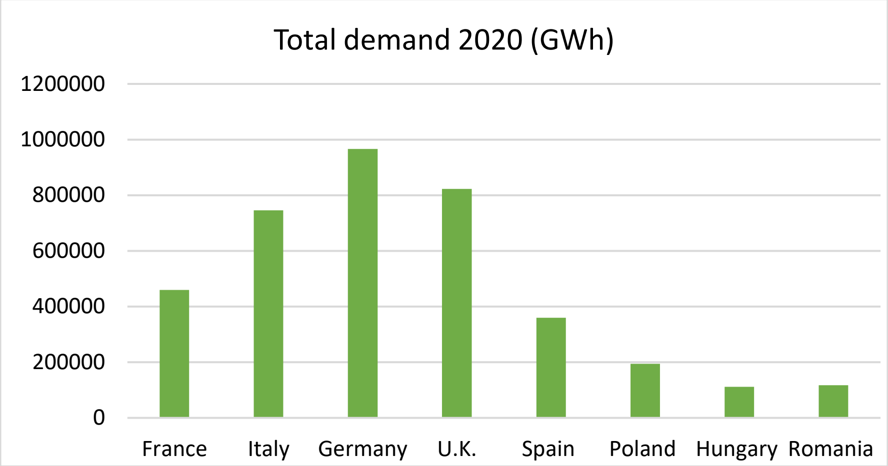

Figure 21. Natural gas total demand (2020) of the 8 top European countries.

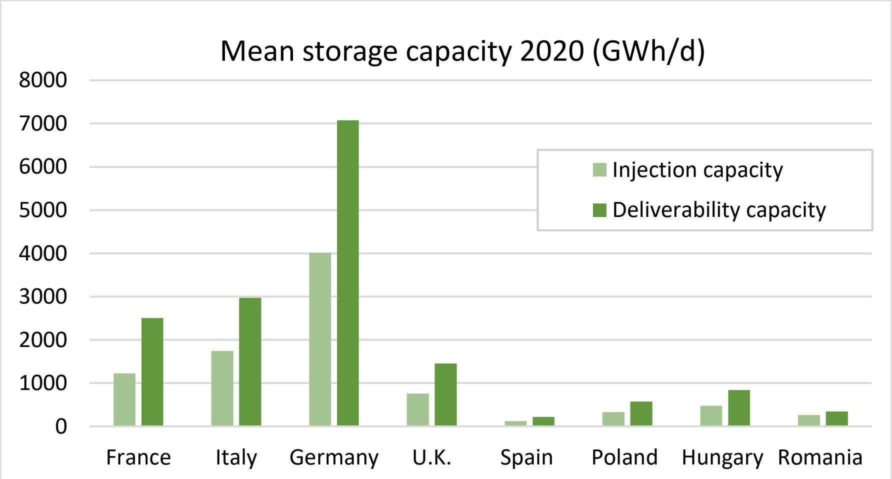

Figure 22. Natural gas mean storage capacity (2020) of the 8 top European countries.

The top four countries resulting through examination of the System Development map are: Germany, Italy, France, and UK.

Determination of the number and capacity of biomethane and biogas plants

The identification of existing biomethane plants relies on a map released from European Biogas Association (EBA) in 2021 (Figure 23). This comprehensive map lists all known biomethane installations running in Europe and has been produced with the information gathered from national biogas associations, energy agencies and companies[10]. The map provides specific details about each biomethane plant, including location, production capacity, start of operation and status of grid connection.

[10] https://www.europeanbiogas.eu/biomethane-map-2021/

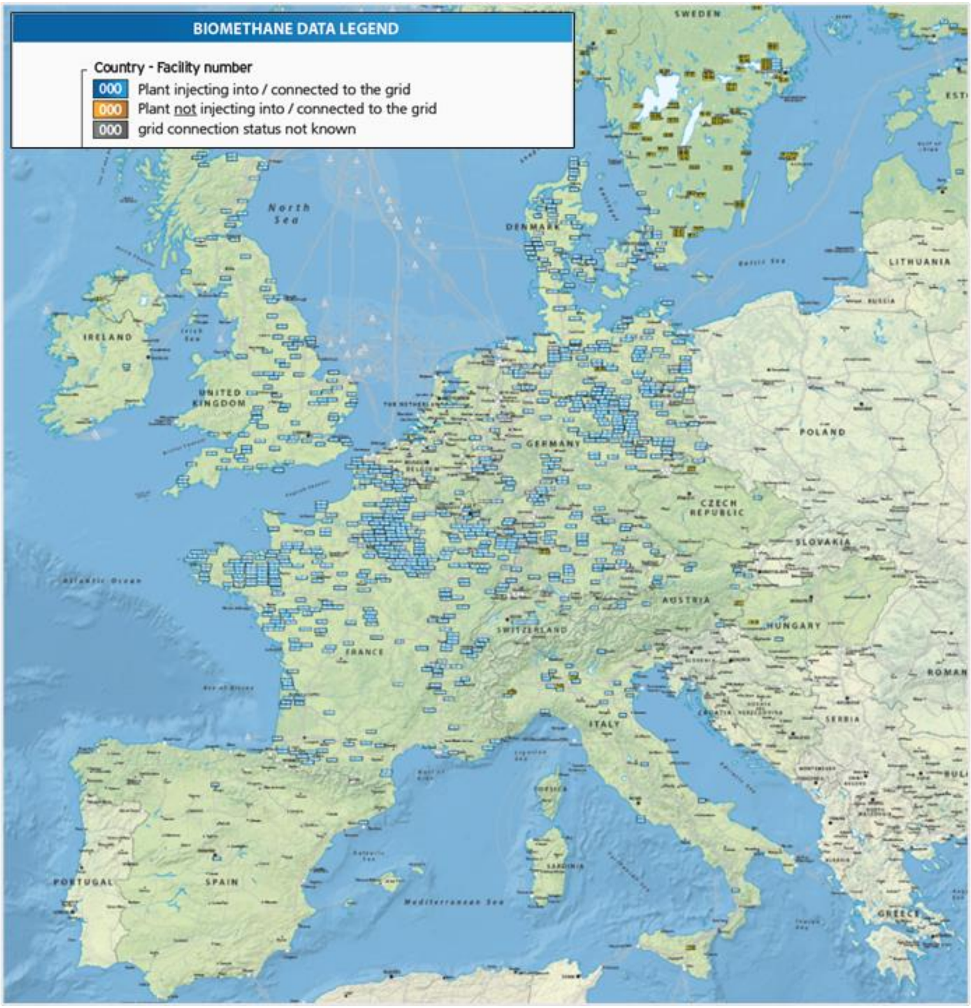

Figure 23. Biomethane plants in Europe. Source: EBA (2021)

The most promising countries identified in terms of number of biomethane plants and production capacity are again France, Germany, Italy, and UK. Collected data are listed in Table 12.

Table 12. Number of biomethane plants and total production capacity of the top four European countries.

Country	Number of biomethane plants	Present production capacity (Nm^3/h)	Connection to the grid
France	337	66,425	100%
Germany	198	111,616	100%
UK	98	79,350	100%
Italy	27	26,455	85%

As regards biogas plants, their number and respective production capacity in the various European countries could not be determined from a single available source. Then, data for France, Germany, Italy, and UK – the top countries in terms of biomethane potential from CC, biomethane current production capacity, as well as the development of the natural gas grid – was gathered using country-specific databases that were accessible online for consultation and download (Table 13).

Table 13. List of online databases used to collect data about number and production capacity of biogas plants in the target countries.

Country	Database	Year	Type of file
Italy	Gestore dei Servizi Energetici (GSE)	2017	xls
France	Association technique energie environnement (ATEE)	2020	shp
Germany	German Biogas Association	2022	pdf
UK	REA (Renewable Energy Association)	2019	shp

As appears from the above table, data collected for the selected countries present different years of reference as well as different formats for download and elaboration. In particular, files downloaded for France and UK could be opened and elaborated directly in the GIS environment and contained information about plants' locations, production capacities, and types of feedstocks and output (Figure 24). The file downloaded for Italy contained a list of biogas plants and corresponding production capacity and locations, but no information about utilized feedstocks and plant output was available (Table 14). However, the list could be used to generate a new layer to open in GIS. For Germany, only a pdf file containing overall number and production capacity for the whole country was available, and no further elaboration could then be produced (Figure 25). Overall results are summarized in Table 15.

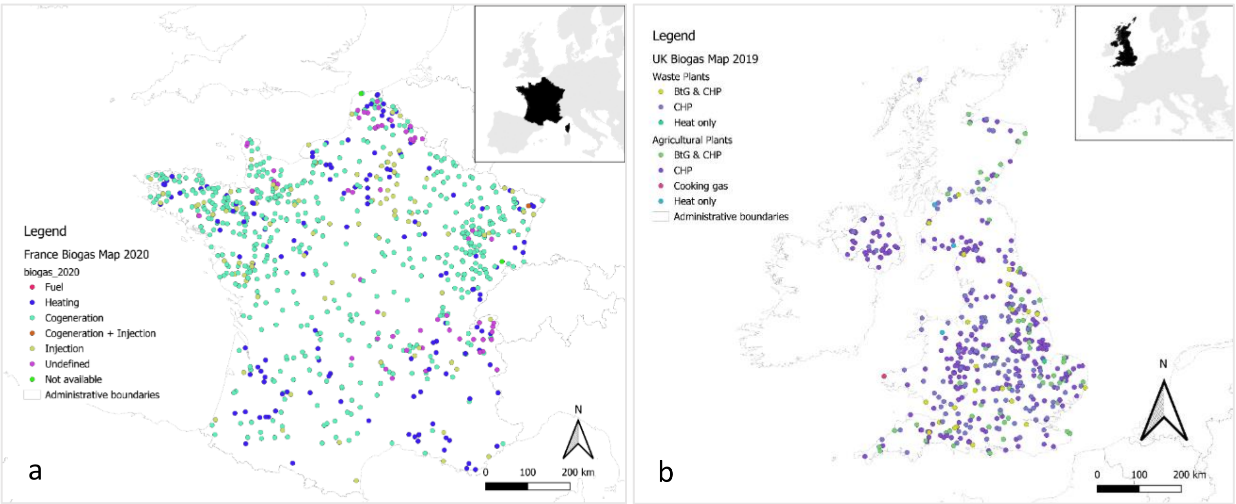

Figure 24. Location of biogas plants in France (a) and UK (b) and corresponding output.

Table 14. Excerpt from the excel file downloaded for Italy and containing information about location and capacity of the biogas plants.

Region	City	Municipality	P.(kWe)
Abruzzo	Chieti	Chieti	625
Abruzzo	Chieti	Cupello	300
Abruzzo	Chieti	Fara Filiorum Petri	100
Abruzzo	Chieti	Lanciano	999
Abruzzo	Chieti	Lanciano	1672
Abruzzo	L'Aquila	Avezzano	999
Abruzzo	L'Aquila	Celano	1027
Abruzzo	L'Aquila	Collarmele	990
Abruzzo	L'Aquila	Ortucchio	998
Abruzzo	L'Aquila	Raiano	100
Abruzzo	L'Aquila	Tagliacozzo	99
Abruzzo	L'Aquila	Trasacco	500
Abruzzo	Pescara	Citta' Sant'Angelo	999
Abruzzo	Pescara	Spoltore	2130
Abruzzo	Teramo	Atri	100
Abruzzo	Teramo	Castellalto	45
Abruzzo	Teramo	Mosciano Sant'Angelo	625
Abruzzo	Teramo	Nereto	100
Abruzzo	Teramo	Notaresco	996
Abruzzo	Teramo	Roseto Degli Abruzzi	999
Abruzzo	Teramo	Teramo	49

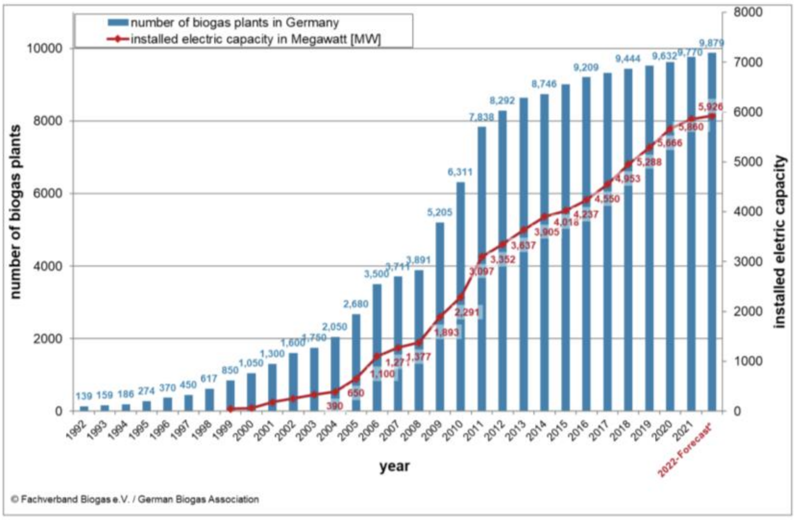

Figure 25. Development of the number of biogas plants and the total installed electric capacity in megawatt [MW] in Germany (as of 10/2022).

Table 15. Total number of biogas plants and installed capacity of the four selected target countries.

Country	Number of plants	Installed capacity (MWe)
Italy	2006	1339
Germany	9770	5926
France	797	182
UK	404	343

In this work, we calculated potential biomethane production in Italy, Germany, France and UK, assuming an upgrading of 90% of the biogas plants by 2030, a mean efficiency of a gas engine of 35%, a methane heating value of 10 kWh/Nm^3, and a methane content in the biogas of 57%.

GTL conversion technologies and factors

The biomethane-to-liquid fuels value chain consists in a decentralized pattern for biomethane production and a centralized pattern for fuel production. As regards liquid fuels production, conversion technologies of biomethane to Fisher -Tropsch (F.T.) diesel and MeOH have been considered. F.T. synthesis is a catalytic process for converting syngas into a petroleum-like product termed as FT crude, readily upgradable into a wide range of transportation grade liquid hydrocarbons. The polymerization of hydrocarbons in a FT reactor is theoretically governed by the Anderson-Shuls-Flory (ASF) distribution, which relates the weight fraction (W_n) of hydrocarbons containing n carbon atoms and the chain growth probability factor (Figure 26).

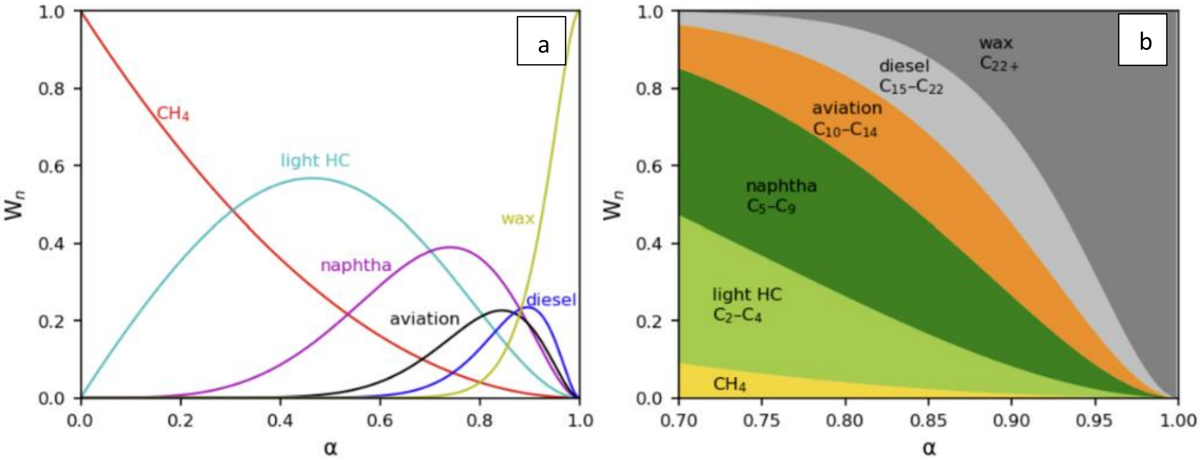

Figure 26. ASF distribution, Wn/n = (1-α)2 αn-1, FT selectivities (a) and high α-values favour long chain products (b)

Commercial-scale F.T. plants include the Pearl GTL from Shell and Qatar Petroleum in Qatar (140,000 bpd capacity), the Mossel Bay GTL from PetroSA in South Africa (36,000 bpd capacity), and the Bintulu GTL from Shell in Malaysia (14,700 bpd capacity), all of which located outside of Europe[11]. These examples represent massive facilities that would not fit in the European BDR for biomethane-to-liquid fuels production reality. However, by taking advantage of new technologies, GTL plants could be scaled down and provide a cost-effective way to make use of smaller biogas and biomethane resources in Europe (Brancaccio, 2021). Another possibility is to consider biomethane as a renewable source for methanol production. Examples of commercial-scale plants include the Titan and Atlas plants from Methanex, with MeOH production capacities of 2500 and 5000 tons/d, respectively[12].

In this work, we evaluated F.T. liquids and MeOH potential production considering conversion factors of 0.817 m^3/tCH_4 and 1.78 $tons/tCH_4$, respectively. The latter were established based on the conversion factors of the existing commercial scale plant.

[11] https://www.etipbioenergy.eu/fact-sheets

[12] https://aenert.com/

3 Results

3.1 Perennial grasses for bioethanol

The following table provides a summary of the outputs obtained from the assessment of perennial grasses case study.

Table 16. Summary of the outputs obtained from data elaboration of perennial grasses case study.

