BIOFUELS PRODUCTION
AT LOW - ILUC RISK
FOR EUROPEAN SUSTAINABLE
BIOECONOMY

D 2.3

Climate positive farming solutions

Dissemination level: PU

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LIST OF ACRONYMS

AD	Anaerobic digestion
ASALS	Kenyan State Department for the arid and semi-arid lands
BDR	Biogas done right
BR	Brassica
CC	Cover crop
CIB	Consorzio Italiano Biogas
CN	Corn
DM	Dry matter
ENI	Ente Nazionale Idrocarburi
EU	European Union
FAO	Food and agriculture organisation
FL	Fallow
GIS	Geographic information system
1G	First generation
2G	Second generation
ha	hectare
HVO	Hydrotreated vegetable oil
I-LUC	Low-Indirect Land Use Change
ISCC	International sustainability and carbon certification
km	Kilometre
kt	Kilo tonne
kWh	Kilo watt hour
L	Litre
MJ	Mega joule
NCP	Net crop produced
NPV	Net present value
RED II	Renewable energy directive II
SB	Soybean
t	tonne
WH	Wheat
yr	year

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Executive summary

This report presents and discusses the outcome of Task 2.3, which focuses on the development of model- and optimisation-based methodologies that address challenges related to climate positive farming solutions. The proposed methodology starts by collecting all relevant information required, followed by the development of decision-support models, and finally the developed models are used to investigate and analyse four case studies: (i) planning of low-Indirect Land Use Change (low-ILUC) biomass feedstock production (case study on brassica), (ii) biomethane production using low-ILUC biomass feedstocks, (iii) integrated production of 1G and 2G bioethanol using Miscanthus, and (iv) production of HVO using castor seeds.

The model developed to support planning of low-ILUC biomass feedstock production is based on a typical farm management optimisation system comprising farmlands, crop management practices, crop types, seasons of the year and biomass storage. The model calculates net farm income, total crop produced and net present value. Input data consists of farmland size, crop yield, unit production cost, unit crop selling price, interest rate, crop rotation sequence and cropping calendar. Case study data were provided by UPM and focuses on the production of *Brassica* for hydrotreated vegetable oil (HVO) in Uruguay. This case study demonstrates the benefit of climate positive farming by analysing two crop management practices: (i) reference case, i.e., the conventional crop rotation practice using non-productive cover crops and (ii) improved case, similar to the reference case but with *Brassica* replacing the non-productive cover crops. Results show that *Brassica* cultivated as winter crop does not affect the yield of summer crops and can increase total biomass produced per hectare as well as net farm income. Considering fluctuations in crop price, the improved case shows better gross margin per hectare in both high and current market price scenarios, while the reference case is better at low crop price. In this case study, farmers can avoid operating at loss by selling their farm products above the breakeven selling price which correspond to 362 €/t, 321 €/t and 381 €/t for soybean, wheat and *Brassica* respectively.

The model developed to support biomethane production using low-ILUC biomass feedstock implements the principle of biogasdoneright®. This model calculates the biomethane potential of various feedstock types produced using monocropping and sequential cropping systems. Input data includes feedstock rate, anaerobic digestion plant capacity, and biomass characteristics such as dry matter/total solid content, volatile solid content, volatile solid degraded in the digester and yield of biomethane. Data for this case study were collected from a journal paper published by CIB. The case study compares biomethane produced using feedstocks from monocropping and sequential cropping systems. Results show that the anaerobic digestion of biomass feedstocks from sequential cropping leads to better biomethane yield per hectare. In addition, digestate produced using feedstock from monocropping is not sufficient to satisfy cropland requirements, therefore chemical fertiliser is used as supplement. On the other hand, digestates produced using feedstocks from

sequential cropping and other feedstock types (cattle slurry, potato scrap and waste from agro-industry) satisfy cropland requirements without the need for chemical fertiliser.

The model developed to support production of 2G bioethanol using Miscanthus is based on a retrofitted 1G bioethanol refinery instead of a new 2G plant. The model calculates the amount of bioethanol and by-product (electricity) produced, total cost, revenue and net present value. Input data includes farmland size, crop yield, unit cultivation cost, distance between farmland and biorefinery, transport type, unit transport cost, capacity of 2G biorefinery, conversion factor Miscanthus to bioethanol and by-product, unit production cost, market price of bioethanol and by-product. Data for this case study were collected from reliable online sources such as BIOPLAT-EU[1] web GIS tool and from Miscanthus Nursery Ltd. This case study assesses the production of 2G bioethanol from Miscanthus cultivated on underutilised land within the UK. Results show that retrofitting an existing 1G plant to allow production of 2G bioethanol is economically feasible. The bioethanol produced from Miscanthus cultivated on underutilised land within 100 km radius to an existing biorefinery is 95 % lower than the plant capacity (40,000 t/yr). Hence cultivation of Miscanthus on underutilised land beyond 100 km radius is required in order to satisfy plant capacity.

The model developed to support HVO production from castor seed cultivated on degraded land consists of four echelons: farmland, oil mill, seaport and biorefinery. The model calculates the quantity of castor seed produced from farmland, amount of castor oil extracted, amount of castor cake, HVO produced at biorefinery, total cost, revenue and net present value. Input data includes farmland size and their corresponding locations, crop yield, cultivation cost, capacity of oil mill, unit production cost, selling price of castor cake, conversion factor castor seed to oil and cake, capacity of biorefinery, unit production cost, conversion factor castor oil to HVO, market price of HVO, distance between supply chain entities, and unit transportation cost. Data for this case study were provided by ENI. The case study assesses the profitability of producing HVO in biorefinery located in Italy and castor seed cultivation on degraded lands located in Kenya. Results show that the HVO value chain is economically feasible, providing income to both local farmers and industrial stakeholders.

The following recommendation can be drawn from this research work: farmers interested in these models are recommended to sell soybean, wheat and brassica above the breakeven price to avoid losses. The estimated selling price for the three crops are 362 €/t, 321 €/t and 381 €/t respectively. To meet the demand of 40,000 t/yr of 2G bioethanol in the UK, approximately 17,094 hectares of underutilised land is required. Policy makers should consider options to support alternatives such as retrofitting, and inter-cropping to avoid or mitigate ILUC. The private sector looking for raw or limited processing of crops need to

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[1] https://bioplat.eu/

consider sustainability issues and standard certifications for the implementation of these models.

1. Introduction

The increasing concerns over climate change and the gradual depletion of fossil fuel have led to the search for alternative sources of energy that are both renewable and sustainable. Biofuels (such as hydrotreated vegetable oil, bioethanol, biomethane, etc.) derived from biomass feedstocks have been used for decades to power the transportation sector in addition to serving as energy source for domestic usage, e.g., household heating, cooking, etc. Apart from providing a sustainable energy source, the used of biofuels also contributes significantly to decarbonisation of the transportation industries[1–3], thus supporting the European Union (EU) ambitious targets to cut down greenhouse gas emissions by at least 55% by 2030[4,5]. Achieving the targets set by EU has the potential to increase demand for land use to cultivate biorefinery feedstocks such as biomass for advance biofuel production. To avoid competition with land used for food production, the EU have put in place policies that mandate sustainable biomass supply through introduction of low-indirect land use change (low-ILUC)[6–9]. Low-ILUC risk biofuels are produced from feedstock that avoid food and feed crop displacement through (i) yield increases from improved agricultural practices or (ii) cultivation on areas not previously used for crop production, for example, unused, abandoned or severely degraded land or (iii) combining cover crop rotations with biomass feedstock production. To speed-up market uptake and certification by international sustainability and carbon certification (ISCC), there is a need for a systematic approach that can assess the benefit of both existing and emerging low-ILUC risk feedstocks, for example *Brassica carinata,* Perennial crops such as *Miscanthus,* Castor oil, etc.

This report proposes four systematic optimisation-based approaches that facilitate climate positive farming. The first approach comprises a mixed integer linear programming model for crop production that incorporates crop rotation. The inputs to the crop production model include a set of crops/crops sequence to be planted, a set of available land, fertiliser consumption, price of crops, production cost, average crop yield, time horizon, while the outputs include land allocated to each crop type, annual biomass produced and net farm income. The second approach comprises a mixed integer linear programming model developed following the principles of biogasdoneright®. The model estimates the biomethane potential of low-ILUC risk feedstocks produced using monocropping and sequential cropping systems. Input data includes feedstock rate, anaerobic digestion plant capacity, and biomass characteristics such as dry matter/total solid content, volatile solid content, volatile solid degraded in the digester, and yield of biomethane. Similarly, both third and fourth approaches comprise a mixed integer linear programming model developed following echelon supply chain. The models estimate the potential of producing bioethanol using Miscanthus cultivated on unused lands and the profitability of HVO production using castor seed cultivated on degraded lands respectively.

The capabilities of the proposed systematic approaches were demonstrated using industrial case studies, in collaboration with UPM, CIB, ENI and Miscanthus Nursery Ltd. Outcomes from this study can be used to facilitate market uptake of European feedstocks with low-ILUC risk status for use in biofuel from 2020 to 2030; inform primarily the bioenergy and biofuels but also other bioproduct sectors (biochemicals/biopolymers, chemical industry); support the sustainable conversion of the chemical industry; provide policy and market stakeholders with new knowledge; and to remove the most prominent barriers against the market uptake of low-ILUC risk biofuels, bioliquids and biomass fuels.

2. Methodology

2.1 Modelling framework for climate positive farming solutions

This section presents the methodology proposed to address challenges related to climate positive farming. As shown in Figure 1, the methodology starts by gathering all information needed by the decision support models. This information can include farm-level datasets (e.g., land size and expected yield), economic data, type of technology used in converting biomass to biofuel, policy information, mode of transportation and agronomic data such as crop yield, date of establishment and harvest, fertiliser requirement, cultivation season, among others.

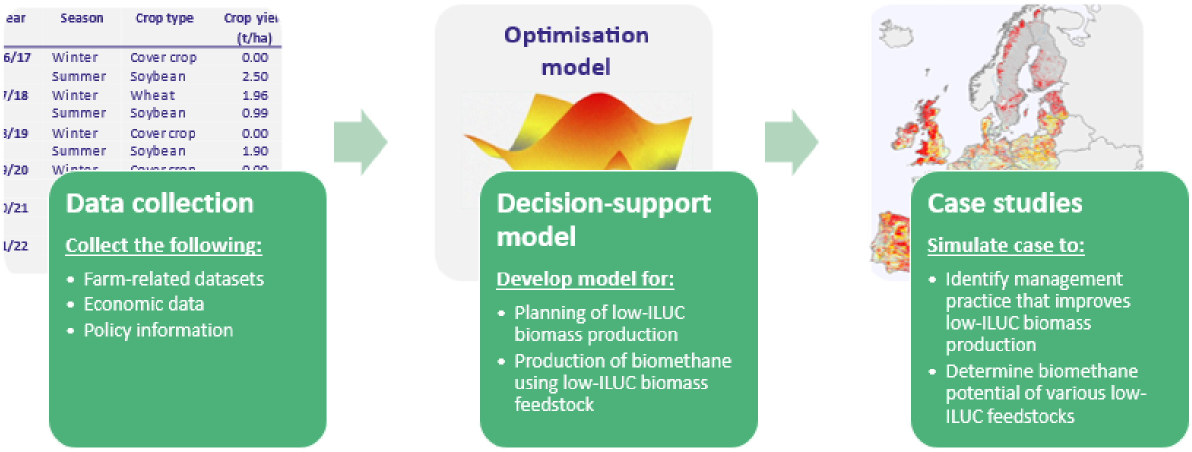

Figure 1.Modelling framework for climate positive farming solutions. ILUC denotes indirect land use change.

This report presents four models to support: (i) planning of low-ILUC biomass production, (ii) production of biomethane using low-ILUC biomass feedstocks, (iii) production of bioethanol using Miscanthus cultivated on unused lands, and (iv) production of HVO using castor seed cultivated on degraded lands. Lastly, a real-world dataset is applied to demonstrate the capabilities of the proposed models.

2.2 Decision-support models

2.2.1 Planning of low-ILUC biomass feedstock production

According to a review of the Renewable Energy Directive II[6], biomass feedstocks can be classified as low-ILUC risk if they are produced following the implementation of sustainable agricultural practices, i.e., (i) cultivation on unused, abandoned, and/or severely degraded land and (ii) productivity increases from improved agricultural practices. The agricultural practices include crop rotation, inter-cropping, cover cropping, etc. In this section, a model that incorporates sustainable agricultural practices is developed to support planning of low-ILUC biomass feedstock production. The model is build based on farm management system presented in Figure 2. The management system consists of farmlands, crop management schemes and their corresponding crops, seasons of the year and biomass storage points.

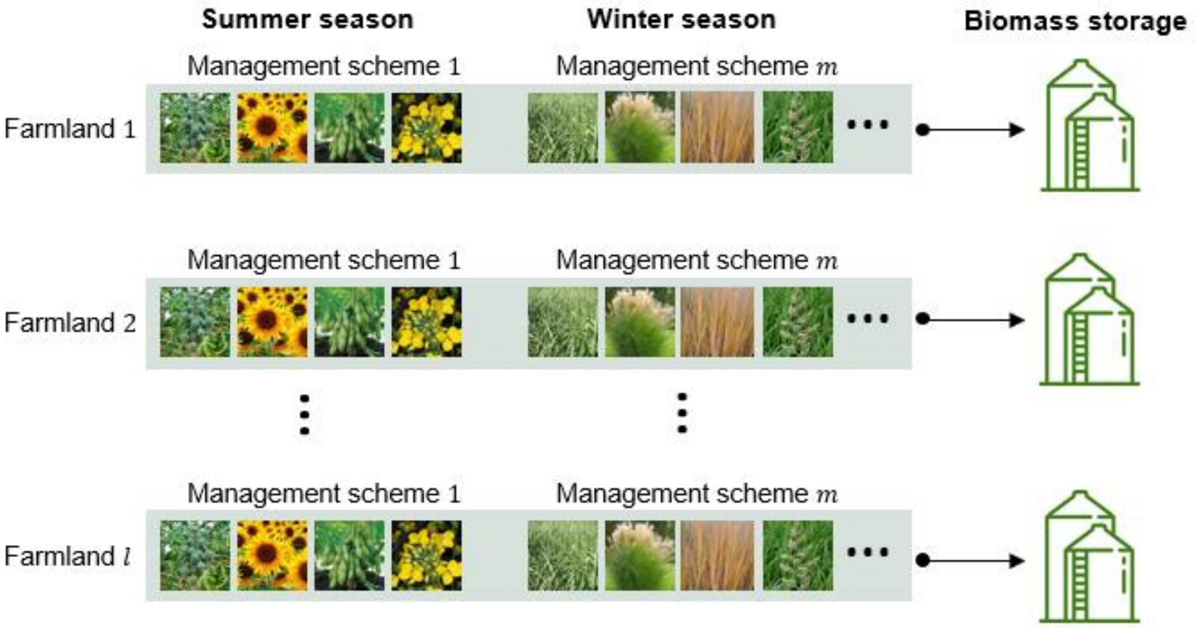

Figure 2.. Schematic representation of the proposed farm management system for low-ILUC biomass feedstock production.

On each piece of farmland, crop rotation principle is implemented, i.e., alternating crops cultivated on a given piece of land over time. This practice enables farmers to improve crop yield, control crop specific pest and increase soil carbon[6]. The proposed farm planning model, derived from Figure 2, can be used to identify the best crop management practice and land allocation that improves total crop yield and/or net farm income. The model inputs include farmland size, crop yield, unit production cost, unit crop selling price, interest rate, crop rotation sequence and cropping calendar. With the aforementioned inputs, the model calculates outputs such as net farm income, total crop yield and net present value. A detailed description of the model can be found in Annex A1. In Section 3.1, a case study is used to demonstrate the applicability of the proposed model.

2.2.2 Biomethane production using low-ILUC biomass feedstock.

To meet government regulations on production of sustainable energy, this analysis implements the principles of biogasdoneright® [10,11] to produce biomethane using low-ILUC biomass feedstocks. Biogasdoneright®, originally developed by CIB, is a system in which energy crops (planted alongside food/feed) are converted into biogas and digestate. The biogas is either upgraded into biomethane and injected into the grid or utilised in a combined heat and power system to produce heat and electricity at efficiencies of approximately 30-37% and 40-50% respectively[12–14]. The digestate from the conversion process is used as organic fertiliser for both food/feed and energy crops.

In this analysis, biogas is converted to biomethane instead of heat and electricity in order to assess the biomethane potential of different types of low-ILUC biomass feedstocks. Figure 3 shows the biomethane value chain considered in this work.

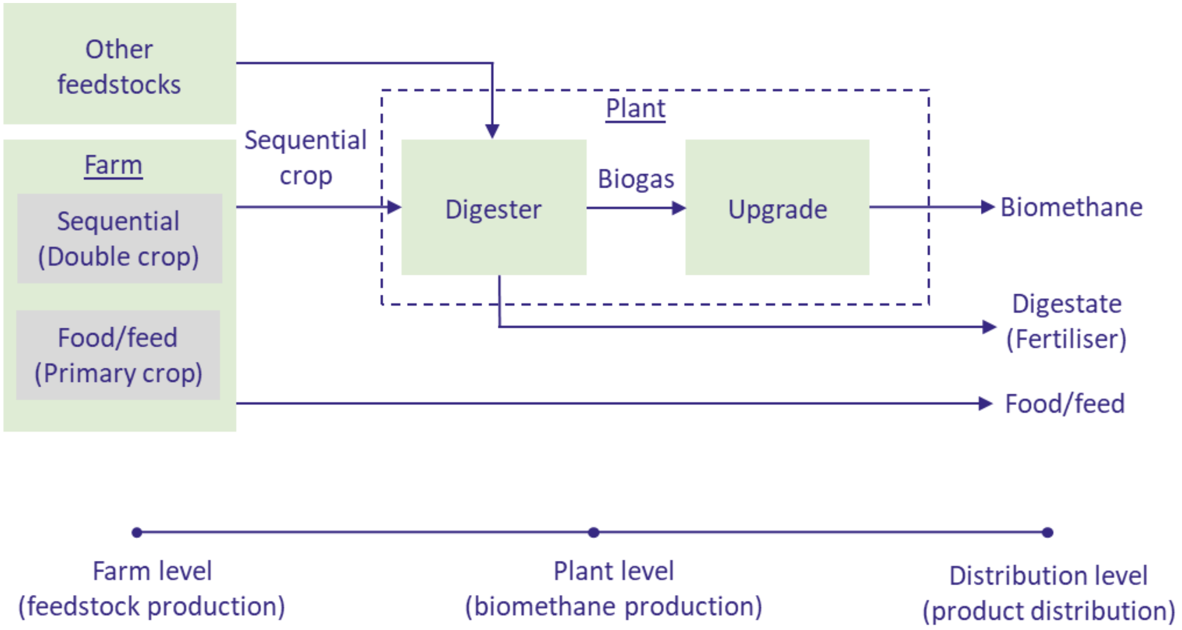

Figure 3. Schematic representation of the three levels of biomethane value chain. In this analysis, biomethane is produce from low-ILUC biomass feedstocks.

At the farm level, energy and food/feed crops are produced by implementing sequential cropping. The food/feed crops are used for consumption while the energy/sequential crops (e.g., cereal silage) and other feedstock types such as manure and agro-industrial waste are transported to the plant site and use as feedstock for anaerobic digestion process.

