BIKE

BIOFUELS PRODUCTION AT LOW - ILUC RISK FOR EUROPEAN SUSTAINABLE BIOECONOMY

D 4.2

Report on the sustainability assessment of the selected low ILUC-risk schemes tested

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List of Acronyms:

2G	Second Generation
ASU	Air separation unit
BDR	Biogas Done Right
CBA	Cost Benefit Analysis
CH4	Methane
CIB	Consorzio Italiano Biogas
ENI	Ente Nazionale Idrocarburi, Italy
EU	European Union
EUROSTAT	Statistical office of the European Union
Esca	Emission savings from soil carbon accumulation
FAO	Food and Agriculture Organization of the UN
FT	Fischer-Tropsch
FSTK	Feedstock
GBEP	Global Bioenergy Partnership
GHG	Green House Gasses
GSE	Energy Services Manager, ITALY
GTL	Gas to Liquid
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
iLUC	Indirect Land Use Change
IPCC	International Panel on Climate Change
IRR	Internal Rate of Return
ISCC-EU	International Sustainability and Carbon Certification

ISTAT	The Italian National Institute of Statistic
LCA	Life Cycle Assessment
NPV	Net Present Value
PM	Person Month
PNRR	National Recovery and Resilience Plan
REDII	Renewable Energy Directive II
SAF	Sustainable Aviation Fuel
SDGs	United Nations (UN) Sustainable Development Goals
SNAM	Italian Energy Infrastructure Company
SVO	Straight Vegetable Oil
TAAT	Technologies for African Agricultural Transformation
UN	United Nations
WP	Work Package

Executive summary

Purpose

The objective of this report is to unveil the outcomes of an investigation into the sustainability aspects of low Indirect Land Use Change (low-ILUC) risk biofuels pathways within the context of the BIKE project. The Food and Agriculture Organization (FAO) is leading the Work Package on to the assessment of the environmental, social, and economic sustainability and viability of low ILUC-risk biofuels, bioliquids, and biomass fuels across multiple value chains in Europe and Kenya. These pathways are defined by the utilization of either unused/marginal lands or productivity enhancement (embodying the concept of additionality). The analysis focuses on the intricate implications of these pathways, extending from feedstock production to fuel distribution, with the aim of optimizing benefits and aligning with both European Union renewable energy objectives and the principles of the EU Green Deal. The BIKE Sustainability Indicators are a tailored tool developed by FAO to quantify the multifaceted impacts of advanced bioenergy value chains. This initiative caters to local, national, and, whenever possible, EU-wide perspectives, laying the groundwork for a holistic evaluation of sustainable biofuel potential based on existing case studies.

Context

The adoption of low-Indirect Land Use Change (ILUC) biofuels within the European Union (EU) has gained significant traction in recent years, marking a notable shift towards more sustainable energy sources. Low-ILUC biofuels, characterized by their reduced impact on land use changes, have emerged as a promising solution to address environmental concerns associated with traditional biofuels. Advanced biofuels are derived from feedstocks that do not contribute directly or indirectly to deforestation or displacement of food crops, thus minimizing their potential negative consequences on ecosystems and food security. The EU's commitment to mitigating climate change and achieving renewable energy targets has spurred efforts to promote the production and use of low-ILUC biofuels as part of its broader energy strategy. This strategic approach not only aims to reduce greenhouse gas emissions and dependency on fossil fuels but also to strike a balance between energy production and environmental preservation. By prioritizing biofuels with low-ILUC impacts, the EU seeks to align its energy agenda with sustainable land management practices, fostering a more ecologically responsible approach to bioenergy while addressing the challenges posed by conventional biofuel production methods.

The Assessment at a glance

Chapter 2 of this report examines the sustainable potential of utilizing low ILUC feedstocks in the production of Sustainable Aviation Fuel (SAF). Against a backdrop of rising Jet Kerosene costs driven by supply constraints and demand pressures, the report explores the Gas-to-Liquid (GTL) conversion route as a potential solution. A rigorous sustainability assessment evaluates the social, economic, and environmental dimensions of this pathway, culminating in recommendations for its enhancement. Despite uncertainties concerning the applicability of the concepts (i.e. BDR model, Biomethane supportive policies) and some data limitations, the proposed model highlighted first in class performances concerning most environmental sustainability indicators. Such favourable results in terms of climate change mitigation potential is attributable predominantly to the long-term carbon sequestration potential of biodigestate into agricultural soils. Social indicators also appear positive overall, with skilled jobs creation and good income performances. Economic indicators, within the given context and enabling policy landscape, offer more opportunities than challenges for a general positive evaluation of this case study.

In a parallel pursuit, Chapter 3 delves into the realm of Hydrotreated Vegetable Oil (HVO) produced from low ILUC feedstock, with a focus on castor oil from Makueni county, Kenya. Building on the International Sustainability and Carbon Certification (ISCC-EU) standard, FAO’s sustainability assessment scrutinizes HVO's implications across its value chain, spotlighting key components, bottlenecks, as well as offering insights to elevate its performance. From the environmental indicators point of view, this case study demonstrates the key role that biochar might play in achieving near-carbon neutrality of the final bioenergy product, in addition to positive water and soil quality impacts. However, current conditions of the value chain do not quite allow for such ambitious achievement just yet. Lack of information of labour contractual conditions and wages did not permit the full measurement of key social indicators, while industrial competitiveness risks affected techno-economic primary data collection and only secondary data analyses could be carried out to assess those relevant indicators.

In Chapter 4, the report shifts its attention to cellulosic ethanol derived from low ILUC risk miscanthus biomass in the UK. This sustainable alternative to conventional fossil fuels holds the promise of reduced greenhouse gas emissions and mitigated food-versus-fuel dilemma. The analysis explores the intricacies of this value chain, ascertaining its potential viability as a contribution to Europe's renewable energy landscape. The economics of the value chain highlighted positive conditions for investing in cellulosic ethanol as of 2023, but this is largely due to the existing energy prices' situation in the UK and in Europe. Shall such conditions remain unchanged over time, the financial attractiveness of this value chain would be high. Particularly positive impacts on several environmental indicators, including the GHG emission savings, and especially on biodiversity conservation potential were assessed for this case study. Although no negative social impacts have emerged from the analysis, the contribution of this value chain to key social development indexes remain limited.

Through these chapters, this report contributes to the discourse surrounding the BIKE project's ambition to foster sustainable bioenergy solutions. This work presents findings of the sustainability assessment and also propounds actionable recommendations, advocating for data-driven decisions, and collaboration across stakeholders to ensure a resilient energy future.

A call for action

The Food and Agriculture Organization (FAO), the United Nations (UN), and the European Union (EU) hold pivotal roles in propelling the adoption of low-Indirect Land Use Change (ILUC) biofuels, intricately weaving together the imperatives of the Green Deal and the United Nations Sustainable Development Goals (SDGs).

The FAO, as a purveyor of technical expertise and knowledge dissemination, should facilitate the transition to sustainable biofuel production. By sharing best practices and encouraging non-food feedstocks, FAO endorses responsible land-use practices, ensuring that these fuels and their value chains are first verified as sustainable. In the context of this assessment FAO devised the set of sustainability indicators and the data collection efforts behind their measurement. Best practices have been discussed throughout the project with case study partners in order to guide virtuous future choices and discuss recommendations for improvement. The project suffered from inadequate data availability in virtually every value chain considered which in one case prevented altogether the measurements of the indicators in one of the originally proposed BIKE value chains. Through proxies and secondary data from peer reviewed literature and FAO publications, the assessment was carried out successfully for the three case study value chains presented in this report. This sustainability assessment remarked the crucial role of monitoring, reporting and verification systems and their use over time. If properly managed, the results of long-term sustainability monitoring will set the basis for formulating guidelines and standards ensuring biofuel production's environmental and social sustainability, as well as capacity building and training initiatives for farmers that can empower communities to embrace sustainable bioenergy. The outcomes of this work call for increased attention to the importance of science-based approaches to assessing bioenergy sustainability and highlight the pivotal role of FAO in informing policymakers and coaching private sector stakeholders towards a common sustainable bioenergy sector.

1. Introduction

1.1. Low ILUC risk feedstock sustainability

As per the Delegated Regulation, the fundamental notion underlying low Indirect Land Use Change (ILUC) risk biofuels centres on the augmentation of biomass production. This augmentation can be achieved either by increasing yields within current crop systems or by cultivating new crops on land that was previously marginal, abandoned, or significantly degraded. In the context of the BIKE project, such augmentation is referred to with the concept of additionality. Considering this, a comprehensive sustainability of the two key low ILUC-risk pathways, namely utilization of unused land and productivity enhancement, takes on great significance. Such an assessment stands to enhance policy discourse and establish a bedrock for analysing the attainment of the European Union's renewable energy objectives and the composition of its future energy landscape.

Figure 1. BIKE sustainability indicators

Under the umbrella of WP4 of the BIKE project, FAO is therefore spearheading efforts aimed at evaluating the environmental, social, and economic sustainability aspects of the low iLUC risk biofuels, bioliquids, and biomass fuels identified and proposed in these project value chains. These evaluations encompass local, national, and, wherever feasible, EU-wide perspectives. This initiative is poised to yield guidelines for optimizing the advantages derived from these production processes, while also paving the path for the future integration of United Nations Sustainable Development Goals (UN SDGs) indicators, aligning with the principles of the EU Green Deal. The imperative to devise novel methodologies and tools for gauging the impact of bioenergy across varying geographical scales has driven FAO's commitment to design an intuitive and customized set of sustainability indicators (Figure 1). These indicators, tailor-made for application within the

BIKE Project's framework, allowed for the quantification of the intricate impacts associated with the advanced bioenergy value chains under scrutiny.

Particularly, the BIKE project has identified two additionality pathways for a total of four case studies that might potentially be obtained from:

1) *underutilized lands:* (i) Miscanthus, which can be grown throughout the EU for the production of bioethanol, and (ii) castor beans, which can be grown in the Mediterranean and semi-arid agroclimatic regions for the production of renewable diesel.
2) *Productivity increase:* The two case studies identified for this additionality route are: (i) *Brassica carinata* for renewable diesel production in the Mediterranean regions and (ii) Biogas Done Right model (BDR) for biomethane- to-liquid fuels in all European territory.

1.2. Data gaps and proxies

A detailed data collection campaign was carried out starting with the preparation of a Data Entry Tool, an excel-based data collection set of spreadsheets predefined by FAO and subdivided into the main components of each of the relevant case study value chains. The DET has been created ad-hoc for the BIKE case studies and represented an initial repository of information for the sustainability assessment. The DET is composed by sheets dedicated to the description of the value chain and the baseline situation, thus it includes statistics on the target area where the bioenergy production takes place with attributes on geographical, demographics, economic, environmental and social items. A project scenario tab is defined for each main step of the studied bioenergy value chain, namely feedstock production, transport, conversion into fuel, and finally distribution to users. Several iterations of the DET have been provided to accommodate for the lack of responsiveness from case study partners, and extensive data verification exchanges and meetings have been necessary to comprehend respondents’ contributions. Data collection challenges have characterized the first 24 months of the project after which data collected and data quality was deemed unsatisfactory. The assessment process navigated the challenges in data collection by employing proxies and frequently resorting to secondary literature. These adaptations were necessitated not only by the data availability issues among project partners to gather and share the requisite data, but also by the classified nature of some industrial data. The assessment rigorously adhered to utilizing official and scientific data as alternative sources of information and proxies. Yet, in cases where scientifically robust data were not accessible, certain sustainability indicators within this assessment remained unquantifiable. Furthermore, due to lack of reliable data, it was impossible to complete the sustainability assessment of one specific case study. Consequently, in this report there are the sustainability assessments of only three out of the four potential low ILUC case studies originally envisaged in BIKE. This limitation emerged from the inherent challenge of procuring data with the requisite credibility and strength to support a rigorous and meaningful assessment process. Despite earnest efforts made to collate pertinent information, the absence of comprehensive data for the particular case study, specifically the one concerning *Brassica carinata* in Uruguay first, and in Greece on a second attempt, underscores the critical significance of data reliability for novel value chains like those analysed in BIKE. These limitations emphasize the critical need for heightened dedication to data collection, particularly primary data collection, and sharing among stakeholders to ensure the accuracy and integrity of future assessments.

1.3. Sustainable Aviation Fuel (SAF) case study:

As supplies become scarce and aviation picks up again, European jet fuel refining margins have returned to pre-pandemic levels. The ban on Russian refined product imports has increased pressure on European supplies, leading to higher Jet Kerosene costs in Europe. Additionally, low Jet Kerosene inventories in the US and high demand have further raised prices in Europe. Refinery outages in the Gulf of Mexico have tightened supply to Europe, resulting in limited items in the Amsterdam-Rotterdam-Antwerp (ARA) storage hub. Some European refineries have switched to jet fuel obtained from diesel to cope with the rising Jet Kerosene costs, but it hasn't been enough to control the price increase (Sasaki, 2023). According to Chem2023, Jet Kerosene costs in Europe are expected to keep rising due to limited capacity expansion and increasing demand. Refiners may struggle to meet the higher jet fuel demand this year. Persistent concerns about diesel demand might also limit jet fuel production. In summary, the combination of supply constraints, high demand, and refinery issues is driving up Jet Kerosene costs in Europe, and this trend is likely to continue (Sasaki, 2023).

In this context, the aviation sector and the fuel industry are looking for alternative, and possibly sustainable, ways to supply commercial airlines with reliable and appropriate fuels. Biofuels may represent a relevant aid to the supply, especially in the context of decarbonization, however several limitations define the production pathway that may be considered a solution to this problem. A promising production pathway for sustainable aviation fuels may be represented by the Gas-to-liquid (GTL) conversion route, where an hydrogen-rich gas (e.g. methane, syngas, etc.) is combined with carbon to produced liquid hydrocarbons for the aviation industry.

Chapter 2 of this report presents the outcomes of the sustainability assessment, delves into the pivotal components of the value chain, and appraises the social, economic, and environmental implications of Sustainable Aviation Fuel (SAF) derived from low ILUC feedstock. Furthermore, the report draws conclusions from the assessment findings and offers recommendations aimed at bolstering the system's overall performance.

1.4. HVO Case study:

BIKE Partner ENI, in 2022, completed successfully its first oilseed collection campaign and installed a pressing plant in Makueni county, Kenya. Such achievement marks a significant milestone in the Company's agro-industrial chain initiatives.

Among other crops, castor is produced in Makueni assuming that only marginal land is dedicated to its cultivation. ENI Kenya's castor supply chain and agri-feedstock are certified under the International Sustainability and Carbon Certification (ISCC-EU) sustainability scheme, one of the main voluntary standards recognised by the European Commission for biofuel certification (RED II) and partner of the BIKE Project.

Starting from the efforts made by ISCC in certifying the low ILUC feedstock, FAO has undertaken a comprehensive sustainability assessment of hydrotreated vegetable oil (HVO) produced in ENI's refinery located in Gela (Italy) using castor oil produced in Makueni county, Kenya. This assessment is based on the set of sustainability indicators previously developed within the framework of BIKE (see D 4.1).

Chapter 3 of this report provides the results of the sustainability assessment, discusses the key elements of the value chain and evaluates the social, economic, and environmental impacts of HVO produced from low ILUC feedstock. In addition, the report provides conclusions on the assessment and provides recommendations for enhancing the performances of the system.

1.5 2G Ethanol Case study:

Cellulosic ethanol is a promising renewable biofuel derived from non-food sources such as agricultural residues, forest biomass, and dedicated energy crops. In recent years, it has gained significant attention in Europe as a sustainable alternative to traditional fossil fuels. Unlike conventional ethanol produced from food crops like corn or sugarcane, cellulosic ethanol offers several advantages, including reduced greenhouse gas emissions and the avoidance of food-versus-fuel conflicts.

According to Chem 2023, in the first quarter of 2023, market ethanol prices followed the inclined trend in the European fuel market. Because of the ease on imports, the European providers received the ethanol consignment from the United States with declined transit time. Biofuel continued to be in high demand in the local market throughout the quarter. The observed rise in energy prices raised production costs as a consequence of ethanol demand for the food industry on the one hand, as well as due to increased demand for ethanol blended fuels. As a result, demand for the product from ethanol-based biofuel companies, as well as the pharmaceutical and food sectors, has increased, affecting final ethanol prices on the European market. Towards the quarter end, ethanol prices were observed at USD 1120 per MT, CFR Hamburg. With any market demand and supply response spike, in addition to price fluctuations, new sourcing routes become more attractive to providers and fuel blenders, and if on one hand this can unlock the potential for low ILUC feedstocks to enter a widening market, on the other can increase substitution on external markets with feedstocks sourced from unsustainable sources. Thus, this assessment has a relevant task to provide additional information to policymakers and market operators on the sustainable potential availability of cellulosic ethanol produced on low ILUC areas in Europe.

Chapter 4 of this document presents the findings of an in-depth analysis focusing on the cellulosic ethanol value chain originating from the production of low ILUC risk Miscanthus biomass.

2. The Sustainable Aviation Fuel (SAF) Case Study

2.1. Case Study Description, Setting, System Boundaries and Main Assumptions

The case study evaluates the sustainability of a promising innovative energy value chain in the Lombardy Region of Italy. In this value chain, biogas is generated using the Biogasdoneright® (BDR) model in decentralized plants. The BDR model is an "additionality" feedstock production pathway, since an energy crop is sawn between two food or feed cropping cycles (double cropping) generating feedstock employed in the biogas system. This model is not leading to direct or indirect land use changes, Since the additional feedstock needed for energy generation is produced on the same parcel of land as the food, only in different times of the year. The biogas produced is then upgraded to biomethane on site and injected into the national natural gas grid. An amount of methane equivalent to the volume of biomethane produced in decentralized plants and injected into the grid, is then withdrawn by a refinery, where a centralized conversion to liquid biofuels takes place (Figure 2). The gas-to-liquid (GTL) plant considered uses the Fischer-Tropsch (FT) synthesis to produce several products, including kerosene, which is the main target of this assessment.

Lombardy, located in the northern part of Italy and bordering Switzerland, is the most populous region of Italy with a population of 9 950 742 people (ISTAT, 2023). The region covers an area of 23 863 square kilometres and has the highest GDP of all 21 regions of the country with € 368 billion in 2022 (ISTAT, 2023). Being among the most industrialized regions of the country Lombardy has high natural gas consumption, with over 17 billion cubic meters consumed annually. Lombardy consumes nearly one fourth of Italy's annual natural gas consumption of 75 billion cubic meters, and 38.5 percent of the 203 million cubic meters of biomethane consumed annually in the country. On the other hand, Lombardy is the leading Italian region in biogas production, with 596 plants out of the 2 000 presents throughout Italy (source: GSE - Atlaimpianti, 2022). Among these, 567 use agricultural feedstocks, namely manure and various agricultural residues, and have a cumulated installed capacity of over 320 MWe. Within the region, are 11 provinces. At the provincial level, Cremona boasts the highest number of biogas plants (165 plants), followed by Brescia with 99, Mantova with 85, Lodi with 81, then Pavia with 68, Bergamo with 34, Milan with 19, Como with 6, Varese with 5, Sondrio with 4, Monza and Brianza with 1. Due to the large amount of biogas plants in the Region, Lombardy is likely the most representative case study for the evaluation of the sustainability impacts of a decentralized biomethane production system in which the renewable fuel is subsequently purchased by a GTL plant for the production of SAF.

The sustainability analysis of this bioenergy value chain focuses on two key steps:

i) BDR model for biomethane production and injection into the national grid:

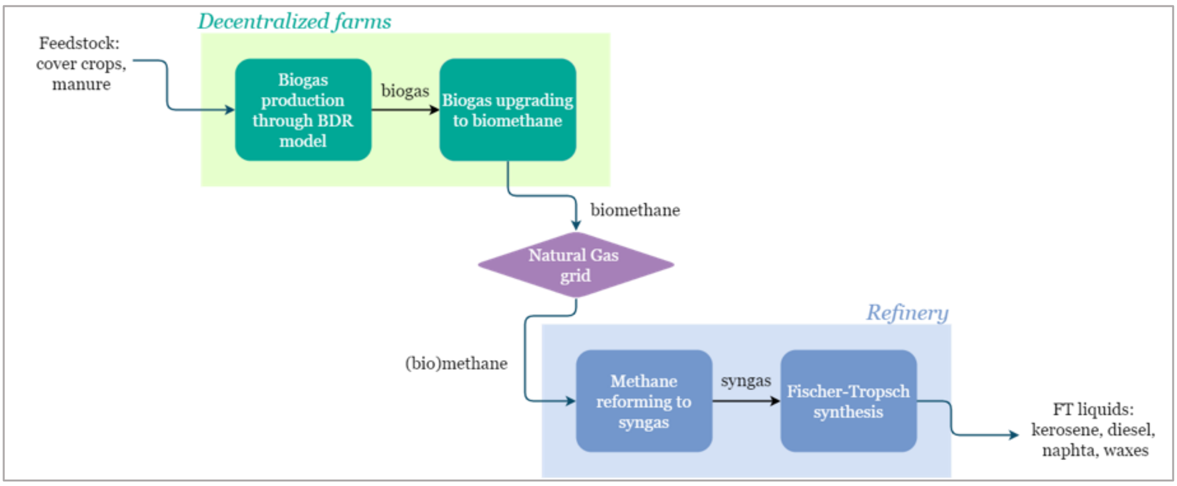
This step involves the decentralized production of biogas using the BDR model. The BDR approach aligns with sustainable practices by emphasizing ecological agricultural intensification and the incremental use of organic waste. It promotes the cultivation of cover crops and double crops, optimizing land utilization and productivity. Biogas is then upgraded to biomethane and injected into the national grid.

ii) Production of renewable kerosene through GTL technology:

Methane is withdrawn from the grid in an equal amount to the biomethane produced in the previous step and it undergoes FT conversion to produce renewable kerosene. GTL technology enables the transformation of biomethane into liquid hydrocarbons suitable for various applications, e.g. as a renewable alternative to conventional kerosene.

By analysing the sustainability of these two critical steps, the case study evaluates the environmental, social, and economic implications of the entire value chain. This assessment provides insights into the potential benefits, challenges, and opportunities associated with implementing this innovative energy value chain that maximizes the utilization of biogas and promotes sustainable fuel production. The following paragraphs provide an introduction on the two steps mentioned above.

Figure 2. Schematics of the whole value chain



2.1.1. Decentralised biomethane production

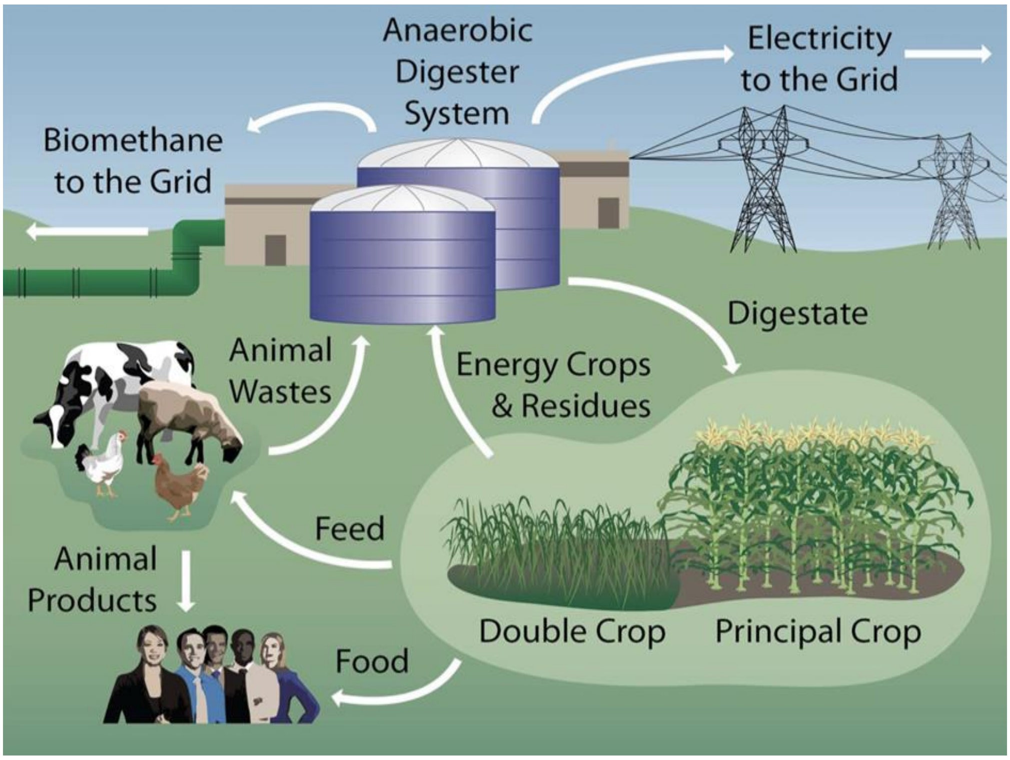
Italy is placing strong emphasis on the development of its domestic biomethane sector, mainly by maximizing energy recovery from organic wastes and by utilizing feedstock sources that have minimal impacts on indirect land use change. Sustainable biomethane is strategic context and is considered a significant factor in achieving National and European decarbonization targets. Biomethane can contribute to reaching the 2030 targets with an overall greenhouse gas savings, compared to the life cycle of fossil methane. At the national level, through the Ministerial Decree 15 September 2022 (Gazzetta Ufficiale della Repubblica Italiana, 2022), the Ministry of Environment and Energy Security has established the rules for accessing biomethane incentives in 2023, which are specifically targeted at businesses operating within the natural gas network. The overall objective of this initiative, supported by a funding pool of € 1.73 billion sourced directly from the National Recovery and Resilience Plan (PNRR), is to foster additional domestic biomethane production, targeting a production of at least 2.3 billion cubic meters by June 30, 2026. Such supporting scheme is made available through a comprehensive incentive program that consists of two distinct measures.

The first measure entails a capital contribution, aimed at enhancing the efficiency of biomethane production facilities. Under this scheme, all eligible systems will be entitled to a capital contribution equivalent to 40% of the incurred expenses, including grid-connection costs. The specific spending limits vary depending on the type of investments made.