Output	Target crop	Target area	Target biorefineries	Scenario /supply distance
1	Switchgrass	Europe	2G bioethanol	Scenario 1 - 70 km
2	Miscanthus	Europe	2G bioethanol	Scenario 1 - 70 km
3	Switchgrass	Europe	1G bioethanol	Scenario 1 - 70 km
4	Miscanthus	Europe	1G bioethanol	Scenario 1 - 70 km
5	Switchgrass	Europe	2G bioethanol	Scenario 2 - 150 km
6	Miscanthus	Europe	2G bioethanol	Scenario 2 - 150 km
7	Switchgrass	Europe	1G bioethanol	Scenario 2 - 150 km
8	Miscanthus	Europe	1G bioethanol	Scenario 2 - 150 km

The results of switchgrass and miscanthus yield modelling, performed using data from the GAEZ data portal, are displayed in the maps in Figure 27 and Figure 28. Switchgrass attainable yield ranges from 0 to 28 dry tons per hectare, while miscanthus attainable yield ranges from 0 to 23 dry tons per hectare. It is important to note that experimental trials often provide higher yields for miscanthus than for switchgrass; yet, we decided to proceed forward with the assessment taking into consideration the output from GAEZ. This decision is supported by the fact that the two crops will be discussed together, as a single case study, and the goal of offering an estimation of potential biomass production in all of Europe is still achieved. However, additional research is advised in order to calibrate the model to experimental findings and produce more accurate outcomes.

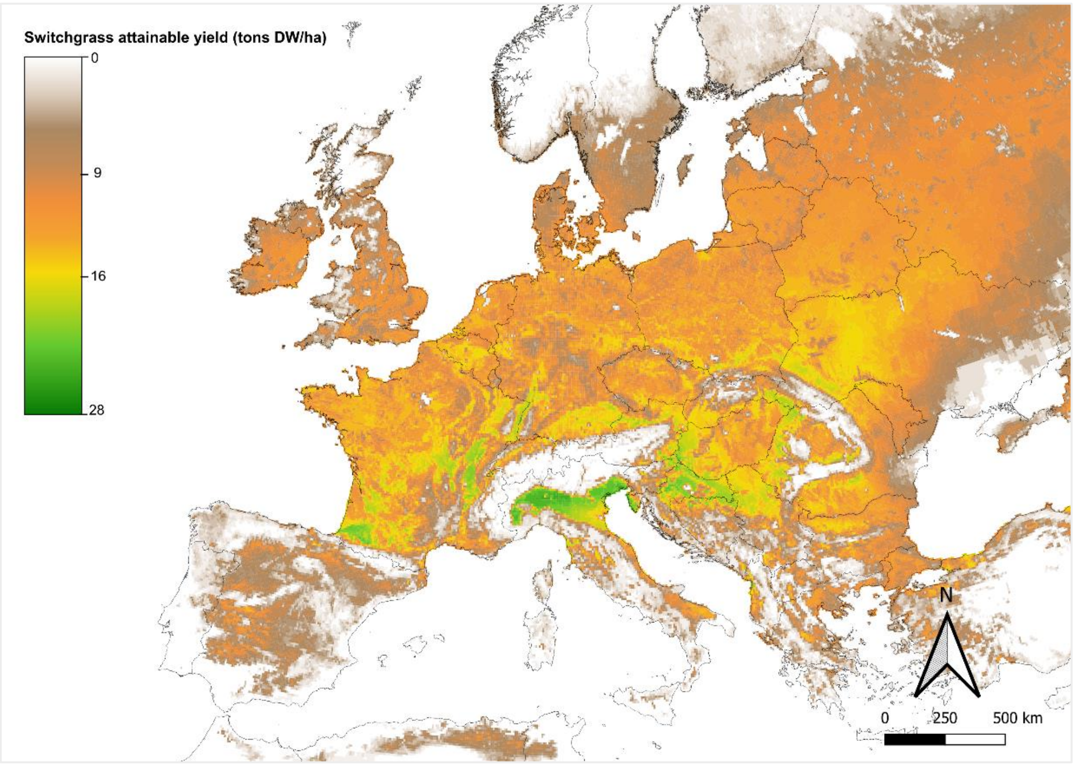

Figure 27. Switchgrass attainable yield in Europe.

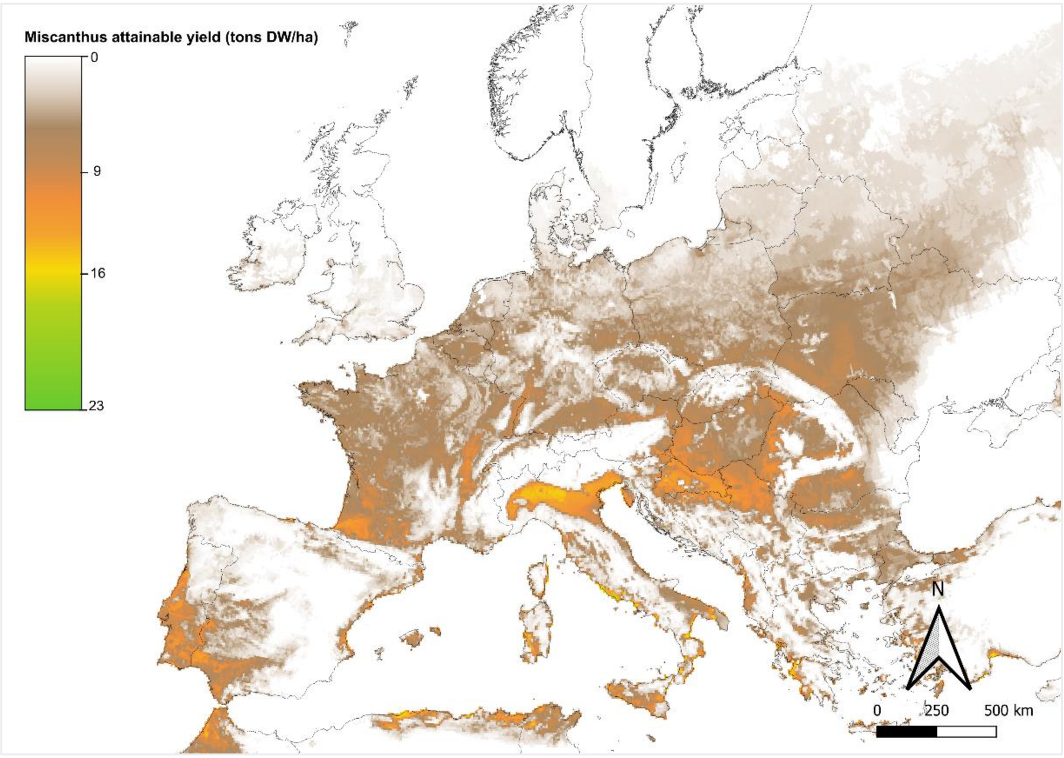

Figure 28. Miscanthus attainable yield in Europe.

The two layers of switchgrass and miscanthus attainable yield were overlayed to the map of underutilized lands retrieved from the BIOPLAT platform and the map of biorefineries created for this project. Considering supply distances of 70 km and 150 km from biorefineries, potential biomass production was calculated. A minimum annual dry biomass production of 100,000 tons was established as a threshold to identify the most promising case studies. Results are shown in the following sections.

3.1.1 Scenario 1 – 70 km distance for biomass supply

Figure 29 and Figure 30 display the outputs that were produced considering second-generation bioethanol plants (both operational and planned/under construction), areas of 70km radius for biomass supply, and switchgrass and miscanthus attainable yields on underutilized lands. A total annual production of 778,540 and 328,784 dry tons is estimated for switchgrass and miscanthus, respectively. Only a single case study located in Romania met or exceeded the threshold value of 100,000 tons, represented by Clariant plant in Podari (Table 17).

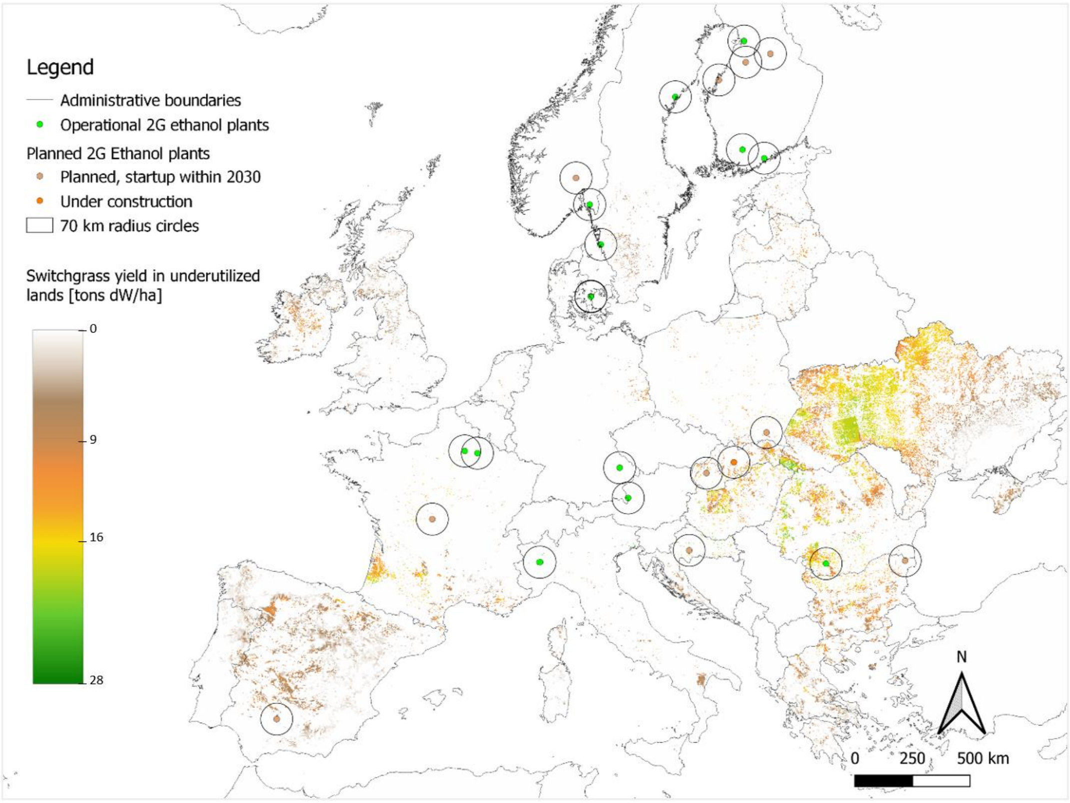

Figure 29. Switchgrass attainable yield in European underutilized lands, second-generation bioethanol plants and 70 km supply radius

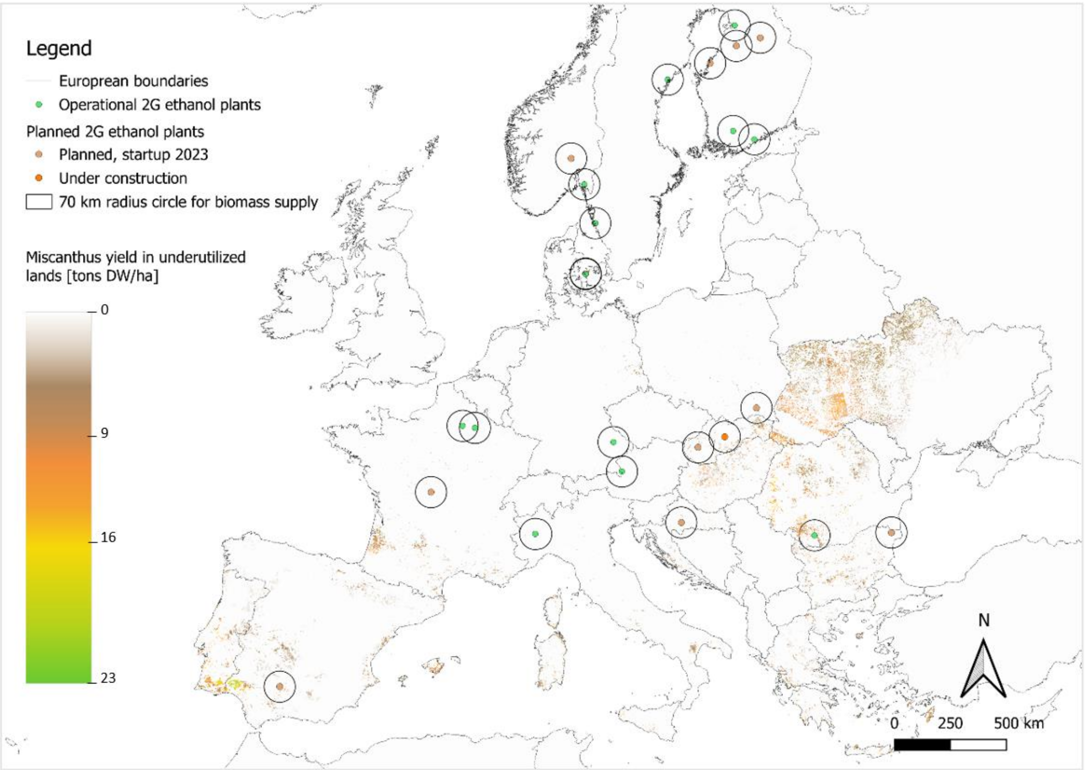

Figure 30. Miscanthus attainable yield in European underutilized lands, second-generation bioethanol plants and 70 km supply radius.

Table 17. Switchgrass and Miscanthus potential production within 70 km distance from second-generation ethanol plants.

Name of the plant	Status	Country	Underutilized lands [hectares]	Switchgrass [t DW/year]	Miscanthus [t DW/year]
Crescentino Bioethanol Plant	Operational	Italy	257	5789	3191
AustroCel Hallein	Operational	Austria	49	123	25
Futurol ARD	Operational	France	29	322	114
Futurol IFP	Operational	France	66	926	343
Clariant AG	Operational	Germany	0	0	0
Clariant Products RO	Operational	Romania	38,615	498,623	200,287
Inibicon	Operational	Denmark	0	0	0
Gothenburg Ethanol Plant	Operational	Sweden	573	1,831	0
Borregaard Industries AS	Operational	Norway	44	144	0
Ornskoldsvik SEKAB	Operational	Sweden	0	0	0
St 1 Bionolix	Operational	Finland	1249	1,929	0
Chemopolis Oy	Operational	Finland	0	0	0
Etanolix Vantaa	Operational	Finland	10	10	0
Sainc Energy Limited	Planned	Spain	8,910	46,066	37,147
RYAM	Planned	France	143	1,639	731
Bioskoh	Planned	Slovakia	4,451	50,789	21,192
Envirals Leopoldov	Planned	Slovakia	6,959	76,819	29,099
Jedlicze Site	Planned	Poland	5,594	76,312	27,197
Clariant Technology	Planned	Bulgaria	350	4,248	614
INA Ethanol	Planned	Croatia	685	12,898	88,44
RE Energy	Planned	Denmark	0	0	0
Cellulonix Pietrarsaari	Planned	Finland	144	72	0
St1 Cellulonix	Planned	Finland	0	0	0
Nordfuel biorefinery	Planned	Finland	0	0	0
Cellulonix Follum	Planned	Norway	0	0	0
			tot	**778,540**	**328,784**

Figure 31 shows the results obtained while taking into account first-generation bioethanol plants with possibility of upgrade to second-generation, areas with a radius of 70 km for biomass supply, and the attainable yields of switchgrass on underutilized lands. A total annual production of 1,296,822 and 355,856 dry tons is estimated for switchgrass and miscanthus, respectively. Five case studies met or exceeded the threshold value of 100,000 tons, of which two located in Spain, one in Hungary and two in Bulgaria (Table 18).

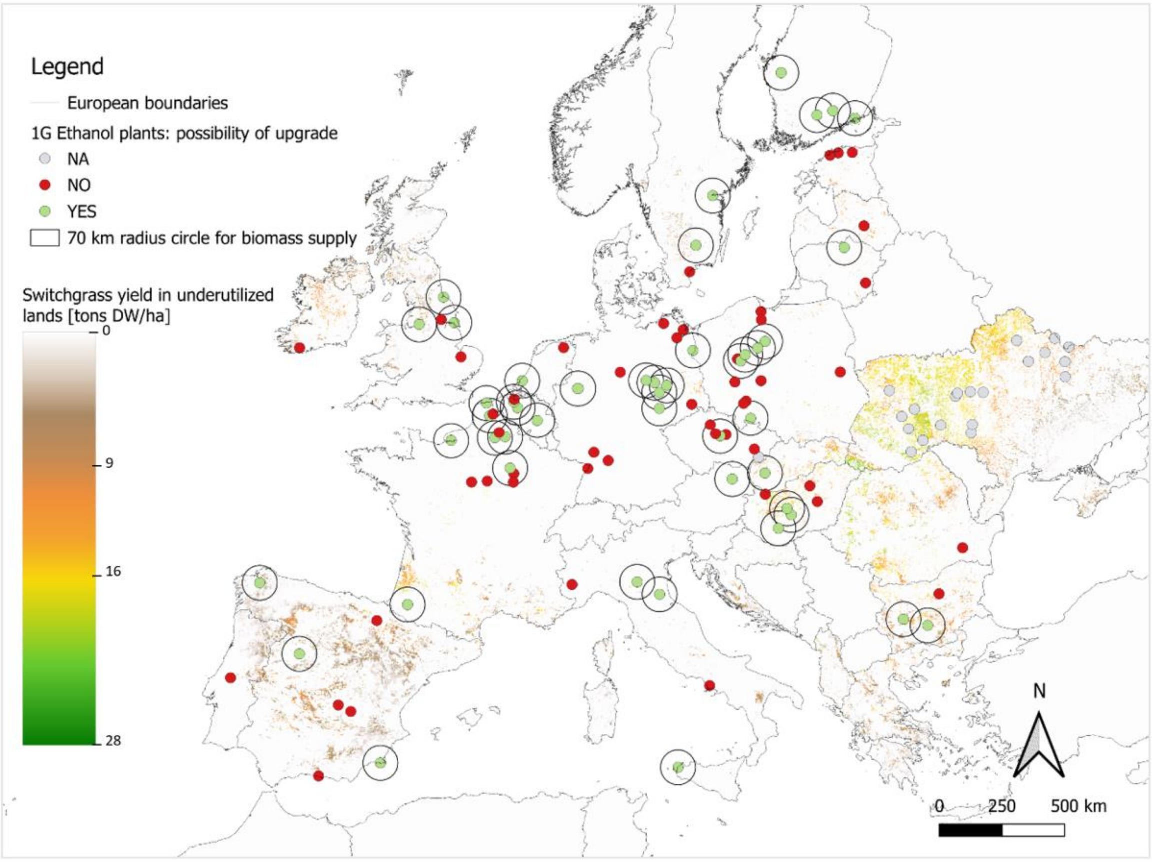

Figure 31. Switchgrass attainable yield in European underutilized lands, first-generation bioethanol plants with possibility of upgrade and 70 km supply radius.