The plant level consists of an anaerobic digestion (AD) plant and a unit that upgrades biogas to biomethane. The AD plant converts feedstocks composed of organic substance (cellulose, hemicellulose, lignin, fats, etc.) into biogas and digestate (by-product) in four main steps: hydrolysis, acidogenesis or fermentation, acetogenesis and methanogenesis. The digester is typically designed to operate either between 20 °C to 40 °C (mesophilic) or 40 °C to 70 °C (thermophilic)[15,16]. While mesophilic digesters are more stable than thermophilic due their low temperature operating range, they require a much larger reactor volume (digestion tank) as a result of slow reaction rate. Aside temperature, other factors affecting biogas production include feedstock solid content and dilution, carbon to nitrogen ratio, pH, loading rate, retention time or hydraulic residence time, toxicity, mixing/agitation and pathogens[17]. Since this work focus on biomethane supply chain, the biomass feedstock conversion at the plant level will be approximated using conversion factors, without detailed modelling of the digester. Similarly, the separation of biogas into biomethane and carbon dioxide will be estimated using recovery fraction without modelling the membrane unit or pressure swing adsorption unit[15].

Lastly, the distribution level injects biomethane directly into the grid and use as supplement to natural gas. The proposed model takes the following inputs: feedstock rate, AD plant capacity and biomass characteristics such as biomass dry matter/total solid content, biomass volatile solid content, volatile solid degraded in the digester and yield of biomethane. Using the aforementioned inputs, the model calculates the biomethane potential of low-ILUC feedstocks.

2.2.4 Integrated production of 1G & 2G bioethanol using low-ILUC biomass feedstock.

In this section, a model is developed to support planning of low-ILUC biomass (Miscanthus) cultivation and production of 2G bioethanol. Figure 4 shows the overall value chain of 2G bioethanol produced from low-ILUC feedstocks.

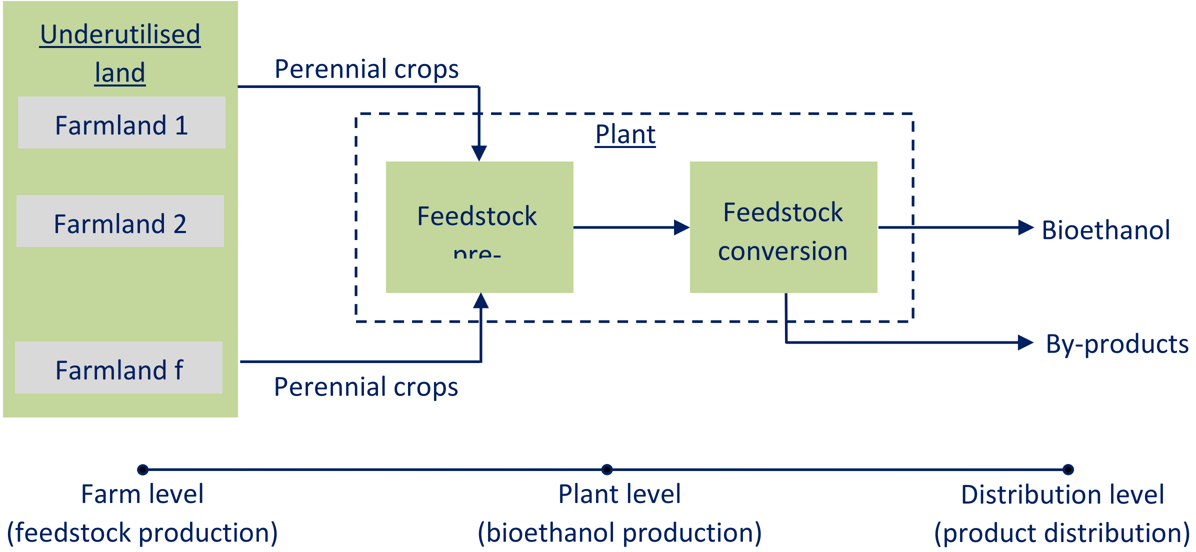

Figure 4. Schematic representation of the proposed supply chain for 2G bioethanol produced using low-ILUC biomass feedstock.

In Figure 4, Miscanthus cultivated on underutilised lands is transported from farm level to plant level where the feedstock is converted to bioethanol. An underutilised land can be defined as a piece of land that has not been in productive use for period of at least five years[6], therefore biomass cultivated on this land can be classified as low-ILUC according to RED II.

At the plant level, the feedstock is first pre-treated followed by conversion to bioethanol. A detailed description of the production process can be found elsewhere[18]. The pre-treatment and ethanol production processes can be co-located or established in different geographical regions. In the current study, both pre-treatment and ethanol production facilities are located in the same place.

At the distribution level, fuel-grade ethanol is supplied and distributed to the EU energy market and sold as alternative to fossil-based gasoline or as blend, i.e., mixture of gasoline and ethanol. The proposed planning model, derived from Figure 4, takes the following inputs: farmland size and geographical coordinates, crop yield, production capacity of 2G bioethanol plant, conversion factors for lignocellulosic biomass to ethanol and by-product (electricity), product demand, transportation modes and their associated cost, tortuosity, interest rate, unit transport cost, unit cultivation cost, unit production cost, and unit selling price of ethanol and electricity. Using the aforementioned inputs, the model calculates the quantity of Miscanthus produced per annum, net ethanol produced, electricity generated, total cost, revenue, and net present value. A detailed description of the model can be found in Annex A3. In Section 5.1, a case study is used to demonstrate the applicability of the proposed model.

2.2.3 Production of hydrotreated vegetable oil using low-ILUC biomass feedstock

In this section, a model is developed to support planning of castor bean cultivation and production of hydrotreated vegetable oil. The value chain, as shown in Figure 5, consists of four echelons and incorporates all essential features of a typical biofuel supply chain.

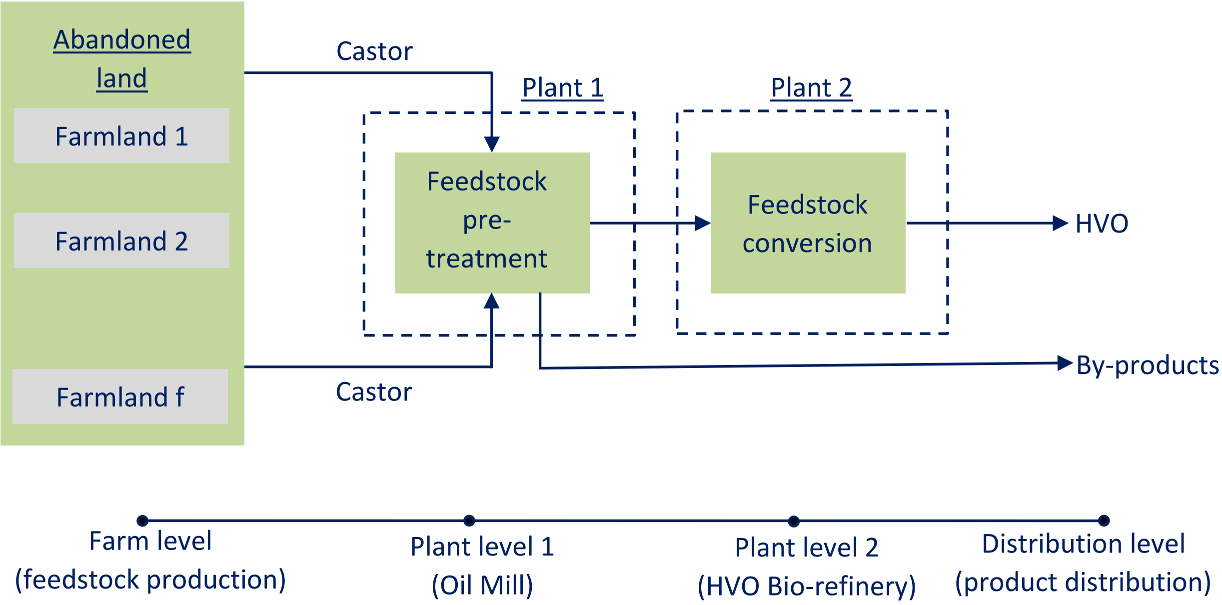

Figure 5. Schematic representation of the proposed supply chain for HVO produced using low-ILUC biomass feedstock.

In Figure 5, castor cultivated on degraded lands is transported from farm level to plant level 1. Plant level 1 comprises an oil mill which is used to extract vegetable oil from castor seeds while in plant level 2, the extracted oil is hydrotreated in a biorefinery to produce HVO, which is a substitute for fossil-based diesel. A detailed description of hydrogenation of vegetable oil can be found in Ref[19].

Lastly, the hydrotreated vegetable oil produced in the biorefinery is distributed and supplied to the EU energy market, thereby sold as alternative to conventional fossil-based diesel. The proposed model, derived from Figure 5, takes the following inputs: farmland size and geographical coordinates, crop yield, production capacity of oil mill and biorefinery, conversion factors for castor seed to vegetable oil as well as castor cake and vegetable oil to HVO, product demand, transportation modes and their associated cost, travel distance between supply chain entities, tortuosity, interest rate, unit transport cost, unit cultivation cost, unit production cost, unit extraction cost and unit selling price of HVO and castor cake. Using the aforementioned inputs, the model calculates the quantity of castor seed produced per annum, castor oil produced, HVO produced, castor cake produced, total cost, revenues, and net present value. Total cost includes cultivation cost, transportation cost, and production cost. A detailed description of the model can be found in Annex A4. In Section 6.1, a case study is used to demonstrate the applicability of the proposed model.

2.3 Data collection

2.3.1 Farm-related datasets

The farm-level information required can be grouped into geographic and agronomic datasets. Geographic data includes farmland location and land size while agronomic data includes crop specific information such as crop yield, cultivation season, date of establishment and harvest, fertiliser requirements, etc. For majority of crop types cultivated across the globe, geographic and agronomic datasets can be collected from US Department of Agriculture[20]. The case study data used in this report were provided by the BIKE partners.

2.3.2 Economic datasets

The estimation of farm profitability requires data for calculating crop production cost and net farm income. Crop production cost includes cost of all activities involve during cultivation, starting from establishment to harvest. Typical sources of crop production cost include historical data collected by farmers. This can be found in government sponsored websites[20,21] or in previous published papers[22–24]. Alternatively, crop production cost can be estimated using the activity-based costing approach[25], which takes into account the costs of all crop cultivation activities.

Furthermore, net farm income can be estimated using the current market value of farm products and by-products. The prevailing price of products can be found in commodity price index[26–28] and government sponsored websites[20].

2.3.3 Policy information

The production of low ILUC biomass must be carried out in accordance with renewable energy directives II. This report considers productivity increases from improved agricultural practices and cultivation on unused, abandoned and/or severely degraded land.

3. Case study 1: Brassica for HVO production

3.1 Cultivation of *Brassica* in Uruguay

The cultivation of Brassica in Uruguay is one out of four case studies considered within BIKE project to demonstrate the benefits of sustainable agricultural practices. The data for this case study (provided by UPM) can be classified into two categories: reference case and improved case. The reference case is the conventional crop rotation practice using non-productive cover crops, see Table 1. In the improved case, Brassica replaces the non-productive cover crops , as shown in Table 2.

Table 1. Historical data for crop management (reference case). Source: UPM

Year	Season	Duration of season	Crop type	Average yield (t/ha)	Total area cultivated (ha)
16/17	Winter	May- December	Cover crop	0	110
	Summer	January- April	Soybean	2.5	110
17/18	Winter	May- December	Wheat	1.96	110
	Summer	January- April	Soybean	0.99	110
18/19	Winter	May- December	NP Cover crop	0	110
	Summer	January- April	Soybean	1.902	110
19/20	Winter	May- December	NP Cover crop	0	110
	Summer	January- April	Maize	5.659	110
20/21	Winter	May- December	Fallow	0	110
	Summer	January- April	Soybean	2.032	110
21/22	Winter	May- December	NP Cover crop	0	110
	Summer	January- April	Soybean	2.5	110

*Table 2**.** Historical data for crop management (improved case). Source: UPM*

Year	Season	Duration of season	Crop type	Average yield (t/ha)	Total area cultivated (ha)
16/17	Winter	May- December	Cover crop	0	110
	Summer	January- April	Soybean	2.5	110
17/18	Winter	May- December	Wheat	1.96	110
	Summer	January- April	Soybean	0.99	110
18/19	Winter	May- December	Cover crop	0	110
	Summer	January- April	Soybean	1.902	110
19/20	Winter	May- December	*Brassica carinata*	1.884	110
	Summer	January- April	Maize	5.659	110
20/21	Winter	May- December	Fallow	0	110
	Summer	January- April	Soybean	2.032	110
21/22	Winter	May- December	*Brassica napus*	1.588	110
	Summer	January- April	Soybean	2.5	110

In both cases, cultivation is carried out on 110 ha farmland over a period of six years (2016 to 2022). The length of summer and winter seasons is four months (January to April) and eight months (May to December) respectively. It takes three years to complete a rotation. Soybean and maize are cultivated in the summer while wheat and Brassica during the winter. Tables 1 and 2 show the rotation sequence and average crop yields for the reference and improved case. The unit production cost and selling price of crops included in the rotation are summarised in Table 3. The unit production costs were collected from Ref[23] and the crop selling price were collected from a commodity price index[26–28].

Table 3. Unit production cost and selling price of crops included in the crop rotation.

Crop type	Unit production cost (€/ha)	Unit price of crop (€/t)
Soybean	358	503
Maize	561	254
Wheat	628	326
Brassica	605	608

In addition to the current crop selling price in Table 3, Figure 6 shows the selling price for both summer and winter crops over a period of five years (2018 to 2022). The crop price distribution is applied in Section 3.2 to investigate the effects of fluctuation in crop price on net farm income. The lowest and highest selling price for each crop, indicated by the whiskers in Figure 6, are used to define high crop price scenario and low crop price scenario respectively.

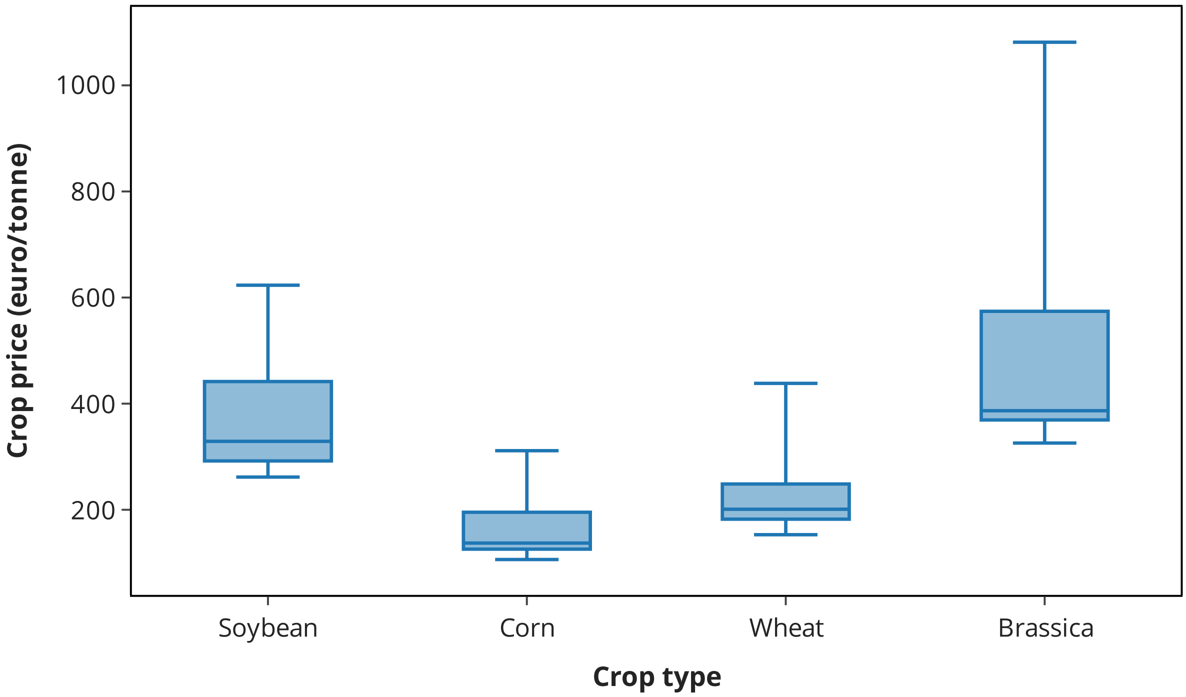

Figure 6. The market value of summer and winter crops over a five-year period (2018 to 2022). The lower and upper whiskers indicate the lowest and highest selling price over the given period. Source: Commodity price index[26–28].

3.2 Results and discussions

The case study information presented in Section 3.1 is applied in the model described in Section 2.2.1 and Annex A1 to investigate the impact of crop management practices on total crop produced and net farm income. Table 4 shows the values of two key performance indicators used in this analysis.

Table 4. Crop produced and NPV of the two crop managements evaluated in this analysis.

Performance indicator	Reference	Improved	Difference	Unit
Net present value	320,211	383,159	62,948	Euro
Net crop produced	1,930	2,312	382	Tonne

In Table 4, the introduction of Brassica as a winter crop in place of non-productive cover crop leads to additional biomass of 382 tonnes per rotation, emphasising the importance of implementing sustainable agricultural practices. Figure 7 shows the breakdown of total crop produced per annum for reference and improved case.

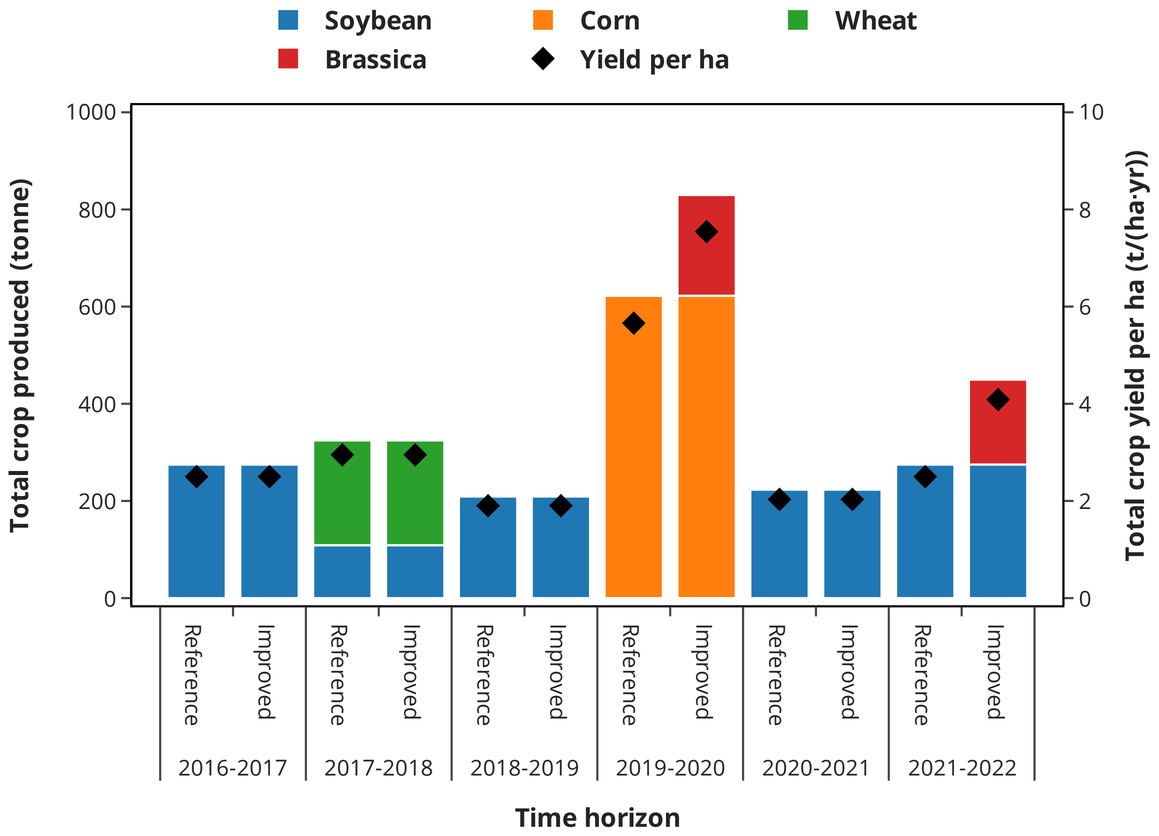

Figure 7. Annual crop produced over the entire planning horizon. Vertical bars with two crop types indicate double cropping where either wheat or Brassica is cultivated as winter crop.