The second measure involves an incentivizing tariff, which will be applied to the net production of biomethane. This tariff-based incentive scheme is designed to foster the development of new or converted biogas plants using agricultural products and by products, as well as facilities utilizing organic waste as a feedstock. The incentivizing tariff will be in effect for a duration of fifteen (15) years, with disbursements commencing from the moment the plant becomes operational. The actual tariff rate for eligible facilities ranges from a minimum of € 62 per megawatt-hour (MWh) to a maximum of € 115 per MWh (MASE, 2023).

In this context, increasing attention has been given to the BDR model (CIB, 2017) (Figure 3), which, by relying on the concept of ecological agriculture intensification and organic waste incremental use, promotes the use of cover crops (second harvest) before or after food/feed traditional crops, and produces double crops in the period of the year when the land was set aside. The BDR approach fits well into the low-ILUC biomass definition (described in the previous chapters) of the European Commission's Renewable Energy Directive (REDII) which reads: "*(i) crop productivity increases by means of improved agricultural practices and (ii) cultivation in land with biophysical marginality*" (which often overlaps with the categories defined in the current REDII as unused, abandoned, or severely degraded) (Panoutsou et al, 2022).

Figure 3. The CIB Biogasdoneright model based on producing additional biomass for biomethane (figure produced by Michigan State University)



Source: https://www.consorziobiogas.it/wp-content/uploads/2017/02/Ecofys_Assessing-the-benefits-of-sequential-cropping-for-CIB_Final-report.pdf

The sustainability assessment of potential biomethane production using the BDR model commenced at the farm level. Subsequently, the regional level (Lombardy) was investigated to identify the effective replicability potential necessary to supply a GTL plant.

Firstly, a comprehensive analysis was undertaken to evaluate the sustainability and economic viability of upgrading an existing dairy farm in with a 1 MW biogas plant to biomethane production. This involved connecting the farm to the national natural gas grid and integrating an agricultural component into the existing livestock production system to provide low iLUC feedstock for the biodigester. The chosen feedstock for this purpose is wheat silage, and to meet the criteria for low iLUC, wheat is cultivated in a double cropping rotation with maize.

The entire wheat crop is harvested and utilized to produce silage, which serves as the feedstock for biogas production.

The total surface of cultivated agricultural land is 103 hectares. For this study, all feedstock-related data has been provided by the Consorzio Italiano Biogas (CIB): based on primary data collected on a case study farm in Italy, wheat silage yields were 30 tonnes per hectare of biomass per year, when cultivated under rainfed regime. It is important to underline that, according to CIB, under the BDR model, wheat production in the case study farm relies solely on digestate as source of nutrients, and that no synthetic fertilizers are employed to reach the yields mentioned above. The total wheat silage annual production of the farm is therefore around 3 090 tonnes per year for a total biogas production of around 562 380 Nm^3/year. Such value represents around 13 percent of the total biogas (3 954 335 Nm3 per year) output of the farm which, in addition to wheat silage, uses cattle manure and a varying list of agricultural residues as they are available locally. Table 1 provides key information on plant capacity and productivity.

Table 1. Key information on biomass, biogas and biomethane production of the case study site in Italy

Item	Value	Unit
Total cultivated surface	103	Ha
Crop yield (Wheat silage)	30	t/yr
Total feedstock production	3 090	t
Plant capacity	999	kW
	530	Nm^3/h
Daily electricity prod.	24	MWh/d
Annual Biogas production	3 954 335	Nm^3/yr
Daily bioCH4 production	5 417	Sm^3/d
Annual bioCH4 production	2 085 714	Sm^3/yr
	1 977 168	Nm^3/yr
Daily bioCH4 production	20 011	MWh/yr
Covered by Low I-LUC	257 930	Nm^3/yr
	13% from wheat silage	
Covered by other feedstock	1 719 238	Nm^3/yr
	87% from other feedstock	

Source: Own calculation based on data from CIB

The existing farm is not equipped with a biomethane upgrading plant, as the majority of the existing biogas plants in Italy (and Europe). The upgrading to biomethane, with the exclusion of the biogas used to generate the required electricity and the potential leakages of the digester, has been modelled using information from technology providers and cross-checked with data from the literature. The result of such assessment applied to the case study site would generate some 257 930 Nm^3 per year of $bioCH_4$ and some 1 934 tonnes of bio digestate. All agricultural farms currently producing biogas (below 1 MW) in Lombardy were identified and included in the study. The investment costs for grid connection were calculated and used as a reference for the analyses. Additional information on the approach is available in the indicators infrastructure and investments.

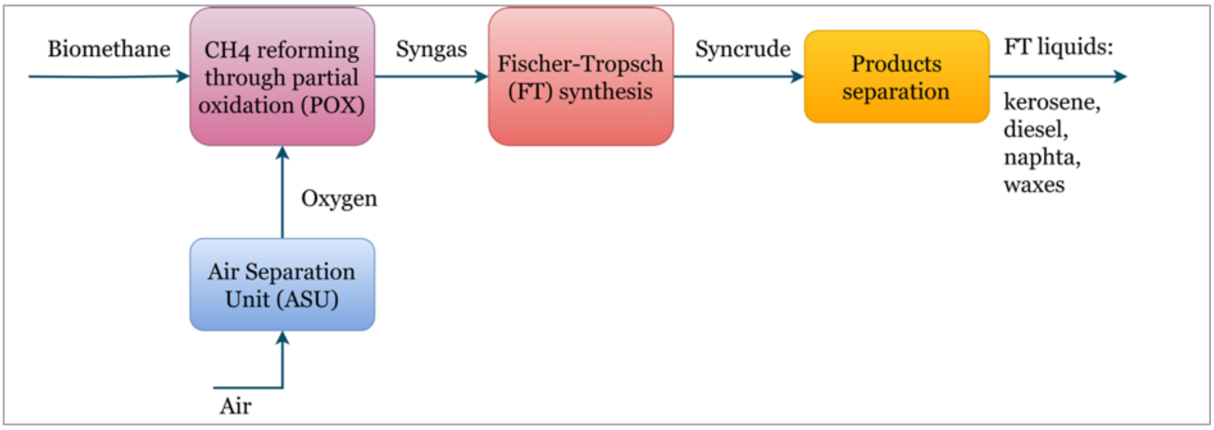
2.1.2. Centralised liquid biofuel production

As introduced, the case study provides for the centralized conversion into liquid biofuels of the biomethane produced by decentralized plants in a gas-to-liquid (GTL) conversion plant. Biomethane is injected into the natural gas grid and an equivalent amount of methane is withdrawn from the natural gas grid by the GTL plant. GTL is a refinery process that converts natural gas or other gaseous hydrocarbons into liquid fuels. The process can either directly convert methane-rich gases into liquid synthetic fuels or use synthetic gas (syngas) as an intermediate. The technology is well-established for large-scale applications, from 22 500 barrels per day (bpd) to 140 000 bpd. However, in recent years, there has been significant interest in the advancement of smaller GTL facilities.

The GTL plant considered in this study is FT-based, and produces several products (such as naphtha, kerosene, diesel, and waxes) for a total output of 1 000 bpd, of which some 6 768 tonnes per year of kerosene are produced. Waxes could be further processed by means of a hydrocracker to hold for a higher yield on a specific product; however, this contingency is not considered in this study.

The plant is composed of different parts, including: (i) a reforming section, where biomethane is converted to syngas; (ii) a FT reactor, where the FT synthesis takes place, and the kerosene-rich FT crude is produced; (iii) a product separation section. In this study, kerosene was considered as the FT product of interest, allowing to produce Sustainable Aviation Fuels (SAF) as a substitute to conventional petroleum-based jet fuel (Figure 4). In Italy, and in general in Europe, no *biomethane-to-liquid* plants are reported in operation. Over the last years, kerosene-type jet fuel used in aviation has been around 900 thousand tonnes of oil equivalent (ktoe) in the country, excluding the biofuel portion.

Figure 4. Scheme of the GTL plant configuration



2.2. Sustainability Assessment Results by Indicator

2.2.1. Air Quality

The study compares the baseline scenario, which involves the traditional fuels used, with the potential introduction of new biofuels. Firstly, the biomethane injected into grid is compared with the natural gas. As second step, the SAF (kerosene) produced through the GTL process is compared with the traditional fossil kerosene used for aviation.

It is common practice to assess the sustainability impact of bioenergy production and use based on greenhouse gas (GHG) emission intensity per unit of energy. The GHG emission intensity is therefore expressed in grams of carbon dioxide equivalent per megajoule of bioenergy produced (gCO2eq/MJ). In the baseline scenario the reference fuels used are natural gas and kerosene (Jet fuel). The total emission intensity of natural gas and kerosene-type Jet fuel is 66.0 gCO2eq/MJ and 71.75 gCO2eq/MJ respectively (EC, 2023).

In the target scenario the emission intensity of biomethane and biokerosene produced in the target area is therefore compared to the emission intensity of the reference fuel and the relative (in percentage) and absolute (in g, kg, or t of CO2) change is reported.

The main contributors and components of a GHG Life Cycle Assessment (LCA) of biofuel production and use are:

- Feedstock production;
- Feedstock transport;
- Feedstock processing into fuel; and
- Fuel transport/distribution/use.

The biomethane production may foresee the use of by- and co-products and thus an allocation among the various products may be required. The most appropriate methodology for the correct allocation and attribution among co-products of the bioenergy value chain is a highly debated topic.

However, as concerns the first phases of the value chain, i.e. anaerobic digestion and biogas upgrading, no products allocation has been done. Indeed, as for the anaerobic digestion, the digestate produced along with biogas is reintegrated in the process in the form of soil fertilizer to produce the feedstock. Furthermore, the CO_2 captured during the biogas upgrading process is not recovered, and therefore no by-products are generated in this phase. When it comes to GTL, several co- products are generated by the process, namely: Naphtha, Kerosene, Diesel, and Waxes. Table 2 shows the products distribution of a GTL FT-based where a 22.4 percent volume allocation is considered for kerosene production. The same value (22.4 percent) was used in this study to allocate the emission produced at the processing level by the GTL plant.

Table 2. 1 000 barrel per day (bpd) GTL FT-based plant: products distribution

Product	bpd	Percentage
Naphtha (C5-C9)	298.10	29.8%
Kerosene (C10-C16)	224.06	22.4%
Diesel (C17-C21)	95.68	9.6%
Waxes (C21+)	382.16	38.2%

Source: Own calculation

The results of the air emission indicator are presented below.

Step 1: Biomethane production compared to natural gas

The baseline emission intensity for natural gas is reported at 66.0 gCO_2eq/MJ, according to the EC (2023), cross-referenced with IPCC (2006). In the target scenario, this study reports a significantly lower emission intensity of 12.21 gCO_2eq/MJ for biomethane produced from low i-LUC feedstock, specifically wheat silage in a BDR model (Table 3).

Table 3. Total emission of GHG and non GHG of biomethane production (aggregated) in g and g/MJ of fuel

Type	Unit	Value	Unit	Value
GHG	gCO_2-eq	112 776 827	gCO_2-eq/MJ $_{CH4}$	12.21
Non GHG	gCO	1 313 923	gCO/MJ $_{CH4}$	0.14
	gNOx	1 386 044	gNOx/MJ $_{CH4}$	0.15
	gSOx	259 175	gSOx/MJ $_{CH4}$	0.03
	gPMx	481 630	gPMx/MJ $_{CH4}$	0.05

Source: Own calculation

Table 4 provides a picture of the GHG and non GHG disaggregated by each step of the value chain. As shown, the step responsible for the higher GHG emission (CO2eq) is the biogas upgrading to biomethane process, followed by the cultivation (feedstock production), while the carbon stored in the soil by the application of the digestate is considered as net emission reduction. The GHG emission of the processing steps (anaerobic digestion and upgrading to biomethane) is purely due to the leakages which occur during the biogas production and storage. The CO_2 emitted during the upgrading phase to biomethane is considered biogenic. For the cultivation step, the GHG emission produced refer to the diesel used for tillage and the direct and indirect emission (calculated applying the TIER 1 of the IPCC guidelines 2006) produced by the application of the digestate in the fields.

Table 4. Emission of GHG and non GHG of biomethane production (disaggregated) in g and g/MJ of fuel for the studied farm (257 930 Nm3 CH4 per year)

Total yearly emission	CULTIVATION	FSTK TRANSPORT	PROCESSING	FUEL TRANSPORT	DIGESTATE APPLICATION
gCO_2-eq	49 369 108	2 214 730	112 452 380	-	-51 259 392
gCO	6 097	308	1 307 519	-	-
gNOx	24 646	1 245	1 360 152	-	-
gSOx	22 570	1 140	235 464	-	-
gPMx	519	26	481 086	-	-
gCO_2eq/MJ_{CH4}	5.347	0.240	12.178	-	-5.551
gCO/MJ_{CH4}	0.001	-	0.142	-	-
$gNOx/MJ_{CH4}$	0.003	-	0.147	-	-
$gSOx/MJ_{CH4}$	0.002	-	0.026	-	-
$gPMx/MJ_{CH4}$	-	-	0.052	-	-

Source: Own calculation

Moreover, the analysis considered the biomethane produced using low i-LUC wheat silage feedstock grown on the farm's 103-hectare area, estimating the total potential annual reduction to be around 738 tonnes of CO_2eq emissions (Table 5). This represents a substantial reduction of approximately 53.8 gCO_2eq/MJ compared to the baseline (fossil fuel), resulting in an 86 percent reduction in emissions (Table 5).

Table 5. Total avoided emission of GHG and non GHG of biomethane production (aggregated) in g and g/MJ of fuel

Type	gCO_2-eq	$gCO_2\text{-}eq/MJ_{CH4}$
$BioCH_4$	112 776 827	12.21
Natural gas	851 168 878	66
Total Avoided	**-738 392 151**	**-53.8**

Source: Own calculation

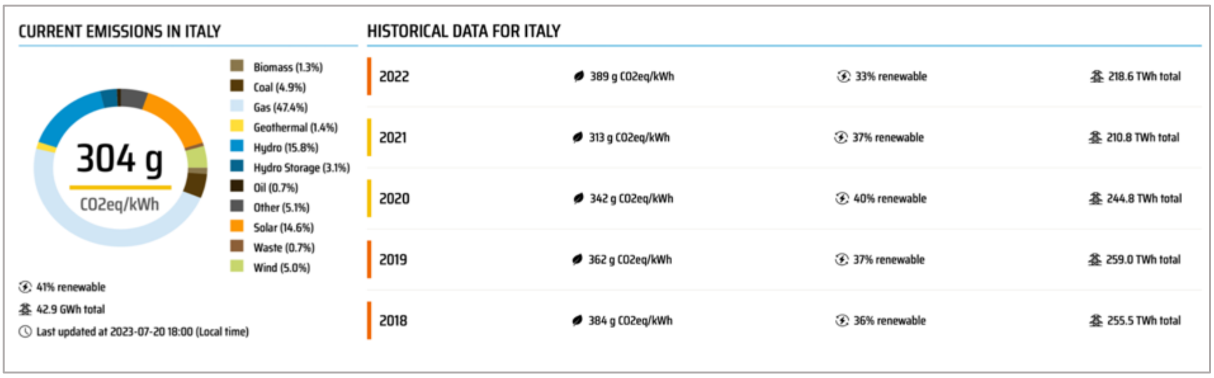
It is essential to mention that, in this study, all the calculations refer exclusively to the biomethane produced from the anaerobic digestion of the dedicated low-ILUC crop. This leads to a potential digestate availability of 20 000 kg per hectare. However, in cases where a larger amount of digestate is applied to the soil (such as on farms producing biogas from both livestock manure and low ILUC dedicated crops), the higher amount of carbon sequestered in the soil might lead to an overall negative GHG emissions. It was estimated that a digestate application rate of 70 000 kg per hectare would result in carbon neutrality.

STEP 2: SAF compared to Kerosene-type aviation fuel

The production of liquid biofuels through GTL conversion uses biomethane as primary feedstock. Therefore, assuming that a 1 000-bpd plant is fed with biomethane produced exclusively from low i-LUC feedstock, when running the LCA, a 12.21 gCO2eq/MJ_{CH4} net emission factor for biomethane (see step 1 above) can be applied. Provided that a 1 000 bdp GTL plant produces a 6 768 tonnes of kerosene per year from around 84.6 million Nm3 of CH4, the total annual CO2eq emissions associated to the biomethane used by the plant is around 36 992 tonnes. Considering the abovementioned 22.4 percent allocation, the final allocated result obtained for the feedstock phase is around 8 138 tonnes CO2eq per year or some 2.6 grams of CO2 per MJ of kerosene produced.

When it comes to the thermochemical conversion taking place in the plant, we can assume that the emissions produced during the entire 1000 bpd GTL process come exclusively from the electricity consumed during the gas compression phase and the air separation unit (ASU), for a total consumption rate of around 0.21 kWh/Nm^3 CH_4 processed. As shown in Figure 5, in 2023 the average carbon intensity of the national electric network in Italy was 304 gCO_2eq/kWh.

Figure 5. Current and past CO2 emissions from the Italian energy mix



Source: https://www.nowtricity.com/country/italy/

The total electricity required to a 1 000 bpd GTL plant to process the 84.6 million Nm3 of CH_4 would therefore be around 17 700 MWh year. GHG emissions would therefore account to some 5 400 tonnes of CO_2eq per year with no allocation. It is calculated that some 34 000 hectares should be cultivated to produce 84.6 million Nm^3 of biomethane exclusively from low i-LUC wheat production. The total emission of the plant allocated to only kerosene production (22.4 percent) would therefore be around 1 188 tonnes of CO_2eq per year or some 3.8 grams of CO_2 per MJ of kerosene produced.

Regarding final product transport, in this study we assumed 50 km as suitable distance to transport the fuel (SAF) from the production site to a final storage facility. The results of the emission calculation for the fuel transport step of the fuel chain are 24.2 tonnes CO_2eq year and some 0.1 gCO_2eq per year and CO_2 per MJ of kerosene produced, respectively. Table 6 provides the results discussed above.

Table 6. Allocated emission for kerosene production through GTL divided by production steps in tonnes of CO2 equivalents and grams of CO2 equivalents per MJ of fuels

Step	tCO_2-eq	gCO_2-eq/$MJ_{kerosene}$
Feedstock (CH_4)	8 138	26
Processing	1 188	3.80
Fuel transport	24.3	0.01
Total (allocated 22.4%)	9 351	30

Source: Own calculation

Moreover, an assessment of the total potential annual emission reductions of SAF produced from biomethane in Lombardy to be around 13 085 tonnes of CO2eq (Table 7). This represents a substantial reduction of approximately 41.75 gCO2eq/MJ compared to the baseline (fossil fuel), or 86 percent reduction in GHG emission intensity compared to fossil Jet A-1 (Table 7).

Table 7. Total avoided emission of GHG and non GHG of kerosene production (aggregated) in g and g/MJ of fuel

Type	tCO_2-eq	gCO_2-eq/MJ_{Fuel}
SAF	9 351	30
Kerosene-type aviation fuel	22 436	71.75
Total Avoided	**-13 085**	**-41.75**

Source: Own calculation

2.2.2. Soil Quality

Assessing the sustainability of a bioenergy value chain requires a comprehensive understanding of various factors, including soil quality. Traditionally, quantitative indicators have been used to evaluate soil quality, but they often present limitations such as site specificity, the need for long-term monitoring, and the requirement for specialized evaluation skills and equipment. Alternatively, due to the unavailability of quantitative data, a qualitative assessment can offer valuable insights into the conditions necessary for maintaining or enhancing soil quality characteristics. In this paragraph, the results of a purely qualitative indicator employed to assess soil quality performances within the studied agricultural soils are presented.

The indicator relies on the identification and frequency of specific management practices implemented. By evaluating the occurrence and frequency of traditional versus improved soil management practices using a scorecard method, this assessment provides an indication of potential benefits or challenges related to soil quality. The scorecard method assigns different scores to various practices, considering that certain operations, such as mechanized plowing and tilling, have been found to have more detrimental effects on soil quality compared to no-tillage and conservation agriculture, for instance. By considering the combination of different practices, this approach offers a qualitative indication of the risk level associated with soil quality maintenance. Best agricultural practices for soil quality enhancement receive a positive score (e.g. +1; +2, etc), if such practices are not applied the scoring is 0, whereas practices documented as detrimental may receive a negative score (-1; -2; etc).

Table 8 presents the results of the agronomic practices investigated by the assessment. Organic matter addition (biodigestate), reduced tillage, crop rotation and continuous cover crops, and the use of biofertilizer are all positive practices that have been considered to produce the bioenergy feedstock. By implementing continuous cover cropping, farmers can protect and improve soil quality and reduce erosion, increase organic matter content, enhance nutrient cycling, maintain soil moisture, suppress weeds, and foster beneficial microbial activity. These practices contribute to sustainable agriculture, long-term soil health, and overtime, may lead to improved crop productivity. On the other hand, organic agriculture and the use of windbreaks and shelter were not applied in the reference case study.

Table 8. Presence and frequency of the best soil quality management practices of the BDR-SAF case study

Item	Value	Score
Organic matter addition (e.g. manure, biochar, etc.)	Applied	1
No-tillage, minimum tillage, reduced tillage	Applied	3
Crop rotation (incl. or excl. fallow, intercropping, etc.)	Applied	1
Continuous cover crop	Applied	1
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Windbreaks, shelterbelts, etc.	Not applied	0
Biofertilizer and living organisms management	Applied	1
	SCORE	**7**

Source: results of the FAO's BIKE set of sustainability indicators

The occurrence and frequency of conventional - and often detrimental - soil management practices were also assessed. As presented in Table 9, deep tillage, irrigation, use of rates of chemical fertilizers, and intensive monocropping do not take place in the case study site Surface (<20 cm) mechanization land preparation is applied.

Table 9. Occurrence and frequency of traditional soil management practices

Item	Value	Score
Mechanized land preparation	Applied	-1
Deep and surface tillage (incl. moldboard plow, ripper, etc.)	Not applied	0
Use and rates of synthesis fertilizers	Not applied	0
Irrigation rates and irrigation systems (e.g. flooding or sprinklers)	Not applied	0
Monocropping (annual crops only)	Not applied	0
	SCORE	**-1**

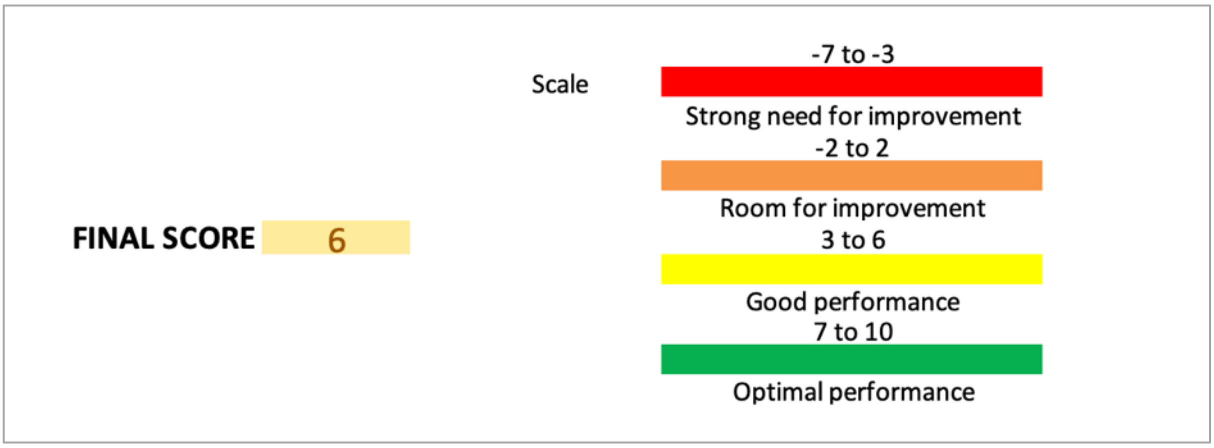
Source: results of the FAO's BIKE set of sustainability indicators

These results demonstrate that minimum tillage operations and the application of digestate can be valid tools to improve agriculture sustainability. The continuous restitution of organic matter (OM) with digestate can support a dynamic C sequestration in soils. Consequently, biogas, especially if produced according to BDR model, can improve efficient use of natural resources. In particular, the increase of soil organic matter can enhance soil fertility and stability and maintain soil nitrogen content. It can increase soil biodiversity, and reduce erosion, nutrient leaching and therefore water pollution. In fact, while chemical fertilizers supply only specific nutrients, organic matter provides a diverse range of nutrients and acts as a source of energy for soil microorganisms (Shankar, 2022).

As reported in Figure 6, the indicator scored 6 points out of 10, demonstrating the potential good performance of the case study. Overall, the positive result of the soil quality indicator aligns with the EU's strategic objectives, such as the RED II and the European Green Deal.

These two pieces of regulation promote sustainable land use, carbon sequestration, climate change mitigation, resource efficiency, and the protection of natural resources. By adopting responsible soil management practices, biomass producers can contribute to a more sustainable and environmentally friendly bioenergy sector in line with EU policies and strategies.