Table 18. Switchgrass and Miscanthus potential production within 70 km distance from first-generation ethanol plants.

Name of the plant	Country	Underutilized lands [hectares]	Switchgrass [t DW/year]	Miscanthus [t DW/year]
IMA, Bertolino	Italy	910	0	12,782
Caviro Distillerie SRL	Italy	112	410	190
Silicompa	Italy	454	3,570	1,394
Vertex Bioenergy, Lacq	France	2,032	38,269	18,702
Connatre-Morains Plant	France	14	78	42
Origny Tereos Plant	France	0	0	0
Nesle Tereos Plant	France	0	0	0
Lillers Tereos Plant	France	24	425	325
Ryssen Akciiks S.A.S., Loon-Plage (CropEnergies)	France	24	425	325
Lillebone tereos Plant	France	43	559	172
Vertex Bioenergy	Spain	25,213	0	0
Vertex Bioenergy Babilafuente	Spain	142,604	347,467	3,528
Vertex Bioenergy Bioetanol Galicia SA	Spain	48,739	157,321	39,219
BioWanze S.A. (CropEnergies)	Belgium	29	358	105
Aalst Tereos-Syral	Belgium	13	184	160
Alco Group, Ghent	Belgium	13	184	160
Alco Energy Rotterdam BV	Netherlands	0	0	107
EAL Euro Alkohol-GmbH	Germany	0	0	0
CropEnergies Bioethanol GmbH	Germany	54	894	163
Verbio Ethanol Zorbig GmbH & Co. KG	Germany	54	894	163
BrüggemannAlcohol	Germany	176	2,118	819
Barby Plant (Cargill)	Germany	24	322	24
Fuel 21 Klein Wanzleben Refinery	Germany	44	514	24
Verbio Ethanol Schwedt GmbH & Co. KG	Germany	125	1,472	224
Manchester Biorefinery (Cargill/Royal Nedalco)	UK	14,293	62,770	28
Vivergo Fuels	UK	68	705	74
Ensus UK	UK	750	4,093	0
Pischelsdorf Biorefinery	Austria	75	529	262
Bioetanol AEG	Poland	16	73	16
Bioetanol AEG	Poland	91	880	188
Ima Polska	Poland	10	65	21
Goswinowice Ethanol Plant (Bioagra S.A).	Poland	338	5,240	2,039
Agrar-beta	Hungary	1,821	29,406	15,337
Pannonia Bio Zrt.	Hungary	4,230	59,292	30,149
Hungrana Bioeconomy Company	Hungary	7,942	104,295	48,217
Almagest AD	Bulgaria	23,314	219,866	83,077
Essentica Ethanol Factory	Bulgaria	17,142	173,195	68,333
Ethanol Energy	Czech Republic	0	0	0
Anora Group Oyj	Finland	563	389	0
Hameenlinna Bionolix Plant (St1 Biofuels Oy)	Finland	12	12	0
Lahti Etanolix Plant (St1 Biofuels Oy)	Finland	21	21	0
St1 Biofuels Oy	Finland	0	0	0
Kurana UAB	Lithuania	216	2,829	346
ENVIRAL	Slovakia	6,951	77,051	29,141
Landsmanne Agroetanol A.B.	Sweden	90	647	0
Lantmännen Maskin AB	Sweden	0	0	0
		tot	**1,296,822**	**355,856**

3.1.2 Scenario 2 – 150 km distance for biomass supply

Figure 32 and Figure 33 display the outputs that were produced considering second-generation bioethanol plants (both operational and planned/under construction), areas of 150km radius for biomass supply, and switchgrass and miscanthus attainable yields on underutilized lands. A total annual production of 3,113,382 and 1,302,401 dry tons is estimated for switchgrass and miscanthus, respectively. Five case studies met or exceeded the threshold value of 100,000 tons, of which one located in Romania, one in Spain, two in Slovakia and one in Poland (Table 19).

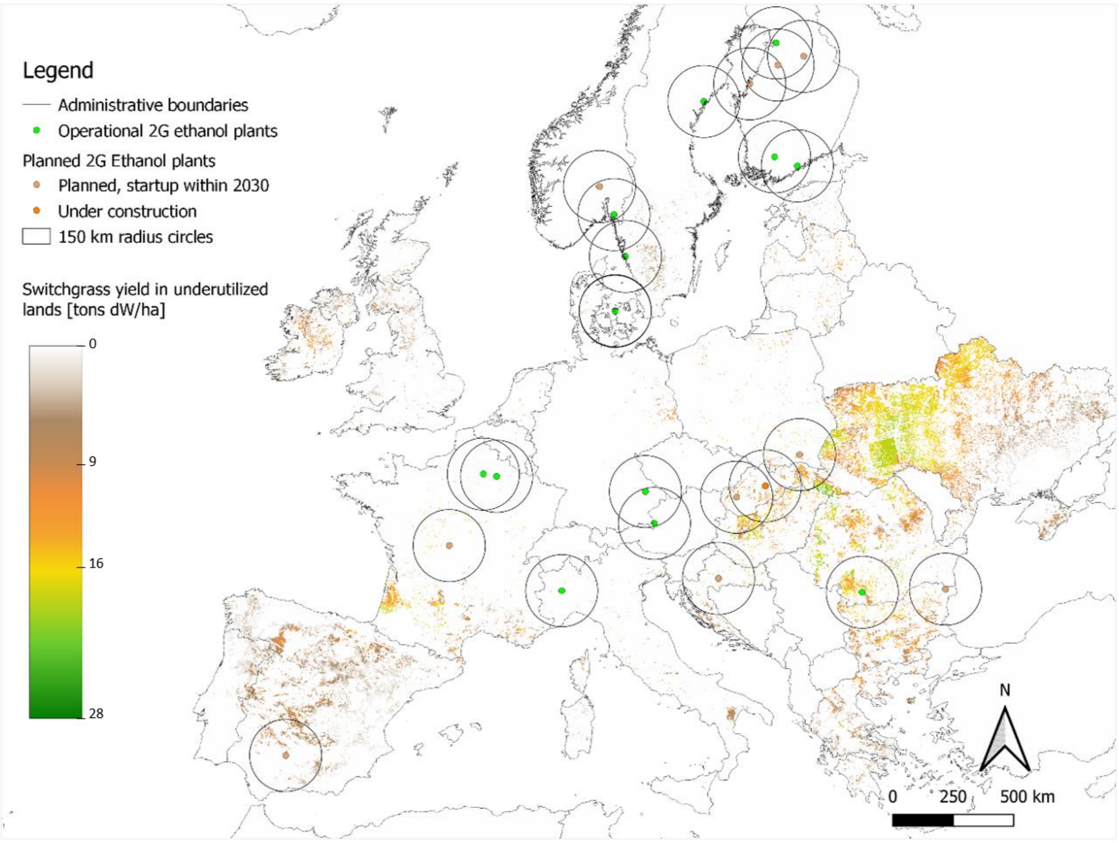

Figure 32. Switchgrass attainable yield in European underutilized lands, second-generation bioethanol plants and 150 km supply radius.

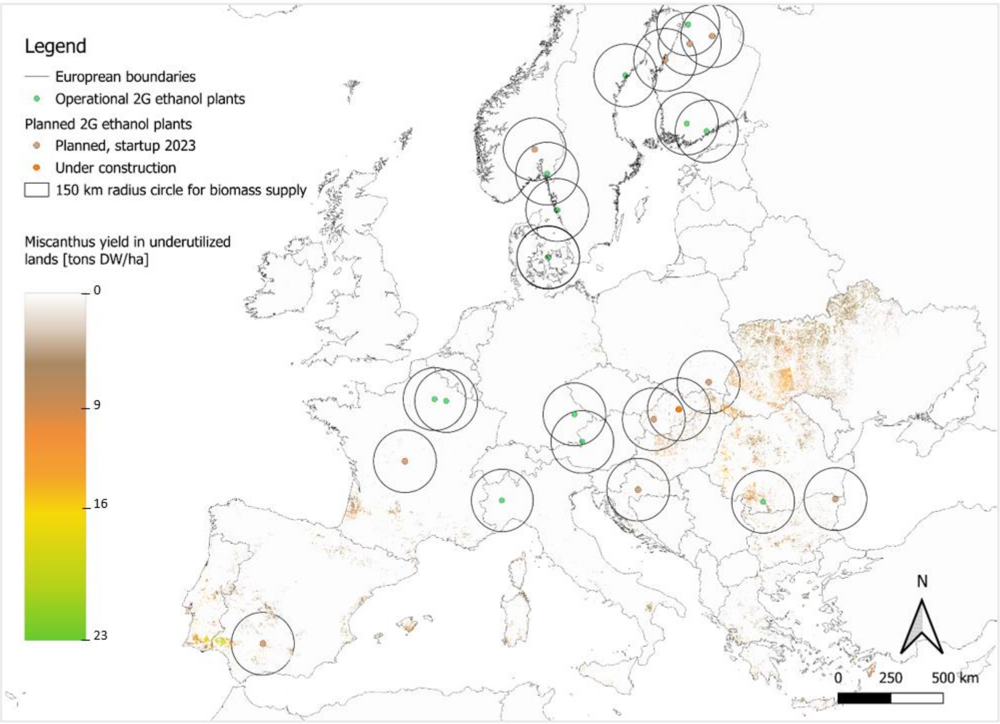

Figure 33. Miscanthus attainable yield in European underutilized lands, 2G bioethanol plants and 150 km supply radius.

Table 19. Switchgrass and Miscanthus potential production within 150 km distance from operational 2G ethanol plants.

Name of the plant	Status	Country	Underutilized lands [hectares]	Switchgrass [t DW/year]	Miscanthus [t DW/year]
Crescentino Bioethanol Plant	Operational	Italy	495	7,617	4,097
AustroCel Hallein	Operational	Austria	160	261	83
Futurol ARD	Operational	France	182	2,071	738
Futurol IFP	Operational	France	324	4,197	1,753
Clariant AG	Operational	Germany	49	123	25
Clariant Products RO	Operational	Romania	79,901	1,131,775	500,168
Inibicon	Operational	Denmark	53	700	42
Gothenburg Ethanol Plant	Operational	Sweden	3,243	17,110	12
Borregaard Industries AS	Operational	Norway	1,278	3,769	0
Ornskoldsvik SEKAB	Operational	Sweden	0	0	0
St 1 Bionolix	Operational	Finland	3,476	6,284	0
Chemopolis Oy	Operational	Finland	0	0	0
Etanolix Vantaa	Operational	Finland	1,099	4,749	0
Sainc Energy Limited	Planned	Spain	105,049	630,856	269,461
RYAM	Planned	France	1,708	27,685	9,999
Bioskoh	Planned	Slovakia	28,739	341,731	120,733
Envirals Leopoldov	Planned	Slovakia	20,966	240,042	106,548
Jedlicze Site	Planned	Poland	42,496	544,118	229,692
Clariant Technology	Planned	Bulgaria	5,799	59,268	16,270
INA Ethanol	Planned	Croatia	15,635	89,815	42,739
RE Energy	Planned	Denmark	53	700	42
Cellulonix Pietrarsaari	Planned	Finland	848	512	0
St1 Cellulonix	Planned	Finland	0	0	0
Nordfuel biorefinery	Planned	Finland	0	0	0
Cellulonix Follum	Planned	Norway	0	0	0
			tot	**3,113,382**	**1,302,401**

For first-generation bioethanol plants, expanding the supply radius to 150 km resulted in a total estimated annual production of 7,164,698 and 2,186,558 dry tons of switchgrass and miscanthus, respectively. Twelve case studies exceeded the threshold value of 100,000 tons, of which one located in France, three in Spain, two in UK, three in Hungary, two in Bulgaria and one in Slovakia (Table 20).

Table 20. Switchgrass and Miscanthus potential production within 150 km distance from first-generation ethanol plants.

Name of the plant	Country	Underutilized lands [hectares]	Switchgrass [t DW/year]	Miscanthus [t DW/year]
IMA, Bertolino	Italy	1637	0	14,826
Caviro Distillerie SRL	Italy	1093	10590	4719
Silicompa	Italy	912	8083	3651
Vertex Bioenergy, Lacq	France	67030	787,757	320,255
Connatre-Morains Plant	France	630	8,677	3,150
Origny Tereos Plant	France	144	1,934	781
Nesle Tereos Plant	France	251	3,552	1,435
Lillers Tereos Plant	France	60	425	325
Ryssen Akciiks S.A.S., Loon-Plage (CropEnergies)	France	60	425	325
Lillebone tereos Plant	France	264	4,044	1,151
Vertex Bioenergy	Spain	374086	191,345	240,783
Vertex Bioenergy Babilafuente	Spain	345461	2,131,886	279,330
Vertex Bioenergy Bioetanol Galicia SA	Spain	283616	585,146	166,532
BioWanze S.A. (CropEnergies)	Belgium	451	4,957	1,901
Aalst Tereos-Syral	Belgium	229	2,271	1,040
Alco Group, Ghent	Belgium	90	996	419
Alco Energy Rotterdam BV	Netherlands	529	5,397	1,991
EAL Euro Alkohol-GmbH	Germany	301	1,893	685
CropEnergies Bioethanol GmbH	Germany	304	4,828	1,538
Verbio Ethanol Zorbig GmbH & Co. KG	Germany	471	6,422	1,924
BrüggemannAlcohol	Germany	2554	31,712	10,567
Barby Plant (Cargill)	Germany	384	4,926	1,375
Fuel 21 Klein Wanzleben Refinery (Nordzucker)	Germany	211	2,870	567
Verbio Ethanol Schwedt GmbH & Co. KG	Germany	5349	62,362	22,441
Manchester Biorefinery (Cargill/Royal Nedalco)	UK	66044	240,431	222
Vivergo Fuels	UK	1101	7,643	137
Ensus UK	UK	51827	179,926	98
Pischelsdorf Biorefinery	Austria	1636	20,376	8,194
Bioetanol AEG	Poland	374	4,761	981
Bioetanol AEG	Poland	355	4,467	916
Ima Polska	Poland	847	10,737	2,248
Goswinowice Ethanol Plant (Bioagra S.A).	Poland	513	7,972	2,994
Agrar-beta	Hungary	19813	272,385	143,277
Pannonia Bio Zrt.	Hungary	21616	288,697	137,228
Hungrana Bioeconomy Company	Hungary	24382	326,583	155,270
Almagest AD	Bulgaria	89480	754,676	253,316
Essentica Ethanol Factory	Bulgaria	96382	877,134	288,726
Ethanol Energy	Czech Republic	185	2,147	596
Anora Group Oyj	Finland	3237	3,092	0
Hameenlinna Bionolix Plant (St1 Biofuels Oy)	Finland	408	594	0
Lahti Etanolix Plant (St1 Biofuels Oy)	Finland	21	21	0
St1 Biofuels Oy	Finland	330	1,600	0
Kurana UAB	Lithuania	5,490	58,728	5,763
ENVIRAL	Slovakia	20,529	236,971	104,881
Lantmännen Agroetanol A.B.	Sweden	621	3,259	0
Lantmännen Maskin AB	Sweden	0	0	0
		tot	**7,164,698**	**2,186,558**

Table 21 and Table 22 represent a list of the most promising case studies identified for scenario 1 and scenario 2, respectively. Only the highest values for potential dry biomass production given by switchgrass have been included. A conversion factor of 174.5 $L_{EtOH}/t_{dry\ switchgrass}$ has been used for calculation of potential bioethanol production for each case study (Larnaudie et al., 2022). We assumed it would be possible to achieve the estimated values of ethanol production by the year 2030 for the second-generation ethanol plants, and by the year 2040 for the first-generation ethanol plants.

Table 21. Scenario 1: summary of promising case studies identified and corresponding potential bioethanol production.