In Figure 7, soybean is cultivated in all summer seasons except 2019/2020 where maize is used. This follows the common practice of introducing a "break crop" into a cropping systems to enable weed and disease control[29,30]. From the results, the introduction of Brassica as winter crop does not affect the yield of summer crop as indicated by the total yield of maize and soybean in 2019/2020 and 2021/2022. Comparing winter wheat in the first rotation (2016 to 2019) and Brassica in the second rotation (2019 to 2022), it can be seen that winter wheat leads to decrease in soybean yield of approximately 60% while Brassica increases soybean yield by 19% (calculated relative to the previous year). Mazzili & Ernst reported approximately 11% increase in soybean yield when Brassica is cultivated instead of winter wheat[23]. The positive effect of Brassica as winter crop can be attributed to increase nutrient availability among other factors[23].

In the improved case, the total yield of winter crop (wheat) in the first rotation is 216 tonne per rotation while in the second rotation the yield of winter crop (Brassica) increases to 382 tonne per rotation because Brassica is cultivated in two winter seasons compared. Therefore, in addition to crop yield increase, the improved case leads to higher land utilisation during winter seasons. In Figure 7, the 110 ha cropland is utilised once over six years in the reference case and three times in the improved case.

The increase in crop yield leads to a corresponding increase in net present value of € 62,948 (see Table 4), calculated over a period of six years and interest rate of 10%. Figure 8 shows the annual cash flow over six-year period.

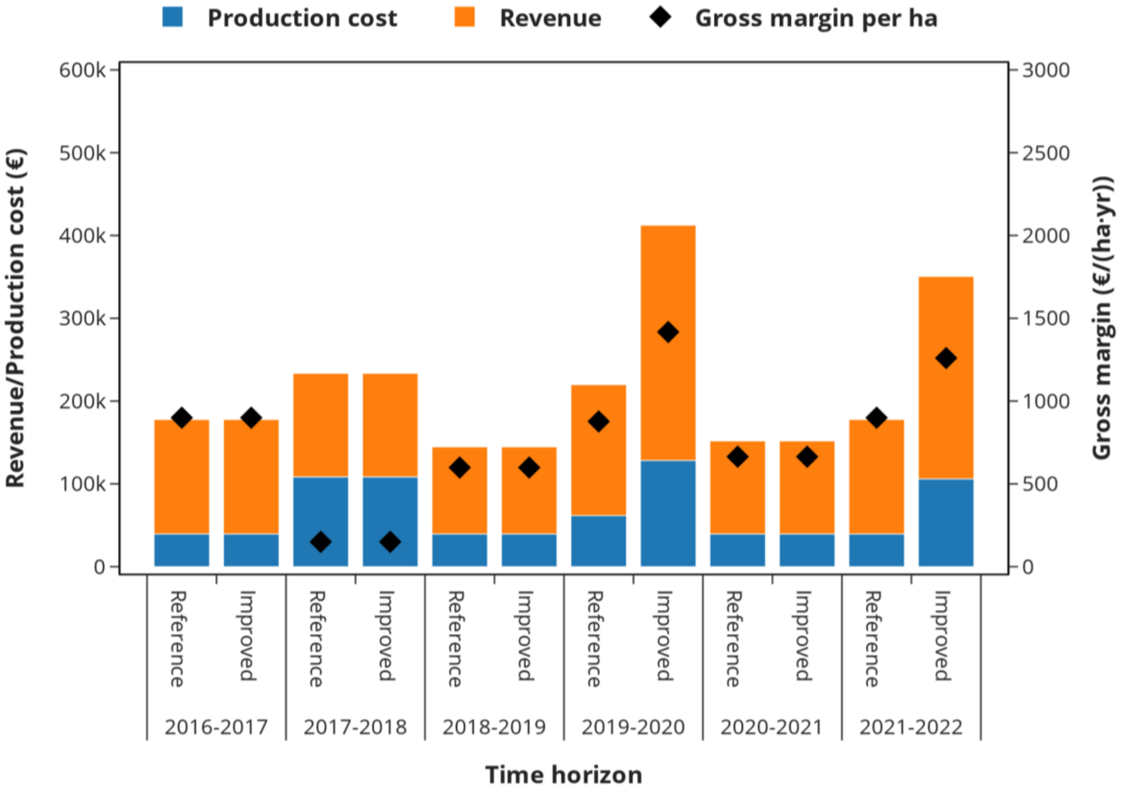

Figure 8. Annual revenue, production cost and gross margin per hectare estimated over the entire planning horizon.

In Figure 8, the annual revenue is greater than the production cost throughout the planning horizon of both reference and improved case, indicating a positive cash flow. The relatively large revenue in 2019/2020 and 2021/2022 results from the sales of additional biomass (Brassica). Also, the gross margin per hectare for wheat-soybean double (2017/2018), Brassica-soybean (2021/2022) and Brassica-maize (2019/2020) correspond to 150 €/ha·yr, 1,260 €/ha·yr and 1,417 €/ha·yr respectively. Overall, the introduction of Brassica increases the gross margin per hectare from 877 €/ha·yr to 1,417 €/ha·yr in 2019/2020 and 900 €/ha·yr to 1,260 €/ha·yr in 2021/2022. Similarly, the yield increase corresponds to 1.88 t/ha·yr and 1.59 t/ha·yr, see Figure 7. Apart from having a positive effect on summer crops, Brassica cultivated as winter crop is more profitable compared to winter wheat in a double cropping system. This economic advantage results from the fact that Brassica has slightly low production cost and sold at almost double the price of wheat.

The results and analysis presented so far focus on the current market price of crops included in the two management practices. However, crop price is subject to change caused by many factors, for example, demand-supply variability[31–33], changes in government regulations/policies[34–36], regional conflict[37–39], etc. To account for the effect of crop price fluctuation on crop management practice, a sensitivity analysis is carried out using high and low values for crop price collected from Figure 6. The results from this analysis are presented in Table 5 and Figures 9 and 10.

Table 5. NPV of the two crop managements considering high and low crop price.

Scenario	Reference	Improved	Difference	Unit
High crop price	459,595	636,194	176,599	euro
Low crop price	35,416	30,582	- 4,834	euro

In the high crop price scenario, the improved case is more profitable than the reference case as indicated by the increase in net present value shown in Table 5. Conversely, the improved case is less profitable in low crop price scenario. This is caused by the decrease in gross margin per hectare, see Figures 9 and 10.

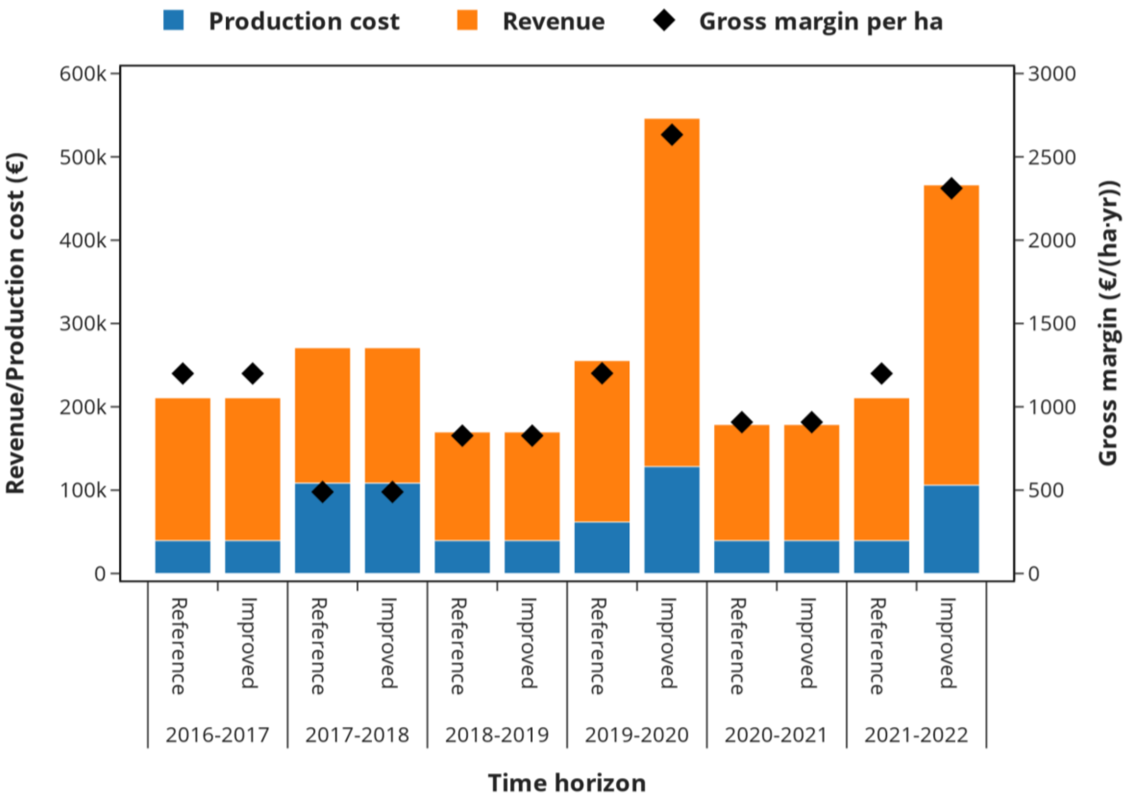

Figure 9. Annual revenue, production cost and gross margin per hectare estimated for high crop price scenario.

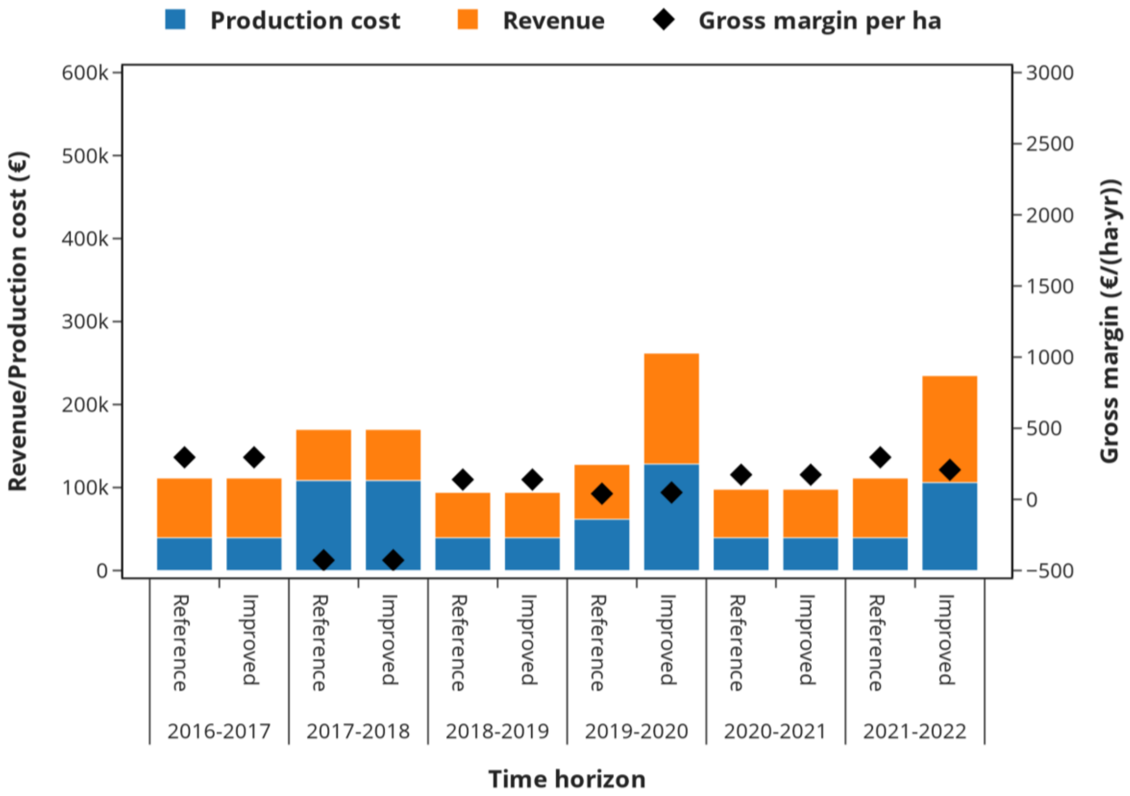

Figure 10. Annual revenue, production cost and gross margin per hectare estimated for low crop price scenario.

Figures 9 and 10 can be used alongside Figures 11 and 12 to identify the crops leading to decreases in gross margin per hectare. In all crop price scenario, only the crop selling price is varied using the information in Figure 6.

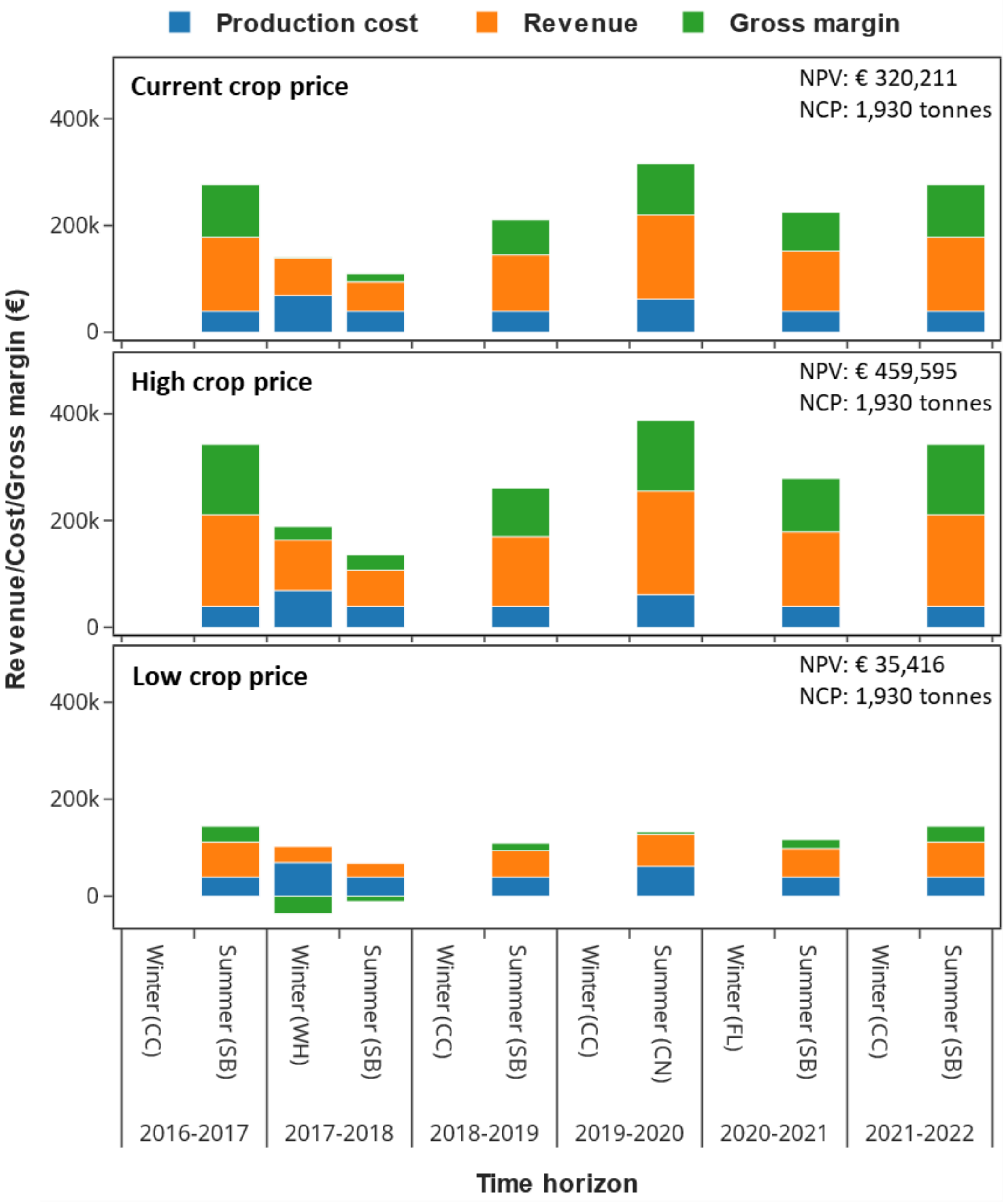

Figure 11. Revenue, production cost, and gross margin for the reference case. CC, SB, WH, CN, and FL denote cover crop, soybean, wheat, maize, and fallow respectively. NPV and NCP denotes net present value and net crop produced.

In the three crop price scenarios, the gross margin per season is positive except Year 2017/2018 of the low crop price scenario. The negative gross margin during winter (wheat) and summer (soybean) seasons results from low revenue due to low selling price. Similar trend is observed in the improved case shown in Figure 12, which also shows that cultivation of Brassica in Year 2021/2022 leads to negative gross margin. The negative gross margin can be attributed to the drop in Brassica yield from 1.88 tonne per hectare in 2019/2020 to 1.59 tonne per hectare in 2021/2022.

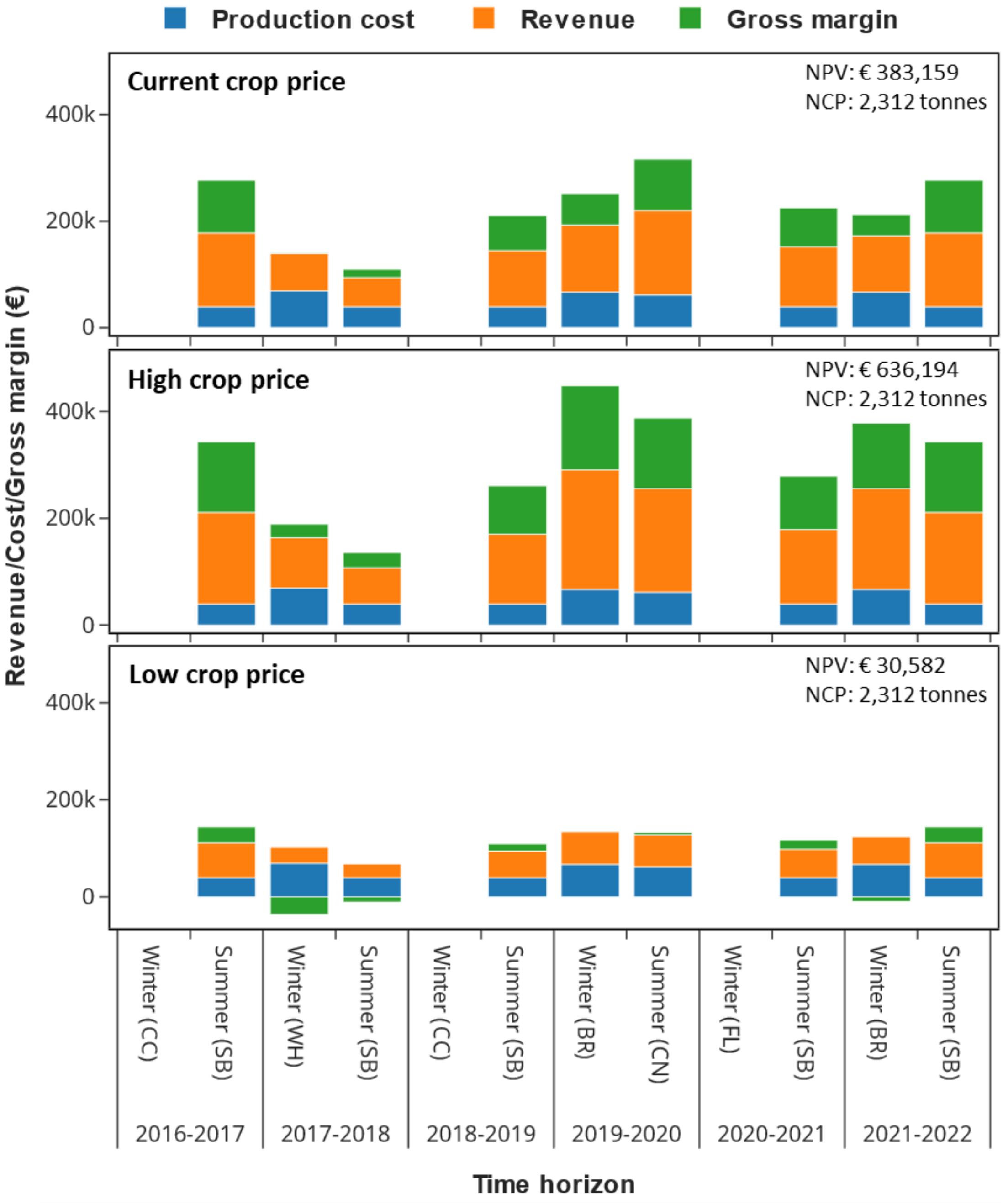

Figure 12. Revenue, production cost, and gross margin for the improved case. CC, SB, WH, CN, FL, and BR denote cover crop, soybean, wheat, maize, fallow, and Brassica respectively.