Figure 6. Final score of the soil quality indicator and related scale of credit score

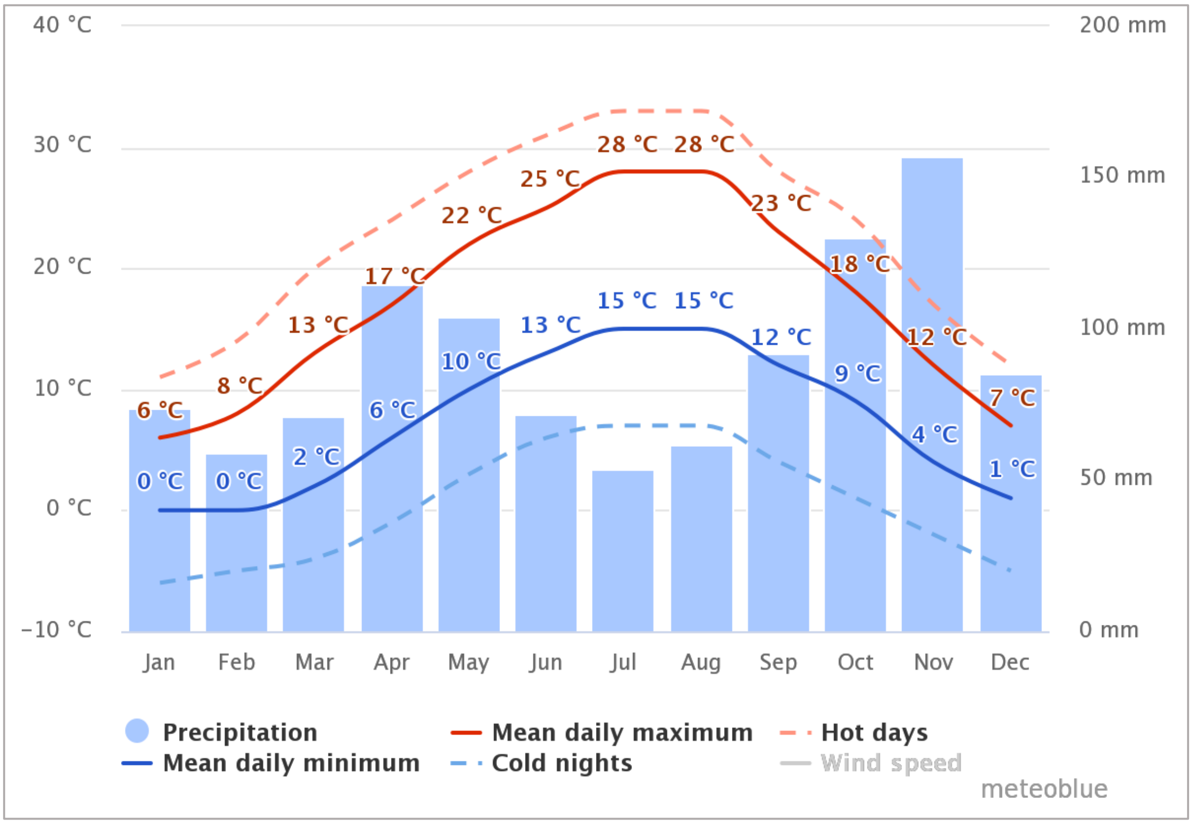


Source: results of the FAO's BIKE set of sustainability indicators

2.2.3. Water Use

Although Lombardy is located in a temperate climate belt, it serves as a transition zone between the Mediterranean climate and the oceanic climate found in Central and Western Europe. Summers in Lombardy are characterized by hot, humid, and sultry conditions, accompanied by moderate rainfall. The plains, particularly in the Pavia province - south of the Po River - and in western Lombardy, experience abundant snowfall due to their sheltered position and the influence of mild and humid air currents. The areas surrounding the large lakes have a mild climate, resembling the Mediterranean more than the continental climate, with winters that are less cold and summers that are hot but also windy. The pre-alpine belt and Oltrepò region have a cool temperate climate, while the mid-alpine mountains have a cold temperate climate, and the peaks are subject to a cold climate (Britannica, n.d.; and Meteoweb.eu, n.d.).

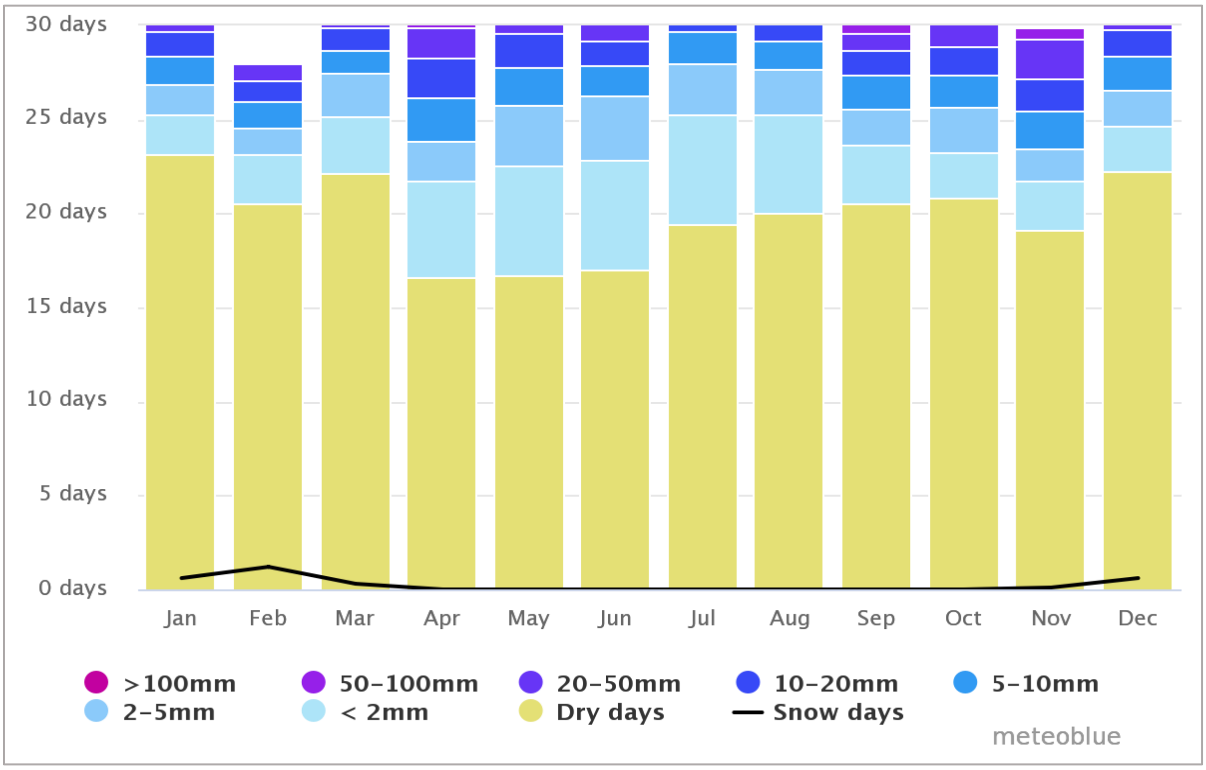
Figure 7. Average Temperatures and Precipitation in Lombardy



Source: Meteoblu (n.d.). Available at: https://www.meteoblue.com/en/climate-change/lombardy_italy_3174618

Overall, the mean daily maximum temperatures in summer reach 28°C, while minimum temperatures approach 0°C in winter (Figure 7). Mean precipitation remains above 50 mm throughout the year, with the lowest levels occurring in summer and peak levels of around 140 mm in November. December, January, and February have the highest number of snowy days, while May and April have the highest number of rainy days, with 13.4 and 14.3 days per month, respectively (Figure 8). Between 1979 and 2021, Lombardy experienced increasing temperatures and precipitation: Mean yearly precipitation followed an upward linear trend, rising by nearly 200 mm during that period (Figure 8).

Figure 8. Yearly precipitation trend detailed, Lombardy, Italy



Source: Meteoblu (n.d.). Available at: https://www.meteoblue.com/en/climate-change/lombardy_italy_3174618

The production of biomass requires no additional irrigation water in the case study site, and it returns yields of around 30 t ha^{-1} yr^{-1}. The Lombardy region offers more water than the wheat uses for biomass production. As shown in Table 10 below, this translates into a total water requirement of 0.00012 km^3/year to provide water to produce biomass (103 ha for 257 930 Nm^3 year of biomethane).

The blue water percentage over total water use of the agricultural phase is zero as the totality of the water used by the plants is green water.

Table 10. Wfstk Renewable - Renewable water used for feedstock production

Item	Value	Unit
Crop yield	30	ton/ha
Cultivated surface	103	ha
Crop ET	450	mm/year
Effective precipitation (Oct-Jun)	780	mm/year
Crop production	3 090	ton
Annual irrigation requirement	-330	mm/year
Unitary water requirement	4 500	m^3/ha
Unitary water requirement	0.0004635	Km^3/year
Unitary water(Irrigation) requirement	-3 300	m^3/ha
Unitary water(Irrigation) requirement	-0.0003399	Km^3/year
Tot. water for feedstock production (Wfstk) renewable	**0.0001236**	**Km^3/year**

Source: Own calculation

Concerning the processing phases, which involves the production of biogas, the upgrading to biomethane and the production of kerosene through the GTL[1] process, the only step which requires a considerable water input is the upgrading to biomethane process. For this reason, this indicator fixes the boundary at the biomethane production stage. As shown in Table 11, the water used by the value chain to produce 1 ton of feedstock is 2.02 m^3.

Table 11. Wfstk Renewable - Renewable water used for kerosene production

Item	Value	Unit
Water consumption (upgrading to biomethane)	0.02418	m^3/Nm^3
	0.000006	Km^3/year
CH4 production	257 939	Nm^3/year
LHV biomethane	35.8	MJ/m^3
Total energy output	9 233 893	MJ/year
Wbioenergy / Etotal	0.000675	m^3/MJ
	0.675419	l/MJ
Production	**2.02**	**m^3/t feedstock**

Source: Own calculation

[1] The GTL plant being considered is composed of: (iii) an Air Separation Unit (ASU), where oxygen is produced, (ii) a reforming section, where methane is converted to syngas through the Partial Oxidation (POX) technology, and (iii) a Fischer-Tropsch reactor. In this last block, hydrocarbons are generated from syngas, along with a considerable amount of water and off gas (light hydrocarbons and unreacted syngas) as side products.

2.2.4. Water Quality

As in the case of soil quality, this indicator relies on the identification and frequency of specific management practices implemented in the case study to derive a qualitative assessment of the impacts on water quality. By evaluating the occurrence and frequency of conventional versus improved water management practices using a scorecard method, this assessment provides an indication of potential benefits or challenges related to water quality. The scorecard method assigns different scores to various practices, considering that certain operations can have a detrimental effect on water quality. By considering the combination of different practices, this approach offers a qualitative indication of the risk level associated with water quality maintenance in bioenergy production under the conditions of the BIKE project.

The indicator considered the following best practices for the sustainability assessment: No tillage, minimum tillage and or reduced tillage, the application of organic agriculture, the use of conservational buffers, erosion sediment control, and wastewater treatment at feedstock and fuel processing levels. As shown in Table 12, organic agriculture and conservation buffers are not applied in the specific case study assessed. This is since chemical weeding and pesticides are instead applied for the cultivation of wheat. On the other hand, minimum tillage is applied which helps retaining soil nutrients, preventing their loss through erosion, or leaching into water bodies. This leads to better nutrient management, reducing the risk of nutrient pollution in water sources. By adopting minimum-tillage practices in agriculture, farmers can play a vital role in protecting water quality, conserving soil resources, and contributing to sustainable agricultural practices that benefit both the environment and agricultural productivity.

In summer in Lombardy, agriculture relies on irrigation and water stress is a significant concern. By treating wastewater, grey water could be reclaimed and reused for agricultural purposes, thus supplementing traditional (blue) water sources, and ensuring a more reliable water supply for crops. This is the case of the treated bio digestate applied to the soil. Biodigestate contains valuable nutrients, such as nitrogen, phosphorus, and potassium, which are essential for plant growth. Through treatment, these nutrients can be recovered from the wastewater and used as fertilizers for crops, reducing the need for synthetic fertilizers and promoting more sustainable nutrient management practices. However, biodigestate can also contain relevant concentrations of unwanted or ever harmful compounds, including heavy metals, and minerals that could accumulate in the soils and in the crops. A characterization of the biodigestate was not carried out in the context of the BIKE project, therefore no quantitative nor risk assessment could be carried out.

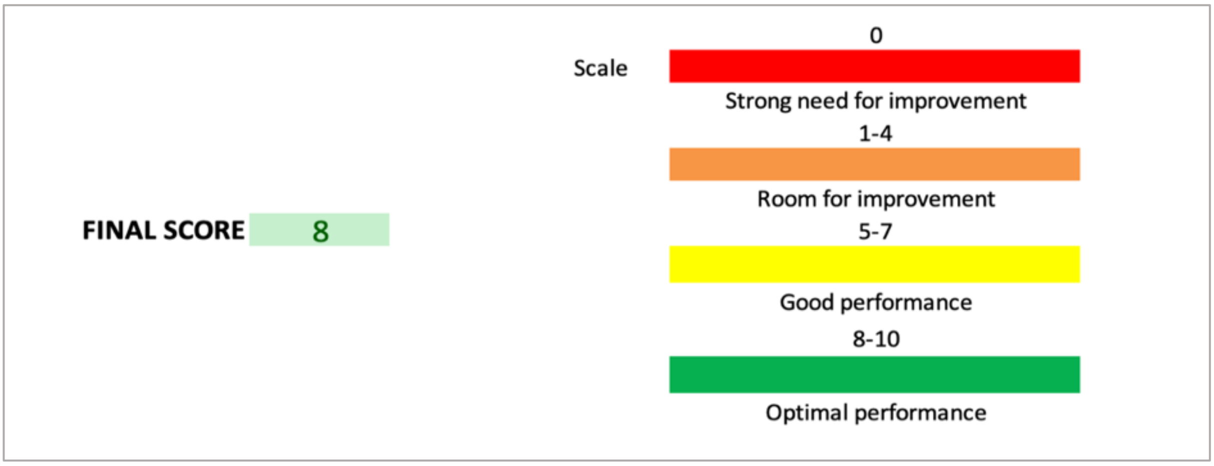
Table 12. Presence and frequency of the best water quality management practices of the BDR-SAF case study

	Value	**Score**
No-tillage, minimum tillage, reduced tillage	Applied	3
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Conservation buffers (buffer zones, corridors, etc.)	Not applied	0
Erosion and sediment control	Applied	2
Wastewater treatment of bioenergy processing	Applied	3
	SCORE	**8**

Source: results of the FAO's BIKE set of sustainability indicators

Based on the limited data available then, as reported in Figure 9, the indicator scored 8 points out of 10, demonstrating the potentially positive performance of the model investigated in this case study in terms of water quality. Overall, the positive result of the water quality indicator aligns with the EU's strategic objectives, such as the RED II and the European Green Deal. It promotes sustainable water use, reuse of wastewater, climate change mitigation, resource efficiency, and the protection of natural resources. By adopting responsible water management practices, biomass producers can contribute to a more sustainable and environmentally friendly bioenergy sector in line with EU policies and strategies. Long-term primary data collection, at both field as well as at water table level are though necessary to confirm the impacts of biodigestate (and the BRD model) on ground water quality.

Figure 9. Final score of the water quality indicator and related scale of credit score



2.2.5. Biodiversity

Agronomic best practices can significantly improve biodiversity in the European Union (EU) by promoting sustainable and eco-friendly farming techniques. These practices focus on preserving natural habitats, implementing crop diversity, reducing chemical inputs, and managing water resources efficiently. By adopting such methods, farmers create a more diverse and resilient ecosystem that supports a wide range of plant and animal species. This approach not only safeguards the environment but also contributes to the health of pollinators, beneficial insects, and soil microorganisms. The indicator relies on the identification and frequency of specific management practices implemented. By evaluating the occurrence and frequency of conventional versus improved biodiversity-related practices using a scorecard method, this assessment provides an indication of potential benefits or challenges related to biodiversity preservation (Table 13).

Table 13. Presence and frequency of the best biodiversity management practices

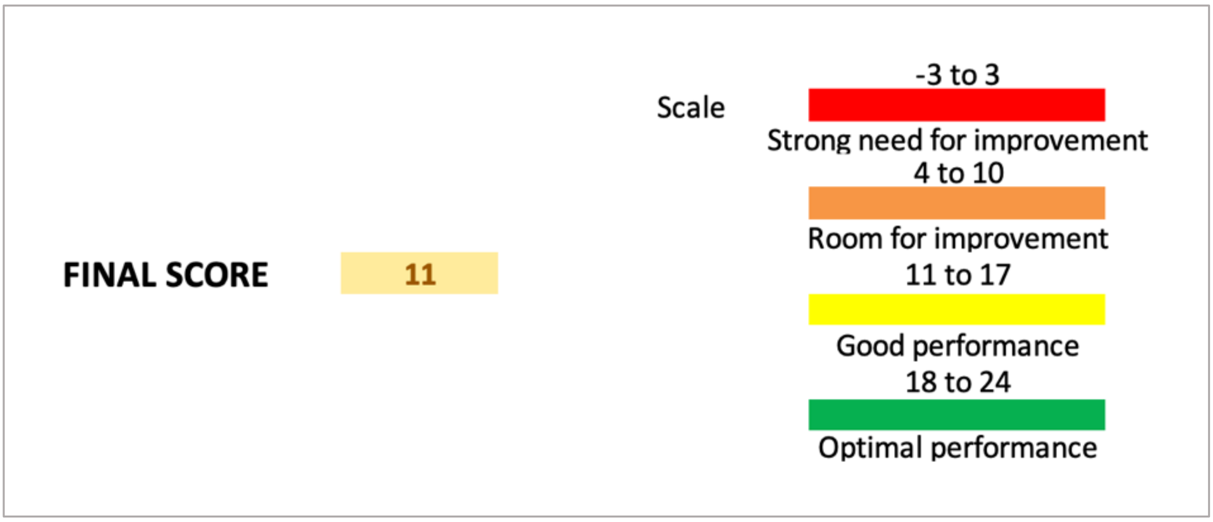
Presence and frequency of the best management practices	**Value**	**Score**
Invasive alien species	Not applied	0
No-tillage, minimum tillage, reduced tillage	Applied	3
Crop rotation (incl. or excl. fallow, intercropping, etc.)	Applied	1
Continuous cover crop	Applied	1
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Windbreaks, shelterbelts, etc.	Not applied	0
Biofertilizer and living organisms' management	Applied	1
Conservation buffers (buffer zones, corridors, etc.)	Not applied	0
No shrubs removal	Not applied	0
Use 1 ha every 100 ha for planting legumes/cereals for wildlife	Not applied	0
Pollinators management (bees, Bumblebees, etc..)	Not applied	0
Avoiding open field burning	Not applied	0
Agroforestry (multi-layers of canopy, etc..)	Not applied	0
Report and protect nest	Not applied	0
Ensure that species are not collected	Not applied	0
Cooperation with environmental or nature protection organizations	Not applied	0
Promote awareness campaigns on biodiversity conservation in agriculture	Not applied	0
Erosion and sediment control	Applied	2
Wastewater treatment of bioenergy processing	Applied	3
	SCORE	**11**

Source: results of the FAO's BIKE set of sustainability indicators

The scorecard method assigns different scores to various practices, considering that certain operations have been found to have detrimental effects on biodiversity whereas other practices are widely recognized as contributors to biodiversity conservation. By considering the combination of different practices, this approach offers a qualitative indication of the risk level associated with biodiversity preservation.

As shown in Table 13, reduced tillage, crop rotations, continuous cover crop, biofertilizers and living organism management, erosion and sediment control and wastewater treatment of bioenergy processing are the considered best practices relevant for biodiversity preservation. In general, biomethane production (and therefore all its downstream products) registers positive performances in terms of biodiversity conservation at farm level, when compared to traditional cropping operations, though no biodiversity-specific practices are employed by farmers producing feedstocks for biomethane production (Figure 10). The assessment of impacts of large refineries (i.e. FT plants) was not included in this qualitative study.

Figure 10. Final score of the biodiversity indicator and related scale of credit score



Source: results of the FAO’s BIKE set of sustainability indicators

2.2.6. Jobs in the bioenergy sector

The total population in the target area (Lombardy Region) is around 10 million inhabitants. The working population (men and women, age group 20-64) is 68.3 percent thus the unemployment rate 30.7 percent. The share of permanent and temporary jobs in the area is 88.6 percent and 11.4 percent, respectively. Most of the jobs are permanent.

Advanced bioenergy value chains have the potential to produce employment in the agriculture sector (feedstock production) as well as in the industrial sector (feedstock processing) and accessory sectors too (e.g. transport of biomass, induced jobs for the production of inputs, machineries, etc.).

As provided in Table 14, in the target scenario at the farm level (only for 258 000 Nm3 CH4 per year), the production of biomethane would employ exclusively skilled workers to sow, cultivate, harvest, and transport the feedstock to the biogas digester for a total of 619 hours year or an average of 6 hours of work/ha. Additional 103 hours per year (1 hour/ha) would be requested to transport the biomass. In addition, the operations and maintenance of the digester and the upgrading facility would generate the demand for some 7 296 hour/year of highly skilled permanent jobs. In total, at the farm level the project would generate around 4.2 skilled job position per year.

Table 14. Results of the job indicator at biomethane plant scale (258k Nm3 CH4/year)

	Skilled positions		Unskilled positions	
Feedstock production phase	Hours/year	Days/year	Hours/year	Days/year
Land preparation	567	71	0	0
Land cultivation	0	0	790 000	98 750
Harvesting	52	6	1 190 000	148 750
Fuel production phase				
Biomethane	7 296	912	0	0
GTL	252	32	0	0
Aggregated workers	0	0	0	0
Transport of biomass				
Drivers/loaders	103	13		
Transport of fuel				
Drivers/loaders	0	0		
TOTAL SKILLED JOB POSITION	4.2	**SKILLED JOB POSITION/m3**		0.0000162
TOTAL UNSKILLED JOB POSITION	0	**UNSKILLED JOB POSITION**		0

Source: results of the FAO's BIKE set of sustainability indicators

At the value chain level, assuming that enough biomethane is produced to feed a 1 000 bpd GTL plant, around 84.6 million Nm^3 obtained producing wheat on more than 33 000 ha, the project would generate some 13 342 skilled job position per year (Table 15) comprehensive of feedstock production, feedstock transport, biogas production and upgrading to biomethane, production of advanced liquid biofuel and transport of the fuel to a storage site. Unfortunately, no data are available on the number of jobs positions potentially produced by the GTL plant operation and management. The construction of the biorefinery would also generate jobs but these are considered indirect and not included in this forecast, as in the previous case studies. In general, for both analysed scenarios, no unskilled job positions are created.

Table 15. Results of the job indicator at the whole value chain level (84.6M CH4 and 6 768 t SAF)

	Skilled positions		**Unskilled positions**	
Feedstock production phase	**Hours/year**	**Days/year**	**Hours/year**	**Days/year**
Land preparation	185 819	23 227	0	0
Land cultivation	0	0	0	0
Harvesting	16 893	2 112	0	0
Fuel production phase				
Biomethane	25 380 000	3 172 500	0	0
GTL	0	0	0	0
Aggregated workers	0	0	0	0
Transport of biomass				
Drivers/loaders	33 785	4 223		
Transport of fuel				
Drivers/loaders	677	85		
TOTAL SKILLED JOB POSITION	13 342.3	**SKILLED JOB POSITION/m3**		0.051
TOTAL UNSKILLED JOB POSITION	0	**UNSKILLED JOB POSITION**		0

Source: results of the FAO's BIKE set of sustainability indicators

2.2.7. Energy access

In the scope of this assessment, it's important to underscore the concept of the energy access indicator, which holds particular relevance in developing countries where inadequate energy access remains a significant challenge. This indicator serves as a metric to quantify the extent to which populations in these regions have reliable and sufficient energy sources, addressing the critical issue of energy scarcity that often prevails.

However, it's important to note that the primary focus of this assessment lies in the enhanced capacity for energy production, particularly in comparison to traditional fossil fuels. This analysis pertains to a specific context that differs from the typical energy access challenges faced by developing countries. Consequently, the measurement of the energy access indicator wasn't included in this evaluation. Rather, the central emphasis was placed on appraising the potential of the investment scenario within the framework of EU standards and regulations, specifically concerning renewable energy pricing and economic viability.

2.2.8. Productivity

This indicator measures the productivity of the bioenergy value chain in terms of quantity of products and unitary costs. The data provided by CIB are an important share of the information included in this indicator. The rest of the data required was retrieved in the literature. The use of double cropping can be a promising model for producing additional biomass without negative repercussions on soil use or food production. In this context, the productivity indicator analyses the economic feasibility of producing Sustainable Aviation Fuel (SAF), focusing on three distinct levels: On farm biomass production costs, biogas production and upgrading costs to biomethane and related annual income. Finally, the off-farm budget of producing liquid biofuel through the GTL (Gas-to-Liquid) process is provided.

On farm production:

As presented in Table 16 operating input costs of biomass production on 103 hectares are seeds and herbicides costs for a total annual expense of around 330 EUR per hectare. While labour costs are mainly made of mechanisation costs (land preparation, sowing, weeding, and applying digestate), harvesting and transporting the biomass for a total annual cost per hectare of 771 EUR. According to that, a production cost of 37 EUR/tonne was calculated for wheat silage produced at farm gate.

Concerning biomethane production, as already described before and reported in Table 1, the study considered a biogas plant with an installed capacity of 1 MW with a daily CH_4 production of 5 714 Nm^3 or some 1 977 168 Nm^3 per year (20 011 MWh year). Around 257 930 Nm^3 per year (13 percent) is produced from low i-LUC biomass while the rest (87 percent or some 1 719 238 Nm3 per year) is produced from a variety of different agricultural residues, including cattle manure, olive pomace and other material produced off-farm. For the calculation of the incentive tariff on biomethane, the Guarantee of Origin formula foresees in this case a price of 22 EUR per MWh (on an energy content basis of biomethane). This was done by considering some 100 EUR per ton as price of CO_2, the REDII reference level of 94 gCO_2/MJ, and 65 percent as the minimum value of GHG savings. Currently, there is no gas Guarantee of Origin (GO) market, and thus, there is no existing benchmark value (Table 17).