Name of refinery	Type of refinery	Country	Supply distance	Target crop	Potential dry biomass production (tons/year)	Potential bioethanol production (tons/year)	Year
Clariant Products	Second-generation	Romania	70 km	Switchgrass	498,623	68,651	2030
Vertex Bioenergy Babilafuente	First-generation	Spain	70 km	Switchgrass	347,467	47,839	2040
Vertex Bioenergy Galicia	First-generation	Spain	70 km	Switchgrass	157,321	21,660	2040
Hungrana Bioeconomy Company	First-generation	Hungary	70 km	Switchgrass	104,295	14,359	2040
Almagest AD	First-generation	Bulgaria	70 km	Switchgrass	219,866	30,271	2040
Essentica Ethanol Factory	First-generation	Bulgaria	70 km	Switchgrass	173,195	23,846	2040

Table 22. Scenario 2: summary of promising case studies identified and corresponding potential bioethanol production.

Name of refinery	Type of refinery	Country	Supply distance	Target crop	Potential dry biomass production (tons/year)	Potential bioethanol production (tons/year)	Year
Clariant Products	Second-generation	Romania	150 km	Switchgrass	1,131,775	155,823	2030
Sainc Energy Limited	Second-generation	Spain	150 km	Switchgrass	630,856	86,857	2030
Bioskoh	Second-generation	Slovakia	150 km	Switchgrass	341,731	47,050	2030
Envirals Leopoldov	Second-generation	Slovakia	150 km	Switchgrass	240,042	33,049	2030
Jedlicze Site	Second-generation	Poland	150 km	Switchgrass	544,118	74,914	2030
Vertex Bioenergy, Lacq	First-generation	France	150 km	Switchgrass	787,757	108,459	2040
Vertex Bioenergy	First-generation	Spain	150 km	Switchgrass	191,345	26,344	2040
Vertex Bioenergy Babilafuente	First-generation	Spain	150 km	Switchgrass	2,131,886	293,519	2040
Vertex Bioenergy Bioetanol Galicia SA	First-generation	Spain	150 km	Switchgrass	585,146	80,563	2040
Manchester Biorefinery (Cargill/Royal Nedalco)	First-generation	UK	150 km	Switchgrass	240,431	33,103	2040
Ensus UK	First-generation	UK	150 km	Switchgrass	179,926	24,772	2040
Agrar-beta	First-generation	Hungary	150 km	Switchgrass	272,385	37,502	2040
Pannonia Bio Zrt.	First-generation	Hungary	150 km	Switchgrass	288,697	39,748	2040
Hungrana Bioeconomy Company	First-generation	Hungary	150 km	Switchgrass	326,583	44,964	2040
Almagest AD	First-generation	Bulgaria	150 km	Switchgrass	754,676	103,904	2040
Essentica Ethanol Factory	First-generation	Bulgaria	150 km	Switchgrass	877,134	120,764	2040
Enviral	First-generation	Slovakia	150 km	Switchgrass	236,971	32,626	2040

In the case of scenario 1, about 68,600 tons of bioethanol could be produced by providing switchgrass at a 70 km supply distance from the existing second-generation bioethanol plant run by Clariant, in Romania. When considering to supply biomass also to the existing first-generation bioethanol facilities (possibly upgraded to second-generation by 2040), the amount could be tripled (around 207,000 tons). In the case of Scenario 2, with a 150 km of supply distance, around 398,000 tons of bioethanol could be produced by existing second-generation bioethanol plants.

This amount would jump to about 1.3 million tons if also fist-generation bioethanol facilities are taken into consideration.

3.2 Castor oil for renewable diesel

The following table provides a summary of outputs obtained from the assessment of castor bean case study.

Table 23. Summary of the outputs obtained from data elaboration of castor bean case study.

Output	Target crop	Target area	Target biorefineries	Scenario/supply distance
1	Castor bean	Mediterranean area	HVO	Scenario 1 - 230 km
2	Castor bean	Mediterranean area	Biodiesel	Scenario 1 - 230 km
3	Castor bean	Mediterranean area	HVO, Biodiesel	Scenario 2 - 500 km

The values obtained from literature regarding castor bean seed yield in mediterranean countries – 1.35 tons/ha in Spain, 1.77 tons/ha in Italy and 2.24 tons/ha in Greece – were overlaid to the map of underutilized lands retrieved from the BIOPLAT platform and the map of biorefineries created for this project. Considering supply distances of 230 km and 500 km from biorefineries, potential oil production was calculated. A minimum annual oil production of 20,000 tons was established as a threshold to identify the most promising case studies. Results are shown in the following sections.

3.2.1 Scenario 1 – 230 km distance from biorefineries for biomass supply

Figure 34 displays the output that was produced considering HVO plants (both operational and planned), areas with 230 km radius for biomass supply, and estimated castor seed yields in Spain (1.35 tons/ha) and Italy (1.77 tons/ha). It is important to highlight that, for some of the biorefineries, the area of biomass supply has been adjusted to include a bigger proportion of the nearby underutilized areas, rather than being centered in the biorefinery itself. A total oil production of 360,811 t/y is estimated for the five operational HVO plants considered in the assessment. Three out of the four evaluated case studies resulted as promising as they met or exceeded the set threshold value of 20,000 tons of annual oil production. The case studies located in Spain – represented by the two operational HVO plants owned by CEPSA and the HVO facility planned by REPSOL– have an estimated annual oil production of 136,815 tons and 191,876 tons, respectively. The case study located in Livorno (Italy) – represented by the HVO facility planned by ENI – has an estimated annual oil production of 29,411 tons (Table 24).

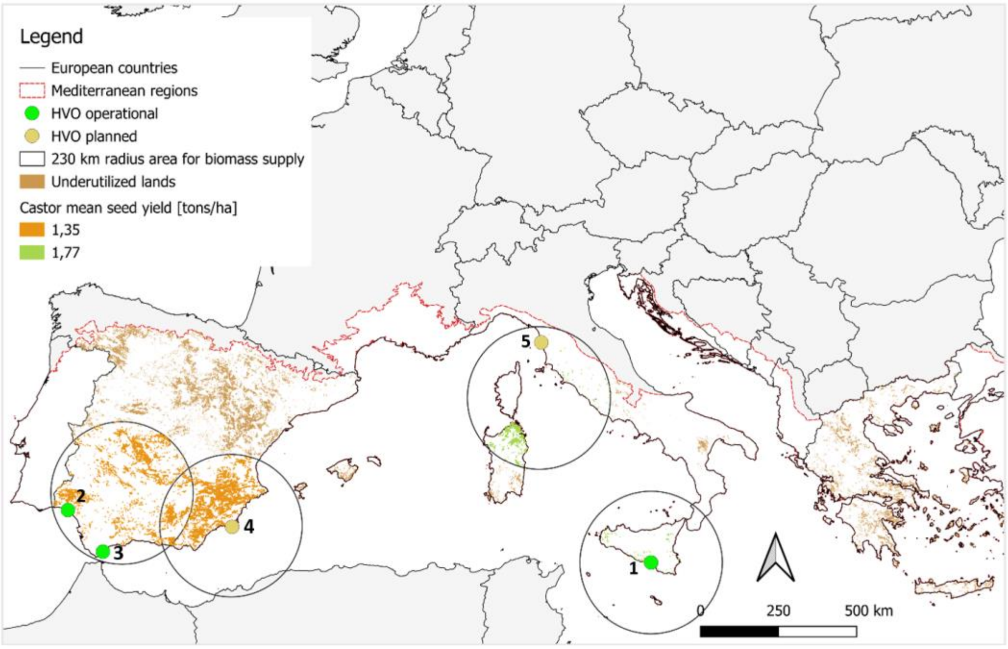

Figure 34. HVO biorefineries in Mediterranean regions, 230 km supply radius and castor mean seed yield.

Table 24. Castor bean oil potential production within a 230 km supply radius from HVO refineries.

Code	Name of the plant	Underutilized lands (hectares)	Mean seed yield (tons/ha)	Mean oil content (%)	Oil production(t/y)
1	Eni raffineria di Gela	3,243	1.77	47.2	2,709
2	La Ribida Energy Park (CEPSA)	217,477	1.35	46.6	136,815
3	Abengoa Biofuel Plant (CEPSA)				
4	Complejo Industrial de Cartagena de Repsol	305,001	1.35	46.6	191,876
5	Eni raffineria di Livorno	35,204	1.77	47.2	29,411
				tot	**360,811**

Figure 35 shows the output that was produced considering three biodiesel plants located in EU mediterranean regions, areas with 230 km radius for biomass supply, and the estimated castor seed yields in Spain (1.35 tons/ha), Italy (1.77 tons/ha) and Greece (2.24 tons/ha). A total oil production potential of 609,853 t/y is estimated. The case study located in Spain – represented by the Biocom refinery – exceeds the threshold value of 20,000 tons annual production with an estimated oil production of 336,230 t/y. The case study located in Greece – represented by the Agroinvest refinery – also gave promising results with an estimated annual oil production of 267,168 tons.

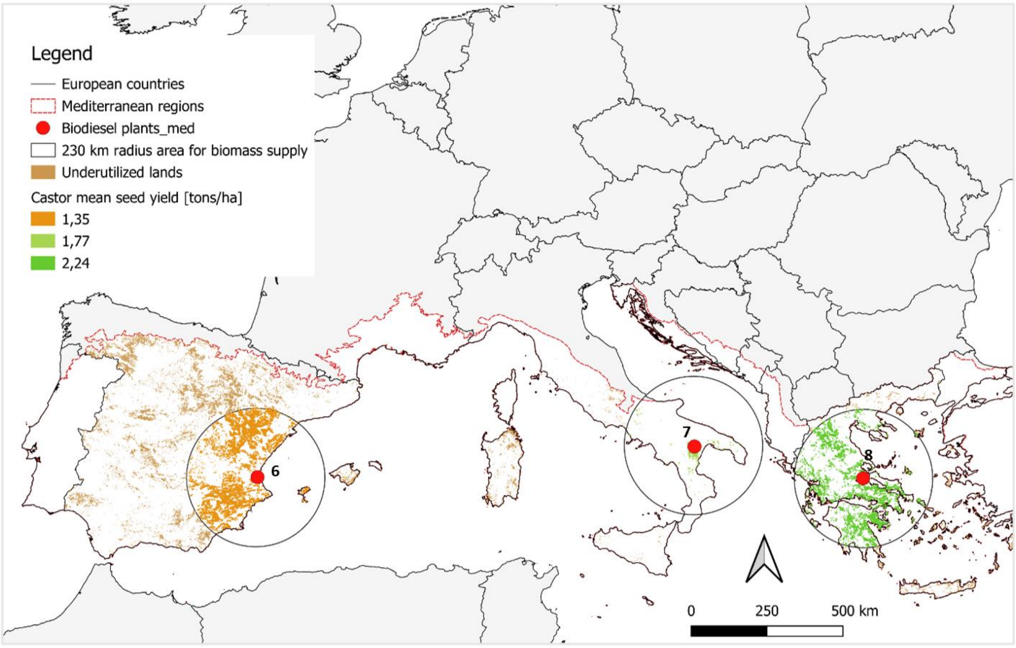

Figure 35. Biodiesel refineries in Mediterranean regions, 230 km supply radius and castor mean seed yield.

Table 25. Castor bean oil potential production within a 230 km supply radius from biodiesel refineries.

Code	Name of the plant	Underutilized lands (hectares)	Mean seed yield (tons/ha)	Mean oil content (%)	Oil production(t/y)
6	Biocom energia	534,462	1.35	46.6	336,230
7	Greenswitch	7,727	1.77	47.2	6,455
8	Agroinvest s.a.	216,857	2.24	55.0	267,168
				tot	**609,853**

3.2.2 Scenario 2 – 500 km distance from biorefineries for biomass supply

Figure 36 displays the output that was produced considering 4 biorefineries – two HVO plants in Spain, one HVO plant in Italy and one biodiesel plant in Greece – areas of 500 km radius for biomass supply, and the estimated castor seed yields in Spain (1.35 tons/ha), Italy (1.77 tons/ha) and Greece (2.24 tons/ha).The three case studies covered all of the underutilized lands located in the mediterranean countries and all exceeded the set threshold value of 20,000 tons annual oil production. In particular, the case study located in Spain has an estimated annual oil production of 927,695 tons, the case study located in Italy has an estimated annual oil production of 63,103 tons, the case study located in Greece has an estimated annual oil production of 990,798 tons (Table 26).

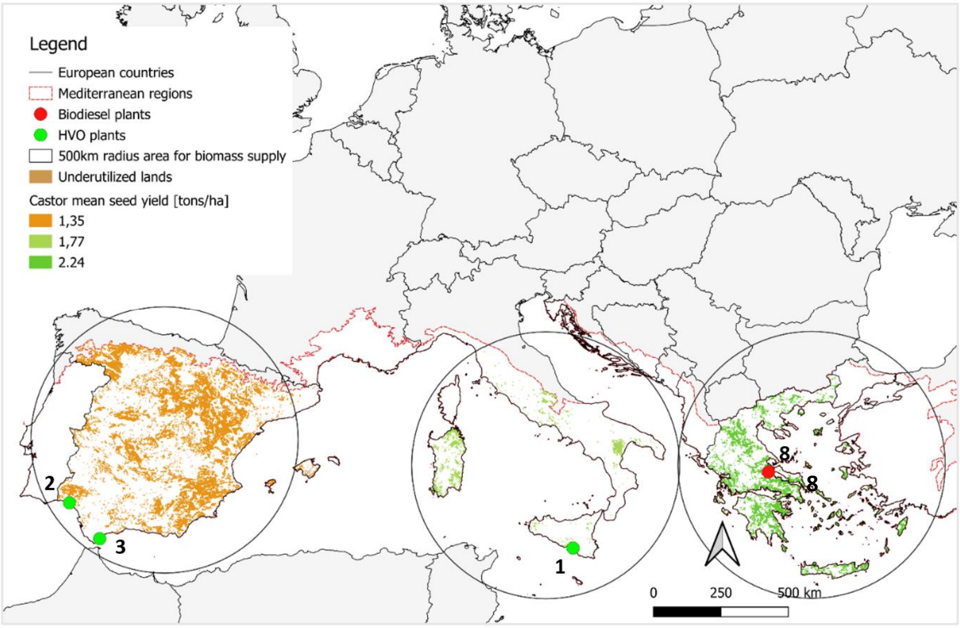

Figure 36. HVO and biodiesel refineries in Mediterranean regions, 500 km supply radius and castor mean seed yield.

Table 26. Castor bean oil potential production within a 500 km supply radius from HVOI and biodiesel refineries.

Code	Name of the plant	Underutilized lands (hectares)	Mean seed yield (tons/ha)	Mean oil content (%)	Oil production(t/y)
1	Eni raffineria di Gela	75,533	1.77	47.2	63,103
2	La Ribida Energy Park (CEPSA)	1,474,638	1.35	46.6	927,695
3	Abengoa biofuel plant (CEPSA)				
8	Agroinvest s.a.	1,550,171	2.24	55.0	990,798
				tot	**1,081,596**

Table 27 represents a summary of the most promising case studies identified for scenario 1 and scenario 2. Potential HVO and biodiesel production from estimated castor oil production has been calculated considering conversion factors of 0.7 and 0.85 $t_{renewable\ diesel}/t_{oil}$, respectively. The latter were identified from conversion factors of the existing refineries included in the assessment. We assumed that estimated values of HVO and biodiesel production would be feasible to achieve by the year 2030.

Table 27. Summary of most promising case studies identified and potential HVO/biodiesel production from castor oil.

Name of refinery	Type of refinery	Country	Supply distance	Potential oil production (tons/year)	Potential HVO/biodiesel production (tons/year)	Year
CEPSA plants	HVO	Spain	230 km	136,815	95,771	2030
Complejo Industrial de Cartagena de Repsol	HVO	Spain	230 km	191,876	134,313	2030
Eni raffineria di Livorno	HVO	Italy	230 km	29,411	20,588	2030
Biocom energia	Biodiesel	Italy	230 km	336,230	285,796	2030
Agroinvest s.a.	Biodiesel	Greece	230 km	267,168	227,093	2030
Eni raffineria di Gela	HVO	Italy	500 km	63,103	44,172	2030
CEPSA plants	HVO	Spain	500 km	927,695	649,387	2030
Agroinvest s.a.	Biodiesel	Greece	500 km	990,798	842,178	2030

Considering a supply radius of 230 km, the cultivation of castor in underutilized lands of mediterranean countries could bring to the production of vegetable oil that can be processed in existing biorefinery to produce around 250,672 tons of HVO and 512,889 tons of biodiesel. Considering a supply radius of 500 km, the estimated production would be of around 693,559 tons of HVO and 842,178 tons of biodiesel.

3.3 Brassica Carinata oil for renewable diesel

The following table provides a summary of the outputs obtained from the assessment of brassica carinata case study.

Table 28. Summary of the outputs obtained from data elaboration of brassica carinata case study.

Output	Target crop	Target area	Target biorefineries	Scenario	Supply distance
1	Brassica carinata	Mediterranean area	HVO operational	Brassica summer cover crop	230 km
2	Brassica carinata	Mediterranean area	HVO planned	Brassica summer cover crop	230 km
3	Brassica carinata	Mediterranean area	Biodiesel	Brassica summer cover crop	230 km
4	Brassica carinata	Mediterranean area	HVO, Biodiesel	Brassica summer cover crop	500 km
5	Brassica carinata	Mediterranean area	HVO, Biodiesel	Brassica winter cover crop	230 km

The results of brassica carinata yield modeling, which was performed using data from the GAEZ data portal, are displayed in the map in Figure 37. Brassica attainable seed yield ranges from 0 to 4.2 tons per hectare. On the same line of castor bean case study, a value of 20,000 tons of annual oil production was considered a threshold for identification of most promising case studies.