At low crop price, the crop yield per hectare needs to improve in order to avoid operating at loss. In Table 2, soybean cultivated in the summer of 2017/2018 has the lowest yield per hectare (0.99 tonne per hectare) compared to other seasons (range: 1.90 to 2.50 tonne per hectare). Likewise, the yield of wheat is 1.96 tonne per hectare in 2017/2018. For farmers to avoid operating at loss, it is necessary to identify the breakeven point for each crop, i.e., the minimum price to sell crops. At the breakeven point, the selling price of soybean, wheat and Brassica correspond to 362 €/t, 321 €/t and 381 €/t respectively. Clearly, the minimum selling price for wheat, soybean and Brassica are well above the values used in the low crop price scenario, see Figure 6.

4. Case study 2: Biomethane production via anaerobic digestion

In this section, the benefit of climate positive farming is demonstrated using two case studies, depending on whether the biomass feedstock is produced based on monocropping system or sequential cropping (aka double cropping) system. The two case studies (collected from Valli et al.[40]) focus on the production of biomethane and organic fertiliser (aka digestate) using low-ILUC biomass feedstocks. Sections 4.1 and 4.2 present the two case studies and Section 4.3 presents the results and discussions.

4.1 AD plant feedstock produced using monocropping system.

This case study is a biogas plant (aka AD plant 1) with capacity of 1000kW located in Northern Italy (the Lombardy region). The plant is fed with maize silage cultivated on 285 ha of cropland located 2.5 km away from the plant. There is no food/feed as the whole crop is used for bioenergy. The digestate is used as fertiliser to supplement chemical fertiliser. Table 6 summarises the information related to anaerobic digestion of feedstock to products.

Table 6. Parameters for AD plant 1 in which biomass feedstock is produced using monocropping system. Source: Valli et al.[40]

Maize plant		
Parameter	Unit	Value
Crop area	ha	284.6
Biomass load	t/y	17945
Biomass TS content	% F.M	35
Biomass VS content	% TS	96
Biomass VS load	t VS per a	6006
VS degraded in digestion	%	89
N content biomass input	g/kg F.M.	4.38
Biogas yield	m^3/kg VS	0.679
% CH_4 in biogas	%	53
BioCH_4 yield	Nm^3 CH_4 per kg VS	0.36

4.2 AD plant feedstock produced using sequential cropping system.

Similar to the case study in Section 4.1, the 1000 kW biogas plant (aka AD plant 2) considered here is located in Northern Italy (also the Lombardy region) at a 600-head dairy cattle farm, including 280 lactating cows, please see Valli et al.[40]. However, the plant is fed with a variety of feedstocks including cattle slurry, by-products from agro-industry (cereal grain and potato scrap), and energy crops which are mostly maize silage produced as sequential crops. The silage/energy crops are produced on 255 ha of cropland divided into seven plots, see Figure 13.

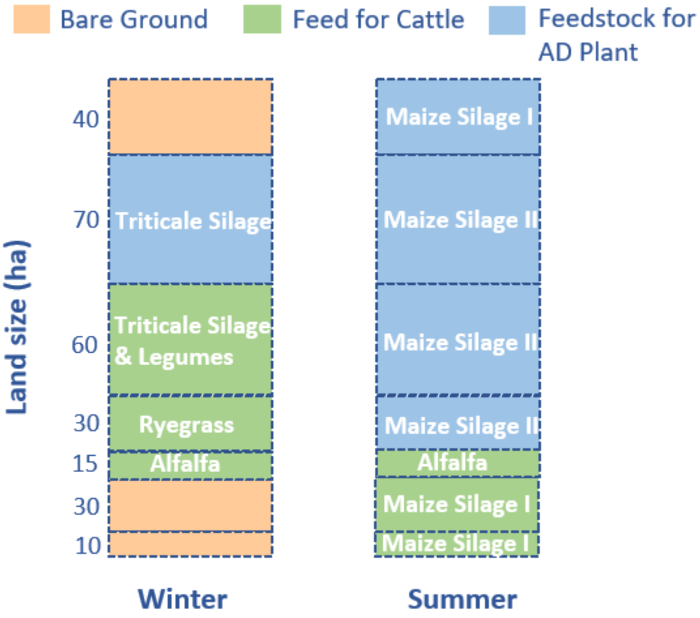

Figure 13. Land-use practices for the northern Italy farm presented in this case study. Source: *Valli et al.*[40]

In Figure 13, 160 ha is dedicated to sequential cropping with winter cereal (triticale or ryegrass) used as forage for animal while 15 ha is used to grow perennial forage (alfalfa) for cattle, please see Valli et al.[40]. The remaining 80 ha is used for monocropping to produce maize silage of which 50% is used as animal feed and 50% as feedstock for bioenergy, please see Valli et al.[40]. Table 7 presents information on conversion of various feedstocks into biogas, biomethane and digestate.

Table 7. Parameters for AD plant 2 in which biomass feedstock is produced using sequential cropping system. Source: Valli et al.[40]

Crop & Manure plant								
Parameter	Unit	Cattle slurry	Potato scraps	Cereal by-products	Maize silage I monocrops	Maize silage II (after ryegrass)	Maize silage II (after triticale)	Triticale silage crop
Crop area	ha				40	30	130	70
Biomass load	t/y	14600	1825	913	2522	1746	6936	3395
Biomass TS content	% F.M	8	8	92	35	35	35	33
Biomass VS content	% TS	83	96	97	96	96	96	94
Biomass VS load	t VS per a	994	140	814	844	584	2321	1055
VS degraded in digestion	%	55	87	78	89	82	82	78
N content biomass input	g/kg F.M.	3.85	1.06	13.69	4.38	4.38	4.38	3.8
Biogas yield	m^3/kg VS	0.429	0.656	0.616	0.679	0.623	0.623	0.594
% CH_4 in biogas	%	56	52	56	53	53	53	53
BioCH_4 yield	Nm^3 CH_4 per kg VS	0.24	0.34	0.345	0.36	0.33	0.33	0.315

4.3 Results and discussions

The information presented in Sections 4.1 and 4.2 is applied in the model described in Section 2.2.2 and Annex A2 in order to assess the biomethane potential of various low-ILUC risk feedstocks. Tables 8 and 9 summarise the products from AD plants 1 and 2 respectively.

Table 8. Biomethane produced via anaerobic digestion of maize cultivated using monocropping system.

AD Plant (feedstock conversion)			
Feedstock type	Value	Product type	Value
Maize	17,945 t/y	Biogas (t/y)	5,366 t/y or 3.64×10^6 m^3/y
		Digestate (t/y)	12,579 t/y
Product upgrade			
Biogas	3.64×10^6 m^3/y	Biomethane	1.93×10^6 m^3/y
		Carbon dioxide	1.71×10^6 m^3/y

Table 9. Biomethane produced via anaerobic digestion of manure, agro-industry waste and silages cultivated using sequential cropping system.

AD Plant (feedstock conversion)				
Feedstock type	Value	Product type		
	t/y	Digestate (t/y)	Biogas (t/y)	Biogas (m^3/y)
Cattle slurry	14,600	14,067	533	0.229×10^6
Potato scraps	1,825	1,703	122	0.079×10^6
Cereal by-product	913	0.277	636	391×10^6
Maize silage I (monocrop)	2,522	1,768	754	512×10^6
Maize silage II (sequential crop)	1,746	1,265	481	299×10^6
Maize silage II (sequential crop)	6,936	5,025	1,911	1.19×10^6
Triticale silage (sequential crop)	3,395	2,574	821	488×10^6
Total	31,937	26,679	5,258	3.191×10^6
Product upgrade				
Biogas	3.191×10^6 m^3/y	Biomethane	1.709×10^6 m^3/y	
		Carbon dioxide	1.482×10^6 m^3/y	

The anaerobic digestion of biomass to produce biogas is an important step toward biomethane production. Table 8 shows the quantity of biomethane produced using biomass feedstock from monocropping system. Out of 17,945 t/y of maize silage, only 30% (w/w) is converted to biogas and subsequently to biomethane which constitute 53% (v/v) of biogas in this case study. Similarly, the quantity of biomethane produced from biomass feedstocks mainly from sequential cropping system is shown in Table 9. Unlike the previous case, the feedstock here consists of cattle slurry, potato scrap, and cereal by-product in addition to maize and triticale silage. The total biomass feedstock rate is 31,937 t/y, of which 17% (w/w) is converted to biogas (contains 53% v/v biomethane). The biogas and biomethane yields from AD plant 2 are slightly lower than AD plant 1 despite having a larger total biomass feedstock rate. The low biogas and biomethane yields are due to low total solid content of cattle slurry (8% total solid content and constitute 46% w/w of total feedstock rate). Recall, biogas yield obtained following the four steps (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) in anaerobic digestion strongly depends on the amount of volatile solid, which is a fraction of total solid content of biomass.

The by-product (digestate) from anaerobic digestion is used as fertiliser for food/feed and energy crop, following the principle of biogasdoneright®. In Tables 8 and 9, the digestate produced by AD plants 1 and 2 corresponds to 12,579 t/y and 26,679 t/y respectively. The digestate produced by AD plant 1 is not sufficient to satisfy cropland requirements, therefore chemical fertiliser is used as supplement. By contrast, AD plant 2 generates sufficient digestate to satisfy demand, hence no chemical fertiliser is needed. Note that the use of chemical fertiliser is likely to increase total production cost.

Typically, the application of digestate on cropland is carried out in accordance with government regulations and in-line with standard practice to avoid the spread of pathogens present in digestates. The rules and regulations mandatory to all EU members Countries include (EC) No. 208/2006 and (EC) No. 1774/2002[41–43]. According to Valli et al.[40], digestate can be applied at four distinct stages of cropping cycle using unique equipment: (i) before sowing the next crop, (ii) at weed control stage, and (iii) at crop growth stage[41].

The feedstocks for AD plants 1 and 2 are cultivated on 285 ha and 255 ha using monocropping and sequential cropping respectively. In the latter, 55 ha is dedicated to feed crop production while 200 ha is used for feed and AD plant feedstock production, see Figure 13. In order to compare biogas and biomethane yield per hectare of cropland, only 200 ha used for feed and AD plant 2 feedstock is considered. Also, biogas and biomethane produced using cattle slurry, potato scrap, and cereal by-product are excluded in this analysis. For AD plant 1, the biogas and biomethane yield correspond to 12,785 m^3/ha·yr and 6,776 m^3/ha·yr respectively. Similarly, AD plant 2 generates 12,451 m^3/ha·yr and 6,599 m^3/ha·yr of biogas and biomethane. Despite having larger land size, the biogas and biomethane yields from AD plant 1 is similar in magnitude to AD plant 2. Without winter crops, the biogas and biomethane yield from AD plant 2 drops to 10,012 m^3/ha·yr and 5,306 m^3/ha·yr respectively.

Biogas and biomethane yield per hectare for various crop types can be found in literature. For example, the yield of biomethane per hectare of maize and triticale ranges between 3,573 to 18,540 m^3/ha·yr and 1,112 to 6,604 m^3/ha·yr respectively[44].

5. Case study 3: Miscanthus for bioethanol production

This case study assesses the potential of producing 2G bioethanol using Miscanthus cultivated on underutilised lands in the UK. To make use of existing resources and avoid large capital investment related to building a new plant, this report analyses the retrofit of an existing 1G bioethanol plant to allow production of 2G bioethanol using Miscanthus as feedstock. Two cases were analysed depending on target area for feedstock cultivation, i.e., cultivation on underutilised lands within 50 km and 100 km radius to an existing biorefinery.

5.1 Cultivation of Miscanthus in the UK

The farmlands used for cultivation of Miscanthus in the UK were identified using the BIOPLAT-EU web GIS tool developed by FAO[45]. The tool identifies only lands not currently in use and excludes areas not suitable for bioenergy feedstock production as a result of various reasons such reserve forest area, water and wetland areas, settlement areas, protected areas such as national parks, steep slope areas, partly agriculturally used areas, and lastly unusable areas such as beach, bare rock and glacier. Tables 10 and 11 show the summary of underutilised farmlands within 50 km and 100 km radius to an existing biorefinery. Further details related to each piece of land can be found in Annex A3.

Table 10. Summary of underutilised lands within 50 km radius to an existing biorefinery

Item	**Value**	**Unit**
Number of underutilised lands	4	[-]
Largest land size	28	ha
Smallest land size	15	ha
Average land size	21	ha
Total land size	82	ha

Table 11. Summary of underutilised lands within 100 km radius to an existing biorefinery

Item	**Value**	**Unit**
Number of underutilised lands	45	[-]
Largest land size	44	ha
Smallest land size	10	ha
Average land size	19	ha
Total land size	858	ha

In the UK, the establishment and harvest date of Miscanthus correspond to November/January and November/February respectively[25], with life span of up to 20 years[46]. Table 12 shows the characteristics of Miscanthus used in this analysis.

Table 12. Crop characteristics

Item	Value	Unit
Crop type	Miscanthus	[-]
Crop yield	6.5 – 9.0	t/ha
Crop production cost	491.5	€/ha
Crop production cost at 6.5 t/ha	75.6	€/t
Crop production cost at 9.0 t/ha	54.6	€/t

5.2 Integrating 2G to an existing 1G bioethanol plant.

This report presents the analysis to retrofit an existing 1G bioethanol plant instead of constructing a new plant in order to convert Miscanthus into 2G bioethanol. The existing plant, located in England, converts wheat into 1G bioethanol. To process Miscanthus, a pre-treatment and enzymatic hydrolysis units were installed to enable the conversion lignocellulosic biomass into simple sugars which can be fed to the existing fermenter unit. The retrofitted plant can produce up to 40,000 tonnes per annum of 2G bioethanol. By-product (lignin) is utilised in a CHP unit to generate electricity. Table 13 shows the parameters of the retrofitted plant.

Table 13. Parameters for the conversion of low-ILUC feedstock to 2G bioethanol

Item	Value	Unit
Feedstock type	Miscanthus	[-]
Plant capacity (tonnes of 2G bioethanol)	40000	t/yr
Unit production cost per litre of ethanol	0.59	€/L
Unit production cost per tonne of ethanol	748	€/t
Conversion factor (feedstock to ethanol)	0.26	t/t DM
Ethanol market price (2023)	1070	€/t
Conversion factor (feedstock to by-product)	1.80	MJ/kg
Conversion factor (feedstock to by-product)	500	kWh/t
By-product market price (2023)	0.38	€/kWh

The transportation of Miscanthus from farmland to biorefinery is carried out using a trailer with a maximum capacity of 15.50 tonnes per trip[47]. It cost approximately € 1.34 to transport feedstock over one kilometre[47]. Transportation cost considers fuel cost, driver wages, maintenance cost, and capital cost. In this case study, travel distance is estimated assuming straight line between supply chain entities. To account for the nonlinear nature of real travel distance, a tortuosity factor of 1.80 is applied. Tables 14 and 15 shows the summary of distance from farmland to biorefinery.

Table 14. Summary of travel distance between existing biorefinery and underutilised lands within 50 km radius

Item	Value	Unit
Number of travel routes	4	[-]
Longest travel distance	32	km
Shortest travel distance	15	km
Average travel distance	25	km
Total travel distance	98	km

Table 15. Summary of travel distance between existing biorefinery and underutilised lands within 100 km radius

Item	Value	Unit
Number of travel routes	45	[-]
Longest travel distance	98	km
Shortest travel distance	15	km
Average travel distance	76	km
Total travel distance	3421	km

5.3 Results and discussions

The case study information presented in Sections 5.1 and 5.2 is applied in the model described in Section 2.2.3 and Annex A3 to assess the potential of producing 2G bioethanol using Miscanthus cultivated on underutilised lands within the UK. Sections 5.3.1 and 5.3.2 present the results for cases 1 and 2, i.e., Miscanthus cultivated on land within 50 km and 100 km to an existing biorefinery.

5.3.1 Bioethanol produced from Miscanthus cultivated on land within 50 km radius to an existing biorefinery.

The total amount of Miscanthus produced on land within 50 km radius to an existing biorefinery is shown in Figures 14 and 15. As can be seen, only four farmlands are available within this target area and the total biomass produced is 536 t/yr and 741 t/yr at crop yield equivalent to 6.5 t/ha and 9 t/ha respectively. As expected, increase in crop yield per ha is accompanied by a net increase total Miscanthus produced (206 t/yr). The cultivation cost is € 492 per hectare in both cases.

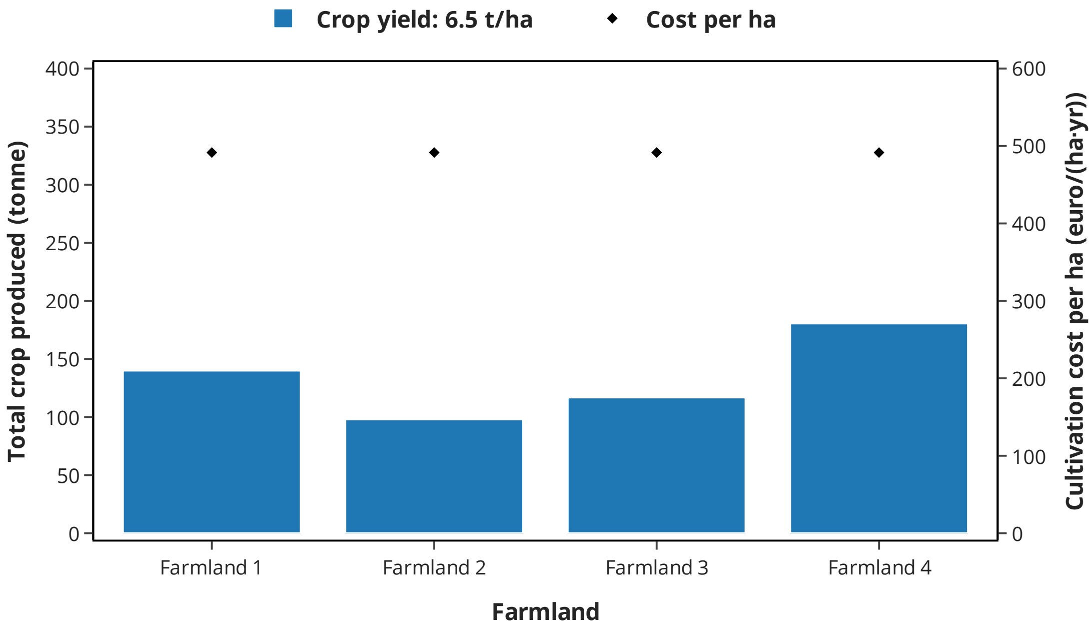

Figure 14. Miscanthus cultivated on underutilised lands located within 50 km radius to an existing bioethanol plant. Crop yield is approximately 6.5 t/ha.