Table 16. On-farm budget Italian case study (feedstock production)

ON FARM – BIOMASS PRODUCTION ITEMS	Annual budget (1HA) €/ha/year
Operating input costs	
Seeds/Plants	250.0
Top Dress Fertilizer	0.0
Basal Fertilizer	0.0
Herbicides	80.0
Pesticides (Pre-harvest)	0.0
Pesticides (Post-harvest)	0.0
Organic fertilizer	0.0
Hiring tractor	0.0
Transport cost	0.0
Irrigation	0.0
Sub-total operating costs	330
Labour costs (on farm)	
Land preparation	200.0
Planting	50.0
Weeding	35.0
Applying fertilizer/manure	36.0
Sprying pesticides	0.0
Harvesting	250.0
Transport	200.0
Sub-total labour costs	771
Feedstock production cost	**37**

Source: results of the FAO's BIKE set of sustainability indicators

Table 17. Economic and financial figures of feed-in tariff for biomethane production (Italy 2023)

Item	Value	Unit
Biomethane market price (Grid)[2]	0.33	€/Nm^3
Incentive (tariff >250Sm3h)[3]	70	€/MWh
Incentive duration[3]	15	years
Natural Gas Price	49.6	€/MWh
Reference tariff	107.8	€/MWh
Guarantee of origin price (GO)	22	€/MWh
GHG savings vs reference	-65	%
Reference level (RED II)	94	gCO_2/MJ
	338.4	kgCO_2/MWh
CO2 saving for bioCH4	-220	kgCO_2/MWh
CO2 price	100	€/t

[2] Menin, L., Benedetti, V., Patuzzi, F. et al. Techno-economic modeling of an integrated biomethane-biomethanol production process via biomass gasification, electrolysis, biomethanation, and catalytic methanol synthesis. Biomass Conv. Bioref. 13, 977–998 (2023). https://doi.org/10.1007/s13399-020-01178-y

[3] Gazzetta Ufficiale della Repubblica Italiana, MINISTERO DELLA TRANSIZIONE ECOLOGICA, DECRETO 15 settembre 2022, https://www.gazzettaufficiale.it/eli/id/2022/10/26/22A06066/sg

Table 18 shows how the production of biomethane can give profitable results also thanks to the incentives to production. A total operative cost (inputs, compression and labour) of around 158 000 EUR year was applied were labour was calculated as 5% of the total OPEX. The Net Margin for a 1MW biomethane plant following the BDR model showed a final annual net margin of around 745 000 EUR per year, of which 111 709 EUR attributable to the share of feedstock certified as low-ILUC.

Table 18. On-farm budget Italian case study (biomethane production)

ON FARM – BIOMETHANE PRODUCTION ITEMS	Annual budget (1MW) €/yr
Operating input costs	
Feedstock	113 403
Farm sludge	0
Other feedstock	0
Transport	0
Biogas production O&M + fixed costs	250 000
Upgrading production O&M + fixed costs	157 143
Labour costs (fixed) Included in O&M	0
Biodigestate storage	0
Total operating expenses	520 546
Revenues	652 465
Incentives (production)	724 387
Savings from fertilizer application	0
Total revenue	1 376 852
Gross Margin	856 307
Net Margin	**856 307**
Net margin from Low I-LUC	**111 709**
Net margin from other feedstock	**744 597.7**

Source: results of the FAO's BIKE set of sustainability indicators

Off farm production:

When it comes to SAF (kerosene) production through GTL process (Table 19), the analysis considered the costs and revenues of an existing 1 000 bpd GTL plant operating in connection with the national natural gas grid and using some 84.6 million Nm^3 of CH_4 at a cost, including the tariffs and GOs, of EUR 28 million. As shown in Table 13, the plant would produce around 6 770, 6 670, 2 900 and 14 500 tonnes per year of kerosene, naphtha, diesel and waxes, respectively. The sale of all these products would lead to an annual total revenue of around

39.2 million EUR (Table 20). After considering a total of around 38 million EUR as total operative and fixed costs, also repaying a loan annuity of around 6.5 million EUR (see investment indicator), the plant would generate around 1.1 million EUR per year of annual net income. Additional analyses on the potential investment are provided in the dedicated "Investment" indicator (see page 42). But, due to its highly innovative nature, the GTL process remains relatively unexplored in terms of available investment information such as CAPEX and OPEX and therefore the findings presented in the report should be considered initial, and additional studies are necessary to refine the analysis.

Table 19. Annual production and co-productions of a 1000 bpd GTL plant using CH_4

Products	Production (Tonnes per year)	Market price (EUR t)
Primary product (SAF)	6 768	755
Co product 1 Naphtha	6 672	521
Co product 2 Diesel	2 895	1 503
Co product 3 Waxes	14 474	1 574

Table 20. Off farm budget Italian case study

OFF-FARM GTL PRODUCTION	*GTL*
ITEMS	**Annual budget**
Revenues	
Primary product (SAF)	5 619 275
Co product 1 Naphtha	3 820 200
Co product 2 Diesel	4 786 304
Co product 3 Waxes	25 065 060
Sub-total revenues	39 290 839
Operating input costs	
Feedstock (CH4)	27 919 402.5
SAF production O&M + labour	3 640 000.0
Loan annuity	6 599 553.1
Sub-total operating costs	38 158 956
Sub-total labour costs	0
Sub-total production costs	38 158 956
Gross Margin	1 131 883
Net Margin	**1 131 883**

Source: results of the FAO's BIKE set of sustainability indicators

2.2.9. Investment

The indicator is based on a financial assessment, where a standard cost-benefit analysis (CBA) approach is applied to quantify potential net profits of the entire low-ILUC biokerosene value chain, from feedstock production to SAF production, passing through intermediate energy carriers such as biogas first and biomethane later. The analysis is done to compute the investment's financial performance indicators and is carried out to assess the potential investment's profitability. The analysis is based on the two-level approach applied to the productivity indicator investigating: i) the On-Farm investment for equipping an existing biogas plant with a biomethane upgrading technology, and to connect it to the national grid natural gas grid; and ii) the Off-Farm component, where the investment analysis of a 1 000 bpd GTL plant is provided. Information on CAPEX and OPEX for the selected investments (both on farm and off farm level) was collected from the available literature. Table 21 provide unitary and total costs of CAPEX and OPEX for both on- and off-farm stages of the value chain.

Table 21. On Farm and Off Farm CAPEX and OPEX specifications for the Italian case study

Item	Level	Value	Unit
Investment cost (CAPEX)	On farm	5 500	€/Nm^3/h
Operating cost – unitary	On farm	435	€/Nm^3/h
O&M costs – annual	On farm	250 000	€ year (1MW plant)
Investment cost (CAPEX)	Off farm	80 000	USD/bpd
O&M costs – annual	Off farm	4 000	USD/bpd

Sources: TU Wien (available at: https://www.membran.at/downloads/2012_BioRegions_BiogasUpgradingTechnologyReview_ENGLISH.pdf); Da Silva Sequeira (available at: https://shareok.org/bitstream/handle/11244/319697/2019_daSilvaSequeira_Pascoela_Thesis.pdf?sequence=1)

On Farm investment:

The analysis of the On-Farm section of the value chain considered the investment necessary to equip an existing biogas plant with a biomethane upgrading plant, and the costs associated with the connection to the national natural gas grid for the injection of the biomethane produced from low-ILUC feedstocks produced on-farm. The biogas plant with an installed capacity of 1 MW is equipped with an upgrading plant capable of generating a daily CH_4 output of 5 714 Nm^3 or some 1 977 168 Nm^3 per year (20 011 MWh year), of which around 257 930 Nm^3 per year (13 percent) comes from low-ILUC dedicated energy feedstocks while the rest (87 percent or some 1 719 238 Nm3 per year) is from different origins (Table 1). As a result, all calculations refer to the share effectively documented as low-ILUC (13% of total). As already mentioned, a capital contribution equivalent to 40% of the incurred expenses (retrofitting + grid connection) is provided by the Italian Government with the Ministerial Decree 15 September 2022 (Gazzetta Ufficiale della Repubblica Italiana, 2022). Costs for the connection to the grid have been calculated on a real case scenario and on a sample of representative BDR farms in Lombardy thanks to the contribution of SNAM. The system has variable costs depending upon geographical and technical factors including the distance from the main pipe, the amount of methane to be injected, the relative and absolute injection pressure, and the roughness of the terrain. Connection costs are not negligible and actually very relevant in the economic and financial balance of such projects. Figure 11 shows the results of the financial CBA, for the On-Farm business scenario. Net Present Value (NPV) and Internal Rate of Return (IRR) were calculated. The analyses showed positive results, particularly where the 40% grant on CAPEX is applied. A 11% IRR and a payback period of 5 years are obtained (Figure 11).

Figure 11. ON FARM Investment analysis of CH4 production in Italy using low i-LUC feedstock

Year	0	1	2	3	4	5	6	7	8	9	10 to 20
Biomethane to Grid											
General											
Annual production (Nm3)	0.00	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77	1,977,167.77
Annual production (MWh)	0.00	20,010.69	20,010.69	20,010.69	20,010.69	20,010.69	20,010.69	20,010.69	20,010.69	20,010.69	20,010.69
Market price tariff (EUR/Nm3)		0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Incentive tariff (EUR/MWh)		36.20	36.24	36.27	36.31	36.35	36.38	36.42	36.45	36.49	36.53
- Asset depreciation		-78,571.43	-78,571.43	-78,571.43	-78,571.43	-78,571.43	-78,571.43	-78,571.43	-78,571.43	-78,571.43	-78,571.43
Cash Flow											
+ Sale of biomethane + incentive	0.00	1,376,852.37	1,378,229.22	1,379,607.45	1,380,987.06	1,382,368.04	1,383,750.41	1,385,134.16	1,386,519.30	1,387,905.81	1,389,293.72
- O&M cost + labour cost + feedstock costs		520,545.86	521,066.40	521,587.47	522,109.06	522,631.17	523,153.80	523,676.95	524,200.63	524,724.83	525,249.55
Operating Cash Flow	**0.00**	**777,735.08**	**778,591.39**	**779,448.55**	**780,306.57**	**781,165.45**	**782,025.19**	**782,885.78**	**783,747.24**	**784,609.56**	**785,472.74**
Investment (upgrading technology)	-1,571,428.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Investment (Connection to grid)	-4,000,000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
- Investments	-5,571,428.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Cash Flow	**-3,342,857.14**	**777,735.08**	**778,591.39**	**779,448.55**	**780,306.57**	**781,165.45**	**782,025.19**	**782,885.78**	**783,747.24**	**784,609.56**	**785,472.74**
Cumulative Cash Flow	-3,342,857.14	-2,565,122.06	-1,786,530.67	-1,007,082.12	-226,775.55	554,389.90	1,336,415.08	2,119,300.86	2,903,048.10	3,687,657.66	4,473,130.40
Payback Year	0.00	0.00	0.00	0.00	0.00	Payback	0.00	0.00	0.00	0.00	0.00
TCF (no Grant)	-5,571,428.57	777,735.08	778,591.39	779,448.55	780,306.57	781,165.45	782,025.19	782,885.78	783,747.24	784,609.56	785,472.74
CCF (no grant)	-5,571,428.57	-4,793,693.49	-4,015,102.10	-3,235,653.55	-2,455,346.98	-1,674,181.53	-892,156.35	-109,270.57	674,476.67	1,459,086.23	2,244,558.97
Payback Year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Payback	0.00	0.00
Loan and capital structure											
Equity private financing	**-3,342,857.14**										
% grant (Decreto biometano)	**-2,228,571.43**	**40%**	of investment								
Project profitability											
Project IRR	**22%**										
Project IRR (without GRANT 40%)	**11%**										
Project NPV	**4,666,630.18**										
Project NPV (no grant)	**2,544,181.20**										
Project payback (years)	**5.00**										
Project payback (years) (without GRANT 40%)	**8.00**										

Off Farm investment:

As already discussed in the productivity indicator, for the Off-Farm SAF (Kerosene) production via GTL process, the analysis considered the costs and revenues for a 1 000 bpd GTL plant operating in connection with the national natural gas grid and using around 84.6 million Nm^3 CH4 to produce a series of advanced liquid biofuels and products. As shown in Table 19, annually the plant would produce around 6 770, 6 670, 2 900 and 14 500 tonnes per year of Kerosene, Naphtha, Diesel and Waxes, respectively. Due to its highly innovative nature, the GTL process remains relatively unexplored in terms of available investment information such as CAPEX and OPEX. However, data from literature revealed a total capital expense of around 80 000 USD or some 72 800 EUR per bpd for the construction of a GTL plant and some operational expenses of 4 000 USD per bpd (4% of CAPEX) as reported in Table 21. Figure 12 shows the results of the financial CBA, for the Off-Farm business scenario. NPV and IRR were calculated. The analyses showed positive results, particularly when a 70 percent capital loan is applied. Information on the structure of the proposed loan is reported in Table 22.

Table 22. Off Farm loan structure Italian case study

Equity private financing	**-21 840 000.00**		
Loan	-50 960 000.00	**70%**	of initial investment
Constant interest rate	5%		
Duration of loan (years)	10		
Grace period (year)	3		
Loan repayment plan	Constant instalments		

As the refinery has to pay both the cost of methane and the guarantee of origin to demonstrate the biological origin of the feedstock used and thereby certify the sustainability of its produced fuels, a sensitivity analysis was conducted to determine the appropriate market price increment to be attributed to low-carbon intensity biofuels produced. This increment (compared to market prices) was set at 10 percent. Therefore, considering a 10 percent increase in selling prices and a loan with a constant interest repaid within a maximum of 10 years at a 5 percent interest rate, the analysis yielded positive results with an IRR of 11% and a positive NPV. The payback period is calculated to be 15 years from the loan agreement (Figure 12).

Figure 12.On Farm Investment analysis of SAF production in Italy using low i-LUC feedstock

Year	0	1	2	3	4	5	6	7	8	9	10 to 25
GTL											
General											
Primary product (SAF) - tonnes	0.00	6,768.34	6,768.34	6,768.34	6,768.34	6,768.34	6,768.34	6,768.34	6,768.34	6,768.34	6,768.34
Market price SAF - EUR	*0.00*	*830.23*	*830.24*	*830.25*	*830.25*	*830.26*	*830.27*	*830.28*	*830.29*	*830.30*	*830.30*
Co product 1 Naphtha - tonnes	0.00	6,672.00	6,672.00	6,672.00	6,672.00	6,672.00	6,672.00	6,672.00	6,672.00	6,672.00	6,672.00
Market price Naphtha EUR	*0.00*	*572.57*	*572.58*	*572.58*	*572.59*	*572.59*	*572.60*	*572.61*	*572.61*	*572.62*	*572.62*
Co product 2 Diesel - tonnes	0.00	2,895.00	2,895.00	2,895.00	2,895.00	2,895.00	2,895.00	2,895.00	2,895.00	2,895.00	2,895.00
Market price Diesel EUR	*0.00*	*1,653.30*	*1,653.32*	*1,653.33*	*1,653.35*	*1,653.37*	*1,653.38*	*1,653.40*	*1,653.42*	*1,653.43*	*1,653.45*
Co product 3 Waxes - tonnes	0.00	14,474.00	14,474.00	14,474.00	14,474.00	14,474.00	14,474.00	14,474.00	14,474.00	14,474.00	14,474.00
Market price Waxes EUR	*0.00*	*1,731.73*	*1,731.75*	*1,731.76*	*1,731.78*	*1,731.80*	*1,731.82*	*1,731.83*	*1,731.85*	*1,731.87*	*1,731.89*
- Asset depreciation (35 years)	0.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00	-2,080,000.00
Cash Flow											
+ Sale of liquid biofuels	0.00	39,290,838.76	39,291,231.67	39,291,624.58	39,292,017.50	39,292,410.42	39,292,803.34	39,293,196.27	39,293,589.20	39,293,982.14	39,294,375.08
- O&M cost + labour cost + feedstock costs		-33,639,402.50	-33,639,738.89	-33,640,075.29	-33,640,411.69	-33,640,748.10	-33,641,084.50	-33,641,420.91	-33,641,757.33	-33,642,093.75	-33,642,430.17
Operating Cash Flow	**0.00**	**5,651,436.26**	**5,651,492.78**	**5,651,549.29**	**5,651,605.81**	**5,651,662.32**	**5,651,718.84**	**5,651,775.36**	**5,651,831.87**	**5,651,888.39**	**5,651,944.91**
- Investments (EUR)	-72,800,000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
- Loan annuity	0	0	0	0	-6,599,553	-6,599,553	-6,599,553	-6,599,553	-6,599,553	-6,599,553	0
Total Project Cash Flow	**-72,800,000.00**	**5,651,436.26**	**5,651,492.78**	**5,651,549.29**	**5,651,605.81**	**5,651,662.32**	**5,651,718.84**	**5,651,775.36**	**5,651,831.87**	**5,651,888.39**	**5,651,944.91**
Cumulative Cash Flow	-72,800,000.00	-67,148,563.74	-61,497,070.96	-55,845,521.67	-50,193,915.87	-44,542,253.54	-38,890,534.71	-33,238,759.35	-27,586,927.48	-21,935,039.08	-16,283,094.17
Payback Year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TCF (to shareholders)	**-21,840,000.00**	**5,651,436.26**	**5,651,492.78**	**5,651,549.29**	**-947,947.33**	**-947,890.82**	**-947,834.30**	**-947,777.78**	**-947,721.27**	**-947,664.75**	**5,651,944.91**
CCF (to shareholder)	-21,840,000.00	-16,188,563.74	-10,537,070.96	-4,885,521.67	-5,833,469.01	-6,781,359.83	-7,729,194.13	-8,676,971.91	-9,624,693.18	-10,572,357.93	-4,920,413.02
Payback Year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Loan and capital structure											
Equity private financing	**-21,840,000.00**										
Loan	**-50,960,000.00**	**70%**	of initial investment								
Constant interest rate	**5%**										
Duration of loan (years)	10										
Grace period (year)	3										
Loan repayment plan	Constant installments										
Loan outstanding (BoP)	**50,960,000**	**50,960,000**	**50,960,000**	**50,960,000**	**50,960,000**	**46,908,447**	**42,654,316**	**38,187,479**	**33,497,300**	**28,572,611**	**23,401,689**
- Interests		0	0	0	2,548,000	2,345,422	2,132,716	1,909,374	1,674,865	1,428,631	0
- Capital repaid		0	0	0	4,051,553	4,254,131	4,466,837	4,690,179	4,924,688	5,170,923	0
Loan outstanding (EoP)	**50,960,000**	**50,960,000**	**50,960,000**	**50,960,000**	**46,908,447**	**42,654,316**	**38,187,479**	**33,497,300**	**28,572,611**	**23,401,689**	**23,401,689**
Project profitability											
Project IRR	**6%**										
Project IRR shareholders	**11%**										
Project NPV	**6,532,014.93**										
Project NPV shareholders	**16,999,056.70**										
Project payback (years)	**13.00**										
Project payback (years) Shareholders	**15.00**										

2.2.10. Net Energy Balance

This indicator calculates the difference in energy inputs necessary to produce the biomass, transport it to the biorefinery/bioenergy plant, process it into advanced biofuel and, lastly, distribute the fuel. At the on-farm level (Table 23), from an energy balance point of view the analysis of the biomethane production obtained from the low-ILUC feedstock returned valuable information about the energy efficiency of the system. Feedstock production (wheat silage) only requires energy for tillage and harvesting operations but does not require any form of additional chemical energy other than the bio-digestate produced at the farm level, which was considered endogenous as generated on-farm biomass transport, however, requires diesel to fuel the tractors delivering the biomass to the biogas plant and the digestate back to the fields. Subsequently, during the processing phase (upgrading to biomethane) the energy needed to upgrade biogas to biomethane is produced by the process itself through the combustion of part of the gas. Compression energy requirement for biomethane grid injection from atmospheric pressure to 20 MPa is 0.35 kWh/m^3 of biomethane (Hakawati, 2017).

Table 23. On farm Energy inputs of the SAF value chain in Italy

ON FARM		
FEEDSTOCK PRODUCTION		
Diesel from Agriculture	*Diesel consumption*	
Land preparation	Kg DIESEL yr-1	2 364 970
Cultivation	Kg DIESEL yr-1	0
Harvesting	L DIESEL yr-1	2 027 117
	Total Yearly Diesel Consumption (Mj)	188 903 673
Chemical inputs for Agriculture		
Amount of fertilization (chemical) N	Kg yr-1	0
Amount of fertilization (chemical) P	Kg yr-1	0
Amount of fertilization (chemical) K	Kg yr-1	0
Amount of applied pesticides	Kg yr-1	0
Amount of biodigestate	Kg yr-1	608 135 160
	Total Yearly Inputs Consumption (Mj)	419 613 261
Biomass transport		
Average distance field to biogas plant	Km	10
Total FSTK production (tot ha*yield)	Tonnes	1 013 559
	Total Yearly Diesel Consumption (Mj)	8 209 825
BIOMETHANE PRODUCTION		
Compression for injection	MJ/Nm3	1.26
	MJ	106 601 355

Source: results of the FAO’s BIKE set of sustainability indicators

At the off-farm level (Table 24), the indicator calculates the difference in energy inputs adding all steps related to the GTL process plus the fuel distribution to storage sites, airports or final retailers.

Table 24. Off farm Energy inputs of the SAF value chain in Italy

OFF FARM		
GTL		
PROCESSING		
Electricity (Total)	MJ year	75 812 400
FUEL TRANSPORT		
Transport: Fuel transport	Km	50
Total fuel produced	Tonnes	6 768
	TOTAL YEARLY DIESEL CONSUMPTION (MJ)	274 118

Source: results of the FAO's BIKE set of sustainability indicators

Energy outputs take into account all co-products of the value chain, including the digestate which, even though not necessarily used for energy purposes, has an energy content that is accounted for as a substitute of the energy necessary for the production of its alternative substitute (e.g. N fertilizers). Table 25 shows the energy outputs at the two levels of the chain.

Table 25. On and Off farm Energy Outputs of the SAF value chain in Italy

ON FARM			
Total CH4 produced		**MJ**	3 028 832 150
Co-products (bio digestate)		Kg/Nm3CH4	7.5
		MJ	437 826 994
OFF FARM			
Primary product (SAF)		Tonnes/year	6 768
	LHV Kerosene	MJ /tonne	46 200
Co product 1 Naphtha		Tonnes/year	6 672
	LHV Naphtha	MJ /tonne	44 900
Co product 2 Diesel		Tonnes/year	2 895
	LHV Diesel	MJ /tonne	43 010
Co product 3 Waxes		Tonnes/year	14 474
	LHV Waxes	MJ /tonne	41 500
		MJ/year	1 337 455 058

Source: results of the FAO's BIKE set of sustainability indicators

Lastly the net energy ratio (EO/EI or TFO/TFI) is presented in Table 26 and Table 27 for the production of biomethane and SAF, respectively. This is the ratio between the energy output attributed to the advanced biofuel and the input necessary for its production. In the case of low-ILUC wheat silage for biomethane the final EO/EI ratio is 4.8. In the case of certified biomethane for SAF the final EO/EI ratio is 2.2.

Table 26. Results of the Net Energy Balance indicator for the biomethane production

GTL (SAF)		
	Total energy input (MJ/year)	723 328 114
	Total energy output (MJ/year)	3 466 659 144
FEEDSTOCK PRODUCTION (Agriculture)	TFI	600
MJ/tfeedstock	TFO	17 450
Net Energy Value	TFO-TFI	16 850
Net Energy Ratio	TFO/TFI	29
FEEDSTOCK TRANSPORT-PROCESSING	TFI	8
MJ/tfeedstock	TFO	3 420
Net Energy Value	TFO-TFI	3 412
Net Energy Ratio	TFO/TFI	422
LIFECYCLE ENERGY EFFICIENCY		
Net Energy Ratio	TFO/TFI	4.8

Source: results of the FAO's BIKE set of sustainability indicators

Table 27. Results of the Energy Balance Indicator for the SAF production

On farm - Only for BDR		
	Total energy input (MJ/year)	799 414 631
	Total energy output (MJ/year)	1 775 282 052
FEEDSTOCK PRODUCTION (Agriculture)	TFI	600
MJ/tfeedstock	TFO	17 450
Net Energy Value	TFO-TFI	16 850
Net Energy Ratio	TFO/TFI	29
FEEDSTOCK TRANSPORT-PROCESSING	TFI	188
MJ/tfeedstock	TFO	1 752
Net Energy Value	TFO-TFI	1 563
Net Energy Ratio	TFO/TFI	9
LIFECYCLE ENERGY EFFICIENCY		
Net Energy Ratio	TFO/TFI	2.2

Source: results of the FAO's BIKE set of sustainability indicators

2.2.11. Infrastructure

Given the goal of achieving a daily production of 1 000 barrels per day (bpd) of Fischer-Tropsch liquids, along with an annual capacity of 6 768 tonnes of kerosene, and a demand for 1 013 559 tonnes of low-iLUC feedstock per year to produce such bioliquids, the analysis for on-farm infrastructure has been conducted considering a distributed farms system that can produce the necessary quantity of biomethane. Considering this, the assumption that the average distance between the different fields and the anaerobic digesters is 10 km was made. Additionally, it was assumed that the transportation of feedstock between these locations is performed using tractors with a loading capacity of 20 tonnes and an average speed of 30 km/h. This leads to a total time during which the transportation takes place of 33 785 hours per year (Table 29). Such value is used to compute on-farm emissions, as well as on-farm jobs creation. for the physical infrastructure for the movement of biomethane is the existing national natural gas grid, but there is an investment required to directly inject the fuel into the national grid; to evaluate the impacts of creating such infrastructural connections for all necessary biomethane plants in Lombardy a simplified feasibility analysis was carried out.

As introduced, the infrastructure of the national natural gas grid plays a key role in the value chain, as it connects the decentralized farms to the refinery, allowing for a remarkable reduction of GHG associated to fuel/feedstock emissions. In Italy, the transportation of natural gas is ensured by SNAM Rete Gas, a subsidiary of the SNAM Group, which holds about 94% of the Transport Network. The transport network is divided into the National network (approximately 8 800 km) and the regional network (over 22 600 km). The former connects the national entry points (gas extracted from production sites or imported) to the Regional Transport Network, which, in turn, includes all the pipelines connecting the national network to consumption centres (delivery points). Società Gasdotti Italia holds the position of the second-largest natural gas transporter in Italy, operating a pipeline network of about 1 300 km, primarily serving the southern region of the country (IEA, 2022). In Italy, biomethane injection into the grid is well supported by the Italian Government that, as mentioned, has established a financial support system for it. The biomethane to be injected into the grid must respect the following regulations (Gazzetta Ufficiale della Repubblica Italiana, 2022):

- Decree of the Ministry of Economic Development of 19th February 2007;

- M/475 Mandate to CEN for standards for biomethane for use in transport and injection in natural gas pipelines.