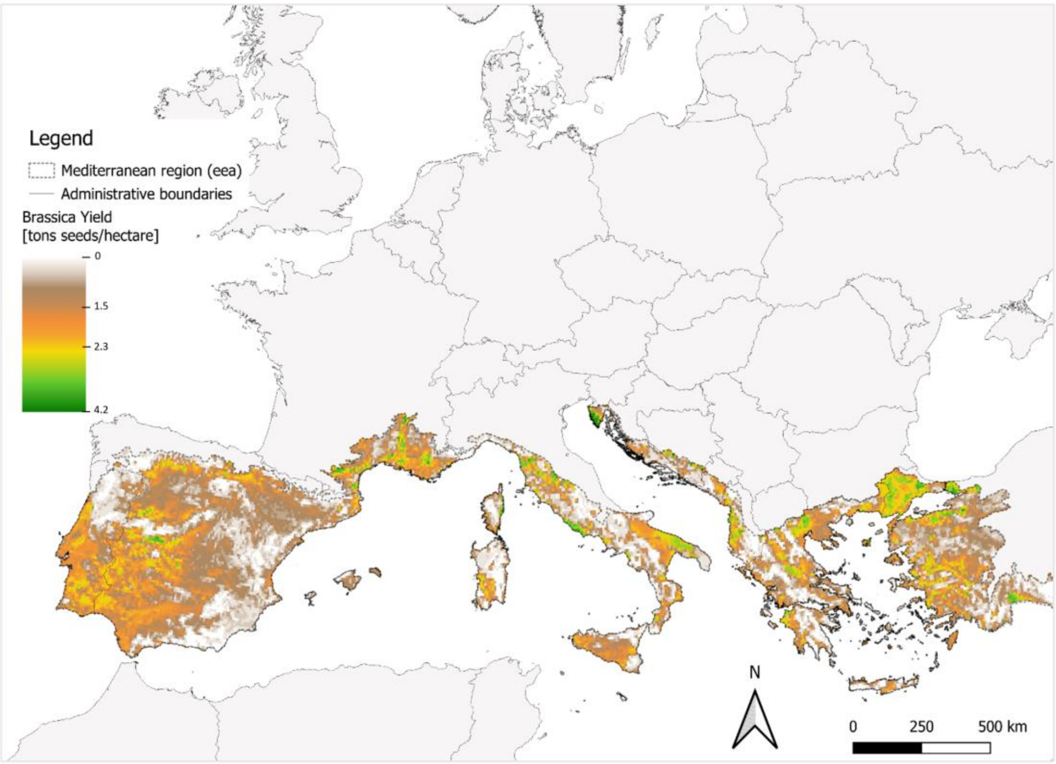

Figure 37. Brassica napus attainable yield in European mediterranean regions.

3.3.1 Scenario 1 – Brassica Carinata as a summer cover crop

In the first scenario assessed, brassica carinata has been integrated in the rotational schemes as a summer cover crop. Figure 38 shows the outputs of annual oil potential production considering the operational HVO plants in the mediterranean countries, areas with 230km radius for biomass supply, and a sub-regional administrative division of the countries. The case studies in Spain and Italy showed promising results. In particular, a total annual oil production of 84,218 tons is estimated for the two plants owned by CEPSA in Spain, while a total annual oil production of 31,856 tons is estimated for the plant in Italy owned by ENI (Table 29).

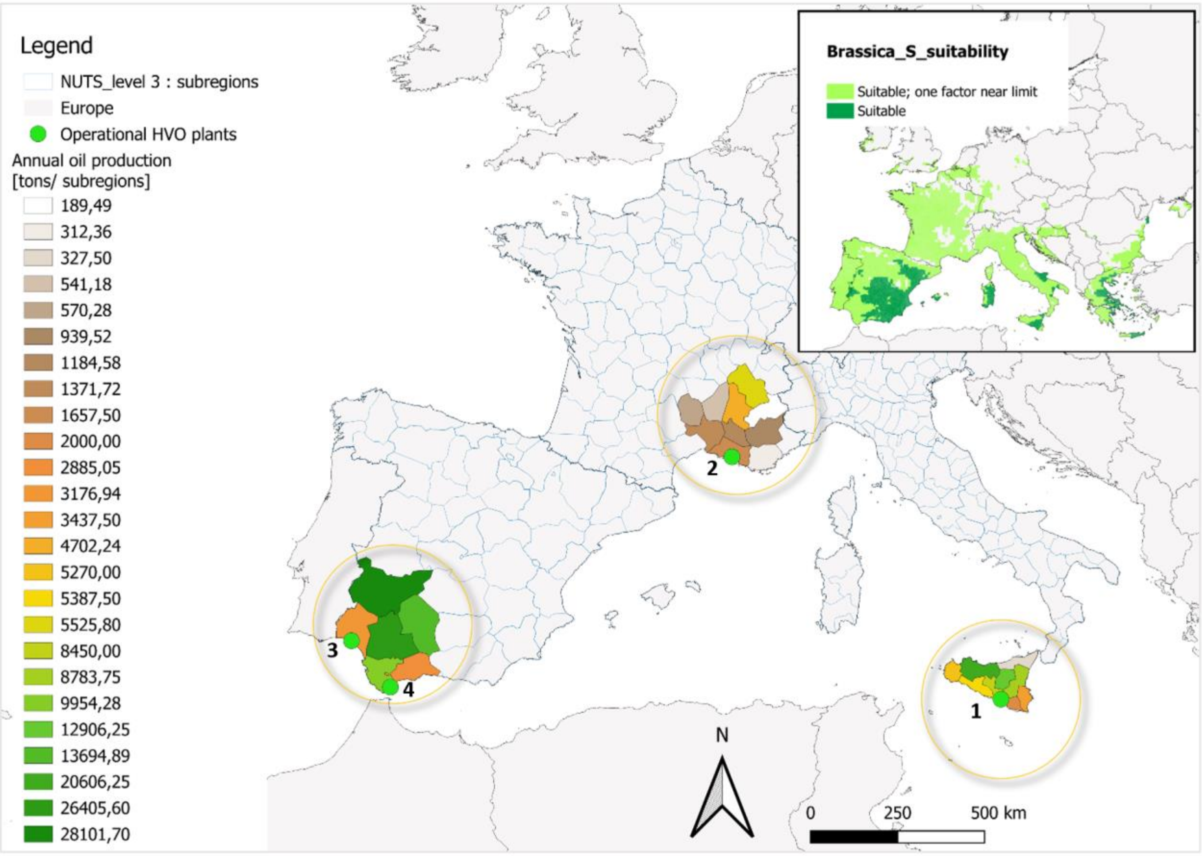

Figure 38. HVO operational refineries, areas of 230 km for biomass supply and estimated annual oil production per sub-region.

Table 29. Estimated annual brassica oil production per HVO operational refinery and 230 km distance for biomass supply.

Nr.	Name of the plant	Surface dedicated to winter cereals [hectares]	Mean brassica yield [tons seeds/hectare]	Seeds [tons/year]	Oil* [tons/year]
1	Eni raffineria di Gela Spa	268,675	1.13	79,640	31,856
2	TOTAL La Mede Biorefinery	114,950	1.40	42,487	16,995
3	La Ribida Energy Park (CEPSA)	549,518	1.44	210,546	84,218
4	Abengoa Biofuel Plant (CEPSA)				
			tot	332,673	133,069

**An oil content of 40% was assumed for calculation of oil production*

Figure 39 shows the outputs of annual oil potential production considering the HVO refineries planned in the mediterranean countries, areas with 230km radius for biomass supply, and a sub-regional administrative division of the countries. Both the case studies in Spain and Italy showed promising results. In particular, a total annual oil production of 27,847 tons is estimated for the plant owned by REPSOL in Spain, while a total annual oil production of 71,396 tons is estimated for the plant in Italy owned by ENI (Table 30).

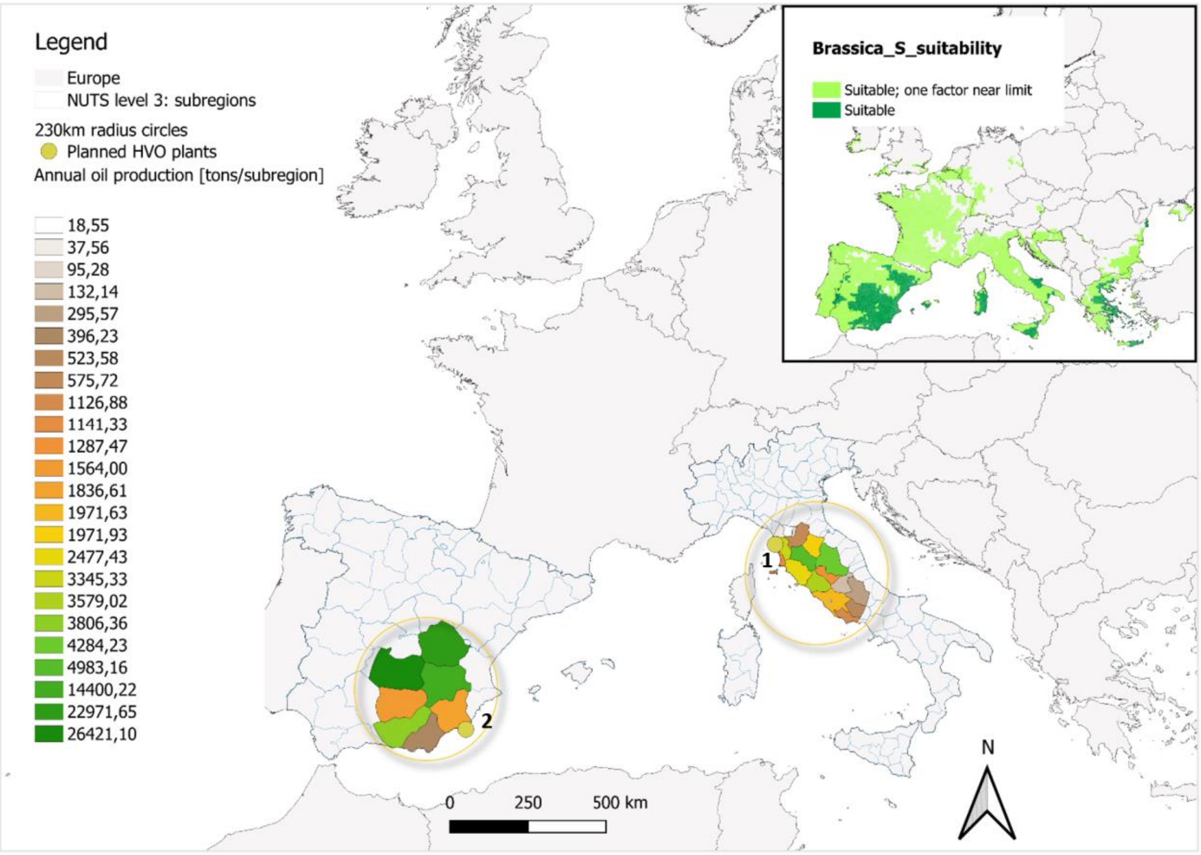

Figure 39. HVO planned refineries, areas of 230 km for biomass supply and estimated annual oil production per sub-region.

Table 30. Estimated annual brassica oil production per HVO planned refinery and 230 km distance for biomass supply.

Nr.	Name of the plant	Surface dedicated to winter cereals [hectares]	Mean Brassica yield [tons seeds/hectare]	Seeds [tons/year]	Oil* [tons/year]
1	Eni raffineria di Livorno	837,297	0.73	178,490	**71,396**
2	Complejo Industrial de Cartagena de Repsol	219,684	1.25	69,617	**27,847**
			tot	**248,107**	**99,243**

**An oil content of 40% was assumed for calculation of oil production*

Figure 40 shows the outputs of annual oil potential production considering three biodiesel plants in the mediterranean countries, areas with 230km radius for biomass supply, and a sub-regional administrative division of the countries. All the three assessed case studies in Spain, Italy and Greece showed promising results. In particular, a total annual oil production of 88,444 tons is estimated for the plant in Spain (Biocom Energia), a total annual oil production of 75,483 tons is estimated for the plant in Italy (Greenswitch), while a total annual oil production of 33,630 tons is estimated for the plant in Greece (Agroinvest) (Table 31).

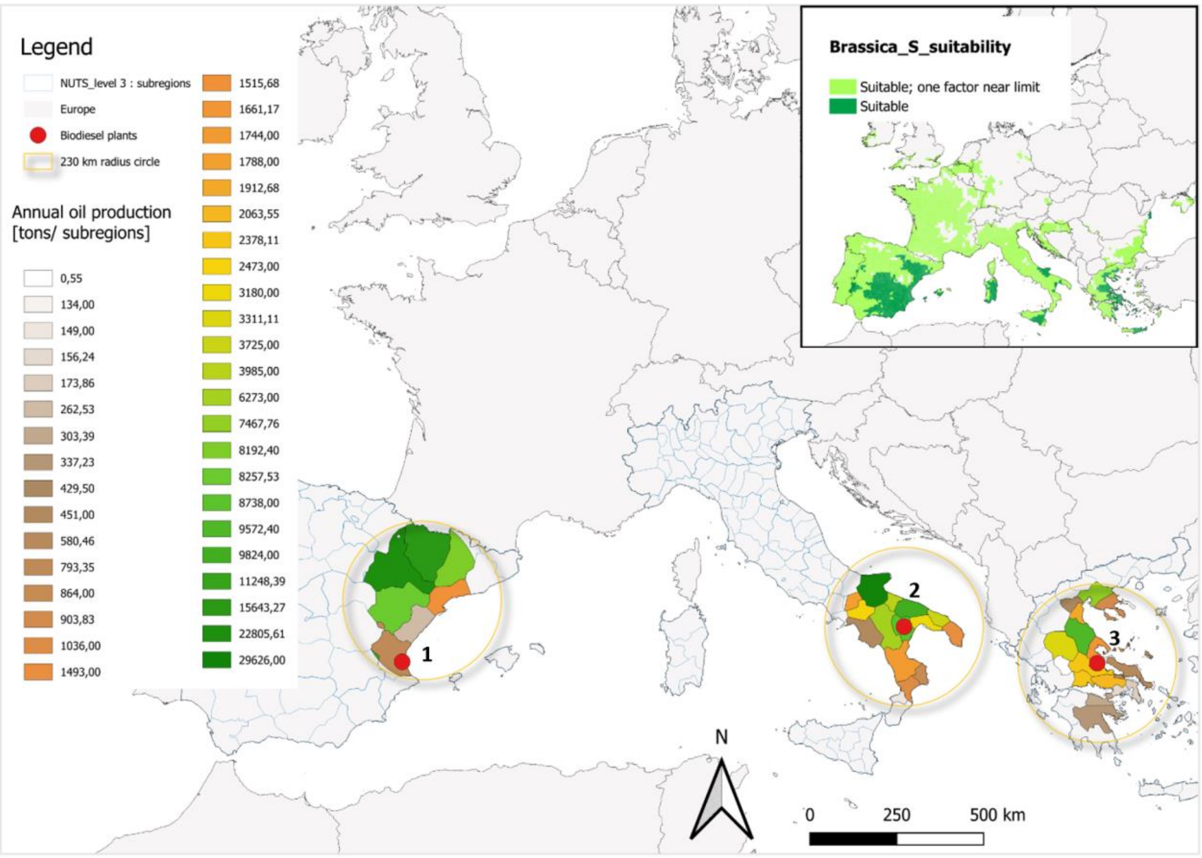

Figure 40.Biodiesel refineries, areas of 230 km for biomass supply and estimated annual oil production per sub-region.

Table 31. Estimated annual brassica oil production per biodiesel refinery.