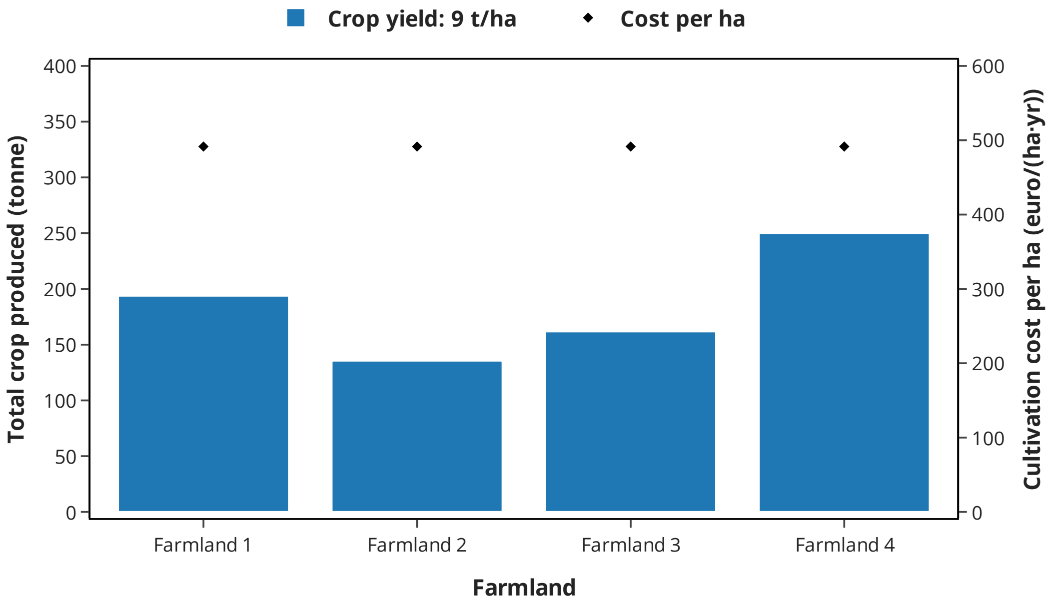

Figure 15. Miscanthus cultivated on underutilised lands located within 50 km radius to an existing bioethanol plant. Crop yield is approximately 9 t/ha.

Table 16 shows the amount of 2G bioethanol produced from Miscanthus and associated cost. The total revenue is the sum of revenue generated from the sale of 2G bioethanol and electricity generated from by-product.

Table 16. Miscanthus supplied, bioethanol and by-product produced, and net present value of bioethanol value chain comprising underutilised lands within 50 km radius to an existing plant.

Item	6.5 t/ha	9 t/ha	Difference	Unit
Feedstock Supplied	535.48	741.43	205.95	t/yr
Bioethanol Produced	139.22	192.77	53.55	t/yr
By-product Produced	267,759.09	370,743.36	102,984.27	kWh
Overall Cost	148,560.54	190,126.76	41,566.22	euro/yr
Revenue	251,662.03	348,455.12	96,793.09	euro/yr
Net Present Value	93,728.63	143,934.87	50,206.24	euro

For the same land size, the amount of 2G bioethanol produced increases by 39 % as crop yield per hectare increase from 6.5 to 9.0. Similarly, the net present value increases by 54 %. The overall cost includes the cost of cultivation, production of 2G bioethanol, and transportation of feedstock from farmland to biorefinery. Despite an increase in overall cost, there is no significant change in cost distribution (see Figure 16) when crop yield increase from 6.5 to 9.0 tonne per hectare.

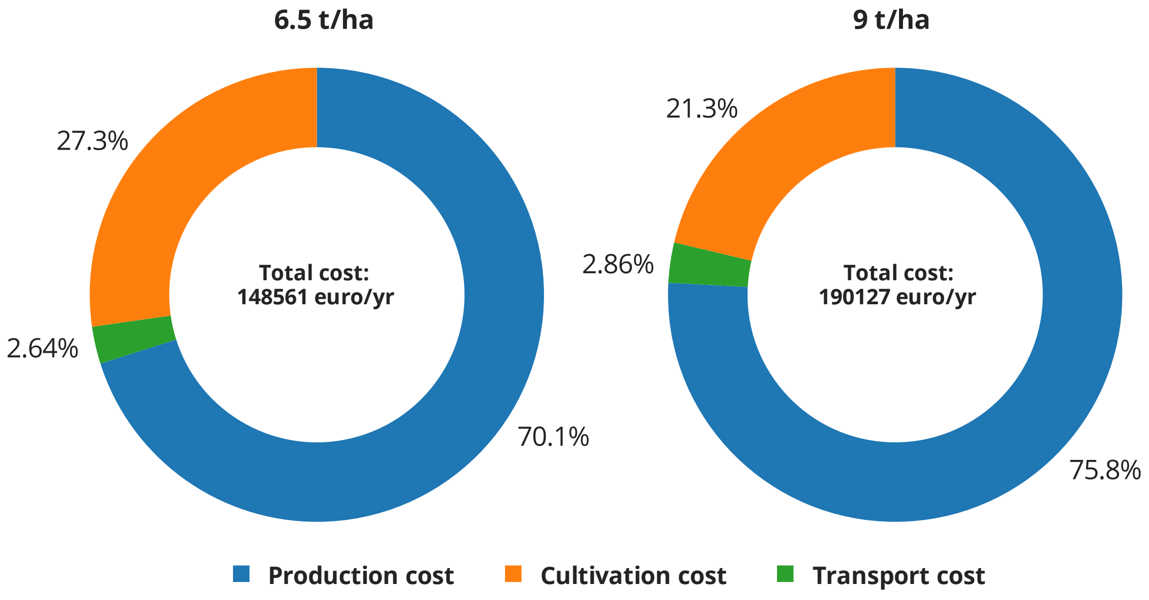

Figure 16. Breakdown of total cost for the production of bioethanol from Miscanthus cultivated on underutilised lands within 50 km radius to an existing bioethanol plant.

Figure 17 shows the structure of value chain for 2G bioethanol produced from Miscanthus cultivated on underutilised lands in the UK. The value chain indicates the locations of biorefinery and all farmlands, links between farmlands and biorefinery, and lastly the amount of Miscanthus produced on each piece of land.

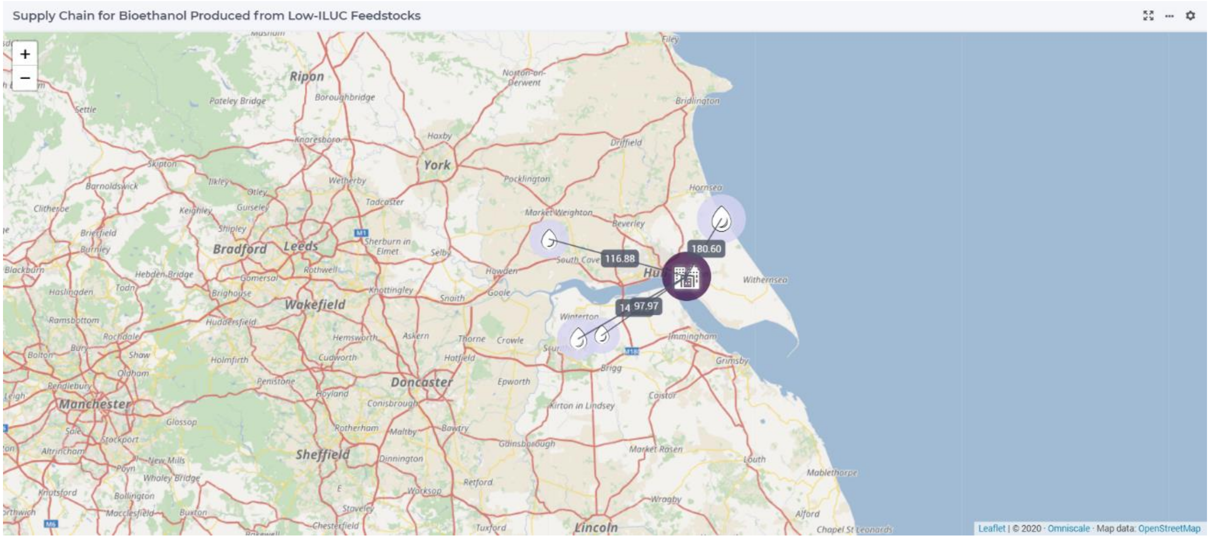

Figure 17. Map showing the supply of low-ILUC feedstock (Miscanthus) from various farmlands to an existing bioethanol plant. The farmlands are located within 50 km radius to the plant.

5.3.2 Bioethanol produced from Miscanthus cultivated on land within 100 km radius to an existing biorefinery.

The amount of Miscanthus produced on farmlands within 100 km radius to an existing biorefinery is shown in Figures 18 and 19. For crop yield of 6.5 t/ha and 9.0 t/ha, the feedstock produced correspond to 5,577 t/yr and 7,722 t/yr respectively. Cultivation cost is approximately € 492 per hectare in both cases.

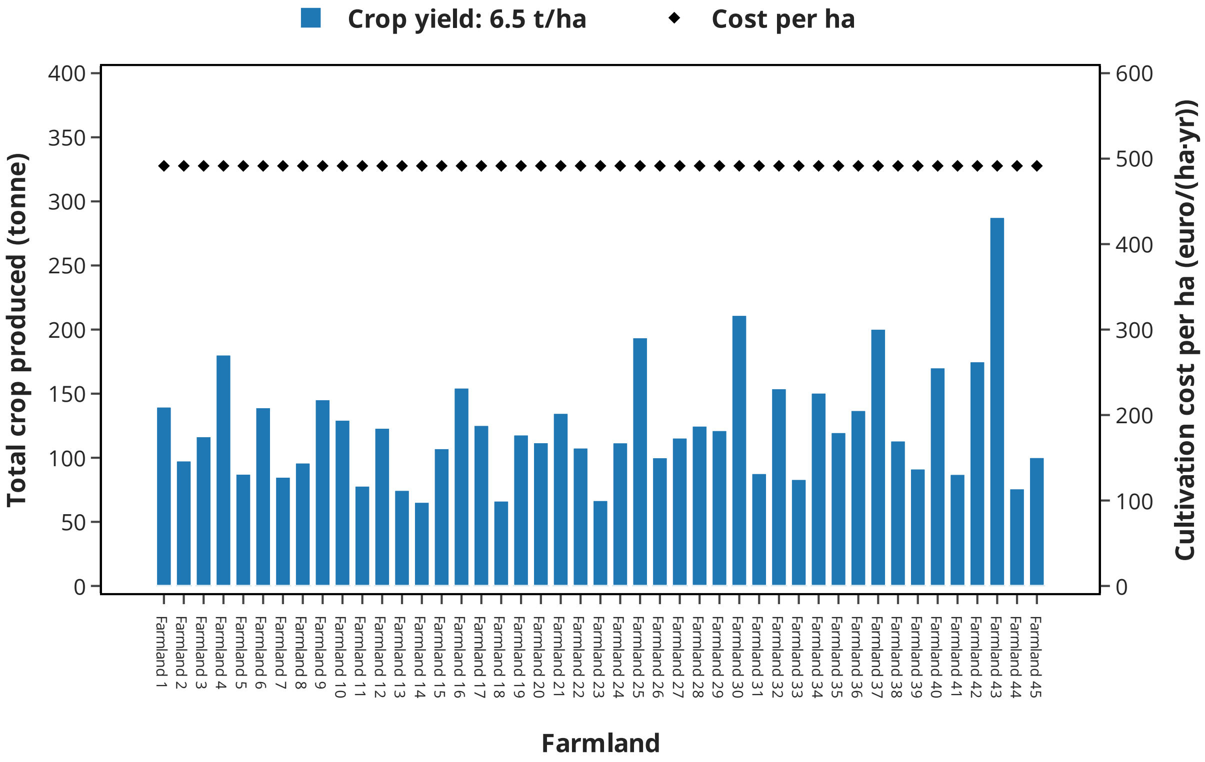

Figure 18. Miscanthus cultivated on underutilised lands located within 100 km radius to an existing bioethanol plant. Crop yield is approximately 6.5 t/ha.

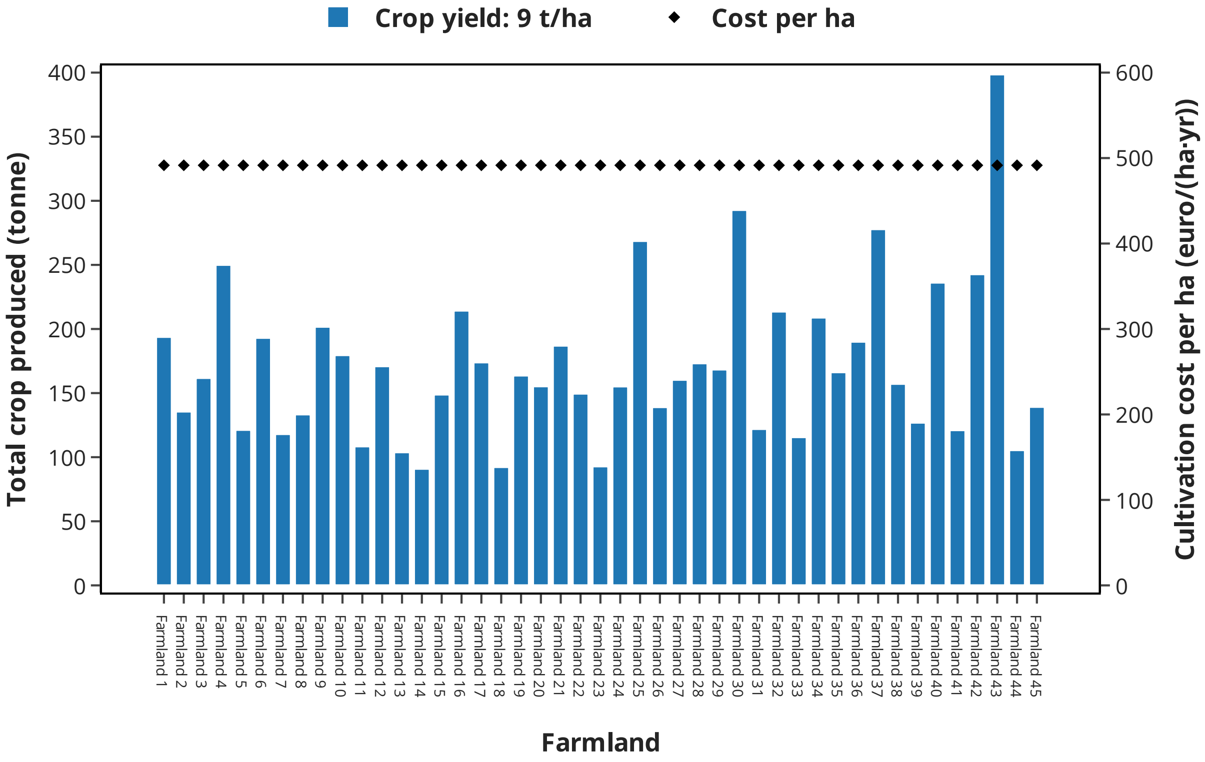

Figure 19. Miscanthus cultivated on underutilised lands located within 100 km radius to an existing bioethanol plant. Crop yield is approximately 9 t/ha.

In Table 17, increase in crop yield from 6.5 t/ha to 9.0 t/ha results to 39 % increase in bioethanol produced. The net present value increased by 55 %.

Table 17. Miscanthus supplied, bioethanol and by-product produced, and net present value of bioethanol value chain comprising underutilised lands within 100 km radius to an existing plant.

Item	6.5 t/ha	9 t/ha	Difference	Unit
Feedstock Supplied	5,576.96	7,721.94	2,144.98	t/yr
Bioethanol Produced	1,450.01	2,007.71	557.70	t/yr
By-product Produced	2,788,702.82	3,861,280.82	1,072,578.01	kWh
Overall Cost	1,636,594.69	2,103,867.62	467,272.93	euro/yr
Revenue	2,621,052.39	3,629,149.47	1,008,097.07	euro/yr
Net Present Value	894,961.55	1,386,619.86	491,658.31	euro

As shown in Figure 20, the cost of bioethanol production dominates overall cost in both cases. In addition, the cost of transporting biomass increases slightly with increase crop yield. This results from the fact that more trips will be required to convey additional biomass from farmland to biorefinery.

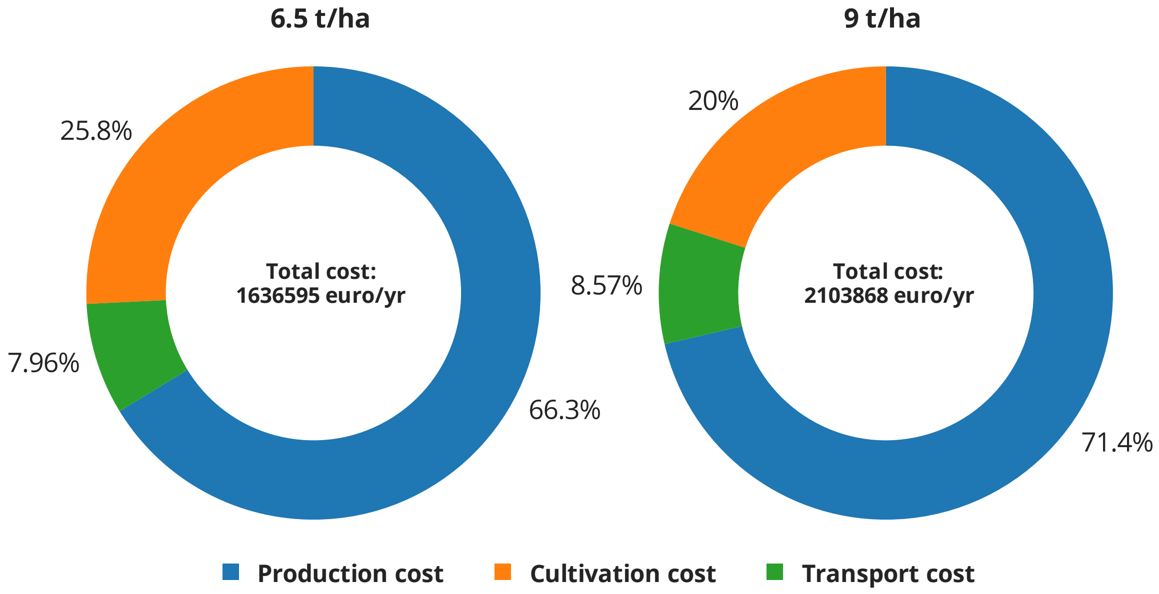

Figure 20. Breakdown of total cost for the production of bioethanol from Miscanthus cultivated on underutilised lands within 100 km radius to an existing bioethanol plant.

The structure of the value chain for 2G bioethanol is presented in Figure 21. Unlike the 50 km case with only four underutilised farmlands (total size ≅ 82 hectares), this case study contains 45 underutilised farmlands with total size of 858 hectares. Each piece of land supplies Miscanthus directly to the biorefinery, see Figure 21. By increasing the target area coverage from 50 to 100 km radius, the total Miscanthus supply increase by 5,042 t/yr and 6,981 t/yr at crop yield of 6.5 t/ha and 9.0 t/ha respectively.