During the initial phase of this sustainability assessment, the main focus was on the Lombardy region. The contribution of SNAM Rete Gas has been key to evaluate the investment costs for grid connection of the farms potentially required to provide the feedstock to the GTL plant. Specifically, the agricultural farms that currently produce biogas in the region, particularly those generating up to 1 MW from biogas have been listed. Information concerning each biogas plant (i.e. location and capacity) was found on the website of the Italian Energy Services Manager (GSE). Such biogas plants have been assumed to convert to biomethane plants and to connect to the natural gas grid. Utilizing data provided by SNAM regarding the distance from the Natural Gas Grid and other grid connection parameters (i.e. "connection complexity", that takes into account the existence of landscape/environmental or urban planning constraints, as well as the morphology, soil type, and degree of anthropization), the investment costs required for connecting these farms to the grid was calculated. In addition to the costs associated with the roll-out of the connection infrastructure to the natural gas network, another key factor that emerged from the assessment of this indicator are the implications in terms of time and workload for SNAM and the other actors involved to deploy the number of entry points required.

Another possible burden is represented by the permission and administrative workload to satisfy numerous connection requests. These implications should be considered holistically in the policymaking process to evaluate the attainability of the targets of reference ministerial decrees. Whether the targets by year 2030 can be met is not solely a matter of investments and national budget (which other indicators have found to be appropriate for the sector and replicable elsewhere) but this analysis has shown that logistical and infrastructural bottlenecks could slow-down the roll-out regardless of the financial resources to support the production of biomethane.

The conversion of (bio)methane would take place in an existing refinery, which would be equipped with an additional component for Fischer-Tropsch synthesis. In Italy, there are currently 15 refineries, as shown in Table 28, for a total capacity of 2 030 500 bpd[4]. BIKE

[4] https://www.bizjournals.com/sanantonio/blog/eagle-ford-shale-insight/2016/01/a-look-at-italian-refineries-that-could-receive.html

Partnet ENI owns a pilot 20 bpd GTL FT-based plant in Sannazzaro, in Lombardy (Advanced Energy Technology – AENERT, 2022). To date, no commercial scale GTL company exists on Italian soil.

Table 28. Main refineries over the Italian territory

Company	Location	Region	Capacity [bpd]
AgipPetroli SPA	Livorno	Tuscany	84 000
AgipPetroli SPA	Porto Marghera	Veneto	70 000
AgipPetroli SPA	Sannazzaro, Pavia	Lombardy	160 000
Api Raffineria di Ancona SPA	Falconara, Marittima	Marche	85 000
Arcola Petrolifera SPA	La Spezia	Liguria	33 000
ExxonMobil Refining + Supply Co.	San Marino Di Trecate	Piedmont	200 000
Iplom SPA	Busalla	Liguria	39 500
Italiana Energia E Servizi SPA	Mantova	Lombardy	55 000
Tamoil Raffinazione SPA	Cremona	Lombardy	80 000
AgipPetroli SPA	Gela, Ragusa	Sicily	100 000
AgipPetroli SPA	Taranto	Apulia	90 000
ERG Reffinerie Medditerranee North	Priolo, Sicily	Sicily	160 000
ERG Reffinerie Medditerranee South	Melilli, Sicily	Sicily	214 000
ExxonMobil Refining + Supply Co.	Augusta, Siracusa	Sicily	190 000
Raffineria di Milazzo SPA	Milazzo, Messina	Sicily	80 000
Raffineria di Roma SPA	Roma	Lazio	90 000
Saras SPA	Sarroch, Sardinia	Sardinia	300 000
		Total	**2 030 500**

In the 1000 bpd GTL plant simulated for this case study, 6 768 tonnes of kerosene are produced. An assumption was made regarding 50 km from the biorefinery to various distribution sites (gas stations, airports). Liquid biofuel transportation is carried out by trucks with a capacity of 20 tonnes and an average speed of 50 km/h, totalling 677 hours per year (Table 29). In total, 34 462 hours per years were calculated by the indicator (Table 29). Such value was used in the sustainability analysis for calculating transportation emissions, job positions created, and related indicators.

Table 29. Results of the infrastructures indicator for the SAF Italy case study

	Distance [km]	production [ton]	Vehicle	Loading capacity [ton]	Average vehicle speed [Km/h]	Hrs.
Fstk transp.	10	1 013 559	Tractor	20	30	33 785
Fuel transp.	50	6 768	Truck	20	50	677
					TOTAL HOURS	34 462

Source: results of the FAO's BIKE set of sustainability indicators

2.2.12. Gross Value Added

This indicator measures the contribution to the GDP of a given bioenergy value chain. In the case study of Lombardy, the products that contribute to GDP are the sales of biokerosene and the sales of the co-products of the FT catalysis (Table 30).

SEA, the company that manages the airports of Milan's Malpensa and Linate, after signing an agreement with Eni in 2021 for the development and supply of aviation biofuels, allocated a fund of EUR 450 000 in 2023 to pay a premium of EUR 500 per ton of pure SAF (Sustainable Aviation Fuel, such as biokerosene) purchased by airlines at Linate and Malpensa airports. The goal of such policy is to cover part of the additional costs that still characterize alternative fuels for aviation. The requests from fuel providers for the first period from April to August exceeded the available funds by approximately 30 times.

Table 30 shows how the gross value added of a 1 000 GTL plant may contribute of around 0.03 percent to the regional annual GDP obtained exclusively through the sales of SAF and the other advanced co-products of FT catalysis. The co-products and biokerosene represent 85% and 15% of the revenues generated by the GTL plant, respectively.

Table 30. Contribution to Lombardy Region GDP of the proposed SAF value chain

Items	Unit	Value
Sales of advanced biofuel	€/year	5 619 275
Sales of co-products	€/year	33 671 564
Variable operating expenses	€/year	38 158 956
GVA	€/year	1 131 883
Contribution to GDP	%	0.03%

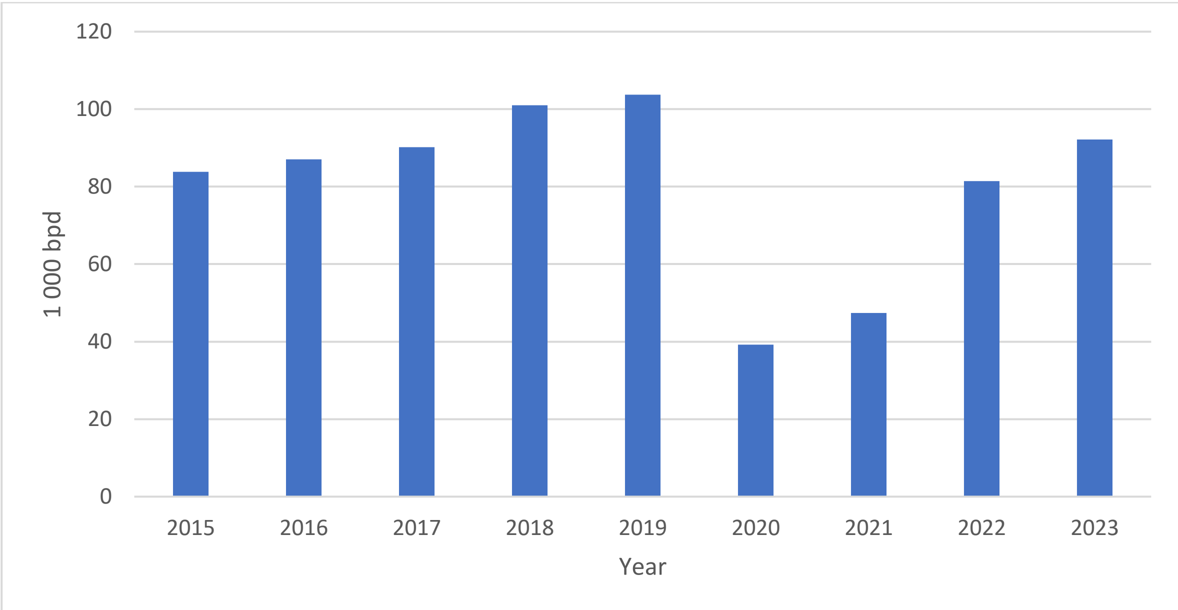
Source: results of the FAO’s BIKE set of sustainability indicators

2.2.13. Capacity

According to the U.S. Energy Information Administration (EIA, 2022) and showed in Figure 13, the consumption of kerosene-type Jet fuel in Italy increased from 83.8 to over 103 thousand bpd between 2015 and 2019. After the 2020 and 2021 drop of Covid 19, the consumption started raising again reaching 81.4 thousand bpd in 2022. Then, according to World data atlas (Knoema, 2023), in April 2023 the consumption of kerosene-type Jet fuel reached the 92.2 thousand bpd or 2 765.88 thousand barrels.

Since no specific data are available regarding kerosene consumption in Lombardy, national level data was inferred on a population-basis to the size of the region. Being the population of Lombardy about 10.6 million (1/6 of the total population of Italy), some 15 300 bpd (461 000 barrel per year) were considered as reference numbers for this assessment.

Figure 13. Jet fuel consumption in Italy per day (barrel per day) 2015-2023



Source: https://www.theglobaleconomy.com/Italy/jet_fuel_consumption/

According to these figures, the additional production of 1 000 bpd of SAF would replace around 6.5 percent and 1.1 percent of the kerosene-type Jet fuel consumption in Lombardy Region and at the national level, respectively, increasing the access to sustainable liquid biofuels in line with EU targets (Table 31).

Table 31. Results of the energy access indicator for the Italian case study site

	Baseline	Target		
Lombardy Region (Target area)				
Biomethane	78 440 000	78 697 930	m^3	0.3%
Italy (National)				
Biomethane	203 640 000	203 897 930	m^3	0.1%
Lombardy Region (Target area)				
Kerosene	15 300	16 300	bpd	6.5%
Italy (National)				
Kerosene	92 200	93 200	bpd	1.1%

Source: results of the FAO's BIKE set of sustainability indicators

An agreement at the European Parliament within the framework of the ReFuelEU Aviation regulation, indicates to include at least 2% of Sustainable Aviation Fuel (SAF) in aviation fuels by 2025, a such share will increase to 6% by 2030 and reach 70% by 2050 (European Parliament, 2022). According to these targets, Table 32 provides the amount of SAF which will be needed at the Italian and EU level and the share potentially covered by the low i-LUC SAF produced by the GTL plant (1 000 bpd), based on 2023 (current) use of aviation fuel.

No data are available on current consumption of SAF in Italy. On the other hand, current SAF supply remains low at less than 0.05% of total EU aviation fuel use (EASA, 2022). These data were used to calculate the baseline and target capacity ratio considering the 1 000-bdp production of the GTL plant, following the three EU target scenarios.

Table 32. Summary of the impacts on the capacity (potential share) of SAF in the fuel consumption of the Italian and European fleet in 2025, 2030, 2050.

Item	Unit	Italy	EU 27
SAF Capacity by 2025 (2%)	bpd	1 844	107 995
SAF Capacity by 2030 (6%)	bpd	5 532	323 984
SAF Capacity by 2050 (70%)	bpd	64 540	3 779 816
Capacity ratio of SAF by 2025	**share**	54%	0.93%
Capacity ratio of SAF by 2030	**share**	18%	.031%
Capacity ratio of SAF by 2050	**share**	2%	0.003%

Source: results of the FAO's BIKE set of sustainability indicators

2.3 Conclusions

The sustainability assessment of the value chain returned interesting information that can inform decision makers at all levels, from farmers to policy makers in many EU countries. The very nature of the SAF Case Study in fact, is intended to assess the sustainability performances of a value chain, although complex and articulated, but which has a vast replication potential elsewhere in the case study country (Italy) as well as in many other EU countries. In fact, biogas production is a widespread and virtuous reality of renewable energy production in Europe. The Italian biogas sector, from which the value chain starts, shares several similarities with its homologous in Germany, Denmark, Austria, France, Belgium, the Netherlands, and many other EU-27 countries. Biomethane, the intermediate energy carrier assessed in this analysis also sees growing interest in the Member States and several upgrading plants have been built and others have been planned. However, a pre-feasibility study of the actual sustainable potential of such technologies, especially when their extreme flexibility of production is factored in, was missing until this report. Biomethane is one of the most versatile intermediate energy carriers in the world and especially in Europe, a highly developed natural gas infrastructure, looks seamlessly at biomethane as a raw material for uncountable uses. This report analysed one of particular relevance for one of the sub-sectors of the transportation sector that shows the greatest demand for sustainable alternatives to fossil fuels, aviation. Through the Gas-To-Liquid process, this report analyses the environmental, social and techno-economic implications of producing biokerosene from biomethane. The Biogasdoneright model for the initial feedstock production has also been thoroughly analysed despite limitations in data availability and quality, to provide a comprehensive assessment of the characteristics of the perspective value chain.

The basic concepts of the BDR model lived up to their promises in terms of environmental performances, although this assessment highlighted crucial points along the feedstock supply chain. Firstly, this assessment revealed numerous constraints linked to the effective scale-up potential of the BDR model outside of specific farms and territories. The conversion of the entire existing biogas sector to BDR for the production of biomethane seem a distant objective given the situation on the ground, as predominantly lack of abandoned and underutilized lands for the production of additional, low-ILUC, feedstock in the vicinity of existing biogas plants – to be converted to BDR model first, and to be equipped with biomethane upgrading equipment subsequently – and the mass balance of the co-products employed for the production of the dedicated feedstock are an ambitious and unlikely goal to meet within a foreseeable timeframe. That being said, where the BDR model can effectively be employed and verified, the environmental impacts of biomethane produced are first in class. The decentralized production of biomethane in the conditions of the case study would return an energy product with a particularly low impact on air quality, including GHG emission intensity (81.5% emission reductions compared to natural gas), and other non-GHG air pollutants. Such favorable results in terms of climate change mitigation potential is attributable predominantly to the long-term carbon sequestration potential of biodigestate into agricultural soils. Positive environmental performances are also confirmed for key indicators, such as soil quality, water availability and biodiversity, with particularly beneficial impacts on the former, again courtesy of the large amount of organic C sequestered in the soil by the application of biodigestate. The resulting aviation fuel also benefits from the advantageous characteristics of its precursors, scoring a considerable emission reduction potential compared to fossil kerosene of 58.5 percent. Social implications of the studied value chain provided useful information on jobs creation and contribution to income. In the case study area, the value chain is fully sustainable from an employment perspective, it contributes to employment rates and especially to elevating the average skill level of the workforce. These results are achieved thanks to the favorable enabling environment found in Italy, which should be used for inspiration by other EU member states. In fact, the production of biomethane can give profitable results to farmers, also thanks to the incentives to production, however these have been proven effective for medium to large scale farms (>100 ha). Economic performances of the system are positive, with net margins and returns on pair if not superior to any comparable agricultural activity while also delivering a diversification of the revenue stream, through a climate change mitigation value chain, with relevant rebounds on the adaptive capacity of those farms. These results are though, once again, fostered by a particularly supportive policy environment which through a system of incentives increases potential margins by reducing initial up-front costs for equipment as well as for connection to the grid, and even for downstream operators purchasing biomethane for the further processing into liquid aviation fuels. In conclusion this study confirms the potential of a GTL industry based on the decentralized biomethane production through the BDR model, but it also shows that the key enablers are policy-driven through monetary contributions along the value chain. The scale up potential has been instead debatable, as so it was the long-term sustainability of incentive schemes applied. However, the capacity and infrastructure indicators highlighted the minor contribution of the case study assessed to the overall demand and capacity to absorb liquid fuels for the aviation industry and thus show particularly favourable perspectives for future replication of this model.

3. The HVO Case Study

3.1. Case Study Description, Setting, System Boundaries and Main Assumptions

3.1.1 Value chain:

The bioenergy value chain involves the production of castor beans (Ricinus seeds) cultivated on a scattered agricultural area of around 10 000 hectares in the Makueni County, Kenya. Castor beans are then transported to a crushing facility (around 150 Km from the fields) where Castor oil is produced. During the crushing and pressing phases a conspicuous amount of residues from both the beans crushing (external and internal shells) and the kernel's pressing (cake) are produced. Castor bean seeds contain, in addition to oil, an alkaloid and a toxic albumin, *ricin*, which is highly poisonous and if ingested can cause illnesses and, in some cases, even death[5] to mammals, including humans and livestock. For this reason, in the operations in Makueni county, Castor residues should be pyrolyzed to produce electricity and biochar as a co-product. At the time of writing of this report, the pyrolysis plant was commissioned but not yet operational. The assessment therefore the current situation scenario (i.e. without the pyrolysis plant) and two scenarios of full operativity (i.e. 1) with the pyrolysis of castor residues and biochar incorporation into soils, and a best case scenario 2) with the pyrolysis of castor residues – including plant material and shells – in addition to all available residues in the target area, including other crops residues). Pyrolysis generates a syngas employed in the processing stages of the castor beans: through an internal combustion engine and a generator, the hydrogen-rich syngas is turned into useful electricity and heat to accomplish the crushing and pressing stages of the value chain. When at regime, the power produced via pyrolysis will displace electricity from the national grid used in the current situation scenario. The Castor oil produced (around 15 000 tonnes per year) is then transported via truck to the port of Mombasa and shipped to Gela, Italy via vessel. Once in Gela, the oil is refined to produce Hydrotreated Vegetable Oil (HVO) through the Ecofining[6] system, ENI's proprietary vegetable oil refining technology. The process can handle various feedstocks, including waste from animal and vegetable fats, as well as used cooking oils. ENI successfully converted two

[5] CDC | Facts About Ricin
[6] Ecofining™: turning organic waste into biofuel | Eni

conventional refineries into biorefineries, one located in Porto Marghera, (Venice), and a refinery in Gela (Sicily) that had contributed to the revitalization of the refining sector of Italy.

3.1.2 Makueni county

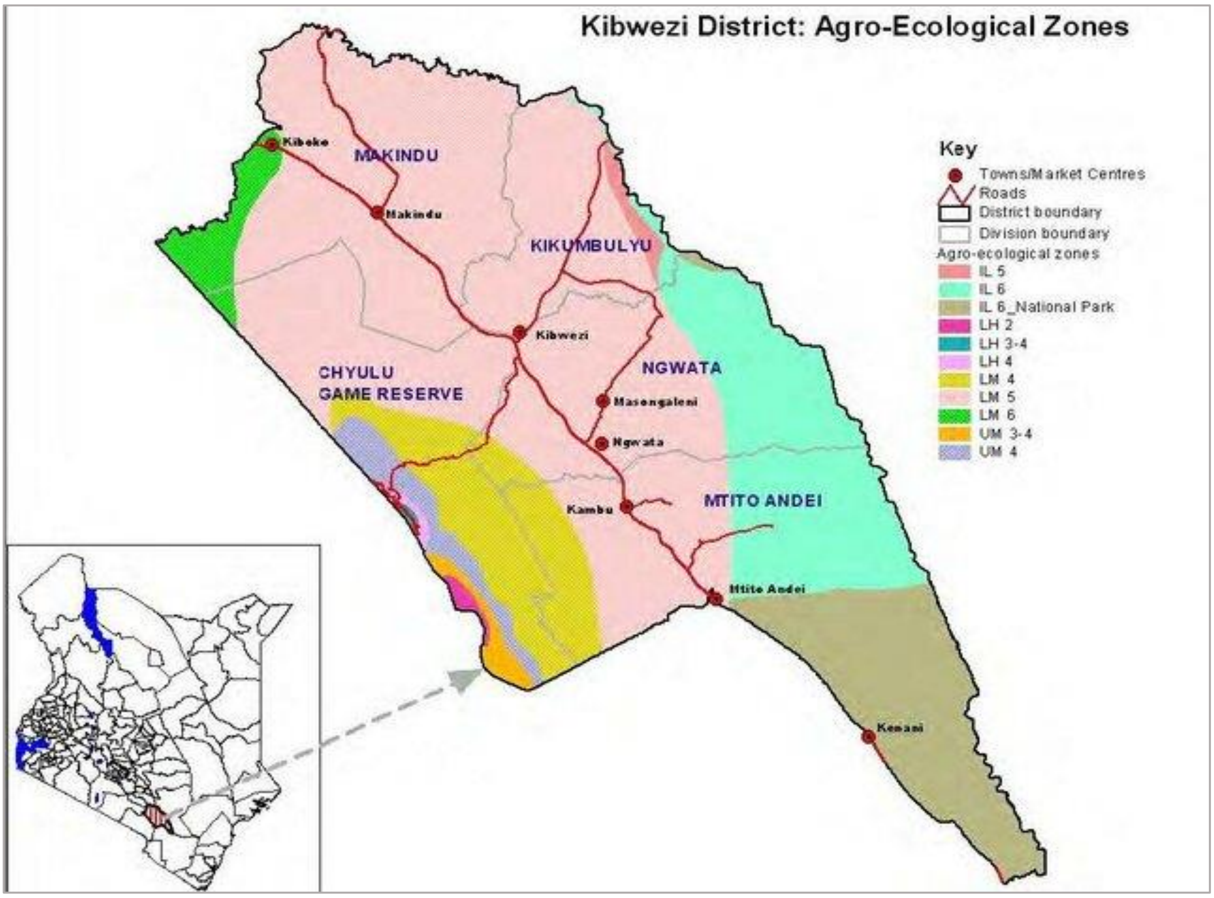
Makueni County, formerly known as Makueni District, is located in the former Eastern Province of Kenya. Its administrative centre and largest urban area is Wote. Geographically, Makueni County is situated between Latitude 1° 35' and 2° 59' South and Longitude 37° 10' and 38° 30' East. It shares borders with Machakos to the North, Kitui to the East, Taita Taveta to the South, and Kajiado to the West. Encompassing a land area of 8 008.9 square kilometers, the county's expanse is characterized by diverse and varying landscapes and agro-ecological zones (Figure 14). The climate in Makueni County is semi-arid. Average temperatures fluctuate between 15°C to 26°C. Annual precipitation patterns show a wide contrast, with lower regions receiving a scanty rainfall of 250mm to 400mm per annum, while higher-altitude areas are endowed with comparatively more substantial rainfall levels, spanning from 800mm to 900mm. As of the last census, Makueni County's total population tallies up to 987 653 individuals, with 497 942 being females (50.4 percent). The county's residential landscape is comprised of 77,495 households, each boasting an average household size of 5.8 persons. This configuration contributes to a population density of approximately 6 people per square kilometer, highlighting the county's relatively moderate population distribution across its expansive terrain.

According to the 2022 report from Technologies for African Agricultural Transformation (TAAT) (TAAT, 2022), Makueni emerges as a crucial testing ground for driving agricultural transformation within the arid landscapes of Africa. This agricultural zone grapples with significant environmental and farming challenges, yet it also holds the promise of development. The prevalence of poverty casts a wide shadow over this community, underscoring the imperative to enhance the well-being of its residents by transitioning toward a more diversified, market-driven agricultural approach.

The Impact of climate change further compounds these difficulties, introducing increasingly unpredictable and sporadic weather patterns that amplify the need for resilience against heightened risks. Paradoxically, this scenario creates a fertile ground for innovative solutions. However, the accessibility to essential resources and investments remains constrained, posing a significant barrier to progress. This issue is particularly pronounced among the youth, who possess access to online information and harbour ambitious aspirations yet encounter limited opportunities to translate their educational achievements into tangible accomplishments.

Makueni's situation and challenged environment may represent a unique opportunity to channel innovation and strategic interventions toward fostering sustainable agricultural development, improving livelihoods, and unlocking the latent promise within this community. But to achieve these goals, all investments in renewable energy solutions should prioritise and include the needs of the local population, such as the improvement of productivity, increase of personal income in rural areas, reduction of poverty in rural areas, increase renewable energy access, rise of organic farming and mitigation/adaptation to climate change.

Figure 14. Map of Makueni County, Kenya showing different Agro-Ecological Zones



Source: Kerina. 2017.

https://www.researchgate.net/publication/324748231_Evaluating_Productivity_of_Three_Legume_Species_at_Different_Agro-ecological_Zones_of_Makueni_County_Kenya

Castor bean is both cultivated as an annual and perennial plant. The seeds yield an oil with medicinal properties, but its greater importance lies as an engine oil, especially for aviation; hence, castor bean cultivation has greatly expanded and widely spread to meet the enormous demands (Mehanna, 2015). Due to the gradual maturation of the fruits, staggered harvesting is necessary (approximately every 20 days), thus requiring continued manual labour. The average production in rainy climate regions or irrigated land varies between 1 and 2.5 tons of shelled seeds per hectare.

In the case study site, mechanised land preparation and high-input agriculture is practiced. The value chain is divided into four main stages. The first stage is the feedstock production, taking place in Kenya. Field operations are mechanised whereas harvesting is performed manually by local farmers and labour. The pods are then transported to a purpose-built seed crushing facility in Makueni county named Agri Hub, located 150 km from the fields. Currently crushing and pressing operations rely on electricity from the national grid. In a separate scenario, the upcoming pyrolysis plant planned to equip the Agri Hub was also modelled. Once vegetable oil is extracted from the seeds, this is sent to the nearest port in Mombasa, and from there it is shipped via the Suez channel into the Mediterranean Sea and finally arrives in Gela, Italy. Processing of the vegetable oil into HVO takes place in the biorefinery of Gela and from there it is transported to blending locations in Italy.

The following chapters will present an overview of the assessment of relevant sustainability indicators for the low-ILUC HVO case study.

3.2. Sustainability Assessment results by indicator

3.2.1. Air Quality

The study compares the baseline scenario, which involves the traditional fuels used (i.e. fossil diesel), with the potential introduction of the low ILUC biofuel studied. It is common practice to assess the sustainability impact of bioenergy production and use based on greenhouse gas (GHG) emission intensity per unit of energy produced. The GHG emission intensity is therefore expressed in grams of carbon dioxide equivalent per megajoule of bioenergy produced (gCO_2eq/MJ).

In the baseline scenario the reference fuels/energy source used is diesel. The reference emission intensity of diesel was considered 88.49 gCO_2eq/MJ (IPCC 2006). In the target scenario, the emission intensity of HVO produced is therefore compared to the emission intensity of the reference fuel and the relative (in percentage) and absolute (in g, kg, or t of CO_2) change is reported. The main contributors and components of a GHG Life Cycle Assessment (LCA) of biofuel production and use are:

- Feedstock production;
- Feedstock transport;
- Feedstock processing into fuel; and
- Fuel transport/distribution/use.

HVO production requires the allocation with other co-products of the same value chain. The most appropriate methodology for the correct allocation and attribution among co-products of the bioenergy value chain is a highly debated topic. Conventionally in sustainability assessment of bioenergy products, when the low heating value (LHV) of all co-products is similar, a quick approximation for the allocation can be an allocation by mass. In this study, mass allocations are selected considering (Table 33) that value chain co-products have the following relative shares: 91 percent HVO, 2.2 percent bio-Gasoline and 6.8 percent Propane.