Nr.	Name of the plant	Surface dedicated to winter cereals [hectares]	Mean Brassica yield [tons seeds/hectare]	Seeds [tons/year]	Oil* [tons/year]
1	Biocom Energia	1,376,591	0.65	221,111	88,444
2	Greenswitch	632,139	1.16	188,707	75,483
3	Agroinvest	308,150	0.98	84,075	33,630
			tot	**493,893**	**197,557**

**An oil content of 40% was assumed for calculation of oil production*

Finally, a scenario with areas of 500 km radius for biomass supply was assessed (Figure 41). In this scenario, only four plants have been included; however, the outcomes are equivalent and interchangeable to the other biorefineries located inside the supply areas. As expected, expanding the supply radius resulted in higher values of estimated annual oil production. In particular, an annual oil production of 283,997 tons is estimated for the two plants located in Spain, an annual production of 123,733 tons is estimated for the plant located in Italy, an annual production of 69,424 tons is estimated for the plant located in Greece (Table 32)

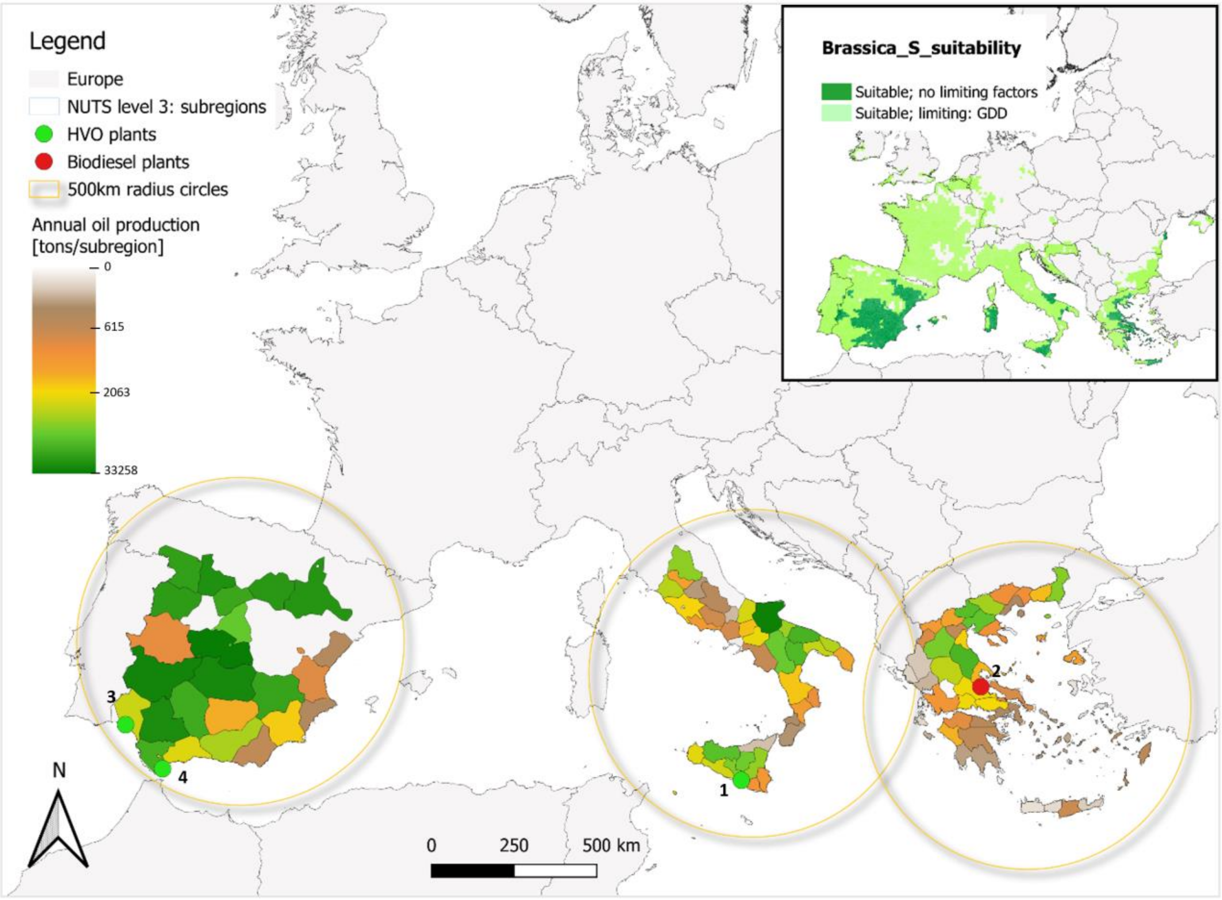

Figure 41. HVO and biodiesel refineries, areas of 500 km for biomass supply and estimated annual oil production per sub-region.

Table 32. Estimated annual oil production considering brassica as a summer cover crop and a supply radius of 500km from biorefineries.

Nr.	Name of the plant	Surface dedicated to winter cereals [hectares]	Mean Brassica yield [tons seeds/hectare]	Seeds [tons/year]	Oil* [tons/year]
1	Eni raffineria di Gela Spa	1,095,879	1.04	285,194	123,733
2	Agroinvest	578,571	0.99	173,561	69,424
3	La Ribida Energy Park (CEPSA)	2,472,160	1.05	709,993	283,997
4	Abengoa Biofuel Plant (CEPSA)				
			tot	1,168,748	477,154

**An oil content of 40% was assumed for calculation of oil production*

3.3.2 Scenario 2 – Brassica Carinata as a winter cover crop

In the second scenario assessed, brassica carinata has been integrated in the rotational schemes as a winter cover crop. Since brassica carinata winter variety presents fewer areas of adaptability compared to the summer variety, only four biorefineries have been considered in the assessment – two biodiesel plants and two HVO plants – with a radius of 230 km for biomass supply. Figure 42 shows the outputs of annual oil potential production considering a sub-regional administrative division of the countries. Only the case study located in Greece and represented by the Agroinvest biodiesel plant gave a promising result, with an estimated annual oil production of 23,493 tons.

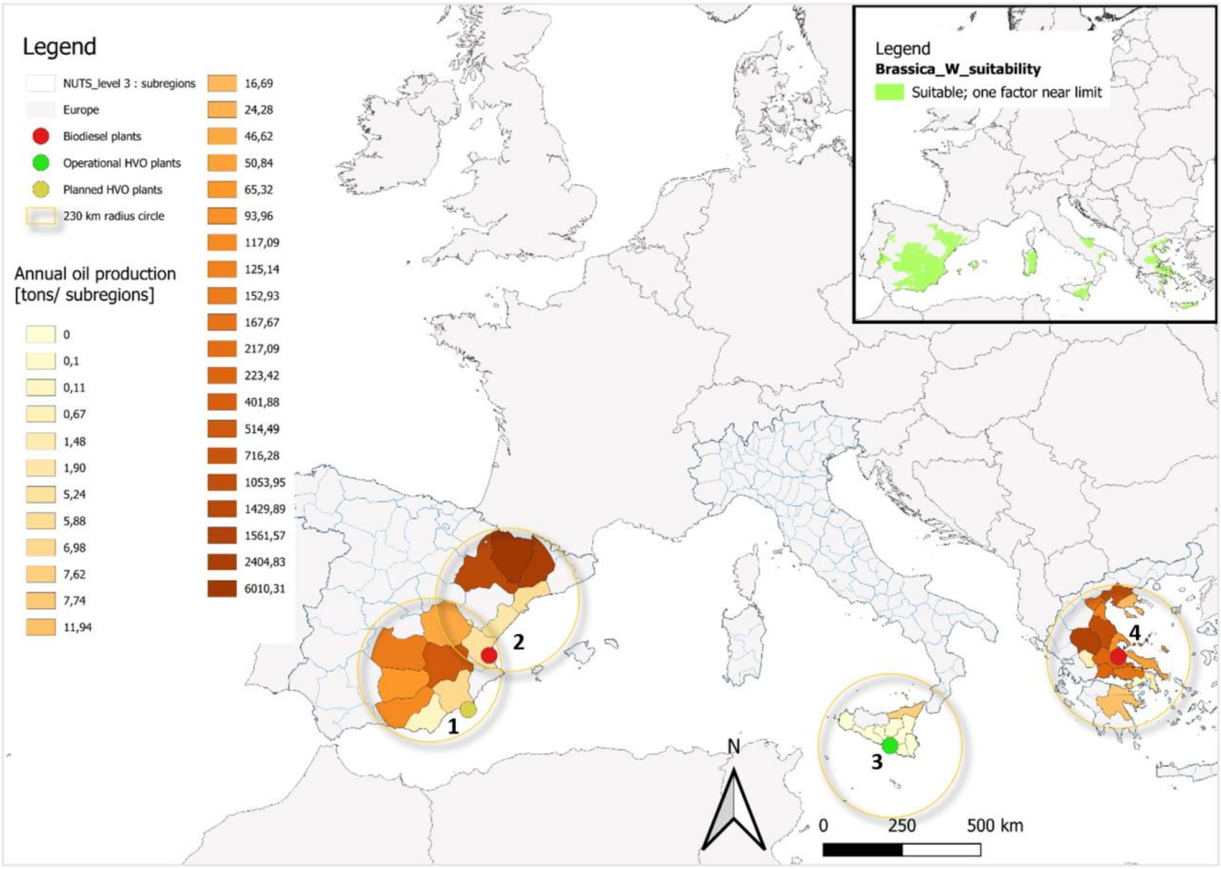

Figure 42. HVO and biodiesel refineries, areas of 230 km for biomass supply and estimated annual oil production per sub-region

Table 33 reports the estimated production of vegetable oil considering brassica as a winter cover crop and a supply radius of 230km from biorefineries

Table 33. Estimated annual oil production considering brassica as a winter cover crop and a supply radius of 230km from biorefineries

Nr.	Name of the plant	Surface dedicated to corn/cotton [hectares]	Mean Brassica yield [tons seeds/hectare]	Seeds [tons/year]	Oil* [tons/year]
1	Complejo Industrial de Cartagena de Repsol	4614	0.73	2258	903
2	Biocom Energia	123,352	0.68	25,711	10,284
3	Eni raffineria di Gela	160	1.15	19	8
4	Agroinvest	207,763**	0.98	58,733	**23,493**
			tot	**86,721**	**34,688**

**An oil content of 40% was assumed for calculation of oil production.*
*** Corn and cotton*

In light of these results, it can be said that brassica summer variety presents more possibilities of integration in the rotational schemes of mediterranean countries, as well as more areas of suitability, if compared to the winter variety. This combination resulted in more encouraging outputs for the scenario of brassica as a summer cover crop; however, recent studies and trials that were discussed with partners of WP6, show that brassica summer variety may present agronomic traits that could be more advantageous for continental climates rather than for mediterranean climates, including a lower incidence of pest and diseases. Upcoming results from new projects – for instance the Carina project[13] – will allow a better understanding of these important aspects.

Finally, Table 34 represents a summary of the most promising case studies identified for each of the evaluated scenarios. Potential HVO and biodiesel production from estimated castor oil production has been calculated considering conversion factors of 0.7 and 0.85 $t_{\text{renewable diesel}}$/t oil, respectively. The latter were identified from conversion factors of the existing refineries included in the assessment. We assumed that estimated values of HVO and biodiesel production would be feasible to achieve by the year 2030.

[13] https://www.carina-project.eu/, Horizon 2020 project, Grant Agreement N° 101081839.

Table 34. Summary of most promising case studies identified and potential HVO/biodiesel production from brassica oil.

Name of refinery	Type of refinery	Scenario	Country	Supply distance	Oil production (t/y)	HVO/biodiesel production (t/y)	Year
Eni raffineria di Gela Spa	HVO	Brassica summer cover crop	Italy	230 km	31,856	22,299	2030
Eni raffineria di Livorno	HVO	Brassica summer cover crop	Italy	230 km	71,396	49,977	2030
CEPSA plants	HVO	Brassica summer cover crop	Spain	230 km	84,218	58,953	2030
Complejo Industrial de Cartagena de Repsol	HVO	Brassica summer cover crop	Spain	230 km	27,847	19,493	2030
Biocom Energia	Biodiesel	Brassica summer cover crop	Spain	230 km	88,444	75,177	2030
Greenswitch	Biodiesel	Brassica summer cover crop	Italy	230 km	75,483	64,161	2030
Agroinvest	Biodiesel	Brassica summer cover crop	Greece	230 km	33,630	28,586	2030
Eni raffineria di Gela Spa	HVO	Brassica summer cover crop	Italy	500 km	123,733	86,613	2030
Agroinvest	Biodiesel	Brassica summer cover crop	Greece	500 km	69,424	59,010	2030
CEPSA plants	HVO	Brassica summer cover crop	Spain	500 km	283,997	198,798	2030
Agroinvest	Biodiesel	Brassica winter cover crop	Greece	230 km	23,493	19,969	2030

As shown in table above, around 151,000 tons of HVO plus 170,000 tons of biodiesel could be produced from brassica carinata grown as a winter cover crop and supplied within a distance of 230 km from existing refineries in the Mediterranean area. Extending the supply distance to 500 km, it is estimated that about 350,000 tons of renewable diesel (HVO plus biodiesel) could be produced within 2030.

3.4 Biogas Done Right (BDR) model for biomethane-to-liquid production

As already described in Chapter 2.3, the fourth BIKE case study has been evaluated considering the top European countries identified in terms of number of biogas plants and corresponding installed capacity, and also development of the natural gas grid. The countries in question are Italy, France, German, and UK. The expected biomethane production from upgrading of 90% of the biogas facilities by 2030 has been compared to the estimated biomethane production from cover crops by 2030 (Schellenbach, 2022). The conversion of biomethane to liquid was then assessed.

3.4.1 Italy

In Italy are currently operating:

- 27 biomethane plants of 0.21 bcm/year total production capacity.
- 2006 biogas plants of 1339 MW installed capacity.

Distribution of biogas plants in Italian municipalities (Figure 43) presents a significant cluster in the North of the country, where cattle farming and swine breeding are very widespread. Installed capacity ranges from a minimum of 1 to a maximum of 16.2 MW

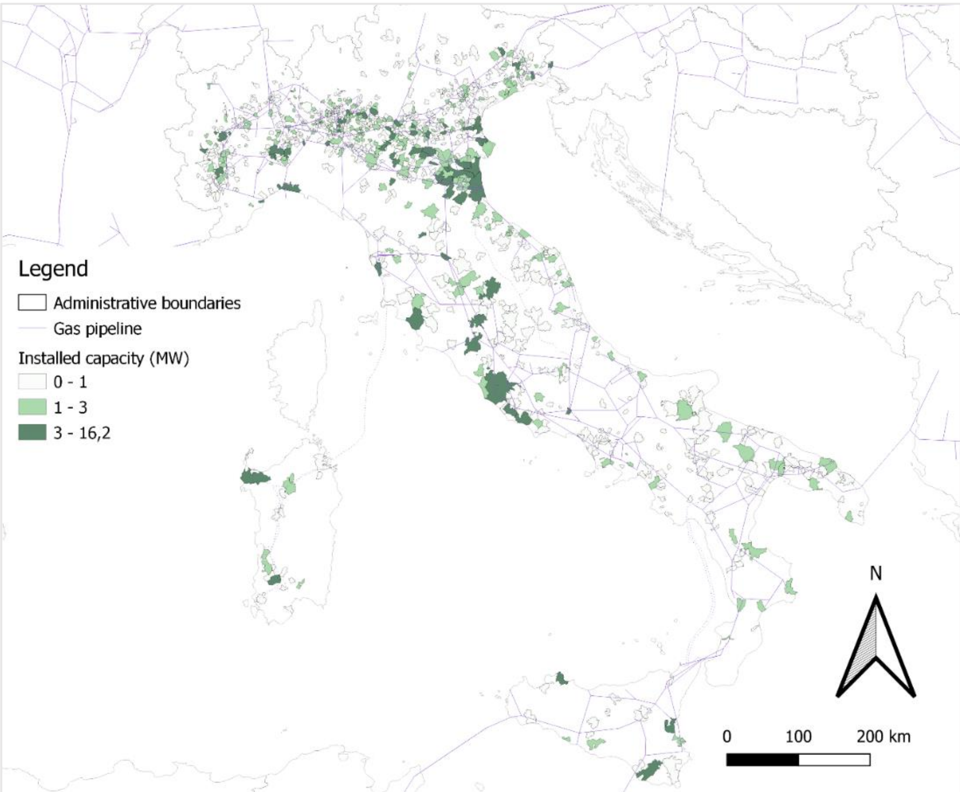

Figure 43. Installed capacity and distribution of biogas plants in Italy.

A biomethane potential of 2.75 bcm is estimated considering a 90% upgrading efficiency of biogas produced by anaerobic digestion plants, which added to the 0.21 bcm currently produced brings to a total potential of 2.96 bcm. The latter could be totally covered by the 3.2 bcm estimated from implementation of cover cropping practices. As shown in Figure 43, the natural gas grid covers almost all the Italian municipalities; however, a further development is required, in order to ensure connection to the grid also for the few plants which are currently far from the network and would otherwise be excluded from the chain (i.e., Sardinia). A hypothetical centralized Fisher-Tropsch plant is then estimated to produce 1.62 million cubic meters of liquid per year, while a centralized MeOH plant is estimated to produce 3.53 million cubic meters of liquid per year (Table 35).

Table 35. Calculation of biomethane and liquid fuels potential production in Italy.

Reference data	**Biogas plants* (2017)**	**Cover crop (2030)**	
Parameter	**Value**	**Value**	**U.M.**
Installed capacity	1,338,879	-	kWe
Efficiency of a gas engine	35	-	%
Methane heating value	10	-	kWh/Nm3
Methane content of the gas	57	-	%
Biomethane potential production (biogas plants upgrading)	2.75	-	bcm/year
Biomethane production (current)	0.21	-	bcm/year
Biomethane potential production (total)	2.96	3.2	bcm/year
GTL conversion factor (FT)	0.82	0.82	m3/tCH4
GTL conversion factor (MeOH)	1.78	1.78	tMeOH/tCH4
Liquid potential production (FT)	1.62	1.87	Mill. m^3/year
Liquid potential production (MeOH)	3.53	3.80	Mill.m^3/year

**Calculation of potential biomethane production considered an upgrading of 90% of the biogas plants and a development of the gas network*

3.4.2 France

In France are currently operating:

- 337 biomethane plants with 0.53 bcm/year total production capacity.
- 797 biogas plants of 182 MW installed capacity.

Distribution of biogas plants in French municipalities (Figure 44) presents a significant cluster in the North of the country. Installed capacity ranges from a minimum of 1 to a maximum of 4.7 MW.