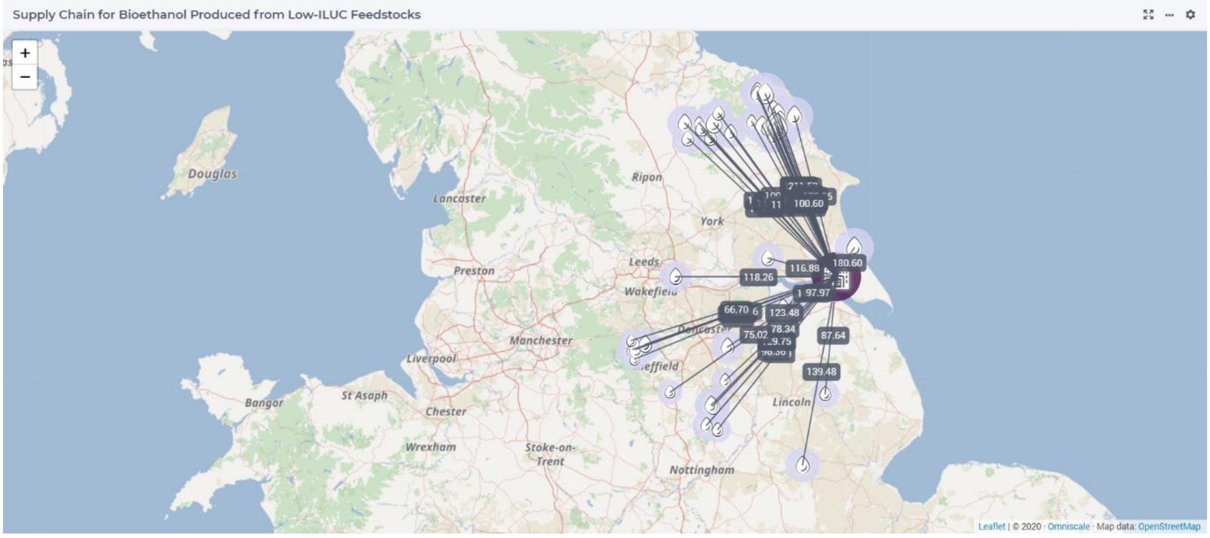

Figure 21. Map showing the supply of low-ILUC feedstock (Miscanthus) from various farmlands to an existing bioethanol plant. The farmlands are located within 100 km radius to the plant.

At crop yield of 9 t/ha, the quantity of Miscanthus produced on farmland within 50 km and 100 km correspond to 741 t/yr and 7,722 t/yr resulting to 2G bioethanol yield of 193 t/yr and 2,008 t/yr respectively. In both cases, the bioethanol yield is lower than the planned capacity of the biorefinery, which is ≅ 40,000 t/yr. The quantity of Miscanthus needed to produce 40,000 t/yr of 2G bioethanol is ≅ 153,846 t/yr (at conversion efficiency equal to 0.26 t/t DM), requiring a cultivation land equivalent to 17,094 hectares (calculated assuming crop yield is approximately 9 t/ha). This land size is larger than the total underutilised lands within 100 km radius (i.e., 858 hectares) to the existing biorefinery. Therefore, to satisfy the plant capacity, underutilised land beyond 100 km radius should be considered. According to BIOPLAT EU web GIS tool, there are 7,748 underutilised lands in the UK with a total size of ≅ 301,797 hectares, distributed across England (61,988 ha), Wales (21,660 ha), Scotland (196,591 ha) and Northern Ireland (21,559 ha). Therefore, there is sufficient underutilised lands in the UK to produce feedstock for the biorefinery.

6. Case study 4: Castor seed for HVO production

This case study evaluates the profitability of HVO production using castor seed cultivated on abandoned or degraded farmland. According to the existing HVO value chain, cultivation of castor seed and extraction of castor oil are carried out in Kenya while conversion of castor oil to hydrotreated vegetable oil is carried out in Italy. The dataset for this analysis was provided by Eni presented in Sections 6.1 to 6.4.

6.1 Cultivation of Castor seed in Kenya

The cultivation of castor seed (*Ricinus communis*) for HVO production is carried out on 3000 hectares farmland located in Kenya, where about 6000 farmers were involve in land preparation as well as planting and harvesting of castor seed, see Table 18 for additional details.

Table 18. Summary of degraded and abandoned lands used for castor cultivation.

Item	Value	Unit
Land type[§,¶]	Arid and semi-arid lands	[-]
Land size[¶]	c.a. 3000 ha, across 6000 farmers	ha
Location	Makueni county, Kenya	[-]

[§] Source: Kenyan State Department for the arid and semi-arid lands (ASALS) and Regional Development

[¶] Source: Eni[48]

The cultivation of castor seed in Kenya is in line with Eni's goal to expand feedstock sources for Gela biorefinery and to support decarbonisation of the transportation sector[49]. In July 2021, Eni signed a memorandum of understanding with Kenya's Ministry of Petroleum and Mining to expands its HVO value chain through the production of castor seed on degraded land, croton trees in agro-forestry systems, etc[50]. The first cargo of castor oil was delivered to Gela biorefinery in October 2022[50].

In Kenya, castor is grown on arid and semi-arid land during the rainy season, i.e., October-November (short rain season) and March-April (long rain season). The full details of crop variety, soil quality requirements, water requirements and other agronomic information can be found in Ref[51]. Table 19 presents the yield per hectare of castor seed in addition to cultivation cost and market selling price.

Table 19. Information on castor cultivation in Kenya

Crop characteristics		
Item	**Value**	**Unit**
Crop type	Castor	[-]
Crop yield[§]	1 – 2	t/ha
Seed purchase cost (at oil mill) [¶]	300 – 600	€/t
Crop production cost[‡]	258 – 558	€/t
Extension services		

Item	Remark
Land preparation	Provided by Eni
Sowing	Planting seed provided by Eni
Fertilisation	Manual
Weeding	Manual
Harvesting	Manual

[§] Source: Kenya Agricultural and Livestock Research Organisation

[¶] Source: Eni[48]. Note that the seed purchase cost includes extension services provided by Eni.

[‡] Crop production cost is not known at the moment of calculation. Therefore, production cost is derived from seed purchase cost assuming farmers make margin of €42 per tonne.

6.2 Oil Mill in Kenya

After harvest, castor seed is transported to oil mill located in Kwa Kathoka, Wote within Makueni county. Extraction of castor oil is carried out using mechanical press and the parameters of the plant is presented in Table 20. Currently, the plant process 24,000 tonnes of castor seed per annum (equivalent to 10,800 t/yr of castor oil), but a scale-up to 30,000 t/yr of castor oil is expected by 2023 through the construction of a second agri-hub[52].

Table 20. Parameters of Makueni agri-hub oil mill

Item	Value	Unit
Feedstock type	Castor seeds	[-]
Plant capacity (tonnes of castor seeds) [§]	24000	t/yr
Unit operating cost per tonne of castor oil[#]	350 – 550	€/t
Unit capital cost per tonne of castor oil[¶]	3 – 5	€/t
Conversion factor (feedstock to castor oil)[‡]	0.45	t/t DM (oil/seed)
Conversion factor (feedstock to castor cake)	0.55	t/t DM (cake/seed)
Castor cake market price[†]	50 – 100	€/t

[#] Note: Excluding feedstock cost – Eni.

[‡] Source: Production reports Eni.

[¶] Source: Eni. Total capital cost is annualised over 20 years.

[†] Source: Eni. Note that given the non-food nature of castor cake, the valorization considered is only for energy purposes or for transformation into biochar.

6.3 HVO Biorefinery in Italy

The extracted oil is pre-treated and converted to hydrotreated vegetable oil in Gela biorefinery located in Sicily, Italy. The parameters of the biorefinery are presented in Table 21. Note that these parameters were provided by Eni except unit production cost and HVO market price which were collected from literature.

Table 21. Parameters of HVO biorefinery

Item	Value	Unit
Feedstock type[§]	Vegetable oil (including castor), Hydrogen	[-]
Plant capacity (tonnes of HVO) [¶]	750000	t/yr
Unit production cost per tonne of oil[†]	209	€/t
Conversion factor (feedstock to HVO) [#]	0.80	t/t (HVO/Oil)
HVO market price[‡]	2000 – 4000	€/t
HVO demand[ǂ]	1.20	MMt/yr

[§] Source: Ref[19] and Eni[48].

[¶] Source: Ref[53], Ref[54], and Ref[55].

[#] Note: Average value taken from Ref[19].

[‡] Source: HVO fuel price provided by Eni[48].

[†] Source: Advance biofuel – Potentials for cost reduction[57].

[ǂ] Source: Total Eni bioRefineries capacity. Information supplied by Eni.

6.4 Transportation

The movement of castor seed, castor oil and hydrotreated vegetable oil along the supply chain is shown in Figure 22. A truck is used to transport castor seed harvested from all farmlands to oil mill where extration of castor oil takes place. The extracted oil is first transported to an intermediate storage facility and then to departing port in Mombasa using a tanker truck. Lastly, a ship is used to deliver the castor oil to Gela biorefinery.

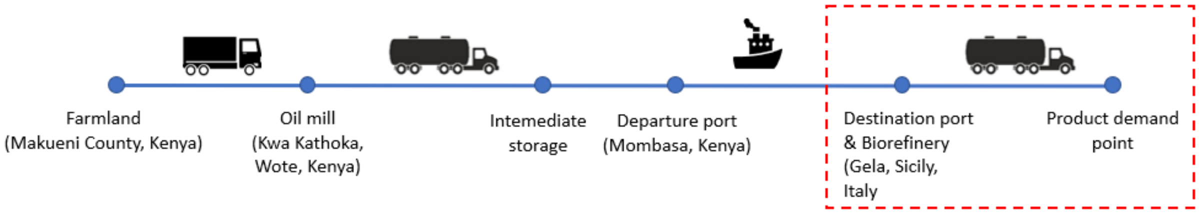

Figure 22. Transportation network.

Tables 22 and 23 present travel distance between supply chain entities and parameters of each transport type considered in the analysis.

Table 22. Travel distance between supply chain entities and corresponding transport types

From	To	Transport type	Value	Unit
Farmland	Oil mill[§]	Truck	150	km
Oil mill	Intermediate storage - Departure port[§]	Truck	380	km
Departure port	Destination port/Biorefinery[¶]	Ship	7334	km
Biorefinery	Market	N/A	N/A	km

[§] Source: Google map[58]. Information supplied by Eni

[¶] Source: Sea travel distance[59]. Information supplied by Eni

Table 23. Parameters of transport type

Commodity	Transport type	Unit transport cost§ (€/t)	Unit transport cost¶ (€/t/km)	Tortuosity (-)
Castor seeds	Truck	58.72	0.391	1.8
Castor oil	Truck	89.48	0.235	1.8
Castor oil	Ship	120.00	0.016	1

§Source: Information supplied by Eni.

¶Source: Calculated based on information supplied by Eni.

6.5 Results and discussions

The case study information presented in Sections 6.1 to 6.4 are applied in the model described in Sections 2.2.4 and Annex A4 to evaluate the profitability of producing hydrotreated vegetable oil from castor seeds cultivated on abandoned or degraded lands.

6.5.1 HVO produced from castor cultivated on abandoned and degraded lands.

As shown in Table 24, the total quantity of castor seed produced is 4,500 tonnes per annum which contains about 45 % (2,025 t/yr) of extractable oil. The revenue generated from the sale of hydrotreated vegetable oil and castor cake outweighs total cost over the entire planning horizon, leading to a positive net present value. Therefore, in this study, the production of hydrotreated vegetable oil using low-ILUC risk feedstocks (castor seed) is profitable.

Table 24. Products and key performance indicators

Item	Value	Unit
Products		
Castor seed produced	4,500	t/yr
Castor oil produced	2,025	t/yr
Castor cake produced	2,475	t/yr
HVO Produced	1,620	t/yr
Performance indicators		
Overall cost	4,038,017	euro/yr
Revenue	5,058,000	euro/yr
Net Present Value	927,257	euro

The cost distribution shown in Figure 23 indicates that transportation cost constitutes the smallest fraction of total cost. The transport cost is estimated over the travel distance (see Figure 24) between supply chain entities: Farmland – Oil mill – Departure port – Biorefinery.

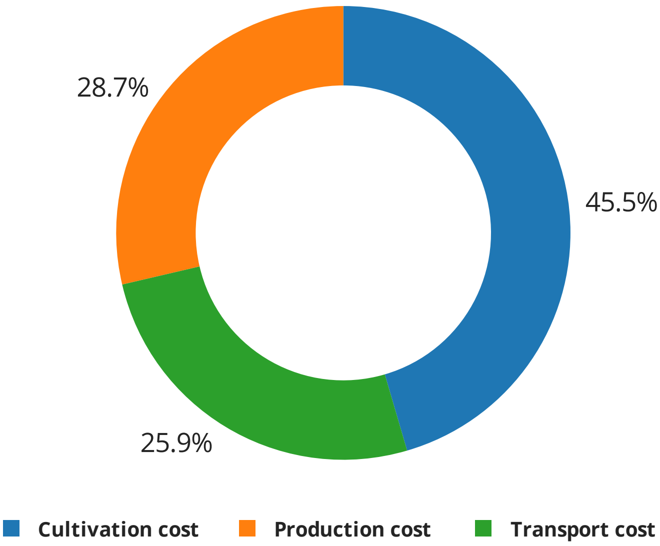

Figure 23. Breakdown of total cost to produce HVO from castor cultivated on degraded and abandoned lands.

The structure of the HVO value chain presented in Figure 24 shows the geographic location of all supply chain entities such as farmland, oil mill, departing seaport and biorefinery. Looking at the supply chain structure, the longest distance is along Departure port – Biorefinery route. Hence total cost can be improved by minimising shipping cost.

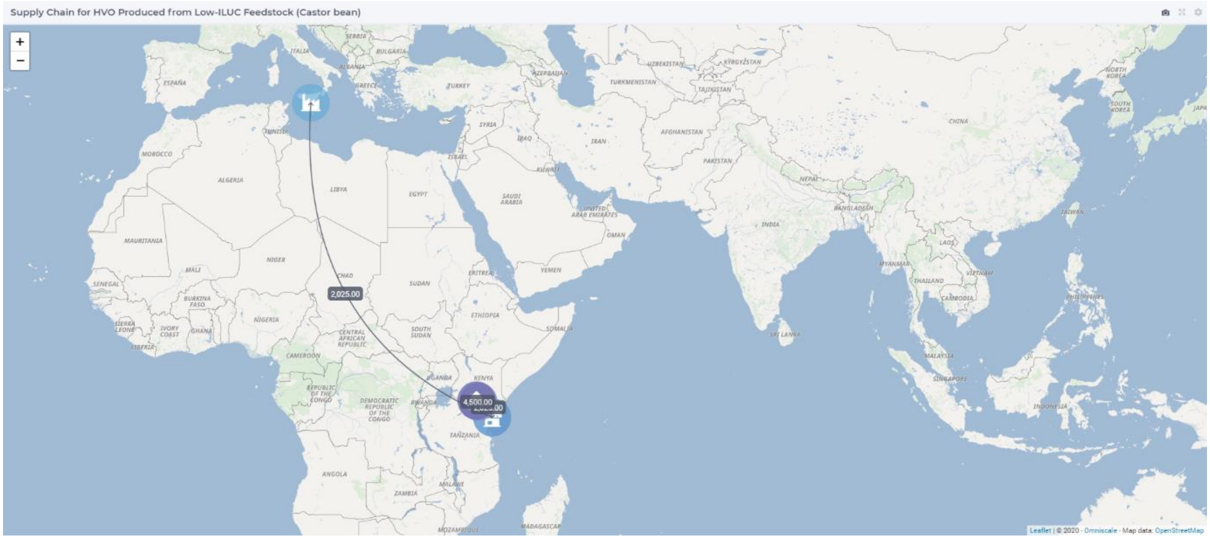

Figure 24. Map showing HVO supply chain. Castor cultivation farm and oil extraction plant are in Kenya while HVO biorefinery is located in Italy.

7. Case studies summary

This section summarises and discusses the key results from the four case studies investigated and analysed in this report. This report focuses on the development of decision-support models that address challenges related to climate positive farming solutions. The decision models developed for two value chains were: (i) productivity increases from improved agricultural practices and (ii) cultivation on abandoned or degraded land. In each case, two alternative cases were investigated. The first investigated *Brassica* for HVO production and BRD for biomethane production, while the latter focused on Miscanthus for bioethanol production and castor for HVO production. Table 25 summarises the key findings from this work.

Table 25. Key findings from case studies on production of biofuels using low-ILUC biomass feedstocks.

Case study	*Brassica* for HVO	BDR for Biomethane	Miscanthus for bioethanol	Castor for HVO
Location	Uruguay	Italy	United Kingdom	Kenya and Italy
BIKE industrial partner	UPM	CIB	Miscanthus Nursery Ltd	ENI
Value chain type	Productivity increases from improved practices	Productivity increases from improved practices	Cultivation on underutilised and abandon land	Cultivation on underutilised and abandon land
Land type	Existing farmland	Existing farmland	Unused land	Degraded land
Agricultural practice	Crop rotation	Crop rotation	Cultivation on unused land	Cultivation on degraded land
Crop type	*Brassica*	Maize & triticale	Miscanthus	Castor
Crop yield	1.588 – 1.884 t/ha/yr	NA	9.0 t/ha/yr	1.5 t/ha/yr
Land size	110 ha	200 ha	858 ha	3000 ha
Additional biomass	382 tonnes *Brassica*	14,569 tonnes maize & triticale silage	7,722 tonnes Miscanthus	4,500 tonnes castor
Total biofuel & bioenergy yield	138 tonnes HVO[§] $\cong 6.1\times10^6$ MJ[¶]	1,319,800 m^3 (989 tonnes) $bioCH_4$ $\cong 47.5 \times10^6$ MJ[†]	2,008 tonnes $bioC_2H_5OH$ $\cong 54.2 \times10^6$ MJ[‡]	1,620 tonnes HVO $\cong 71.3\times10^6$ MJ[¶]
Biofuel yield per hectare	0.572 – 0.678 t/ha/yr	6,599 m^3/ha·yr or 4.9 t/ha/yr*	2.34 t/ha/yr	0.54 t/ha/yr

[§] Calculated assuming 45 % extractable oil Ref[61] and Oil to HVO conversion factor of 0.80 Ref[19].

[¶] Conversion factor: 1 litre HVO = 34.4 MJ Ref[62]

[†] Conversion factor: 1 m^3 biomethane = 36 MJ Ref[63]

[‡] Conversion factor: 1 litre bioethanol = 23.6 MJ Ref[62]

*Density of biomethane = 0.75 kg/m^3 Ref[64]

This report presented the analysis for addressing challenges related to climate positive farming solutions. The methodology starts by collecting all relevant information required, followed by the development of two decision-support models, and lastly the models are used to investigate and analyse four case studies: (i) planning of Brassica cultivation, (ii) BDR for biomethane production, (iii) Miscanthus for bioethanol production, and (iv) castor for HVO production. BIKE industrial partners – UPM, CIB, ENI, and Miscanthus Nursery Ltd – provided datasets for the four case studies.

Analysis of the case study on production of low-ILUC biomass feedstock indicates that introduction of Brassica in place of non-productive cover crop leads to additional biomass feedstock, consequently increasing net farm income. Here net farm income is estimated as the gap between revenue generated from the sales of farm products and the total cost incurred during crop production. The improved case leads to better gross margin per hectare in both current crop price scenario and high crop price scenario, while the reference case is better at low crop price. The breakeven selling price of soybean, wheat and Brassica correspond to 362 €/t, 321 €/t and 381 €/t respectively.