Table 33 Allocation of Green diesel HVO co-products of the HVO case study

Item	tonnes/year	Mass allocation (percentage)
Green Diesel (HVO)	5 400	91
Bio gasoline	135	2.2
Propane	388	6.8

Source: ENI

The analysis is delineated into two distinct scenarios. The first scenario delves into the existing value chain, where Castor seed crushing and pressing in Makueni is procured utilizing energy derived from sources including the national electricity grid and fossil diesel. In the second scenario, a novel dimension is introduced—the establishment of a pyrolysis plant that is planned by the case study leader (ENI) to be operational in the foreseeable future. This plant serves the dual purpose of fully powering the Vegetable Oil (VO) production process and producing biochar which in turn is applied to local soil to contribute to carbon sequestration.

Scenario 1:

The study compares the baseline scenario, which involves the traditional fuels used, with the potential introduction of the green diesel (HVO).

The baseline emission intensity for Diesel is reported as 88.49 gCO_2eq/MJ, according to the IPCC 2006. According to the University of Oxford (Figure 15), in 2022, the carbon intensity of Kenyan electricity was around 101 grams of CO_2 per kilowatt hour produced.

Figure 15. Carbon intensity of electricity, 2000 to 2022(g CO_2eq/kWh)

Source: https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=chart&country=~KEN

Concerning the target scenario, this study calculated an overall emission intensity of 33.77 gCO_2eq/MJ for HVO produced from the low i-LUC Castor beans (Table 34).

Table 34. Total emissions of GHG and non GHG air pollutants of HVO production (aggregated and allocated) in total and unitary terms

Type	Unit	Value	Unit	Value
GHG	tCO_2-eq	9 067	gCO_2-eq/MJ HVO	33.77
Non GHG	KgCO	2 024	gCO/MJ HVO	0.01
	KgNOx	7 826	gNOx/MJ HVO	0.03
	KgSOx	5 310	gSOx/MJ HVO	0.02
	KgPMx	220	gPMx/MJ HVO	0.00

Source: results of the FAO's BIKE set of sustainability indicators

Table 34 provides an overview of aggregated GHG and non GHG air emissions. As shown in Table 34 (disaggregated GHG and non GHG emissions), the step responsible for the higher GHG emission (CO_2eq/MJ of fuel) is the feedstock cultivation, followed by feedstock processing and transport.

Castor cultivation and transport:

For the cultivation of castor beans, diesel is used for land preparation, pre-sowing and biomass transport, while, according to the data provided by ENI, all other operations are hand-made (e.g. harvesting) with no diesel consumption. As provided in Table 35, in total, every year to produced 15 000 tonnes of Castor beans and to transport it to the crushing facility, around 756 000 and 42 374 kg diesel are consumed, respectively. information on agricultural inputs is also provided.

Table 35. Annual inputs for castor bean production in Makueni (15 000 tonnes fstk/year)

Item	Kg/year	Kg/ha
Diesel (Soil preparation and cultivation)	756 000	90
Diesel (Biomass transport to crushing site)	42 374	-
N from N fertilizers	220 000	22
P fertilizers	400 000	40
K fertilizers	500 000	50
Pesticides	35 000	3.5

Source: Data collected from ENI

The application of chemical inputs into the soil also contributes with direct and indirect emissions to the emission intensity of the final product.) and used to assess indirect emission as per the IPCC 2006 methodology. As shown if Table 37, it is calculated that the agricultural phases of the value chain generate some 4 777 tonnes of CO_2eq per year, over 15 000 ha cultivated with castor (for all co-products). The allocated result only considering HVO production are responsible for the emission of 4 348 tonnes of CO_2eq per year, which in unitary terms equals 18.30 g CO_2eq /MJ of HVO.

Fuel processing and transport:

The GHG emission of the first processing steps of the HVO value chain (Vegetable Oil production from Castor beans crushing) was calculated using information provided by Eni (Table 36). The total electricity from the grid for crushing is around 2 362 MWh per year. In addition, to run the crushing facility some 536 500 MJ of diesel per year are also consumed, likely to make up for blackouts and power cut offs. In total, around 286 tonnes of CO_2eq are produced annually for seed crushing and oil extraction phases.

Table 36. HVO production details

Item	Value	Unit
Total annual Castor beans production	15 000	t year
Annual VO	6 750	t year
LHV VO	37 000	MJ/t
Moisture of cake	12.00%	%
Dry Cake	6 600	t year
Energy requirement for crushing	0.01	kWh/MJ oil
Electricity used for crushing	2.3	GWh year
Diesel consumption (unitary)	0.0022	MJ/MJ oil
Diesel consumption (total)	549 450	MJ year
Hydrogenation (HVO)	9.34	gCO2eq/MJ fuel

Source: Data provided by Eni

When it comes to fuel transport, as reported by ENI, Castor oil is transported by truck from the crushing facility of Makueni County to the port of Mombasa. In total, 6 750 tonnes of vegetable oil are transported for some 380 Km with a total consumption of around 2 million MJ of diesel every year. Once in Mombasa, the VO is shipped by vessel to Gela (Italy). It will take some 7 300 Km to get to the biorefinery and a total energy consumption of around 10 million MJ of Heavy Fuel Oil (HFO). In total the fuel transport phase produces around 1 105 (allocated to HVO) tonnes of CO_2eq or 1.65 g CO_2eq /MJ of HVO.

Aggregated information about the Ecofining process efficiency and related carbon intensity have been provided by ENI. A total of 12 gCO_2eq/MJ of HVO are emitted during the hydrogenation stage taking place in the biorefinery in Gela, Italy. Such value is in line with comparable technologies as per the relevant literature and the estimates of the International Energy Agency (IEA 2018). In the current scenario (Scenario 1), however, seed crushing taking place in Makueni relies on electricity from the national grid, which although having a relatively low emission-intensity, contributes with just 1.2 gCO_2eq/MJ of HVO for a total emission intensity of the processing of castor seeds into HVO of 13.20 g CO_2eq /MJ of HVO. Further scenarios consider the production of electricity for the crushing from renewable sources, such as pyrolysis syngas, and therefore in further Scenarios the value of 12 g CO_2eq /MJ of HVO is used for the calculations of the emission intensity of the processing stages of HVO.

Table 37. Emission of GHG and non GHG of HVO production (disaggregated and allocated) in total and unitary (i.e. gCO2eq /MJ) amount of fuel (total case study production: 5 400 tonnes of HVO per year)

Emissions	CULTIVATION	FSTK TRANSPORT	PROCESSING	FUEL TRANSPORT
tCO2-eq	**4 347**	**146.7**	**3 136**	**1 025**
emission share of total	**50%**	**2%**	**36%**	**5%**
KgCO	1 746	20.4	-	134.1
KgNOx	6 704	82.5	-	542.4
KgOx	4 283	75.6	-	496.7
KgMx	196.5	1.7	-	11.4
gCO2-eq/MJ $_{HVO}$	**18.30**	**0.62**	**13.20**	**1.65**
gCO/MJ $_{HVO}$	0.01	0.00	-	0.000
gNOx/MJ $_{HVO}$	0.03	0.00	-	0.000
gSOx/MJ $_{HVO}$	0.02	0.00	-	0.000
gPMx/MJ $_{HVO}$	0.00	0.00	-	0.000

Source: results of the FAO's BIKE set of sustainability indicators

In conclusion, the analysis of Scenario 1 estimated a final potential annual GHG emission reduction of around 17 213 tonnes of CO_2eq. This represents a substantial reduction of approximately 55 gCO_2eq/MJ compared to the baseline (fossil diesel fuel), resulting in a 62 percent emission reduction (Table 38). About 54 percent of the total emission intensity of the product is attributable to the feedstock production phase. Tillage operations and chemical inputs are not provided in heavy amounts however, due to the relatively low productivity of the crop in the conditions of the case study (marginal land), these are responsible for the majority of the emissions of the HVO produced.

Table 38. Total avoided emission of GHG and non GHG of kerosene production (aggregated and allocated) in g and g/MJ of fuel

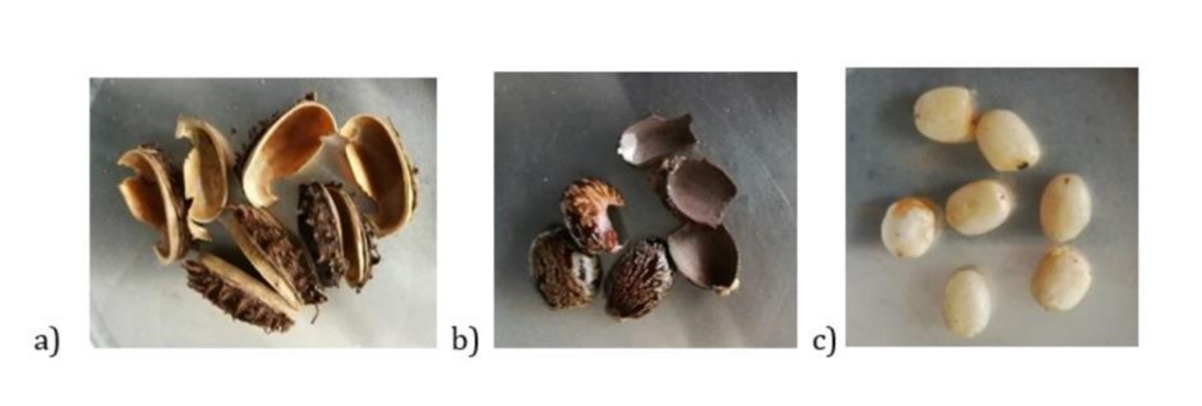
Type	tCO_2-eq	gCO_2-eq/MJ $_{CH4}$
HVO	9 067	33.77
Diesel	26 280	88.48
Total Avoided	-17 213	-54.71

Source: results of the FAO's BIKE set of sustainability indicators

Scenario 2: pyrolysis of locally produced castor residues and biochar application to soil

Castor bean (Ricinus communis) plays a crucial role as a non-edible oilseed crop, primarily valued for its production of castor oil. This versatile oil finds application across various industries, encompassing cosmetics and biofuels. However, the process of extracting castor oil results in the generation of substantial quantities of de-oiled castor cake. This residue contains ricin, a glycoprotein known for its potent toxicity, necessitating proper treatment before it can be effectively utilized.

Figure 16. Components of castor oil seed used for gasification: a) outer shell, b) internal shell, c) seed



Source: https://ibimapublishing.com/articles/IJREB/2019/529157/

This scenario focuses on the production and utilization of biochar, obtained through a controlled process of slow pyrolysis at 550°C. Biochar is derived from two by-products of castor oil production, castor stalks and de-oiled castor cake. The objective behind this endeavour is to explore ways for valorising these by-products, while abating health risks associated with improper management of these harmful materials with a particular emphasis on the potential for large-scale cultivation of castor beans in Africa. By converting castor-derived residues into biochar, the value chain contributes to the development of an ecologically sound approach to dealing with castor oil production residues. Furthermore, it addresses the challenge posed by ricin-containing de-oiled castor cake, which requires proper management. This utilization of biochar potentially offers promise in aligning castor bean cultivation with sustainable practices, thereby benefiting both economic and environmental facets. Finally, syngas produced during the pyrolysis process is used to cover 100 percent of the electricity and the diesel needed by the crushing facility in scenario 1. Table 39 provides the products distribution of the castor bean crushing in tonnes and percentage.

Table 39. HVO value chain products mass distribution

Product	Tonne/tonne feedstock	Percentage
Vegatable Oil	0.45	45%
Cake	0.43	43%
Water (in cake)	0.12	12%

Source: Data collected from ENI

As already described, the production of green electricity would allow to reduce emissions produced during the crushing phase of the value chain. In addition, as shown in Table 40, the application of biochar to soil would allow to annually store some 6 167 tonnes of CO_2eq per year. Specifically, the total C content of castor cake biochar considered is 68% (Hilioti, 2017), of which 97% is stored into soil in the long term (Phillips, 2022).

Table 40. Yearly carbon storage from biochar application for the HVO case study

Item	Value	Unit
Applied biochar	2 550 000	Kg year
Total C (before application)	1 734 000	Kg year
Total C stored into soil	1 681 980	Kg year
Total CO2e sequestred	**6 167 260**	**Kg year**

Source: results of the FAO's BIKE set of sustainability indicators

On the other hand, it should be noted that biochar in this scenario is transported by truck from the crushing site to the feedstock production sites (average distance is 150 Km) and this would generate some 27.4 tones of CO_2eq per year (Table 41).

Table 41. Transport of biochar. From production site to crushing - TRUCK

Item			**Unit**	**Value**
Transport: Biochar transport			Km	150
Total Biochar production			Tonnes	2 550
Total Diesel consumed			MJ	309 825
	Unit	**Value**	**Unit**	**Value**
	gCO	3 814	g CO_2fossil	26 386 851
	gNO_x	15 417	g CO_2biogenic	0
	gSO_x	14 119	g CH_4fossil	40 978
	gPM_x	325	g CH_4biogenic	0
			g N_2O	162
			Kg CO_2 eq	**27 415**

Source: results of the FAO's BIKE set of sustainability indicators

In conclusion, the analysis of Scenario 2 of the HVO produced from castor estimated a final potential annual emission reduction of some 23 639 tonnes of CO_2eq. This represents a substantial reduction of approximately 79 gCO_2eq/MJ compared to the baseline (fossil fuel), resulting in an 89 percent emission reduction (Table 42). The role of pyrolysis, and biochar production and incorporation into the soil, is key to obtaining high sustainability performance for this bioenergy value chain.

Table 42. Emission of GHG of HVO production (disaggregated and allocated) in gCO2eq /MJ and percentage of total Scenario 2

Emissions	CULTIVATION	FSTK TRANSPORT	PROCESSING	FUEL TRANSPORT	BIOCHAR SEQUESTRATION
tCO2-eq	**4 347**	**146.7**	**3 136**	**393**	**6 167**
gCO2-eq/MJ HVO	**18.30**	**0.62**	**12.00**	**1.65**	**- 25.96**

Table 43. Total avoided emission of GHG and non GHG of diesel production (aggregated and allocated) in overall and unitary terms

Type	Emission Intensity in gCO_2eq/MJ_{HVO}	Percentage
HVO	6.82	8%
Diesel	88.48	100%
Total Avoided	-81.66	-92%

Source: results of the FAO's BIKE set of sustainability indicators

Scenario 3: pyrolysis of all available agricultural residues in the target area and biochar application to soil

In addition, upon request from the case study partner, FAO carried out the assessment of a *best case scenario* which considers and increased biochar production due to the pyrolysis of all agricultural residues available in the target area and their incorporation into the soils used for the production of castor. In addition to castor bean press cake (2 550 tons), the maximum theoretical residue availability in the area of castor production includes the availability of agricultural crops such as sugarcane bagasse, coconut residues and others. These account for an additional 4 050 tons of biochar potentially produced per year. Increased biochar production would lead to increased emissions from transport, which have been factored consistently with the previous scenario.

The analysis of this *best case scenario* returned interesting results. Incorporating large amounts of biochar (660 kg/ha) into the soils used for the cultivation of a bioenergy feedstock, has the potential to store more carbon than it is emitted by the biofuel produced in the value chain and much less than its fossil alternative. Total achievable emission savings from soil carbon accumulation (Esca) is estimated at -67.18 grams of CO_2 equivalent for each Megajoule of fuel produced. By putting this reduction into context, the overall net emission intensity of the HVO would therefore be obtained by subtracting the emission savings from soil carbon accumulation to the emission intensity of HVO from Scenario 1 (i.e. 33.77 gCO_2eq/MJ) for a total negative emission of -34.24 gCO_2eq/MJ (-139% reduction compared to diesel). The European Commission, with Regulation (EU) 2022/996 of 14 June 2022, regulates the verification of sustainability and greenhouse gas emissions saving criteria and low indirect land use change-risk criteria of biofuels. Although the results obtained with this exercise reveal a potential sequestration of CO_2 eq into the soils of 67.18 grams per MJ of fuel, existing regulations capped the admissible reduction to 45 gCO_2eq/MJ. Recalculating the final emission intensity of HVO produced in Scenario 3 considering the existing cap in terms of Esca, would result in an emission of -12.06 gCO_2eq/MJ or a saving of -114% compared to fossil diesel.

Table 44. Emission of GHG of HVO production (disaggregated and allocated) in gCO2eq /MJ and percentage of total Scenario 3

Emissions	CULTIVATION	FSTK TRANSPORT	PROCESSING	FUEL TRANSPORT	BIOCHAR SEQUESTRATION
tCO2-eq	**4 347**	**146.7**	**3 136**	**393**	**15 962**
gCO2-eq/MJ $_{HVO}$	**18.30**	**0.62**	**12.00**	**1.65**	**- 67.18**

Table 45. Total avoided emission of GHG and non GHG of diesel production (aggregated and allocated) in overall and unitary terms

Type	Emission Intensity in gCO_2eq/MJ_{HVO}	Percentage	Emission Intensity Esca in gCO_2eq/MJ_{HVO}	Percentage Esca
HVO	-34.24	-39%	-12.06	-14%
Diesel	88.48	100%	88.48	100%
Total Avoided	-122.72	-139%	100,54	-114%

As for the previous scenario, Scenario 3 clearly shows the pivotal role of biochar production and incorporation into the soil and its potential for long-term carbon sequestration as an effective mitigation strategy.

3.2.2. Soil Quality

Assessing the sustainability of a bioenergy value chain requires a comprehensive understanding of various factors, including soil quality. Traditionally, quantitative indicators have been used to evaluate soil quality, but they often present limitations such as site specificity, the need for long-term monitoring, and the requirement for specialized evaluation skills. Alternatively, due to the unavailability of quantitative data, a qualitative assessment can offer valuable insights into the conditions necessary for maintaining or enhancing soil quality characteristics. In this paragraph, the results of a purely qualitative indicator employed to assess soil quality performances within the studied agricultural soils are presented.

The indicator relies on the identification and frequency of specific management practices implemented. By evaluating the occurrence and frequency of traditional versus improved soil management practices using a scorecard method, this assessment provides an indication of potential benefits or challenges related to soil quality. The scorecard method assigns different scores to various practices, considering that certain operations, such as mechanized ploughing and tilling, have been found to have more detrimental effects on soil quality compared to others (e.g., monocropping). By considering the combination of different practices, this approach offers a qualitative indication of the risk level associated with soil quality maintenance.

Table 43 presents the results of the agronomic practices investigated by the assessment. Organic matter addition (biochar), crop rotation and windbreaks are all positive practices that has been considered to produce the bioenergy feedstock. Biochar, a soil enhancer, creates pores for improved air and water movement, curbing erosion. With its high porosity, it retains water, aiding plants in dry spells. Nutrient-rich biochar adsorbs and holds vital elements, bolstering plant growth while preventing pollution from leaching. A haven for beneficial microorganisms, it fosters nutrient cycles and soil health. Biochar's carbon stability aids climate action by sequestering carbon, and its pH effects stabilize soil, mitigating erosion risks.

Crop rotation, the sequential planting of diverse crops on the same land across seasons, offers multifaceted benefits. It optimizes nutrient management, curbs pests and diseases, controls weeds, improves soil structure, prevents erosion, boosts organic content, enhances biodiversity, and fosters sustainability by reducing monoculture and chemicals. This practice nurtures soil health, ecological balance, and long-term farm productivity.

Table 46. Presence and frequency of the best soil quality management practices of the HVO-Kenya case study

	Value	Score
Organic matter addition (e.g. manure, biochar, etc.)	Applied	1
No-tillage, minimum tillage, reduced tillage	Not applied	0
Crop rotation (incl. or excl. fallow, intercropping, etc.)	Applied	1
Continuous cover crop	Not applied	0
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Windbreaks, shelterbelts, etc.	Applied	1
Biofertilizer and living organisms management	Not applied	0
	SCORE	**3**

Source: results of the FAO's BIKE set of sustainability indicators

In addition, occurrence and frequency of traditional soil management practices was also assessed. As presented in Table 44, mechanization applying deep tillage, use of chemical fertilizers, are all practices that are implemented in this case study. On the other hand, irrigation systems and monocropping are not implemented.

Table 47. Occurrence and frequency of traditional soil management practices of the HVO case study

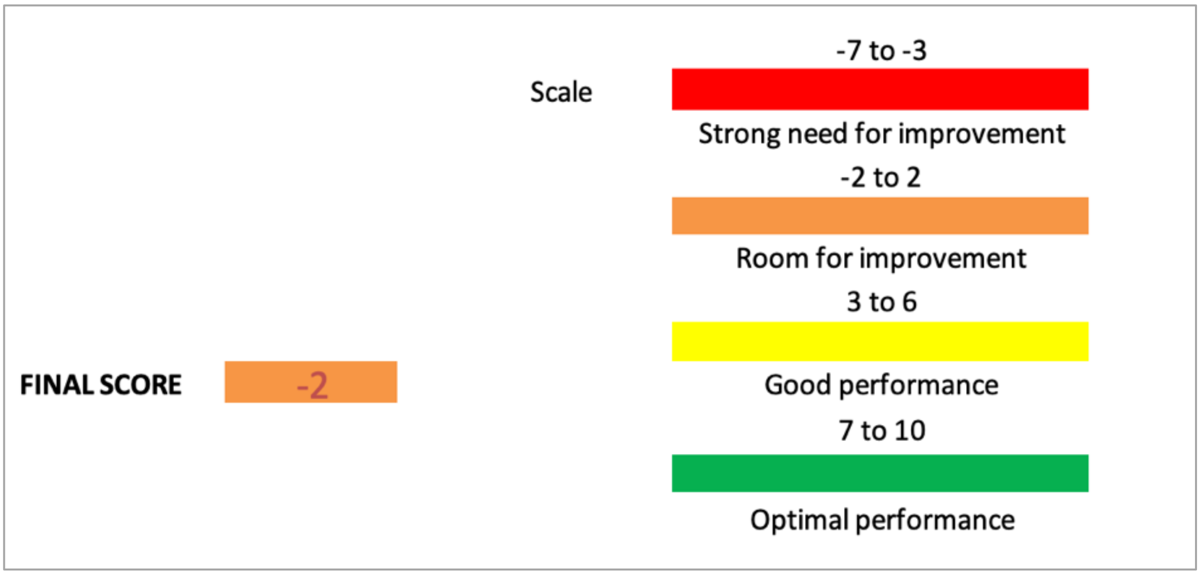
	Value	Score
Mechanized land preparation	Applied	-1
Deep and surface tillage (incl. moldboard plow, ripper, etc.)	Applied	-3
Use and rates of synthesis fertilizers	Applied	-1
Irrigation rates and irrigation systems (e.g. flooding or sprinklers)	Not applied	0
Monocropping (annual crops only)	Not applied	0
	SCORE	**-5**

Source: results of the FAO's BIKE set of sustainability indicators

These results demonstrate that crop rotations and the application of biochar can be valid tools to improve agriculture sustainability. The continuous restitution of organic matter (OM) with biochar can support a dynamic C sequestration in soils. In particular, the increase of soil organic matter can enhance soil fertility and stability and maintain soil nutrients. It can increase soil biodiversity, and reduce erosion, leaching and water pollution. In fact, while chemical fertilizers supply only specific nutrients, organic matter provides a diverse range of nutrients and acts as a source of energy for soil microorganisms.

As reported in Figure 17, the indicator scored -2 points in a scale between -7 and 10, demonstrating the moderate performance of the case study. Overall, the result of the soil quality indicator is hampered by traditional tillage operations, particularly deep ploughing, and the of heavy pre-sowing machinery, two practices proven to lead to long-term decay of soil quality. The introduction of further sustainable agronomic and soil quality practices (e.g. IPM, continuous cover, etc) should be considered.

Figure 17. Final score of the soil quality indicator and related scale of credit score for the HVO-Kenya case study



Source: results of the FAO's BIKE set of sustainability indicators

3.2.3. Water Use

According to Nkurunziza 2022, Makueni experiences a bimodal rainfall pattern, with an extended rainy season from March to May (MAM) and shorter rains from October to December (OND). Cropping commencement varies due to unpredictable rainfall. While short rains are more reliable, long rainy seasons often lack predictability, leading to one-season cropping. Rainfall ranges from 250 to 400 mm in low-lying parts and 800 to 900 mm in hilly regions. Monthly temperature averages 20-26°C in hills and up to 35.8°C in low-lying areas. Crop-growing seasons exceeding half the potential evapotranspiration are rare, with many receiving under 250 mm, unsuitable for maize and other food crops. Although the changing climate conditions represent a potential barrier to maise and other intense water need agricultural crops, castor production, with an evapotranspiration between 300 and 400 mm per year, may represent an alternative solution particularly during dry seasons. In Makueni, agricultural production is mainly rainfed-subsistence, although a small proportion (~100 ha; 900 households) of the cultivable area in Makueni is under irrigation (Nkurunziza, 2022).

Makindu meteorological station data indicates average MAM and OND rainfall of 280 mm and 294 mm. Figure 18 shows long-term and short-term average rainfall and temperature.

Figure 18. Long-term average rainfall (1961–2012) and short-term (2015–2019) average annual rainfall and temperature in the two main growing seasons in Makueni: March, April, and May (MAM) and October, November, and December (OND).

Growing season	Rainfall (mm)						Temperature (°C)				
Season	1961–2012	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
MAM	280	318	247	155	560	139	26.4	27.1	26.7	24.7	27.3
OND	294	414	261	213	364	695	26.3	26.7	26.0	25.6	24.9

Source: **Nkurunziza**, 2022. https://www.frontiersin.org/articles/10.3389/fclim.2021.766583/full

The production of biomass requires no additional irrigation water in the case study site and it returns yields of around 1.5 t ha-1 yr-1. Makueni County offers more water than the Ricinus uses for biomass production. As shown in Table 45 below, this translates into a total water requirement of 0.03 km3/year to provide water to produce biomass (10 000 ha for 5 400 tonnes per year of HVO). The blue water percentage over total water use of the agricultural phase is zero as the totality of the water used by the plants is green water.