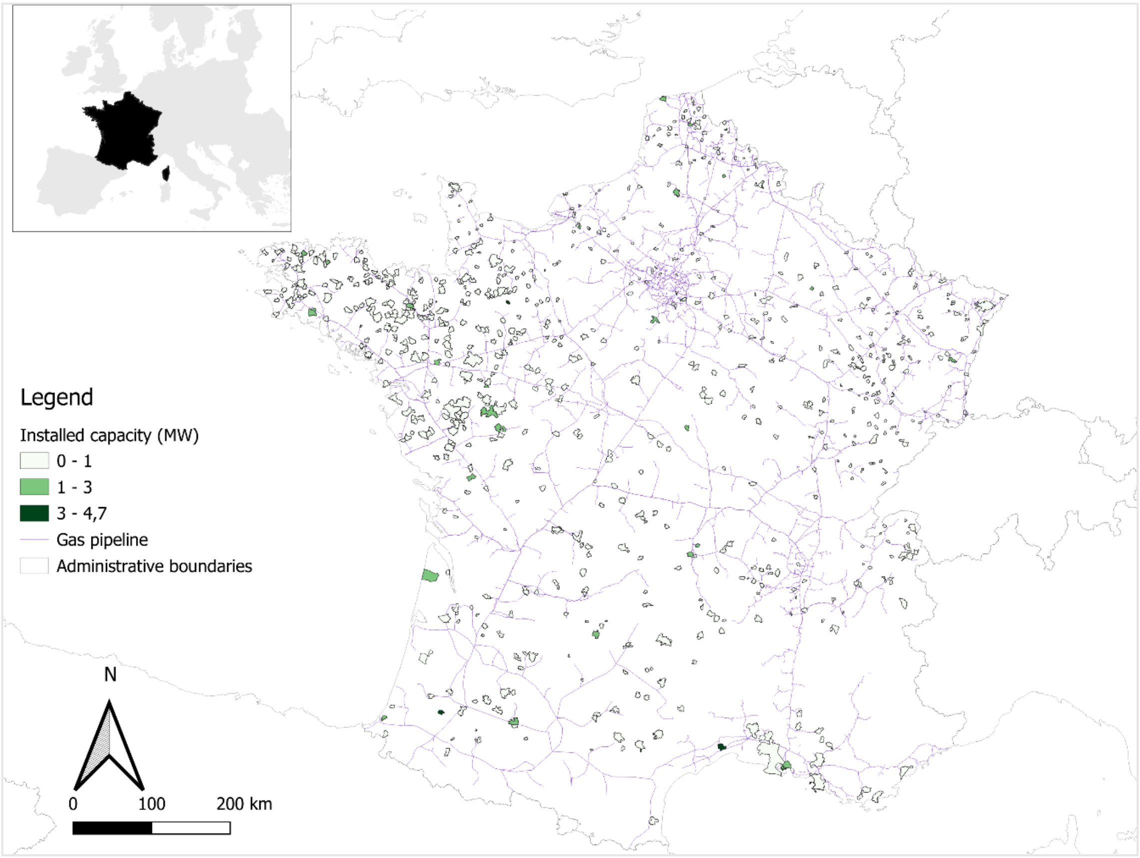

Figure 44. Installed capacity and distribution of biogas plants in France.

A biomethane potential of 0.37 bcm is estimated from upgrading of 90% biogas plants, which added to the 0.53 bcm currently produced brings to a total potential of 0.9 bcm. The latter could be totally covered by the 1.65 bcm estimated from implementation of cover cropping practice. As shown in Figure 44, the natural gas grid is mostly developed in the northern part of the country, where also the most biogas plants are located. Further injection of biomethane in the grid and transport to a hypothetical centralized Fisher-Tropsch plant is estimated to produce 0.49 million cubic meters of liquid per year, while a centralized MeOH plant is estimated to produce 1.08 million cubic meters of liquid per year (Table 36).

Table 36. Calculation of biomethane and liquid fuels potential production in France.

Reference data	**Biogas plants*** ***(2020)***	**Cover crop** ***(2030)***	
Parameter	**Value**	**Value**	**U.M.**
Installed capacity	181,906	-	kWe
Efficiency of a gas engine	35	-	%
Methane heating value	10	-	kWh/Nm^3
Methane content of the gas	57	-	%
Biomethane potential production (upgrading of biogas plants)	0.37	-	bcm/year
Biomethane production (current)	0.53	-	bcm/year
Biomethane potential production (total)	0.9	1.65	bcm/year
GTL conversion factor (FT)	0.82	0.82	m^3/tCH_4
GTL conversion factor (MeOH)	1.78	1.78	tMeOH/tCH_4
Liquid potential production (FT)	0.49	0.97	Mill. m^3/year
Liquid potential production (MeOH)	1.08	1.96	Mill. m^3/year

**Calculation of potential biomethane production considered an upgrading of 90% of the biogas plants and a development of the gas network*

3.4.3 Germany

In Germany are currently operating:

- 198 biomethane plants with 0.89 bcm/year total production capacity.
- 9770 biogas plants of 5926 MW installed capacity.

It was not possible to elaborate and display distribution of facilities in Germany, due to lack of detailed information from available databases. However, Germany represents the most developed and promising country of Europe in terms of overall number of biomethane/biogas plants and corresponding production capacity. An upgrade of 90% the biogas plants is estimated to produce 12.19 bcm of biomethane, which added to the 0.89 bcm already produce would bring to an overall production of 13.08 bcm. The latter is consequently estimated to be much higher compared to the contribution estimated from cover cropping practices (1 bcm). Further injection to the grid and transport to a hypothetical F.T. centralized plant is estimated to produce 7.14 million cubic meters of liquid, while an MeOH plant is estimated to produce 15.56 million cubic meters of liquid.

Table 37. Calculation of biomethane and liquid fuels potential production in Germany.

Reference data	**Biogas plants*** ***(2022)***	**Cover crop** ***(2030)***	
Parameter	**Value**	**Value**	**U.M.**
Installed capacity	5,926,000	-	kWe
Efficiency of a gas engine	35	-	%
Methane heating value	10	-	kWh/Nm^3
Methane content of the gas	57	-	%
Biomethane potential production (upgrading of biogas plants)	12.19	-	bcm/year
Biomethane production (current)	0.89	-	bcm/year
Biomethane potential production (total)	13.08	1	bcm/year
GTL conversion factor (FT)	0.82	0.82	m^3/tCH_4
GTL conversion factor (MeOH)	1.78	1.78	tMeOH/tCH4
Liquid potential production (FT)	7.14	0.59	Mill. m^3/year
Liquid potential production (MeOH)	15.56	1.19	Mill. m^3/year

**Calculation of potential biomethane production considered an upgrading of 90% of the biogas plants and a development of the gas network*

3.4.4 UK

In France are currently operating:

- 98 biomethane plants with 0.63 bcm/year total production capacity.
- 404 biogas plants of 343 MW installed capacity.

Biogas plants in UK municipalities (Figure 45) presents are equally distributed in the country. Installed capacity ranges from a minimum of 1 to a maximum of 6.2 MW.

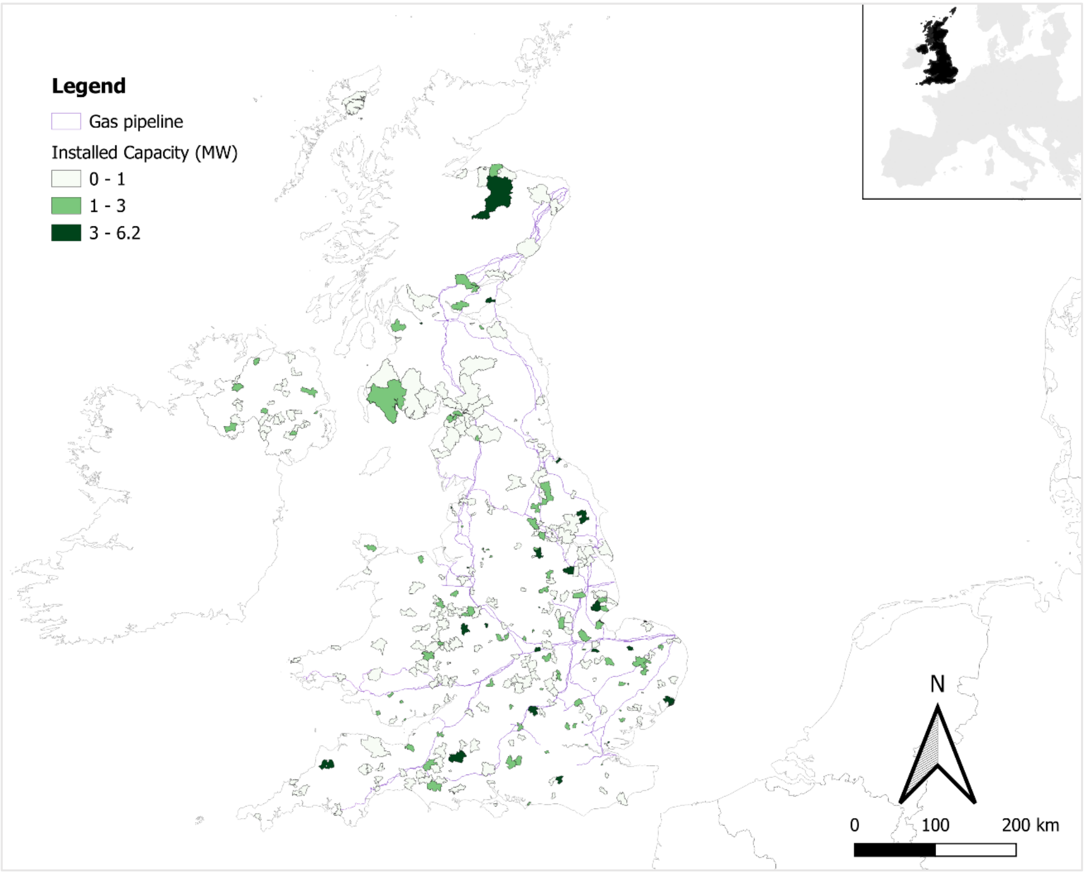

Figure 45. Installed capacity and distribution of biogas plants in UK.

A biomethane potential of 0.71 bcm is estimated from upgrading of 90% biogas plants, which added to the 0.63 bcm currently produced brings to a total potential of 1.34 bcm. The latter which could be partially covered by the 0.25 bcm estimated from implementation of cover cropping practices. As shown in Figure 45, the natural gas grid is equally developed in the country, with the exception of the South-western coast and Northern Ireland, and a further development is required on this sense in order to allow inclusion of biogas plants located in these parts of the country. Further injection of biomethane in the grid and transport to a hypothetical centralized Fisher-Tropsch plant is estimated to produce 0.73 million cubic meters of liquid per year, while a centralized MeOh plant is estimated to produce 1.59 million cubic meters of liquid per year (Table 38).

Table 38. Calculation of biomethane and liquid fuels potential production in UK.

Reference data	**Biogas plants*** ***(2019)***	**Cover crop** ***(2030)***	
Parameter	**Value**	**Value**	**U.M.**
Installed capacity	342,798	-	kWe
Efficiency of a gas engine	35	-	%
Methane heating value	10	-	kWh/Nm^3
Methane content of the gas	57	-	%
Biomethane potential production (upgrading of biogas plants)	0.71		bcm/year
Biomethane production (current)	0.63		bcm/year
Biomethane potential production (total)	1.34	0.25	bcm/year
GTL conversion factor (FT)	0.82	0.82	m^3/tCH_4
GTL conversion factor (MeOH)	1.78	1.78	$tMeOH/tCH_4$
Liquid potential production (FT)	0.73	0.15	Mill. m^3/year
Liquid potential production (MeOH)	1.59	0.30	Mill. m^3/year

**Calculation of potential biomethane production considered an upgrading of 90% of the biogas plants and a development of the gas network*

5 Discussion

The report examined the replicability potential of the four BIKE case studies in European countries, considering the two selected value chains of cultivation in unused, abandoned or severely degraded lands and productivity increase from improved agricultural practices.

For the first value chain, the layer of underutilized lands provided by BIOPLAT has been used and potential biomass production in these lands has been determined. As already mentioned in the previous chapters, this map considers only those lands that have not shown any sign of human activity in the past five years, while all those lands that are currently in use but severely degraded as well as all those lands that are likelihood to be abandoned in the future are not included.

In this regard, a possible new definition of marginality is currently under revision, and other new factors that are representative of soil status of degradation could be included. Among these factors, the Soil Organic Carbon (SOC) is considered a crucial indicator to determine the degradation of a soil. According to G. Louwagie et al, 2009[14], around 45% of soils in Europe have a low or very low organic matter content (meaning 0-2% SOC), while 45% have a medium content (meaning 2-6% SOC). Soils with very low SOC were found in the Southern countries, where 74% of the soil has less than 2% organic carbon, but also in parts of France, United Kingdom, Germany, and Sweden[15].

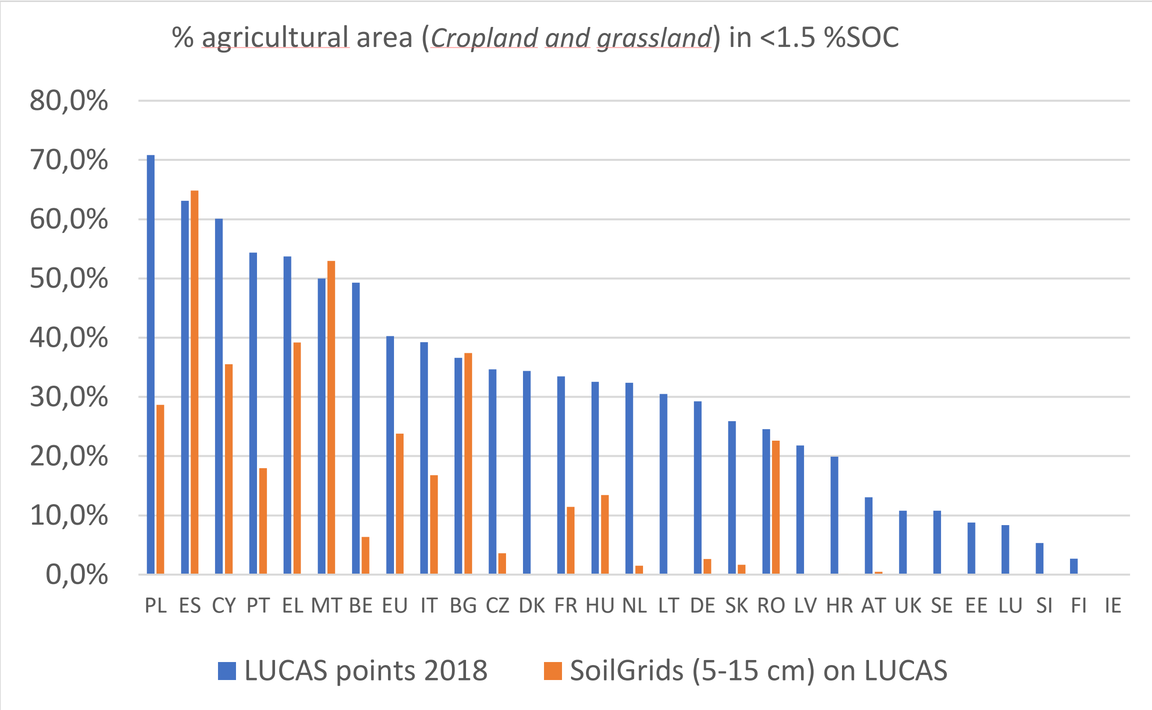

Figure 46. % agricultural area with less than 1.5 % SOC

As visible in Figure 46, < 1.5 % SOC applies to 40% of the European agricultural area. Moreover, < 0.75 % SOC applies to 7.4% of the European agricultural area, while < 0.5 %SOC applies to 2.2 % of the European agricultural area[16]. In case agricultural land with a Soil Organic Carbon of less

[14] G. Louwagie, S. H. Gay, and A. Burrell, Final report on the project 'Sustainable Agriculture and Soil Conservation (SoCo)' JRC Scientific and Technical Reports (Luxembourg: European Commission, Joint Research Centre, 2009).

[15] EEA-ETC-DI (Baritz et al, 2021); EEA (2022); SmartSOIL (Merante et al., 2014)

[16] https://esdac.jrc.ec.europa.eu/projects/lucas

than 0.75 % SOC would be considered as a severely degraded, around 11.6 million hectares of agricultural land could become suitable for Low ILUC Risk biomass feedstock cultivation, which is a much higher value if compared to the 5.3 million hectares of underutilized lands resulting from BIOPLAT and adopted for this assessment.

For the second value chain, the potential of target crops integration as cover crops in the existing rotational schemes has been evaluated. Sequential cropping system has recently gained attention to combine food and renewable energy production in a sustainable way, as well as for carbon sequestration. As already mentioned in the introductive chapter, the use of cover crops still represents a small percentage of the total EU cropland area, and little is known on the potential of expanding this practice in the countries of Europe. Despite all the limitations – which will be better discussed in the following paragraphs – our work represents an effort to contribute to a better understanding of this practice, which is expected to play a pivotal role in the future.

The identification of biorefineries located in the European countries was conducted combining data from different sources. This process led to the creation of a new layer – which can be considered as one of the most updated layers currently available – that displays all operating and planned biorefineries in Europe.

As regards yield modelling of the target crops, there are some aspects that need to be highlighted and discussed. The GAEZ modelling of switchgrass and miscanthus attainable yield in Europe resulted in higher values for switchgrass compared to miscanthus, while experimental trials usually give higher yield for miscanthus. Consequently, additional research is advised in order to calibrate the model to experimental findings and produce more accurate outcomes. In the assessment of castor bean case study for renewable diesel production, no data was available in GAEZ for castor yield modelling, or on any other modelling tool or platform. Due to this lack of information, only Spain, Greece and Italy have been considered in the assessment, and castor yield was estimated by collecting information from available literature and from results obtained in the context of BIKE open labs. In the upcoming months, however, the GAEZ dataset is expected to be updated, and Castor will be added to the dataset. Following that, it will be possible to update our assessment, providing results that are more accurate and consistent with the methodology adopted for the other case studies. In the assessment of Brassica Carinata case study for renewable diesel production, yield of the target crop has been assimilated to yield of rapeseed (*Brassica Napus*) , available in the GAEZ dataset. However, as for the case of castor, also brassica carinata is expected to be included in the GAEZ dataset in the near future, so that an update of our assessment will also be possible.