The production of biomethane via anaerobic digestion process indicates that biomass feedstocks from sequential cropping lead to better biogas and biomethane yield per hectare compared to monocropping. Furthermore, an AD plant fed with sequential crops and other feedstock types (cattle slurry, potato scrap and waste from agro-industry) generates sufficient digestate that covers cropland requirements.

The retrofit of an existing 1G plant to allow the production of 2G bioethanol reduces capital investment cost and enables utilisation of existing infrastructure, for example, fermenter, distillation units, CHP unit, etc. The production of 2G bioethanol using Miscanthus cultivated on underutilised lands in the UK is economically feasible as indicated by a positive net present value. At maximum expected crop yield per hectare (9 t/ha), the total Miscanthus produced on underutilised lands within 100 km radius to an existing biorefinery is 95 % lower than the amount needed to satisfy the capacity (40,000 t/ha) of the retrofitted plant. Consequently, target area must be expanded beyond 100 km radius to meet plant capacity.

The production of HVO in the Gela biorefinery (located in Italy) using castor seed cultivated on degraded land in Makueni (located in Kenya) is economically feasible and generates income to both local farmers and industrial stakeholders. Analysis of results indicates that transportation cost dominates overall cost. Hence, the profitability of the value chain can be improved by implementing measures that can minimise total transportation cost.

8. Conclusions and recommendations

The modelling for the four case studies allowed to analyse the possibilities of different crops and process that will allow to avoid or mitigate ILUC within the REDII definitions. These examples are encouraging for cases not just in the EU but also abroad.

Some key conclusions are as follows:

- Introducing brassica as winter crop in place of non-productive cover crop leads to additional biomass feedstock without affecting the yield of summer crops.
- Sequential cropping together with biogasdoneright© model produces biomethane and sufficient amount of digestate that meets cropland requirements, therefore avoiding the need to use chemical fertiliser derived from fossil fuel.
- Miscanthus produced on farmland within 100 km to an existing biorefinery satisfies only 5 % of the 2G plant capacity.
- The existing value chain for HVO production is profitable, providing income to both local farmers and industrial stakeholders. However, profitability can be improved by implementing measures that minimises transport cost between departing port (in Mombasa, Kenya) and biorefinery (in Gela, Italy).
- Additional sustainability issues will need to be coupled to the technical analysis

For these systems and methodological analysis some key recommendations are suggested as follows:

- From the results, farmers interested in these models are recommended to sell soybean, wheat and brassica above the breakeven price to avoid losses. The estimated selling price for the three crops are 362 €/t, 321 €/t and 381 €/t respectively.
- To meet the demand of 40,000 t/yr of 2G bioethanol in the UK, approximately 17,094 hectares of underutilised land is required.
- Policy makers should consider options to support alternatives such as retrofitting, and inter-cropping to avoid or mitigate ILUC
- The private sector looking for raw or limited processing of crops need to consider sustainability issues and standard certifications for the implementation of these models

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Annex I Model description.

A1. Planning model for low-ILUC biomass feedstock production

This section presents the detail description of the used in planning the production of low-ILUC biomass feedstock and assessing various crop management practices.

i. Nomenclature

Item	Description
Model inputs	
LA_l^{max}	Maximum size of farmland l
$CropYield_{c,r,t}$	Yield of crop c in rotation practice r at time period t
$UPC_{c,l,t}$	Unit production cost of crop c in farmland l and time period t
UC_c	Unit selling price of crop c
df_t	Discount factor at time period t

Item	Description
Model outputs	
NPV	Net present value
$Revenue_t$	Revenue per time period t
$Costs_t$	Production cost per time period t
$Crop_{c,l,t}$	Crop c produced on farmland l at time period t
$LA_{l,c,r,t}$	Land l used to cultivate crop c using rotation scheme r at time t
$Y_{c,l,t}$	Binary variable: 1 if farmland l is allocated to crop c at time t and 0 otherwise

Item	Description
Model index	
c	Crop
l	Farmland
r	Crop rotation scheme
t	Time horizon

ii. Model formulation

Objective function: Net present value

$$NPV = \sum_t df_t(Revenue_t - Costs_t) \qquad (1)$$

Revenue

$$Revenue_t = \sum_{c,l} Crop_{c,l,t} \cdot UC_c \qquad \forall\, t \in T \qquad (2)$$

Production cost

$$Costs_t = \sum_{c,l,r} LA_{l,c,r,t} \cdot UPC_{c,l,t} \qquad \forall\, t \in T \qquad (3)$$

Constraints

Farmland allocation and size limitation

$$LA_{l,c,r,t} \leq LA_l^{max} \cdot Y_{c,l,t} \qquad \forall\, c \in C, l \in L, r \in R, t \in T \qquad (4)$$

Each farmland can be utilised twice per time period (i.e., summer and winter)

$$\sum_c Y_{c,l,t} \leq 2 \qquad \forall\, l \in L, t \in T \qquad (5)$$

Crop production per land and time period

$$Crop_{c,l,t} \leq \sum_r LA_{l,c,r,t} \cdot CropYield_{c,r,t} \qquad \forall\, c \in C, l \in L, t \in T \qquad (6)$$

A2. Mixed integer linear programming model for biomethane production from low-ILUC biomass feedstocks

This section presents the detail description of the used in assessing the biomethane potential of various low-ILUC biomass feedstock.

Biomethane supply chain model

The mathematical formulation (MILP) used to estimate the potential of producing biomethane from a variety of low-ILUC biomass feedstocks is summarised below. The indices i, j, and t denotes feedstock type, AD plant, and time period respectively.

Feedstock production

$$FS_{ijt} \leq FS_{it}^{max} \qquad \forall\, i \in I, j \in J, t \in T \qquad (1)$$

where FS_{it}^{max} is maximum quantity of feedstock type i available in time period t (tonne/year). FS_{ijt} is the quantity of feedstock type i to be process in AD plant j at time period t.

Biomethane production via AD process

At the plant level, the conversion of biomass to biogas and subsequent upgrade to biomethane are determine using conversion factors reported in literature.

$$BM_{ijt} = (PDM_i \cdot PVS_i \cdot VSD_i \cdot FBM_i) \cdot FS_{ijt} \qquad \forall\, i \in I, j \in J, t \in T \qquad (2)$$

$$DT_{ijt} = FS_{ijt} - (PDM_i \cdot PVS_i \cdot VSD_i) \cdot FS_{ijt} \qquad \forall\, i \in I, j \in J, t \in T \qquad (3)$$

where BM_{ijt} and DT_{ijt} denote respectively the quantity of biomethane and digestate produced from feedstock i via AD plant j at time period t.

For each feedstock type i, PDM_i, PVS_i, VSD_i, and FBM_i denote biomass dry matter/total solid content, biomass volatile solid content, volatile solid degraded in digester, and yield of biomethane (Nm^3 CH$_4$ per VS) respectively.

$$BM_t^{Produced} = \sum_{i \in I, j \in J} BM_{ijt} \qquad \forall\, t \in T \qquad (4)$$

$$DT_t^{Produced} = \sum_{i \in I, j \in J} DT_{ijt} \qquad \forall\, t \in T \qquad (5)$$

Equations 4 and 5, $BM_t^{Produced}$ and $DT_t^{Produced}$ denote the total biomethane and digestate produced at time period t.

Capacity limitation

The inequality below imposes a lower ($\underline{FS_{ijt}}$) and upper ($\overline{FS_{ijt}}$) bound on the amount of feedstock type i that can be co-digested in AD plant j at time t. x_{ijt} is equal to one when feedstock type i is processed in plant j at time period t and zero otherwise.

$$x_{ijt} \cdot \underline{FS_{ijt}} \leq FS_{ijt} \leq \overline{FS_{ijt}} \cdot x_{ijt} \qquad \forall\, i \in I, j \in J, t \in T \qquad (6)$$

$$\sum_{i \in I} FS_{ijt} \leq AD_j^{cap} \qquad \forall\, t \in T \qquad (7)$$

$$\sum_{i \in I, j \in J} x_{ijt} \leq 1 \qquad \forall\, t \in T \qquad (8)$$

where AD_j^{cap} is the maximum capacity of AD plant j, taking into account all feedstock types.

Objective function: total biomethane produced.

The objective is to maximise the total biomethane produced over the planning horizon.

$$BM_T^{Produced} = \sum_{t \in T} BM_t^{Produced} \qquad (9)$$

$$Maximise \quad BM_T^{Produced} \qquad (10)$$

A3. Planning model for integrated production of 1G and 2G bioethanol using low-ILUC biomass feedstocks.

This section presents the detail description of the model used in planning the production of 2G bioethanol using low-ILUC biomass feedstock.

Nomenclature

Index	**Description**
c	Crop type
f	Farmland
t	Time period
p	Bioethanol production plant
v	Transportation mode

Parameter	**Description**
LA_f	Size of available underutilised land f (ha)
CY_{cft}	Yield per hectare of crop c cultivated in farmland f in time period t (t/ha)
$PCAP_p$	Maximum production capacity of plant p (t/y)
γ_{cp}	Conversion factor of lignocellulosic biomass to 2G bioethanol (-)
β_{cp}	Conversion factor of lignocellulosic biomass to by-product (-)
DE_{cpt}	Demand of 2G bioethanol at refinery gate (t/y)
$QCAP_v$	Maximum capacity of transportation mode v (t/trip)
$QMAX$	Maximum quantity of biomass to be transported per time period (t/y)
TD_{fp}	Travel distance from farmland f to plant p (km)
UCC_c	Unit cultivation cost of crop type c (€/t)
UTC_v	Unit transportation cost of crop type c using vehicle v (€/km)
σ_{fp}	Tortuosity for distance between farmland f and plant p (-)
UPC_p	Unit production cost at bioethanol plant p (€/t)
USP	Unit selling price of bioethanol (€/t)
r	Interest rate

Variable	**Description**
FS_{cft}	Quantity of low-ILUC feedstock c cultivated on farmland f at time period t (t/y)
Q_{cfpvt}	Quantity of low-ILUC feedstock c cultivated on farmland f transported to bioethanol plant p using transportation mode v in time period t (t/y)
X_p	Binary variable indicating the existence of bioethanol plant p
BE_{cpt}	Quantity of bioethanol produced in plant p using low-ILUC feedstock c in time period t (t/y)
BP_{cpt}	Quantity of by-product produced in plant p using low-ILUC feedstock c in time period t

NT_{cfpvt}	Number of trips needed to transport low-ILUC feedstock c from farmland f to plant p using vehicle v in time period t (trip)
CC_t	Total cost of cultivating low-ILUC feedstock in time period t (€/y)
TC_t	Total transportation cost in time period t (€/y)
PC_t	Total production cost in time period t (€/y)
OC_t	Overall cost (€/y)
RV_t	Revenue generated from the sales of bioethanol in time period t (€/y)
NPV	Net present value estimated over the planning horizon (€)

Farm level

(a) Feedstock production

$$FS_{cft} \leq LA_f \cdot CY_{cft} \qquad \forall\, c \in C, f \in F, t \in T \qquad (1)$$

where FS_{cft} is the quantity of crop c produced on farmland f in time period t. CY_{cft} denotes the yield per hectare of crop c cultivated on farmland f at time period t while LA_f denotes availability of underutilised farmland f within a specific target area. Also, the quantity of biomass transported Q_{cfpvt} per time period cannot exceed the total biomass produced.

$$\sum_{p \in P} \sum_{v \in V} Q_{cfpvt} \leq FS_{cft} \qquad \forall\, c \in C, f \in F, t \in T \qquad (2)$$

Plant level

(b) Capacity of biomass processing facility

This constraint ensures that the quantity of biomass c transported, Q_{cfpvt}, from farmland f to plant p do not exceeds the plant processing capacity $PCAP_p$. The integer variable X_p is one if plant p is established and zero otherwise.

$$\sum_{c \in C} \sum_{f \in F} \sum_{v \in V} Q_{cfpvt} \leq PCAP_p \cdot X_p \qquad \forall\, p \in P, t \in T \qquad (3)$$

(c) Production of 2G bioethanol and associated by-product

$$BE_{cpt} = \sum_{f \in F} \sum_{v \in V} Q_{cfpvt} \cdot \gamma_{cp} \qquad \forall\, c \in C, p \in P, t \in T \qquad (4)$$

where BE_{cpt} represents the amount of 2G bioethanol produced using low-ILUC feedstock c in time period t while γ_{cp} represents the conversion factor of feedstock c to bioethanol in plant p. Similarly, Eq. 6 represents the production of by-product BP_{cpt}.

$$BP_{cpt} = \sum_{f \in F} \sum_{v \in V} Q_{cfpvt} \cdot \beta_{cp} \qquad \forall\, c \in C, p \in P, t \in T \qquad (5)$$

Distribution level

(d) Product demand

The equation below ensures that the amount of bioethanol produced do not exceed market demand, which is denoted by DE_{cpt}.

$$BE_{cpt} \leq DE_{cpt} \qquad \forall\, c \in C, p \in P, t \in T \qquad (6)$$

(e) Transportation

$$Q_{cfpvt} \leq QMAX \qquad \forall\, c \in C, f \in F, p \in P, v \in V, t \in T \qquad (7)$$

where $QMAX$ is the maximum quantity of biomass to be transported per time period.

$$NT_{cfpvt} = Q_{cfpvt} / QCAP_v \qquad \forall\, c \in C, f \in F, p \in P, v \in V, t \in T \qquad (8)$$

where $QCAP_v$ is the capacity of transportation mode v. In Eq. 9, NT_{cfpvt} represents the number of trips needed to transport feedstock Q from farmland f to plant p using transport mode v in time period t.

Objective function: maximise net present value.

The objective is to maximise net present value estimated over the planning horizon. Net present value is calculated by multiplying gross margin with discount factor, see Eq. 16. Gross margin is the difference between overall cost and revenue generated from the sales of bioethanol. Overall cost, defined in Eq. 14, is the sum of feedstock cultivation cost, feedstock storage cost, transportation cost and processing cost.

(f) Cultivation cost

$$CC_t = \sum_{c \in C} \sum_{f \in F} FS_{cft} \cdot UCC_c \qquad t \in T \qquad (9)$$

where CC_t and UCC_c represent cultivation cost at time period t and unit cultivation cost of crop c.

(g) Transport cost

$$TC_t = \sum_{c\in C}\sum_{f\in F}\sum_{p\in P}\sum_{v\in V} 2\cdot NT_{cfpvt}\cdot TD_{fp}\cdot \sigma_{fp}\cdot UTC_v \qquad t\in T \tag{10}$$

where TC_t, TD_{fp}, UTC_v and σ_{fp} represent transport cost a time period t, travel distance from farmland f to plant p, unit transport cost of vehicle v, and tortuosity to account for the fact that the distance between farmland f and plant p is not linear.

(h) Production cost

$$PC_t = \sum_{c\in C}\sum_{p\in P} BE_{cpt}\cdot UPC_p \qquad t\in T \tag{11}$$

In Eq. 13, PC_t and UPC_p represent production cost at time period t and unit production cost associated to plant p.

(i) Overall cost

The overall cost OC_t at time period t is the sum of feedstock cultivation cost, transportation cost and processing cost.

$$OC_t = CC_t + TC_t + PC_t \qquad t\in T \tag{12}$$

(j) Revenue

In Eq. 15, RV_t and USP denote revenue generated from the sales of bioethanol at time period t and unit selling price respectively.

$$RV_t = \sum_{c\in C}\sum_{p\in P} BE_{cpt}\cdot USP \qquad t\in T \tag{13}$$

(k) Net present value

$$NPV = \sum_{t\in T}\frac{RV_t - OC_t}{(1+r)^t} \tag{14}$$

where NPV denotes net present value estimated over the entire planning horizon.

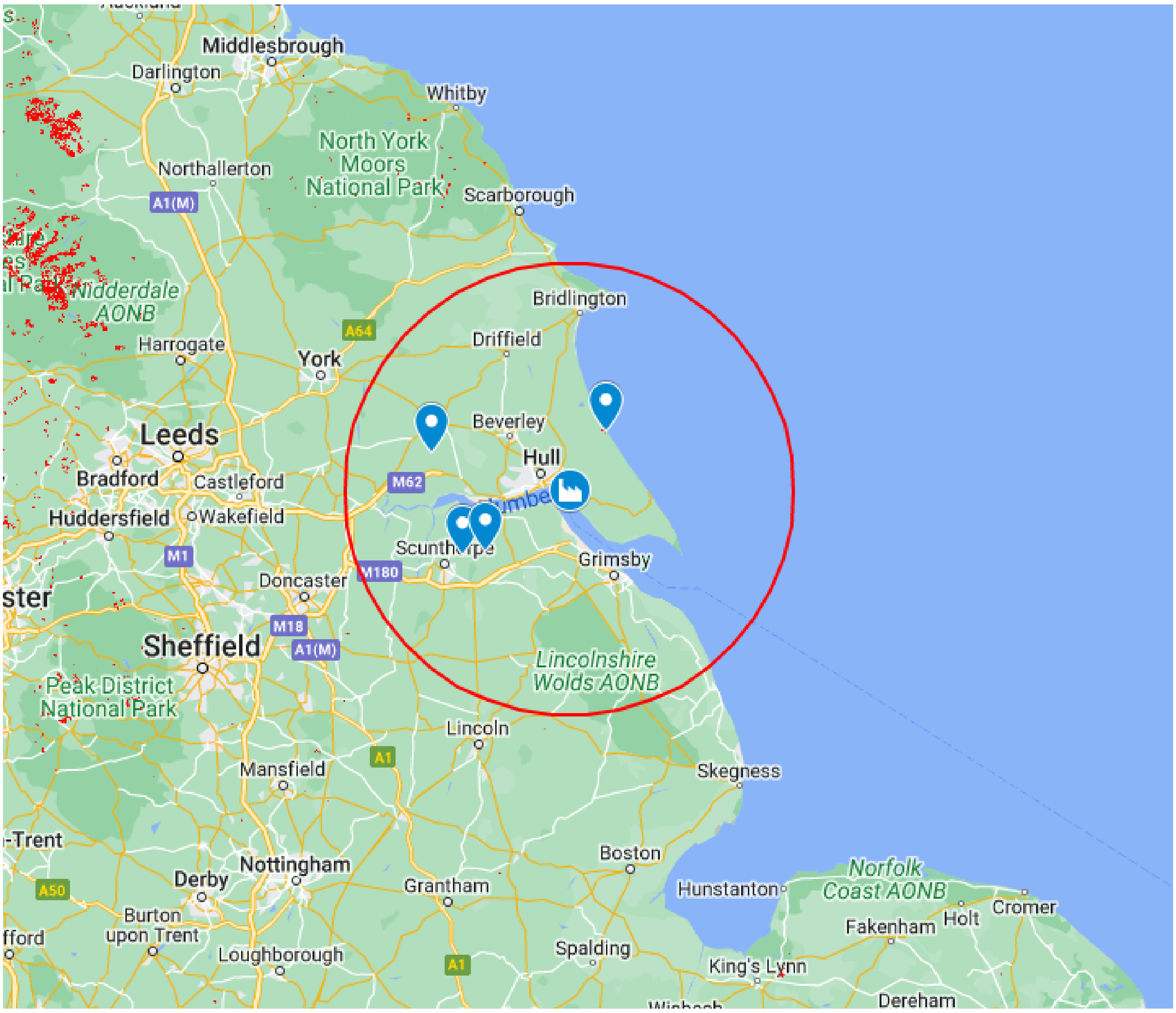
$$\text{maximise} \quad NPV \tag{15}$$

Biorefinery information

Name of Plant: Saltend Bioethanol Plant operated by Vivergo Fuels Limited	
Location: Saltend Bioethanol Plant, Saltend Lane Hedon Road Hull HU12 8DS	
Year of establishment: 2012-2013	
Latitude & Longitude	53.73504369586053, -0.233494238824056 84