Table 48. Renewable (blue) water used for feedstock production

Item	Value	Unit
Crop yield	1.5	ton/ha
Cultivated surface	10 000	ha
Crop ET	300	mm/year
Effective precipitation (Oct-Jun)	600	mm/year
Crop production	15 000	ton
Annual irrigation requirement	-300	mm/year
Unitary water requirement	3 000	m_3/ha
Unitary water requirement	0.03	Km_3/year
Unitary water(Irrigation) requirement	-3 000	m_3/ha
Unitary water(Irrigation) requirement	-0.03	Km_3/year
Tot. water for feedstock production (Wfstk) renewable	0	Km_3/year

Source: results of the FAO's BIKE set of sustainability indicators

Concerning the processing phases, which involves the production of VO, and the hydrogenation to HVO, the impact of water use and efficiency of the water requirements of the processing stage is represented mainly by the refining process' requirements for water makeup which is 3.2 m^3 per ton of feedstock (Table 46). The refinery is located in Gela, a semi-arid and water-stress prone area of Italy. In case water is withdrawn by wells (groundwater) even the limited amounts necessary for the processing stages of the value chain might, in the long run, require some form of compensation or conservation practice.

Table 49. Renewable water used for HVO production

Item	Value	Unit
Water consumption	3.21	m^3/tfstk
	0.000048	Km^3/year
VO production	5 400	tonnes/year
LHV HVO	44	MJ/m^3
Total energy output	237 600 000	MJ/year
Wbioenergy / Etotal	0.000203	tonne/MJ
	0.202652	l/MJ
Production	3.2	$m^3/t_{feedstock}$

Source: results of the FAO's BIKE set of sustainability indicators

3.2.4. Water Quality

The indicator relies on the identification and frequency of specific management practices implemented. By evaluating the occurrence and frequency of traditional versus improved water management practices using a scorecard method, this assessment provides an indication of potential benefits or challenges related to water quality. The scorecard method assigns different scores to various practices, considering that certain operations, such as processing water treatment, have been found to have more detrimental effects on water quality compared to others. By considering the combination of different practices, this approach offers a qualitative indication of the risk level associated with water quality maintenance.

The indicator considered the following best practices for the sustainability assessment: No tillage, minimum tillage and or reduced tillage, the application of organic agriculture, the use of conservational buffers, erosion sediment control and the wastewater treatment at the feedstock and fuel processing level. As shown in Table 47, only conservation buffers and processing waste-water treatment are applied in the case study.

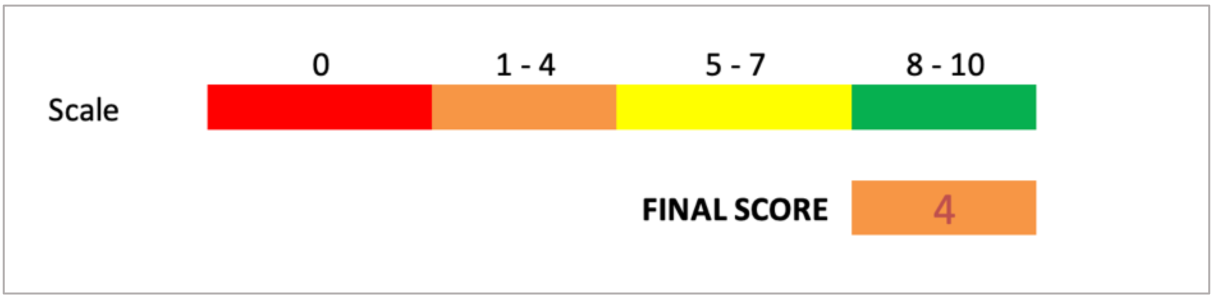
Table 50. Presence and frequency of the best water quality management practices of the HVO case study

	Value	Score
No-tillage, minimum tillage, reduced tillage	Not applied	0
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Conservation buffers (buffer zones, corridors, etc.)	Applied	1
Erosion and sediment control	Not applied	0
Wastewater treatment of bioenergy processing	Applied	3
	SCORE	**4**

Source: results of the FAO's BIKE set of sustainability indicators

As reported in Figure 26, the indicator scored 4 points out of 10, demonstrating the room for performance improvements of the water quality indicator for this case study. Overall, the case study promotes wastewater treatment and the presence of conservation buffers (not verified in the context of this assessment), and to an extent the protection of natural resources. By adopting additional responsible water quality management practices, however, HVO producers can contribute to a more sustainable and environmentally friendly bioenergy sector in line with EU policies and strategies.

Figure 19. Final score of the water quality indicator and related scale of credit score



Source: results of the FAO’s BIKE set of sustainability indicators

3.2.5. Biodiversity

Agronomic best practices can significantly improve biodiversity in the European Union (EU) by promoting sustainable and eco-friendly farming techniques. These practices focus on preserving natural habitats, implementing crop diversity, reducing chemical inputs, and managing water resources efficiently. By adopting such methods, farmers create a more diverse and resilient ecosystem that supports a wide range of plant and animal species. This approach not only safeguards the environment but contributes also to the health of pollinators, beneficial insects, and soil microorganisms.

Table 51. Presence and frequency of the best biodiversity management practices of the HVO-Kenya case study

Presence and frequency of the best management practices	**Value**	**Score**
Invasive alien species	Applied	-3
No-tillage, minimum tillage, reduced tillage	Not applied	0
Crop rotation (incl. or excl. fallow, intercropping, etc.)	Applied	1
Continuous cover crop	Not applied	0
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Windbreaks, shelterbelts, etc.	Applied	1
Biofertilizer and living organisms management	Not applied	0
Conservation buffers (buffer zones, corridors, etc.)	Applied	1
No shrubs removal	Applied	2
Use 1 ha every 100 ha for planting legumes/cereals for wildlife	Not applied	0
Pollinators management (bees, Bumblebees, etc..)	Applied	2
Avoiding open field burning	Applied	1
Agroforestry (multi-layers of canopy, etc..)	Applied	2
Report and protect nest	Not applied	0
Ensure that species are not collected	Not applied	0
Cooperation with environmental or nature protection organizations	Applied	2
Promote awareness campains on biodiversity conservation in agriculture	Applied	2
Erosion and sediment control	Not applied	0
Wastewoter treatment of bioenergy processing	Applied	3
	SCORE	**14**

Source: results of the FAO's BIKE set of sustainability indicators

The indicator relies on the identification and frequency of specific management practices implemented. By evaluating the occurrence and frequency of traditional versus improved water management practices using a scorecard method, this assessment provides an indication of potential benefits or challenges related to biodiversity preservation. The scorecard method assigns different scores to various practices, considering that certain operations have been found to have more detrimental effects on biodiversity compared to others. By considering the combination of different practices, this approach offers a qualitative indication of the risk level associated with biodiversity preservation.

As shown in Table 48, a substantial number of good practices are applied for the production of Castor in Makueni and its processing into fuel. Best practices, such as crop rotations, presence of buffer zones and windbreaks, and soil erosion control, play a crucial role in biodiversity preservation. Through diverse crop rotations, soil health and nutrient availability are enhanced, creating favourable conditions for a variety of plant and animal species to thrive. Windbreaks provide habitats for birds and insects, promoting biodiversity within agricultural landscapes. Additionally, effective soil erosion control prevents sediment runoff into water bodies, preserving aquatic ecosystems and their inhabitants. By incorporating these practices, agronomy contributes directly to the conservation of biodiversity by nurturing resilient ecosystems and habitats. On the other hand, intensive tillage operations, use of pesticides and chemical fertilizers, the use of invasive alien species are all factor which could potentially impact negatively local biodiversity.

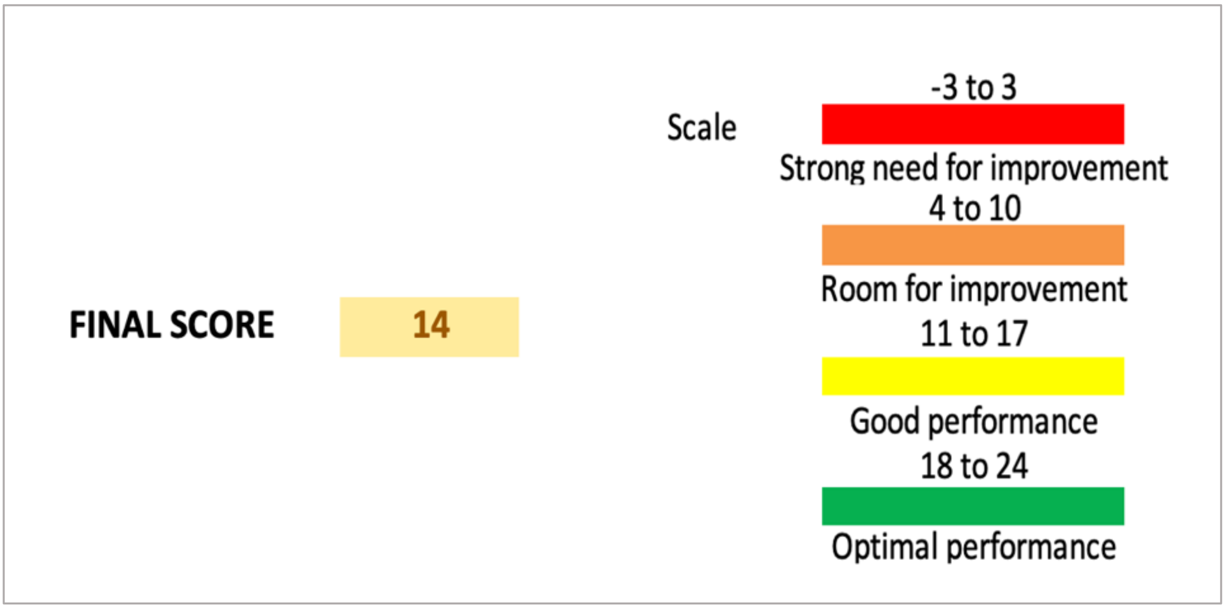
Other practices, more directly related with biodiversity such as conservation buffers and corridors, no shrubs removals, pollinators management, avoiding open field burning are employed in the case study, and are conducive to a favourable score in this qualitative assessment.

Cooperation with local organization and creation of awareness within stakeholders and farmers are also activities which can potentially be done in loco. Indeed, alongside agronomic best practices, fostering cooperation with local organizations and raising awareness among stakeholders and farmers are essential activities to effectively preserve biodiversity within a given area. Collaborating with local environmental and conservation organizations enables the pooling of resources, knowledge, and expertise, resulting in more holistic and impactful conservation efforts. These partnerships can facilitate the identification of key biodiversity hotspots, the implementation of habitat restoration projects, and the establishment of protected areas or wildlife corridors. Creating awareness among stakeholders, including farmers, local communities, and businesses, is pivotal in promoting a collective sense of responsibility and understanding about the importance of biodiversity. Through educational workshops, community engagement events, and outreach campaigns, stakeholders can be informed about the role of diverse ecosystems in sustaining food security, clean water, climate regulation, and overall human well-being. This awareness can lead to a shift in attitudes and behaviours, encouraging the adoption of sustainable land-use practices that prioritize biodiversity conservation.

Engaging farmers in this process is particularly impactful, as they are directly connected to the land and often play a central role in shaping the landscape. Providing training on biodiversity-friendly farming techniques, such as agroforestry, intercropping, and habitat preservation within agricultural fields, empowers farmers to integrate conservation practices into their daily operations. By showcasing the potential benefits of these practices, such as increased crop resilience, improved soil quality, and enhanced ecosystem services, farmers can become champions of biodiversity preservation within their communities. Incorporating local traditional knowledge and cultural practices can also strengthen the sense of stewardship for the land and its biodiversity.

As shown in Figure 20, the measurement of the indicator for the HVO case study returned good performance of this value chain with regards to biodiversity conservation.

Figure 20. Final score of the biodiversity indicator and related scale of credit score for the HVO case study



Source: results of the FAO's BIKE set of sustainability indicators

3.2.6. Jobs in the bioenergy sector

Makueni County demonstrates subpar performance across various socio-economic indicators. The county's Human Development Index (HDI) stands at 0.48[7], aligning closely with the national average. This index, encompassing factors like life expectancy, educational attainment, and income, highlights the county's developmental shortcomings. Evident poverty is pervasive, translating into unfavourable socio-economic outcomes encompassing inadequate nutrition, healthcare, and education, as well as restricted access to fundamental services. A pressing concern is unemployment, particularly among the youth segments. Most of the population engages in agricultural activities, with limited prospects within commercial enterprises and the public sector. Given the swift population growth, an influx of young individuals into the labour force is projected to intensify the strain on available employment opportunities.

Advanced bioenergy value chains have the potential to produce employment in the agriculture sector (feedstock production) as well as in the industrial sector (feedstock processing) and accessory sectors too (e.g. transport of biomass, induced jobs for the production of inputs, machineries, etc.). According to the strategic intervention 7 of the Annual Development Plan (adp) 2020/21 (GMK, 2019) developed by the Makueni's Department of Finance & Socio-Economic Planning, the main industrial crop in the county is sisal (a fibre crop grown mostly in Eastern Africa) in lower zone (Kibwezi East Sub County) and coffee and macadamia produced in the upper zone of the county (Mbooni and Kaiti Sub County). A clear goal of the County's development Plan is to promote increased production of industrial crops, through a list of support actions, such as: enhancement of access to credit by the farmers through local commercial banks, facilitate access to inputs such as certified seeds and fertilizer, enhancement of the capacity of the extension officers on promoting the industrial crops, enhancement of marketing and market linkages, strengthening the cooperatives along the industrial crops value chains, capacity build on skills development in precision processing for export market standards, and support in processing equipment to the youth and women empowerment programme (GMK, 2019).

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7 https://data.humdata.org/dataset/kenya-human-development-index-per-county/resource/b46703cc-196f-4e40-860f-e1dd1709d81c

In this context, castor can create new income activities through the creation of additional job opportunities and to increase industrial productions which can be more resilient to climate change. As provided in Table 49, in the target scenario at the farm level, the production of castor beans would employ both skilled and unskilled workers to plant, cultivate, harvest and transport the feedstock to the crushing site. It is estimated that 10 000 hectares would produce annually some 69 skilled and 1 031 unskilled job positions. In addition, considering the transportation of the VO to Mombasa commercial port, a total of 71 skilled positions (truck drivers) are created by the value chain.

No information on employment was provided for the biorefinery in Gela, Italy, and it was thus impossible to evaluate the potential impact on employment of the second part of the HVO value chain.

Table 52. Results of the job indicator in Kenya (VO from Castor)

	Skilled positions		**Unskilled positions**	
Feedstock production phase	**Hours/year**	**Days/year**	**Hours/year**	**Days/year**
Land preparation	70 000	8 750	0	0
Land cultivation	60 000	7 500	790 000	98 750
Harvesting	0	0	1 190 000	148 750
Fuel production phase				
Vegetable oil extraction	1	0	0	0
oil refining	252	32	0	0
oil hydrogenation	0	0	0	0
Pyro-gasification	0	0	0	0
Aggregated workers (Alternatively)	0	0	0	0
Transport of biomass				
Drivers/loaders	3 000	375		
Transport of fuel				
Drivers/loaders	2 138	267		
TOTAL SKILLED JOB POSITION	71			
TOTAL UNSKILLED JOB POSITION	1 031			

Source: results of the FAO's BIKE set of sustainability indicators

3.2.7. Energy access

***Makueni County**:* According to Makueni Government (GMC, 2018), only 7 per cent of households in the County use electricity for lighting compared to a national average of 22.9 per cent with the distribution of population by mode of lighting is lantern 63.3%, tin lamp 25.3%, electricity 5.7 per cent and solar 3.8 per cent. In its Development Program, Vision 2030, (adopted in 2008) the Kenyan government acknowledges the challenges within the electricity sector and places a strong emphasis on enhancing both production and efficiency. To realize this goal, the program outlines a comprehensive strategy involving ongoing energy sector reforms, the establishment of a robust regulatory framework, and attractive incentives to encourage private investment, while concurrently fostering the exploration and exploitation of emerging energy sources such as geothermal and renewable energies.

Unfortunately, based on the simulations of the castor oil production value chain, no surplus electricity is expected to be produced, even when the pyrolysis plant will be operational. Pyrolysis products in fact can only cover internal Agri Hub demand for crushing and oil extraction and surplus electricity once the needs of the plant are satisfied is not foreseen. Generating surplus electricity to be fed to a mini-grid would have expanded energy access, or could have made up for the periods of blackout of the national grid, also contributing with modern energy services to the development of the area.

Potentially, in this context the developers could initiate an assessment to evaluate the availability of additional biomass resources within Makueni County and size the pyrolysis plant accordingly, to generate value in the form of surplus electricity and exploiting economies of scale for enhanced efficiency of the pyrolysis/gasification systems. This assessment would involve identifying potential sources of biomass, such as agricultural residues, forestry by products, and organic waste, which could be utilized as feedstock for the pyrolysis plant. This can be done by running surveys, engaging with local communities and stakeholders, and analysing existing data to determine the quantity and sustainability of these biomass resources.

***Italy and EU 27**:* Regarding HVO production, the analysis considers Italy and the EU but additional availability of HVO on the local, national or EU market, does not directly expand access to energy – which for liquid fuels in the EU context is not constrained like in the case of electricity in Kenya – this indicator is not relevant. The additional HVO produced however has an impact on the capacity of use of advanced biofuels in both national and EU markets and this feature is investigated in the related indicator in this assessment.

3.2.8. Productivity

Unfortunately, reliable information on the productivity of the castor value chain could not be shared by ENI due to industrial competitivity limitations and therefore this indicator could not be measured for this case study. Particularly, the evaluation of the studied value chain is hampered by the lack of available socio-economic and financial data concerning wages, market prices, production costs and revenues, etc. Despite several attempts to collect information or derive proxies, such data gap prevents a thorough analysis of the project's potential to drive economic empowerment among local beneficiaries. Primary data collection, surveys and sample interviews should be carried out and data presented in aggregated form to avoid exposing to competitivity issues the developers.

3.2.9. Investment

As for the productivity indicator, reliable information on the investment of the castor value chain could not be shared by ENI and therefore this indicator could not be measured for this case study.

3.2.10. Net Energy Balance

This indicator calculates the difference in energy inputs necessary to produce the biomass, transport it to the biorefinery/bioenergy plant, process it into advanced biofuel and, lastly, distribute the fuel. The existing castor value chain is assessed, and it does not include the potential future implementation of the pyrolysis unit.

At the farm level, annual energy inputs and outputs are reported in Table 50. At feedstock production phase (castor beans), cultivation of the crop requires energy for land preparation (tillage) and fertilization operations. Fertilization includes the application of chemical fertilizers. Pesticides are also applied, and their embedded energy is considered as an input into the system as well. Biomass transport is also considered as an energy input due to the diesel consumption of the tractors and trucks delivering the biomass.

Table 53. Castor bean cultivation energy inputs of the HVO value chain

FEEDSTOCK PRODUCTION		
Diesel from Agriculture	Diesel consumption	
Land preparation	Kg DIESEL yr-1	756 000
Cultivation	Kg DIESEL yr-1	0
Harvesting	L DIESEL yr-1	0
	Total Yearly Diesel Consumption (MJ)	32 515 560
Chemical inputs for Agriculture		
Amount of fertilization (chemical) N	Kg yr-1	500 000
Amount of fertilization (chemical) P	Kg yr-1	400 000
Amount of fertilization (chemical) K	Kg yr-1	500 000
Amount of applied pesticides	Kg yr-1	35 000
Amount of biodigestate	Kg yr-1	0
	Total Yearly Inputs Consumption (MJ)	51 294 800
Biomass transport		
Average distance field to crushing plant	Km	150
Total FSTK production (tot ha*yield)	Tonnes	15 000
	Total Yearly Diesel Consumption (MJ)	1 822 500

Source: results of the FAO's BIKE set of sustainability indicators

Subsequently, during the crushing phase (vegetable oil extraction) the energy needed to produce castor oil involves both electricity from the national grid (8 505 000 MJ/year) and diesel fuel (536 507 MJ/year) (Table 51).

Table 54. SVO Production Inputs (Crushing)

Total electricity for crushing (GRID)	MJ	8 505 000
Total diesel for crushing	MJ	536 507

Source: results of the FAO's BIKE set of sustainability indicators

Concerning the transport of the VO from the crushing facility to the Mombasa port, the total diesel consumption accounts for 2 077 650 MJ per year. Castor oil is then transported by ship from Mombasa to Gela, Italy, for a total HFO consumption of 9 900 900 MJ (Table 52).

Table 55. Castor oil (SVO) transport inputs (MJ) - Production site to Gela (Italy)

Transport of VO from crushing to Mombasa		-
Total DIESEL consumed	MJ	2 077 650
Transport of VO from Mombasa to Gela		-
Total HFO consumed	MJ	9 900 900

Source: results of the FAO's BIKE set of sustainability indicators

HVO production passes through different stages, the main ones being hydrogen production for the hydrotreatment. Hydrogen production is usually carried out in a steam reformer, where water and natural gas are mixed and react to form hydrogen and carbon monoxide. As showed in Table 53, to produce HVO from the castor oil produced in Makueni some 270 000 MJ of electricity and around 3 547 800 MJ to generate steam are needed for the VO pre-treatment process. Additionally, around 23.7 million MJ of electricity and around 508.6 million MJ of natural gas are needed for the hydrogen production process. Finally, some 577 800 MJ of electricity and 156 600 MJ used to generate steam are needed for the hydrogenation phase. In total, some 536 million MJ are required as energy input for the HVO production process in this case study (Table 53).

Table 56. HVO production energy inputs (MJ) by processing phase

VO Pre-treatment Process		
Electricity	**MJ**	270 000
Steam generation	**MJ**	3 547 800
Hydrogen Production Process		
Electricity	**MJ**	23 760 000
Natural Gas	**MJ**	508 680 000
HVO Production Process Inputs (hydrogenation)		
Electricity	**MJ**	577 800
Steam generation	**MJ**	156 600
TOTAL	**MJ**	536 992 200

Source: **Roque**. 2023. https://www.sciencedirect.com/user/identity/landing?code=K02XdNAfyndrXbTI5XdfeUIf9EmwaE91sDxFw7ly&state=retryCounter%3D0%26csrfToken%3D672c4541-cf33-4f49-b3e4-412833bc80d7%26idpPolicy%3Durn%253Acom%253Aelsevier%253Aidp%253Apolicy%253Aproduct

%253Ainst_assoc%26returnUrl%3D%252Fscience%252Farticle%252Fpii%252FS0959652623001476%253Fvia%25253Dihub%26prompt%3Dnone%26cid%3Darp-db531bfd-3b90-4288-a766-502bccb30a1b

The energy outputs of the process consist of HVO, but also bio gasoline, propane, and the other valuable energy-rich co-products. As presented in Table 54, energy exits the systems for a total of around 891 million MJ per year.

Table 57. Energy output of the HVO value production of the HVO case study

Cake from crushing	MJ	129 525
Total HVO produced	MJ	237 600 000
Biogasoline	MJ	5 859 000
Propane	MJ	18 040 320
Steam	MJ	9 180 000
Hydrogen (surplus)	MJ	620 784 000
Total	MJ	891 592 845

Source: results of the FAO's BIKE set of sustainability indicators

The net energy ration is calculated for the entire value chain and considers the several energy-rich co-products. This was necessary because an allocation was not possible due to lack of process-specific information on the Ecofining system. The net energy ratio of the HVO value chain (EO/EI or TFO/TFI) is presented in Table 55. This is the ratio between the energy output attributed to the advanced biofuel and all its co-products and the input necessary for its production. In the case of low-ILUC castor oil for HVO production the final EO/EI ratio is 1.4.

Table 58. Results of the Net Energy Balance indicator for the HVO case study

HVO		
	Total energy input (MJ/year)	643 645 117
	Total energy output (MJ/year)	891 592 845
FEEDSTOCK PRODUCTION (Agriculture)	TFI	5 587
MJ/tfeedstock	TFO	39 500
Net Energy Value	TFO-TFI	33 913
Net Energy Ratio	TFO/TFI	7
FEEDSTOCK TRANSPORT-PROCESSING	TFI	37 322
MJ/tfeedstock	TFO	59 440
Net Energy Value	TFO-TFI	22 117
Net Energy Ratio	TFO/TFI	2
LIFECYCLE ENERGY EFFICIENCY		
Net Energy Ratio	TFO/TFI	1.4

Source: results of the FAO's BIKE set of sustainability indicators

3.2.11. Infrastructure

The analysis of the infrastructure for the logistics of transport of biomass and biofuels, adds to the information discussed under the indicator on water use and efficiency to present a complete overview of the characteristics of the studied value chain from this point of view. This indicator has a quantitative and a qualitative component. The quantitative component requires the user to assess the distances between the production areas and the hypothetical site of the biorefinery. Subsequently, using web-based tools, the actual distances between the production sites and the collection site are calculated. Based on the characteristics and the status of maintenance of the infrastructure the indicator measures the time spent to collect and deliver the biomass at the biorefinery's gate. The qualitative analysis of information in this indicator looks at the logistics side of operations within the value chain.

Table 59. Results of infrastructure indicator for the HVO-Kenya case study

	Distance [km]	Total produced feedstock [ton]	Vehicle type	Loading capacity [ton]	Average vehicle speed [Km/h]	Hrs
Feedstock transport	150	15 000	Truck	30	50	3 000
Fuel transport	380	6 750	Truck	30	80	2 138
Fuel transport	7334	6 750	Vessel	6 750	40	367
					TOTAL HOURS	**5 138**

Source: results of the FAO's BIKE set of sustainability indicators

Feedstock transport:

In the context of a bioenergy value chain in a developing country, the transportation of biomass to the processing site holds dual significance, encompassing both the potential for job creation and potential impacts on the environment (GHG emissions, etc). It is imperative to comprehensively calculate the routes and time spent in transporting biomass to ensure a well-informed evaluation of the project's social and environmental impacts. However, it is equally essential to acknowledge the potential emissions associated with biomass transportation. Emissions can arise from diverse sources, such as the use of fossil-fuel-powered vehicles, release of greenhouse gases during biomass handling and transport, and potential changes in land use due to increased demand for biomass feedstock. These emissions carry environmental implications, including air pollution and their contribution to climate change.