Always referring to brassica carinata case study, in this report we proposed two different calendars for application of brassica carinata as a sequential crop in the Mediterranean agroclimatic regions of Europe. During development of crop calendars, some issues have emerged when considering brassica carinata as a cover crop to alternate with the main crop for food/feed production. In particular, the long cycle of this crop – which necessitates from five to seven months to complete the growth and produce the seeds – could represent an obstacle for its integration in the existing rotation schemes. Our suggestion is either to substitute brassica carinata with oilcrops that have shorter growing cycles (i.e., Camelina), or to invest in the development of new genotypes that are able to produce seeds in less than 5/6 months. Furthermore, in this work we considered brassica as a summer cover crop in the mediterranean area – which was the target area of this case study – while recent findings seem to demonstrate the better suitability and adaptability of summer variety in the continental areas of Europe. Findings from new ongoing projects (e.g., Carina project) will provide new evidence of brassica performances in the different European climates.

In the case study of Biogas Done Right (BDR) model for biomethane-to-fuel production, the estimation of replicability potential was conducted only for Italy, France, Germany, and UK, which resulted as the top countries in terms of development of the natural gas grid, but also number of biomethane and biogas operating plants. To provide a reliable outcome, it was crucial for us to identify the precise location and production capacity of biomethane and biogas plants in the selected countries. For biomethane plants, data were gathered from the map released from EBA (European Biomethane Map, 2021). For biogas plants, data were gathered from different, country-specific databases, which presented different levels of precision and different years of reference. As a final observation, an update of current biogas plants status in terms of number and installed capacity is required. This would allow for a more realistic evaluation of biomethane to fuel production.

5 Conclusions

In the case study of perennial crops cultivation for bioethanol production, Romania and Spain showed the most promising results in terms of potential biomass production, given by the good combination of high number of underutilized lands and high expected yields of switchgrass and miscanthus. Considering only the promising case studies identified and a supply radius of 70 km, estimated bioethanol production ranges from 14,359 tons/year (Hungrana Bioeconomy Company, Hungary) to 68,651 tons/year (Clariant Products, Romania). If considering a supply radius of 150 km, estimated bioethanol production ranges from 24,772 tons/year (Ensus, UK) to 293,519 tons/year (Vertex Bioenergy Babilafuente, Spain).

In the case study of castor cultivation for renewable diesel production, only Spain, Italy and Greece have been considered in the assessment. Greece is the country with the highest estimated yield (2.24 tons seeds/ha), followed by Italy (1.77 tons seeds/ha) and Spain (1.35 tons/seeds/ha). Greece and Spain both showed good results in terms of potential oil production, while Italy showed the least promise due to a shortage of underutilized lands in the country. Considering only the promising case studies identified, estimated renewable diesel production ranges from 20,588 tons/year (Eni raffineria di Livorno, Italy) to 227,093 tons/year (Agroinvest s.a, Greece), considering a supply radius of 230 km. Expanding the supply radius to 500 km, estimated renewable diesel production ranges from 44,172 tons/year (Eni raffineria di Gela, Italy) to 842,178 (Agroinvest s.a, Greece).

In the case study of Brassica Carinata for renewable diesel production, two possible scenarios have been assessed, one considering Brassica as a summer cover crop and one considering Brassica as a winter cover crop. In the scenario of Brassica as summer cover crop, Spain showed the most promising results – both with 230 km and 500 km radius for biomass supply – followed by Italy and Greece. In the scenario of Brassica as a winter cover crop, only Greece gave encouraging values of potential oil production, while Spain and Italy did not met or exceed the set threshold value of 20,000 tons of annual oil production. Considering only the promising case studies identified, and the scenario of brassica as a summer cover crop, estimated renewable diesel production ranges from 19,493 tons/year (Complejo Industrial de Cartagena de Repsol, Spain) to 75,177 tons year (Biocom Energia, Spain), within a supply radius of 230 km. Expanding the supply radius to 500 km, estimated renewable diesel production ranges from 59,010 tons/year (Agroinvest s.a., Greece) to 198,798 tons/year (CEPSA refineries, Spain). As anticipated above, for the scenario of brassica as a winter cover crop, the only promising output was given by the case study of Agroinvest refinery, Greece, with an estimated renewable diesel production of 19,969 tons/year.

In the case study of Biogas Done Right (BDR) model for biomethane-to-fuel production, Italy, France, Germany, and UK resulted as the top countries in terms of development of the natural gas grid, but also number of biomethane and biogas operating plants. Germany gave the most promising results in terms of biomethane and liquid potential production by 2030 (13.08 bmc/year of biomethane, 7.14 mill. m^3 of F.T. diesel, 15.56 mill. m^3 of MeOH) followed by Italy (2.96 bcm/year of biomethane, 1.62 mill. m^3 of F.T. diesel, 3.53 mill. m^3 of MeOH), UK (1.34 bcm/year of biomethane, 0.73 mill. m^3 of F.T. diesel, 1.59 mill. m^3 of MeOH), and France (0.9 bcm/year of biomethane, 0.49 mill.m^3 of F.T. diesel, 1.08 mill.m^3 of MeOH).

In conclusion, this study showed that the four BIKE case studies present an encouraging replicability potential in the European countries, even if with some differences and limitations. Around 1.3 mil. tons of bioethanol, 1.5 mil. tons of advanced biofuel from castor oil, and 0.4 mil. tons of advanced biofuel from brassica carinata could be produced by the existing biorefineries in the short-, mid-term. Moreover, in case all existing biogas plants of Germany, Italy, France and UK would be converted to biomethane, this biomethane could generate up to 10 mil. tons of F.T. diesel. The findings confirm that there are significant opportunities to cultivate the selected crops in European agro-ecological zones with sustainable agronomic practices, both in unused lands and in agricultural lands. Even though sustainable biofuels represent an important tool for the decarbonisation of transport, it is key to understand that the promotion of the low ILUC-risk concept may open doors for the integration of new crop types and farming techniques into the EU agricultural landscape, with benefits for soils, climate, and economy that go beyond bioenergy.

6 Supplementary data

Table 39. List of second-generation bioethanol plants planned in Europe by 2030.

Name	Country	City	Owner	Production capacity (t/y)	Notes
Sainc Energy Limited	Spain	Cordoba	Sainc Energy Limited	150,000	Commercial
RYAM	France	Sarzay	RYAM Rayoner Advanced Materials INnc.	21,000	Commercial
Bioskoh	Slovakia	Lubietova	Energochimica	55,000	Commercial
Envirals Leopoldov Site	Slovakia	Leopoldov	Enviral	50,000	Commercial
Jedlicze Site	Poland	Jedlicze	ORLEN Poludnie	25,000	Commercial
Cellulosic Ethanol Plant Clariant Technology	Bulgaria	Toshevo	Eta Bio	50,000	Commercial
INA Ethanol	Croatia	Sisak	INA	55,000	Commercial
RE Energy	Denmark	Kalundborg	RE Energy	5000	Commercial
Cellulonix Pietrarsaari	Finland	Pietrarsaari	St1	40,000	Commercial
St1 Cellulonix Kajaani	Finland	Kajaani	St1	40,000	Commercial
Nordfuel biorefinery	Finland	Haapavesi	Kanteleen Voima	65,000	Demo plant
Cellulonix Follum	Norway	Ringerike	St1	40,000	Commercial

Table 40. List of first-generation bioethanol plants in Europe and possibility of upgrade to second-generation.

Name	Country	City	Possibility of upgrade
IMA, Bertolino	Italy	Trapani	YES
Euralcool Mb SRL	Italy	Napoli	NO
Caviro Distillerie SRL	Italy	Faenza	YES
Villapana S.p.A.	Italy	Faenza	NO
Silicompa	Italy	Correggio	YES
Etea Group	Italy	Saluzzo	NO
Vertex Bioenergy, Lacq	France	Lacq	YES
Artenay Plant (Tereos)	France	Artenay	NO
Cristal Union, Villette-sur-Aube	France	Villette-sur-Aube	NO
Connatre-Morains Plant	France	Connatre	YES
Origny Tereos Plant	France	Origny-Sainte-Benoite	YES
Nesle Tereos Plant	France	Mesnil-Saint-Nicaise	YES
Cristal Union, Sainte Emilie	France	Villers-Faucon	NO
Lillers Tereos Plant	France	Lillers	YES
Lestrem Starch Biorefinery	France	Lestrem	NO
Ryssen Akciiks S.A.S., Loon-Plage (CropEnergies)	France	Loon-Plage	YES
Lillebone tereos Plant	France	Lillebone	YES
Roquette-Bioethanol-Beinheim	France	Beinheim	NO
Agralco S.Coop.	Spain	Estella-Lizarra	NO
Vertex Bioenergy	Spain	Cartegena	YES
Azucarera del Gualdafeo S.A.	Spain	Salobrena	NO
Aceites, Vinos y Alcoholes, S.A. (AVIALSA)	Spain	Villarrobledo	NO
International de Alcoholes	Spain	Alcazar de san Juan	NO
Vertex Bioenergy Babilafuente	Spain	Babilafuente	YES
Vertex Bioenergy Bioetanol Galicia SA	Spain	Curtis	YES
Ferreira Gomes & Filhos	Portugal	Sao PEDRO DE TOMAR	NO
BioWanze S.A. (CropEnergies)	Belgium	Wanze	YES
Aalst Tereos-Syral	Belgium	Aalst	YES
Alco Group, Ghent	Belgium	Gent	YES
Cargill BV	Netherlands	Terneuzen	NO
Alco Energy Rotterdam BV	Netherlands	Rotterdam	YES
Suiker Unie Vierverlaten	Netherlands	Groningen	NO

L. Breggeman GmbH & CO KG	Germany	Heilbronn, Stadt	NO
BERKEL Pfalzische Spritfabrik GmbH & Co, KG	Germany	Ludwigshafen am Rhein, Stadt	NO
EAL Euro Alkohol-GmbH	Germany	Lüdinghausen, Stadt	YES
KWST GmbH	Germany	Hannover, Landeshauptstadt	NO
CropEnergies Bioethanol GmbH	Germany	Zeitz, Stadt	YES
Verbio Ethanol Zorbig GmbH & Co. KG	Germany	Zorbig, Stadt	YES
BrüggemannAlcohol	Germany	Wittenberg, Lutherstadt	YES
Barby Plant (Cargill)	Germany	Barby, Stadt	YES
Fuel 21 Klein Wanzleben Refinery (Nordzucker)	Germany	Wanzleben-Börde, Stadt	YES
Verbio Ethanol Schwedt GmbH & Co. KG	Germany	Schwedt/Oder, Stadt	YES
Agrar Destillerie GmbH	Germany	Neubrandenburg, Stadt	NO
Suiker Unie GmbH	Germany	Anklam, Stadt	NO
Baltic Distillery	Germany	Dettmannsdorf	NO
Manchester Biorefinery (Cargill/Royal Nedalco)	United Kingdom	Trafford	YES
ETEA Sedamyl	United Kingdom	Selby	NO
Vivergo Fuels	United Kingdom	East Riding of Yorkshire	YES
Pischelsdorf Biorefinery	Austria	Zwentendorf an der Donau	YES
Komers International	Poland	Pruszcz Gdanski	NO
Destylarnia Sobieski	Poland	Starogard Gdanski	NO
Bioetanol AEG	Poland	Chelmza	YES
Bioetanol AEG	Poland	Nowa Wies Wielka	YES
Destylacje Polskie	Poland	Oborniki	NO
Ima Polska	Poland	Murowana Goslina	YES
Akwawit-Brasco SA	Poland	Leszno	NO
AWW	Poland	Zelazkow	NO
Podlaskie Gorzelnie SURWIN	Poland	Wohyn	NO
Akwawit-Brasco SA	Poland	Wroclaw	NO
Cargill	Poland	Kobierzyce	NO
Goswinowice Ethanol Plant (Bioagra S.A).	Poland	Nysa	YES
Amochim	Romania	Municipiul Slobozia	NO
Agrar-beta	Hungary	Dombovar	YES
Pannonia Bio Zrt.	Hungary	Dunaföldvá	YES
Hungrana Bioeconomy Company	Hungary	Szabadegyháza	YES

Gyor	Hungary	Gyor	NO
Kall Ingredients Kfr	Hungary	Tiszapüspöki	NO
Zaharni Zavodi	Bulgaria	-	NO
Almagest AD	Bulgaria	Verinsko	YES
Essentica Ethanol Factory	Bulgaria	-	YES
Slovliker	Czech Republic	Kunovice	NA
Tereos TTD, a.s.	Czech Republic	Kojetìn	NO
Chrudim Plant (Tereos)	Czech Republic	Chrudim	NO
Ethanol Energy	Czech Republic	Vrdy	YES
Bioferm	Czech Republic	Kolin	NO
Dobrovice Plant (Tereos)	Czech Republic	Dobrovice	NO
Onistar	Estonia	Rakvere linn	NO
AS Remedia	Estonia	Kuusalu vald	NO
Liviko AS	Estonia	Tallin	NO
Anora Group Oyj	Finland	Ilmajoki	YES
Hameenlinna Bionolix Plant (St1 Biofuels Oy)	Finland	Hameenlinna	YES
Lahti Etanolix Plant (St1 Biofuels Oy)	Finland	Lahti	YES
St1 Biofuels Oy	Finland	Hamina	YES
AB Vilniaus degtine	Lithuania	Vilniaus miesto savivaldybe	NO
Kurana UAB	Lithuania	Pasvalio rajono savivaldybe	YES
Kalsnava Distillery	Latvia	Madonas novads	NO
ENVIRAL	Slovakia	Leopoldov	YES
Gnidava Sugar Plant	Ukraine	-	NA
Zarubynskyi spirit plant	Ukraine	-	NA
Khorostkivskyi sugar plant	Ukraine	-	NA
Luzhanskyi spitit plant	Ukraine	-	NA
Dovzhotskyi spirit plant	Ukraine	-	NA
Teofiopolskyi sugar plant	Ukraine	-	NA
Barskyi spirit plant	Ukraine	-	NA
Chervonenskyi spirit plant	Ukraine	-	NA
Andrushivskyi spitit plant	Ukraine	-	NA
Trostianetskyi spirit plant	Ukraine	-	NA
Haisynskyi spirit plant, Interkrait Ltd.	Ukraine	-	NA
Fazor Ltd.	Ukraine	-	NA

Uzyn sugar factory	Ukraine	-	NA
Popivskyi experimental plant	Ukraine	-	NA
Lokhvytskyi spitir plant	Ukraine	-	NA
Budylskyi Plant, EcoEnergy Ltd.	Ukraine	-	NA
Naumivskyi Spirit plant	Ukraine	-	NA
Ivashkivskyi spirit plant	Ukraine	-	NA
Dublianskyi spirit plant	Ukraine	-	NA
Zhovtnevyi spirit plant	Ukraine	-	NA
Lantmännen Agroetanol A.B.	Sweden	Norrköping	YES
Absolut	Sweden	Kristianstad	NO
Vallée du Loing, Souppes-sur-Loing	France	Souppes-sur-Loing	NO
Cristal Union, Buchères	France	Cristal Union	NO
British Sugar PLC	UK	Wissington	NO
Ensus UK	UK	Lasenby	YES
Carbery Group Limited	Ireland	Cork	NO
Müllermilch, Leppersdorf	Germany	Leppersdorf	NO
Viresol	Hungary		NO
Lantmännen Maskin AB	Sweden	Växjö	YES
BGW Sp. z o.o.	Polland	Rąbczyn	YES

Table 41. List of HVO plants in Europe.

Name	**Owner**	**Country**	**City**	**Capacity (t/y)**	**Status**
Eni raffineria di Gela Spa	Eni	Italy	Gela	750,000	Operational
TOTAL La Mede Biorefinery	TOTAL	France	Châteauneuf-les-Martigues	500,000	Operational
Eni raffineria di Venezia	Eni	Italy	Venezia	360,000	Operational
Rotterdam Neste Biorefinery	Neste	Netherlands	Rotterdam	800,000	Operational
Abengoa plant	Cepsa	Spain	San Roque	50,000	Operational
La Ribida	Cepsa	Spain	Palos de la Frontera	50,000	Operational
Neste Biorefinery in Kilpilahti Refinery	Neste	Finland	Porvoo	190,000	Operational
UPM Lappeenranta Biorefinery	UPM	Finland	Lappeenranta	130,000	Operational
SunPine	SunPine	Sweden	Pitea	40,000	Operational
Premraff Goteborg	Preem	Sweden	Goteboprg	290,000	Operational
Galp | Refinaria	Galp	Portugal	Sines	N.R.*	Planned
Eni raffineria di Livorno	Eni	Italy	Livorno	500,000	Planned
Complejo Industrial de Cartagena de Repsol	REPSOL	Spain	Murcia	250,000	Planned
SCA biorefinery	SCA	Sweden	Ostrand	156,000	Planned
Preemraff Lysekil	Preem	Sweden	Goteborg	950,000**	Planned
Greenenergy plant	Greenenergy	UK	Corringham	N.R.	Planned
Fintoil Hamina biorefinery	Fintoil	Finland	Hamina	78,000	Planned
UPM Kotka refinery	UPM	Finland	Kotka	500,000	Planned
St1 Gothenburg	St1 and SCA	Sweden	Gothenburg	200,000	Under construction

**Not Reported*
***m^3/y*

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