Underutilised land within 50 km radius to an existing biorefinery

MUC_ID	LAU_CODE	Size	Distance from plant	Lat	Long
		[ha]	[km]		
UK00001763	E06000013	21.54198187	28	53.61036	-0.60128
UK00001761	E06000013	15.07207521	23	53.6163	-0.52186
UK00001813	E06000011	17.98151966	32	53.81115	-0.70046
UK00001803	E06000011	27.78524586	15	53.8512	-0.11585

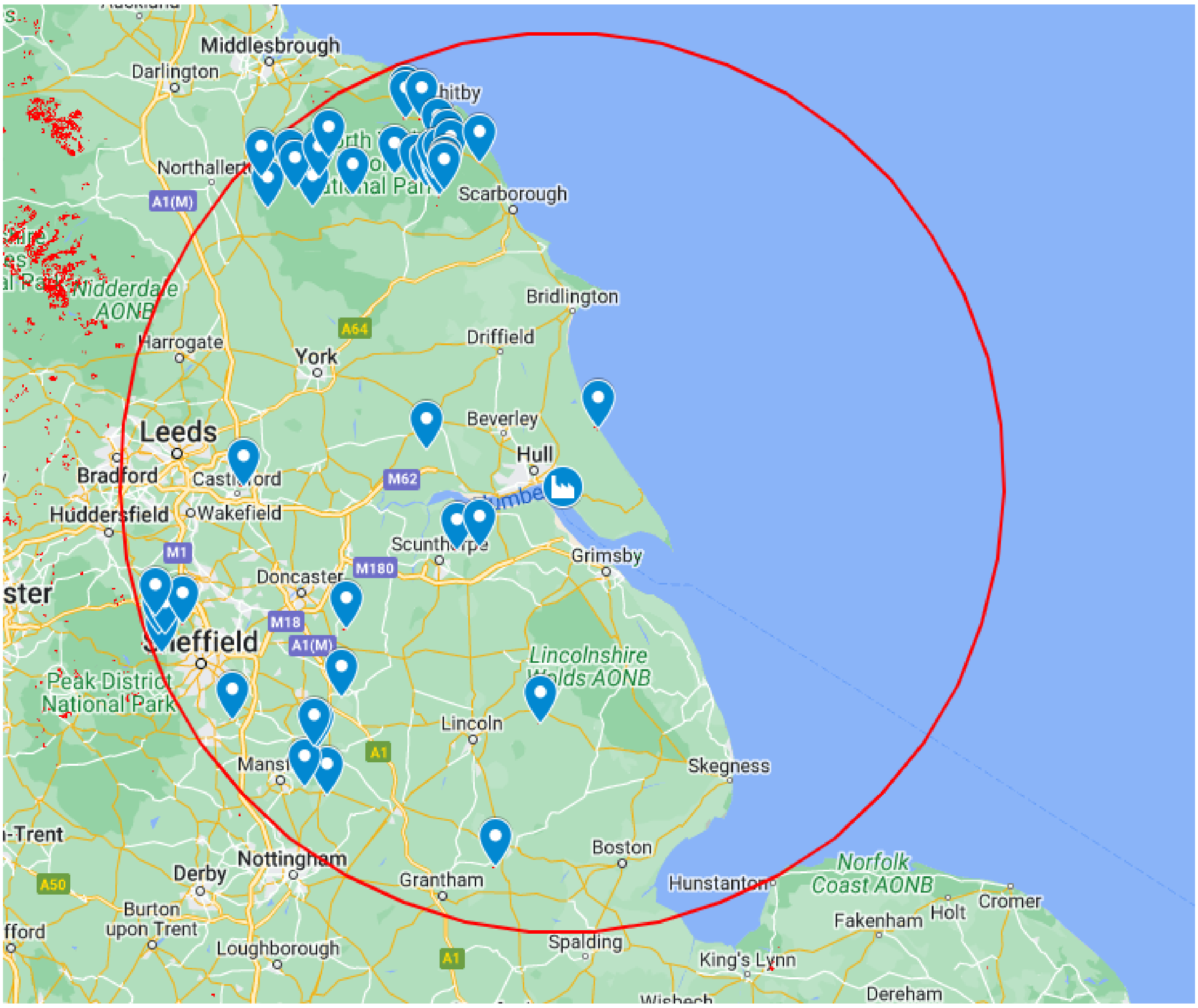


Map showing underutilised land within 50 km radius to an existing biorefinery.

Underutilised land within 100 km radius to an existing biorefinery

MUC_ID	LAU_CODE	Size	Distance from plant	Lat	Long
		[ha]	[km]		
UK00001763	E06000013	21.54198187	28	53.61036	-0.60128
UK00001761	E06000013	15.07207521	23	53.6163	-0.52186
UK00001813	E06000011	17.98151966	32	53.81115	-0.70046
UK00001803	E06000011	27.78524586	15	53.8512	-0.11585
UK00001638	E07000142	13.48283863	53	53.26288	-0.31295
UK00001588	E07000139	21.4590607	87	52.97059	-0.46621
UK00001617	E07000175	13.12135513	87.3	53.11705	-1.0453
UK00001620	E07000175	14.82488715	89	53.1347	-1.12113
UK00001644	E07000175	22.42022318	80.5	53.21297	-1.07443
UK00001648	E07000175	19.96223032	81	53.2151	-1.08676
UK00001669	E07000171	12.05295517	68.5	53.31579	-0.99231
UK00001746	E07000171	18.99716013	58.6	53.45142	-0.98047
UK00001661	E07000034	11.54157795	91.4	53.2686	-1.36915
UK00001748	E08000019	10.11024259	98.2	53.40156	-1.60865
UK00001756	E08000019	16.5445495	97.1	53.44355	-1.61929
UK00001754	E08000019	23.82068721	95.8	53.4436	-1.59774
UK00001757	E08000016	19.33288906	91.3	53.46027	-1.53577
UK00001759	E08000019	10.26145479	96.5	53.47842	-1.62936
UK00001792	E08000035	18.19408972	72.3	53.7371	-1.332
UK00002052	E07000164	17.2595559	90.4	54.28773	-1.24684
UK00002134	E07000164	20.78289543	96.1	54.34801	-1.26666
UK00002046	E07000167	16.62420826	83.7	54.2921	-1.09234
UK00002121	E07000167	10.3206104	91.5	54.34731	-1.16881
UK00002084	E07000167	17.24866683	89.2	54.32685	-1.15331
UK00002153	E07000167	29.85552302	87.6	54.34882	-1.07005
UK00002108	E07000167	15.45609889	89.5	54.38567	-1.03822
UK00002061	E07000167	17.82241679	79.9	54.31466	-0.95321
UK00002189	E07000168	19.25328126	89.3	54.47217	-0.77461
UK00002183	E07000168	18.71593249	88.4	54.46295	-0.77451
UK00002180	E07000168	32.54254379	87.6	54.46231	-0.72148
UK00002144	E07000168	13.55860955	80.2	54.4096	-0.66554
UK00002106	E07000168	23.73845272	77.1	54.38746	-0.63112
UK00002083	E07000167	12.85194193	76.8	54.35636	-0.81076
UK00002057	E07000167	23.21758637	75	54.33914	-0.74127
UK00002049	E07000167	18.47699667	73	54.3303	-0.70233
UK00002033	E07000167	21.1231798	70.3	54.31352	-0.66437
UK00002034	E07000167	30.87983468	70	54.31294	-0.65644
UK00002018	E07000167	17.47132497	68.1	54.29287	-0.66235
UK00002065	E07000167	14.10886885	74.3	54.34852	-0.68031
UK00002069	E07000167	26.24547438	74.6	54.35303	-0.66171
UK00002072	E07000168	13.45638273	74.7	54.36627	-0.62015

UK00002079	E07000168	26.97674218	74.1	54.37879	-0.52037
UK00002050	E07000167	44.29496208	71.9	54.3353	-0.63815
UK00002045	E07000167	11.72801722	71.1	54.32675	-0.6442
UK00002041	E07000167	15.47663411	70.7	54.32216	-0.64456



Map showing underutilised land within 100 km radius to an existing biorefinery.

A4. Planning model for HVO production using low-ILUC biomass feedstocks.

This section presents the detail description of the model used in planning the production of HVO using low-ILUC biomass feedstock.

Nomenclature

Index	**Description**
c	Crop type
f	Farmland
t	Time period
m	Oil mill
s	Seaport
b	HVO Bio-refinery
v	Transportation mode

Parameter	**Description**
LA_f	Size of available abandoned or degraded land f (ha)
CY_{cft}	Yield per hectare of crop c cultivated in farmland f in time period t (t/ha)
$MCAP_m$	Maximum production capacity of oil mill m (t/y)
γ_{cm}	Fraction of oil that can be extracted from feedstock c in oil mill m (-)
β_{cm}	Fraction of by-product/castor cake obtained from feedstock c in oil mill m (-)
α_b	Conversion factor of vegetable oil feedstock to HVO in plant b
$BCAP_b$	Maximum production capacity of HVO Bio-refinery b (t/y)
HVO_{bt}^{Demand}	Demand of HVO at refinery gate (t/y)
$Q1MAX$	Maximum quantity of castor seeds that can be transported to oil mill per time period
$Q2MAX$	Maximum quantity of castor oil that can be transported to seaport per time period
$Q3MAX$	Maximum quantity of castor oil that can be transported to biorefinery per time period
$PTM1_{fmv}$	Permissible transport type between farmland f and oil mill m (-)
$PTM2_{msv}$	Permissible transport type between oil mill m and seaport s (-)
$PTM3_{sbv}$	Permissible transport type between seaport s and biorefinery b (-)
$TD1_{fm}$	Travel distance from farmland f to oil mill m (km)
$TD2_{ms}$	Travel distance from oil mill m to seaport s (km)
$TD3_{sb}$	Travel distance from seaport s to biorefinery b (km)
$\sigma1_{fmv}$	Tortuosity for distance between farmland f and oil mill m (-)
$\sigma2_{msv}$	Tortuosity for distance between oil mill m and seaport s (-)
$\sigma3_{sbv}$	Tortuosity for distance between seaport s and biorefinery b (-)
UCC_c	Unit cultivation cost of crop type c (€/t)
$UTC1_{vfm}$	Unit transport cost of transport type v from farmland f to oil mill m (€/t/km)
$UTC2_{vms}$	Unit transport cost of transport type v from oil mill m to seaport s (€/t/km)
$UTC3_{vsb}$	Unit transport cost of transport type v from seaport s to biorefinery b (€/t/km)
UEC_m	Unit extraction cost at oil mill m (€/t)
UPC_b	Unit production cost at HVO biorefinery b (€/t)
USP	Unit selling price of HVO (€/t)
UCP	Unit selling price of castor cake (€/t)
r	Interest rate

Variable	Description
FS_{cft}	Quantity of castor c cultivated on farmland f at time period t (t/y)
$Q1_{cfmvt}$	Quantity of castor c cultivated on farmland f transported to oil mill m using transportation mode v in time period t (t/y)
$Q2_{cmsvt}$	Quantity of castor oil extracted from crop c that is transported from oil mill m to seaport s using transportation mode v in time period t (t/y)
$Q3_{csbvt}$	Quantity of castor oil extracted from crop c that is transported from seaport s to HVO biorefinery b using transportation mode v in time period t (t/y)
X_m	Binary variable indicating the existence of oil mill m
Y_b	Binary variable indicating the existence of HVO Bio-refinery b
VO_{mt}	Quantity of castor oil produced in oil mill m in time period t (t/y)
VP_{mt}	Quantity of by-product (castor cake) produced in oil mill m in time period t (t/y)
HVO_{bt}	Quantity of HVO produced in bio-refinery b in time period t (t/y)
CC_t	Total cost of cultivating castor in time period t (€/y)
TC_t	Total transportation cost in time period t (€/y)
PC_t	Total production cost in time period t (€/y)
OC_t	Overall cost (€/y)
RV_t	Revenue generated from the sales of HVO in time period t (€/y)
NPV	Net present value estimated over the planning horizon (€)

Farm level

(a) Feedstock production

In Eq. 1, FS_{cft} denotes the quantity of crop c produced on farmland f in time period t and CY_{cft} denotes the yield per hectare of crop c cultivated on farmland f at time period t. The degraded land or abandoned land available for feedstock cultivation is denoted by LA_f.

$$FS_{cft} \leq LA_f \cdot CY_{cft} \qquad \forall\, c \in C, f \in F, t \in T \qquad (1)$$

Plant level 1: Oil Mill

(b) Processing capacity of oil mill

In each time period t, the quantity of castor transported, $Q1_{cfmvt}$, from farmland f to oil extraction plant m should not exceed plant processing limit $MCAP_m$. In Eq. 2, the integer variable X_m is one if oil mill m is established and zero otherwise.

$$\sum_{c \in C} \sum_{f \in F} \sum_{v \in V} Q1_{cfmvt} \leq MCAP_m \cdot X_m \qquad \forall\, m \in M, t \in T \qquad (2)$$

(c) Oil extraction

$$VO_{mt} = \sum_{c \in C} \sum_{f \in F} \sum_{v \in V} Q1_{cfmvt} \cdot \gamma_{cm} \qquad \forall\, m \in M, t \in T \qquad (3)$$

where VO_{mt} represents the amount of vegetable oil produced in oil mill m in time period t while γ_{cm} represents the fraction of oil that can be extracted from feedstock c in oil mill m. Similarly, Eq. 4 represents the production of by-product VP_{mt} from the oil extraction process.

$$VP_{mt} = \sum_{c\in C}\sum_{f\in F}\sum_{v\in V} Q1_{cfmvt} \cdot \beta_{cm} \qquad \forall\, m \in M, t \in T \qquad (4)$$

Plant level 2: HVO Bio-refinery

(d) Processing capacity of Bio-refinery

The maximum processing capacity of bio-refinery b is denoted by $BCAP_b$. Equation 5 ensures that the quantity of vegetable oil transported, $Q3_{csbvt}$, from seaport s to bio-refinery site b do not exceeds the processing capacity of the plant. The integer variable Y_b is one if bio-refinery b is established and zero otherwise.

$$\sum_{c\in C}\sum_{s\in S}\sum_{v\in V} Q3_{csbvt} \le BCAP_b \cdot Y_b \qquad \forall\, b \in B, t \in T \qquad (5)$$

(e) Production of HVO

$$HVO_{bt} = \sum_{c\in C}\sum_{s\in S}\sum_{v\in V} Q3_{csbvt_{cmbvt}} \cdot \alpha_b \qquad \forall\, b \in B, t \in T \qquad (6)$$

where HVO_{bt} represents the amount of HVO produced in bio-refinery b in time period t. α_b represents the conversion factor of vegetable oil feedstock to HVO in plant b.

Distribution level

(f) Product demand

The equation below ensures that the amount of HVO produced do not exceed market demand, which is denoted by HVO_{bt}^{Demand}.

$$HVO_{bt} \le HVO_{bt}^{Demand} \qquad \forall\, b \in B, t \in T \qquad (7)$$

(g) Transportation

In Equations 8 to 10, $Q1MAX$, $Q2MAX$, and $Q3MAX$ are the maximum quantities of castor seeds and castor oil that can be transported per time period. Parameters $PTM1_{fmv}$, $PTM2_{msv}$ and $PTM3_{sbv}$ specify the permissible transport type for routes between farmland and oil mil, oil mill and seaport, and lastly seaport and biorefinery.

$$Q1_{cfmvt} \le Q1MAX \cdot PTM1_{fmv} \qquad \forall\, c \in C, f \in F, m \in M, v \in V, t \in T \qquad (8)$$

$$Q2_{cmsvt} \leq Q2MAX \cdot PTM2_{msv} \qquad \forall\, c \in C, m \in M, s \in S, v \in V, t \in T \qquad (9)$$

$$Q3_{csbvt} \leq Q3MAX \cdot PTM3_{sbv} \qquad \forall\, c \in C, s \in S, b \in B, v \in V, t \in T \qquad (10)$$

Objective function: maximise net present value.

$$\text{maximise} \quad NPV \qquad (11)$$

(h) Net present value

$$NPV = \sum_{t \in T} \frac{RV_t - OC_t}{(1+r)^t} \qquad (12)$$

where NPV denotes net present value estimated over the entire planning horizon.

(i) Revenue

In Equation 15, RV_t, USP and UCP denote revenue generated from the sales of HVO at time period t, unit selling price of HVO and unit selling price of castor cake respectively.

$$RV_t = \sum_{b \in B} HVO_{bt} \cdot USP + \sum_{m \in M} VP_{mt} \cdot UCP \qquad t \in T \qquad (13)$$

(j) Overall cost

The overall cost OC_t at time period t is the sum of feedstock cultivation cost, transportation cost and total production cost.

$$OC_t = CC_t + TC_t + PC_t \qquad t \in T \qquad (14)$$

(k) Cultivation cost

$$CC_t = \sum_{c \in C} \sum_{f \in F} FS_{cft} \cdot UCC_c \qquad t \in T \qquad (15)$$

where CC_t and UCC_c represent cultivation cost at time period t and unit cultivation cost of crop c.

(l) Transport cost

$$TC_t = \sum_{c\in C}\sum_{f\in F}\sum_{m\in M}\sum_{v\in V} Q1_{cfmvt}\cdot TD1_{fm}\cdot \sigma 1_{fmv}\cdot UTC1_{fmv} + \sum_{c\in C}\sum_{m\in M}\sum_{s\in S}\sum_{v\in V} Q2_{cmsvt}\cdot TD2_{ms}\cdot \sigma 2_{msv}\cdot UTC2_{msv} + \sum_{c\in C}\sum_{s\in S}\sum_{b\in B}\sum_{v\in V} Q3_{csbvt}\cdot TD3_{sb}\cdot \sigma 3_{sbv}\cdot UTC3_{sbv} \qquad t\in T \qquad (16)$$

where TC_trepresents total transport cost a time period t. $UTC1_{fmv}$, $UTC2_{msv}$, and $UTC3_{sbv}$ denote the unit transport cost of transport type v from farmland to oil mill, oil mill to seaport, and seaport to biorefinery. $TD1_{fm}$, $TD2_{ms}$, and $TD3_{sb}$ denote travel distance from farmland to oil mill, oil mill to seaport, and seaport to biorefinery. Lastly, σ is the tortuosity to account for the non-linear nature of travel distance between supply chain entities.

(m) Production cost

$$PC_t = \sum_{m\in M} VO_{mt}\cdot UEC_m + \sum_{b\in B} HVO_{bt}\cdot UPC_b \qquad t\in T \qquad (17)$$

In Equation 17, PC_t, UEC_m and UPC_b represent production cost at time period t, unit oil extraction cost at oil mill m and HVO production cost at biorefinery b.

Annex II Supplementary information

A3. Case study 1: Brassica for HVO production

Table S1. Data type and their corresponding sources

s/no	Data type	Sources	Verified
	Geographic data		
1	Farmland size	UPM	Yes
2	Farm location	UPM	Yes
	Agronomic data		
3	Crop yield	UPM	Yes
4	Cultivation season	UPM	Yes
5	Duration of season	UPM	Yes
6	Crop sequence	UPM	Yes
	Economic data		
7	Unit crop selling price	Literature	Partially
8	Unit production cost	Literature	Partially

A4. Case study 2: Biomethane production via anaerobic digestion

s/no	Data type	Sources	Verified
	Geographic data		
1	Farmland size	Literature	Partially
2	Farm location	Literature	Partially
	Agronomic data		
3	Crop yield	Literature	Partially
4	Cultivation season	Literature	Partially
5	Duration of season	Literature	Partially
6	Crop sequence	Literature	Partially
	Feedstock conversion		
7	Biomass total solid content	Literature	Partially
8	Biomass volatile solid content	Literature	Partially
9	Volatile solid degraded in digester	Literature	Partially
10	Biogas yield	Literature	Partially
11	Biomethane yield	Literature	Partially