Hence, a meticulous assessment of biomass transportation routes and their characteristics is crucial. The average yearly transport time of the biomass was calculated starting from the average loading capacity of the vehicles used (tractor, truck, vessel, train, etc.) for each stage of the transport (field to road, road to biorefinery gate, etc.), the average speed admitted on the specific trait of road in km/h, and the averaged real distance between the various production sites and the collection site (Table 56) obtained from Open Street Maps. In general, to transport the 15 000 tonnes of biomass produced in the fields of Makueni each growing season, of 3 000 hours are required in total.

Castor Oil (SVO) transport:

In the examined value chain, the vegetable oil produced in Makueni is initially transported overland to the port of Mombasa, and subsequently shipped by sea to the Gela biorefinery in Sicily, Italy. Overland transportation within Kenya needs to be calculated to assess its potential for job creation, while the maritime transportation must be estimated to facilitate the calculation of emissions for the air emission indicator. Figure 21 shows the existing commercial route that can be eventually used to transport castor oil to Italy.

Figure 21. Commercial route Mombasa (Kenya) - Gela (Italy)

Source:https://www.routescanner.com/app/voyages?departure=2023-08-10&sort=emission_co2&fromType=locode&from=KEMBA&fromLabel=Port+of+Mombasa&toType=locode&to=ITGEA&toLabel=Gela&limit=3&originsNearby=1&destinationsNearby=1&modalities=sea%2Crail%2Cbarge%2Ctruck&voyageIndex=0

As shown in Table 56, the time required to transport castor oil (6 750 tonnes) from the crushing facility to Mombasa port would be around 2 138 hours by truck. On the other hand, only 367 hours would be required to ship the vegetable oil to Gela. The logistics are therefore much more complicated for the overland part of the value chain where infrastructure is poor, average speeds are low and several concerns arise in terms of efficiency and operator' safety. If on the one hand transport is a crucial step of the value chain and a key contributor to employment creation, it is not free from risks and impacts on social and environmental indicators. Maritime transport does not pose relevant limitations to the infrastructural sustainability of the value chain, though this analysis concerned the quantities of vegetable oil considered in this case study, and potentially larger volumes (Gela's installed capacity is 736 000 tons of VO per year) may return different results. Investments in road development and safety are recommended as the main action to enhance the infrastructural capability of the low ILUC case study assessed.

3.2.12. Gross Value Added

This indicator measures the contribution to the GDP of a given bioenergy value chain. In the case study of HVO produced in Gela, the products that contribute to GDP are the sales of green diesel (HVO) and the sales of its co-products (Table 57).

Table 60. Annual production, Market prices and Annual potential revenues of the main product and co products of HVO Kenya case study

Item	tonnes/year	Market price (€/Kg)	Potential Revenues (€/year)
Green Diesel	5400	1.508	8 143 200
Bio gasoline	135	1.62	218 700
Propane	388.8	0.36	139 968

Source: results of the FAO's BIKE set of sustainability indicators

Unfortunately, no information has been provided by the industrial partner regarding the production costs of the fuel. Such lack of data has hindered the measurement of the indicator, thus preventing the generation of a report on the economic impact of the value chain on the GDP of the target area.

3.2.13. Capacity

Advanced biofuels are one of the tools to contribute to the reduction of CO_2 emissions in the transportation sector, to the extent that the European Union promotes their use through specific directives such as Directive 2018/2001, also known as "RED II," aimed at promoting the use of energy from renewable sources. In October, Eni has definitively ended the supply of palm oil at the Venice and Gela biorefineries for production of hydrogenated biofuels. In 2022, the production of HVO in Italy amounted to approximately 428 ktonnes according to certifications in use (European RED and related directives). In 2020, the biodiesel incorporation rate across the EU-27 was 7.5% in energy terms, and 8.1% in volumes. Biodiesel consumption, including renewable diesel or HVO, increased by 1.6% compared to 2019 to reach a historic high of 13 169 ktoe or some 14 964 ktonne (epure, 2022). According to these figures, the additional production of 5 400 tonnes of green diesel (HVO) would generate additional production of around 100 percent, 1.26 percent and 0.04 percent in Sicily Region, Italy and at the EU level (EU 27), respectively, increasing the access to sustainable liquid biofuels as in line with the EU targets of sustainability (Table 58).

Table 61. Additional HVO production for the HVO-Kenya case study at the regional (Sicily), National (Italy) and EU (EU 27)

HVO for transport	**Baseline**	**Target**		
Sicily, Italy	0	5 400	tons	100%
Italy	428 000	433 400	tons	1.26%
Europe (EU 27)	14 964 000	14 969 400	tons	0.04%

Source: results of the FAO's BIKE set of sustainability indicators

When calculating the capacity, it is estimated the consumption of diesel in Sicily, Italy and EU 27 in 2021 was 1 576 000, 22 081 396 and 193 897 161 tonnes, respectively. With the additional HVO production of 5 400 tonnes, the final capacity is calculated as 0.31, 0.024 and 0.003 percent (Table 59).

Table 62. Capacity of HVO production for the HVO-Kenya case study at the regional (Sicily), National (Italy) and EU (EU 27)

HVO for transport	**Baseline (Diesel)[8]**	**Target**		
Sicily, Italy	1 576 000	1 581 000	tons	0.31%
Italy	22 081 396	22 086 796	tons	0.024%
Europe (EU 27)	193 897 161	193 902 561	tons	0.003%

Source: results of the FAO's BIKE set of sustainability indicators

[8] https://ec.europa.eu/eurostat/databrowser/view/NRG_CB_OIL__custom_7144613/default/table?lang=en

The contribution of HVO produced in the case study to the capacity of the regional as well as national and EU diesel sectors is limited. The Gela biorefinery has a capacity of some 700 000 tons/year of HVO and assuming that enough low ILUC feedstock is available, the impacts on capacity at any level would be considerable. Considering this, it is through key that in-depth assessments of sustainability beyond certification of single operators are carried out at the intended scale, as the analysis contained in this report would not be fully representative.

3.3 Conclusions

The castor HVO value chain has been assessed, although with relevant difficulties linked to data availability and quality, in its key indicators. The ever-evolving nature of the selected case study required a creative yet scientifically sound approach for which current and perspective scenarios have been analysed in isolation. This methodological approach allowed a clearer understanding of the implications of determining actions and practices of the value chain. The first scenario delves into the existing value chain, where Castor seed crushing and pressing in Makueni is procured utilizing energy derived from sources including the national electricity grid and fossil diesel. In the second scenario, a novel dimension is introduced—the establishment of a pyrolysis plant that is planned by the case study leader (ENI) to be operational in the foreseeable future. This plant serves the dual purpose of fully powering the Vegetable Oil (VO) production process and producing biochar which in turn is applied to local soil to contribute to carbon sequestration. The analysis revealed the crucial role of organic carbon, in the form of biochar, for the overall sustainability of the value chain. Emission calculations have been based partly on primary data provided by the case study partner, and in part from secondary data available in the literature. The results in terms of air quality (GHG and non GHG emissions) are positive in all three scenarios, however an emission reduction of 62 percent with regards to the baseline (fossil diesel) is attainable without the pyrolysis of agricultural residues, whereas with biochar incorporation into the soils the GHG reduction compared to diesel reach -114 percent, placing HVO produced with this model as a carbon negative biofuel. This assessment however, as mentioned above and throughout this report, is only indicative since several data sources have been matched and harmonized, and the collection of primary data from FAO was not possible due to limited resources available and logistical difficulties. The dichotomy of the two scenarios considered is even more evident in other environmental indicators of reference, such as the assessment of soil quality. It is apparent the early level of maturity of the feedstock supply chain, for which several best practices are planned but to date not applied. This reflects in a number of ways on soil and water quality - and to a lesser extent on biodiversity conservation – performances, all indicators exhibiting ample room for improvement that though it appears to be understood and to an extent already sought after by the Industrial partner. Social implications of a transboundary value chain like the one object of this study are to be carefully evaluated.

Castor cultivation can create new income opportunities for local farmers through the creation of additional jobs, and its transformation into HVO can increase industrial production. The assessment once again was affected by lack of data completeness. It was possible to estimate that 10 000 hectares of formerly underutilized farm land devoted to the cultivation of feedstock for HVO production would generate annually some 69 skilled and 1 031 unskilled job positions. In addition, considering the transportation of the VO to Mombasa commercial port, a total of 71 skilled positions are created by the value chain. Especially for the agricultural stages of the value chain, the lack of data on wages, land tenure rights and contractual agreements between the workers and landowners has affected the completeness of this assessment for a social viewpoint. Relevant opportunities for social development linked to the exploitation of local natural resources are awaiting and can generate enhanced acceptance and ownership among citizens in Makueni. These could not be assessed through this study but a recommendation is made to seek relentlessly any ancillary and long-lasting social development activity. Energy access in rural villages near the castor bean cultivation areas is a challenge. Further developments of the production scenario which foresees the pyrolysis plant in the Agri Hub no longer sized to treat the available biomass for the sole production of the raw vegetable oil to be exported to Italy, but also a scenario in which plant size is scaled-up to accept additional available agricultural residues and generate energy for a local mini-grid should be taken into consideration. The surplus co-products (energy and biochar) on the one hand would contribute to improving even further the environmental performances of the castor value chain, and on the other would share value through social development actions (e.g. increased access to modern energy services) that in turn would benefit the social sustainability of the project.

Economic sustainability indicators for this case study could not be measured in their entirety, due to industrial competitivity limitations that prevented the case study leader from sharing sensible information with FAO, despite several attempts from both sides to find an effective solution. Information on wages, contracts and working conditions were also not documented making it difficult to evaluate the related indicators.

Technical aspects such as Net Energy Balance, Infrastructure readiness and Capacity of use of the biofuel produced all returned positive results, leading to evaluating the HVO value chain a sustainable solution from a purely technical point of view. Nevertheless, limitations to the infrastructural indicators might arise in the future, when full capacity of production is reached or increased from current plans, but these are expected predominantly at domestic level in the feedstock production areas for which again, social and infrastructural development actions could be an asset. In future iterations of this sustainability assessment, monitoring would benefit from primary data collection, surveys and sample interviews while data should be presented in aggregated form to avoid exposing stakeholders to industrial competitivity issues.

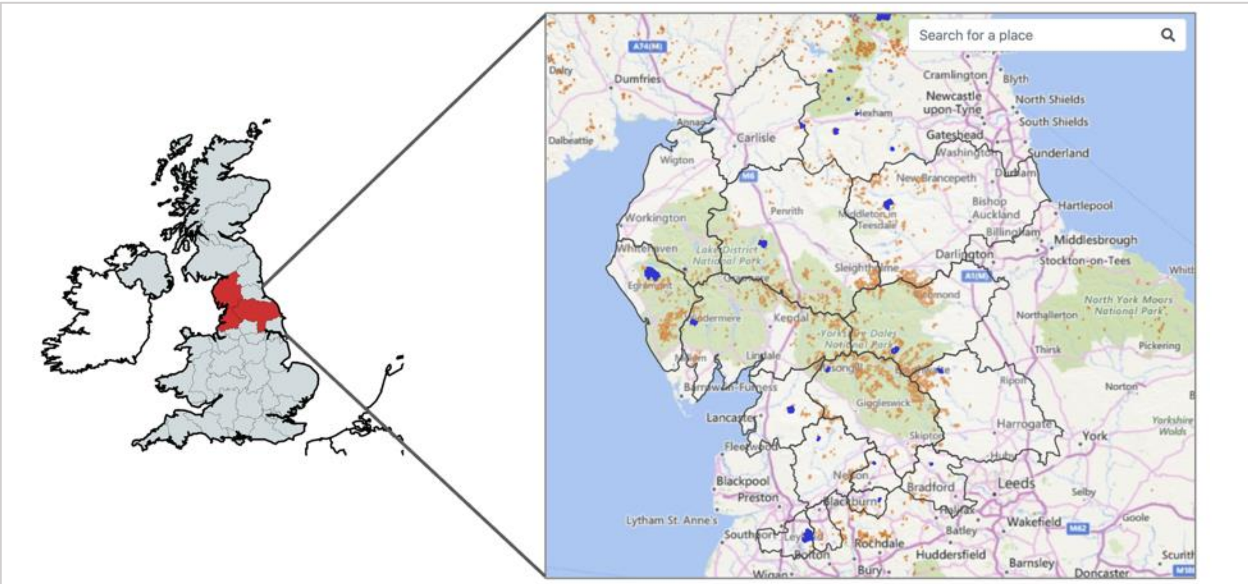
4. The 2G Ethanol Case Study

4.1. Case Study Description, Setting, System Boundaries and Main Assumptions

4.1.1 The reference target area:

An assessment was conducted to evaluate the sustainability of a prospective cellulosic ethanol value chain focusing on marginal and degraded lands in two regions in the UK, namely the North-west and York Shire. The sustainability of cellulosic ethanol gains an even more compelling edge when its feedstock is sourced from marginal and abandoned lands. These neglected landscapes, often unsuitable for traditional agriculture, can be harnessed to yield valuable biomass for energy production. By utilizing land that would otherwise remain unproductive, cellulosic ethanol production minimizes competition with food crops and conserves valuable arable land. This approach mitigates concerns about indirect land-use changes and prevents deforestation or habitat destruction that might occur with the expansion of energy crop cultivation.

Figure 22. The target area of North-west and York Shire, UK



The target area involved several potential biomass production areas where marginal and underutilized land are available. These areas were identified by using of the publicly available web-GIS tool[9] of the Bioplat-EU project[10], where the mapping of underutilized land was based on a remote sensing time series approach using Landsat data with a spatial resolution of 30 m. The selected municipalities/districts are: the Blackburn with Darwen, County Durham, Allerdale, Carlisle, Copeland, Eden, South Lakeland, Burnley, Chorley, Hyndburn, Lancaster, Pendle, Preston, Ribble Valley, Rossendale, South Ribble, Craven, Harrogate, Richmondshire, Bradford, Calderdale.

In total, the reference target area used for the assessment of the sustainability of the selected bioenergy value chains has a surface of 1,760,000 ha and is the sum of the surfaces of the municipalities listed above and reported in the following table (Table 60). According to Bioplat-EU's maps, around 40,000 hectares of underutilized and marginal lands are potentially available within the 21 districts selected.

Table 63. List of district and municipalities considered by the North-West and York Shire case study in UK

Municipality	Total population (2021)	Total area	GDP (million £, 2020)
Blackburn with Darwen	154,800	13,700	3,639
County Durham	522,100	267,600	10,240
Allerdale	96,100	124,200	1,989
Carlisle	110,000	104,000	3,128
Copeland	67,100	73,170	1,594
Eden	54,700	214,200	1,544
South Lakeland	104,500	153,400	2,840
Burnley	94,700	158,200	2,311
Chorley	117,800	20,300	2,428
Hyndburn	82,200	7,300	1,582
Lancaster	142,900	56,700	3,319
Pendle	95,800	16,900	1,867
Preston	147,900	14,200	4,703
Ribble Valley	61,500	58,300	1,938
Rossendale	70,800	13,800	1,162
South Ribble	111,000	11,300	4,009
Craven	56,900	117,700	1,674
Harrogate	162,700	130,800	4,728
Richmondshire	49,700	131,900	1,002
Bradford	546,400	37,040	11,295
Calderdale	206,600	36,390	5,795

Source: *England and Wales, Office for National Statistics: Census 2021*

[9] https://webgis.bioplat.eu/#/map
[10] https://bioplat.eu

4.1.2 The value chain:

The bioenergy pathway selected is lignocellulosic (also known as *second generation, o 2G*) ethanol with the presence of a Combined Heat and Power plant within the biorefinery. The identified source of biomass is Miscanthus under rainfed management system. According to data provided by the local partner, the average potential yield of Miscanthus in the region can range between 4 and 9 tons per hectare, and average yield of 8 tons per hectare was considered for this study.

Miscanthus x giganteus, commonly known as giant miscanthus, stands as a remarkable and highly sought-after perennial grass species in the realm of bioenergy production. Originating from the hybridization of two Miscanthus species, this robust plant has garnered substantial attention due to its exceptional biomass yield, low input requirements, and suitability for marginal and abandoned lands. Its unique characteristics make it a prime candidate for sustainable bioenergy production. Giant miscanthus exhibits towering stature, often reaching heights of up to 12 feet, along with dense and lush foliage that effectively captures sunlight. This prolific growth is underpinned by its efficient conversion of solar energy into biomass, resulting in high yields of cellulose-rich material that can be harnessed for cellulosic ethanol and other biofuel production. Notably, its deep and extensive root system provides stability to the soil, mitigating erosion and enhancing soil carbon sequestration. One of the standout features of giant miscanthus is its low demand for resources. Once established, it requires minimal inputs in terms of water, fertilizers, and pesticides, making it well-suited for cultivation on lands that are less suitable for food crops. Its tolerance to a range of climatic conditions further enhances its adaptability, enabling cultivation in diverse geographic regions. The following table (Table 61) shows the relevant agronomic information collected from the local partners through the use of the BIKE data entry tool in Excel.

Table 64. Agronomic information of the UK case study obtained submitting the FAO's excel data entry tool

Item	Value	Unit
Total Diesel used for Miscanthus production	37.5	l/ha/yr
Amount of fertilization (chemical) N	100	Kg/ha/yr
Amount of fertilization (chemical) P	15	Kg/ha/yr
Amount of fertilization (chemical) K	100	Kg/ha/yr
Amount of applied pesticides	0	Kg/ha/yr

Giant miscanthus is typically harvested annually in late winter or early spring after senescence, when the plant has accumulated substantial biomass while preserving its energy content. The harvested biomass can be utilized for various bioenergy applications, including combustion for heat and power generation or conversion into biofuels like cellulosic ethanol as given in this analysis. Additionally, the lignin-rich byproducts from the processing can find use in producing bioproducts or serving as a potential carbon source for biochemical processes.

The production of cellulosic ethanol involves a multi-step process that transforms non-food plant materials, such as agricultural residues, forestry waste, and energy crops, into a renewable and sustainable biofuel. The primary steps in the cellulosic ethanol production process are as follows: **Feedstock Preparation:** The process begins with the collection and preparation of the chosen feedstock, which can include materials like corn stover, wood chips, grasses, and agricultural residues. These feedstocks are often sourced from marginal or abandoned lands to avoid competition with food crops. The feedstock is then cleaned, dried, and sometimes pre-treated to make it more amenable to subsequent processes. **Pre-Treatment:** The pre-treatment stage involves breaking down the complex cellulose and hemicellulose structures in the feedstock into simpler sugars. This step is crucial to increase the accessibility of cellulose to enzymatic hydrolysis in the next stage. Pre-treatment methods can include mechanical, chemical, or biological processes. **Enzymatic Hydrolysis:** In this step, enzymes are used to further break down the cellulose and hemicellulose into individual sugar molecules, mainly glucose and xylose. Enzymatic hydrolysis is vital because these sugars will serve as the raw materials for the fermentation process. **Fermentation:** The enzymatically hydrolyzed sugars are then subjected to fermentation by specialized microorganisms, typically yeast or bacteria. During fermentation, the microorganisms consume the sugars and convert them into ethanol and carbon dioxide through a metabolic process. This produces the cellulosic ethanol product. **Distillation and Purification:** Once fermentation is complete, the resulting mixture contains a mixture of ethanol, water, and other byproducts. The ethanol is separated and purified from the mixture through distillation and other separation techniques. This process removes impurities and increases the ethanol concentration. **Dehydration:** The purified ethanol is often dehydrated to further increase its concentration. Dehydration processes help remove the remaining water from the ethanol, resulting in a higher-grade biofuel. **Byproduct Utilization:** Throughout the process, various byproducts like lignin and leftover sugars are generated. These byproducts can have potential uses in various industries, such as in the production of bioplastics, chemicals, and energy generation. **Final Product:** The end result of the cellulosic ethanol production process is a renewable fuel source that can be blended with gasoline to reduce the carbon intensity of transportation fuels. It has the potential to significantly reduce greenhouse gas emissions compared to fossil fuels.

The case study explores the possibility of building a new plant for the production of lignocellulosic ethanol in the North-west region of England, in the UK. The target output of the hypothetical biorefinery is 40,000 tons of ethanol per year and the technology employed is the PROESA® (steam-explosion, Enzymatic liquefaction, SSF) developed by Biochemtex, now acquired by Versalis, a subsidiary of ENI. This technology has been implemented for the first time at the Crescentino plant (Italy) (Figure 23)

Figure 23. Aerial view of the Versalis (ENI) 2G ethanol plant in Crescentino, Italy

Source: https://www.eni.com/en-IT/operations/italy-crescentino-renewables-chemicals-integrated-plant.html

In the tested scenario, given expected yields of 8 t ha-1 yr-1, Miscanthus would require some 25,000 ha to produce the amount of biomass that the biorefinery requires (200,000 tons per year).

4.2. Sustainability Assessment results by indicator

4.2.1 Air Quality

The study examines both the baseline scenario, which relies on traditional fuels, and the possibility of introducing new biofuels.

Assessing the sustainability impact of bioenergy production and use involves evaluating the greenhouse gas (GHG) emission intensity per unit of energy produced by the process. Such GHG emission intensity is measured in grams of carbon dioxide equivalent per megajoule of bioenergy produced (gCO_2eq/MJ). In the baseline scenario, petrol serves as the reference fuel, with a total emission intensity of 93.3 gCO2eq/MJ (Biograce version 4, 2020).

In the target scenario, the emission intensity of cellulosic ethanol produced in the designated area is compared to the emission intensity of the reference fuel. The resulting relative change (expressed as a percentage) and absolute change (measured in grams, kilograms, or tons of CO_2) are then reported.

The primary contributors and elements involved in a GHG Life Cycle Assessment (LCA) of biofuel production and utilization encompass:

- Feedstock production;
- Feedstock transport;
- Feedstock processing into fuel; and
- Fuel transport/distribution/use.

Lignocellulosic ethanol production may involve also by- and co-products, leading to the requirement of allocation among the various products. In this instance, the lignin generated during the processing of miscanthus serves as fuel for a combined heat and power (CHP) plant, meeting the biorefinery's internal energy requirements while generating a certain surplus electricity intended for sale to the grid.

The most appropriate methodology for correctly allocating and attributing co-products within the bioenergy value chain is a highly debated topic. In general, allocation based on energy content of the co-products or on their economic value, or also on the mass or volume value of the co-products can all provide reliable results, depending on the intended scope of the analysis and the characteristics of the value chain.

Nonetheless, this holds true when conducting a comparison in the current or short-term context. However, when looking at a longer time frame (10+ years), the unpredictability of market conditions makes it challenging to rely solely on the present economic value for projecting the distribution of impacts among the various co-products of the bioenergy value chain into the next decade.

In order to avoid these uncertainties, in this exercise the energy content method was chosen to attribute to each co-product its share of impacts.

Summarizing the extensive calculations performed on this aspect, the 40 000 tons of lignocellulosic ethanol produced yearly (target production) are equal to 1 072 400 000 MJ. The generation of 103. 9 GWh of electricity (co-product) in excess to what is used in the processing stages, equals to a further 374 112 000 MJ. This means that a correct allocation among co-products in energy terms is done as follows:

- Ethanol: 74.14 percent;
- Surplus electricity: 25.86 percent.

The results of the air emission indicator are presented below.

The baseline emission intensity for petrol is reported as 93.3 gCO_2eq/MJ, according to Vourliotakis et al. (Vourliotakis, 2020). In the target scenario, this study reports a significantly lower emission intensity of 26.22 gCO_2eq/MJ for lignocellulosic ethanol produced from low i-LUC feedstock (Table 62).

Table 65. Total emission of GHG and non GHG of lignocellulosic ethanol production (aggregated and allocated) in g and g/MJ of fuel

Type	Unit	Value	Unit	Value
GHG	gCO_2-eq	28 120 897 231	gCO_2-eq/MJ $_{EtOH}$	26.22
Non GHG	gCO	154 994 062	gCO/MJ $_{EtOH}$	0.14
	gNOx	167 025 338	gNOx/MJ $_{EtOH}$	0.15
	gSOx	30 803 831	gSOx/MJ $_{EtOH}$	0.03
	gPMx	56 152 899	gPMx/MJ $_{EtOH}$	0.05

Source: results of the FAO's BIKE set of sustainability indicators

As presented in Table 63, the primary contributor to the GHG emission intensity are the processing stages. Within the feedstock production operations, mechanized operations like soil preparation and harvesting play a significant role and are the main contributors to emissions during this phase of the value chain.

Table 66. Emission of GHG and non GHG of 2G ethanol production (disaggregated and allocated) in g and g/MJ of fuel in UK (40 000 tonnes 2G ethanol per year)

Total yearly emission	CULTIVATION	FSTK TRANSPORT	PROCESSING	FUEL TRANSPORT
tCO_2-eq	**3 690**	**265.2**	**24 021**	**143.3**
tCO_2-eq share	**13%**	**1%**	**85%**	**1%**
KgCO	2 273	36.8	151 851	19.9
KgNOx	6 496	149.1	157 964	80.6
KgOx	2 367	136.5	27 346	73.8
KgMx	203 440	3.1	55 872	1.6
gCO_2-eq/MJ $_{CH4}$	**3.44**	**0.25**	**22.40**	**0.13**
gCO/MJ $_{CH4}$	0.00	0.00	0.14	0.000
gNOx/MJ $_{CH4}$	0.01	0.00	0.15	0.000
gSOx/MJ $_{CH4}$	0.00	0.00	0.03	0.000
gPMx/MJ $_{CH4}$	0.00	0.00	0.05	0.000

Source: results of the FAO's BIKE set of sustainability indicators

In conclusion, the analysis of the 2G ethanol in UK produced with Giant Miscanthus estimated a final potential annual emission reduction of around 71 934 tonnes of CO_2eq . This represents a substantial reduction of approximately 66.81 gCO_2eq/MJ compared to the baseline (Petrol), resulting in a 72 percent emission reduction (Table 64).

Table 67. Total avoided emission of GHG and non GHG of 2G ethanol production (aggregated and allocated) in g and g/MJ of fuel

Type	tCO_2-eq	gCO_2-eq/MJ CH_4
Ethanol	28 120	26.22
Petrol	100 054	93.03
Total Avoided	71 934	-52.05

Source: results of the FAO's BIKE set of sustainability indicators

4.2.2 Soil Quality

Soil quality is one of many aspects that requires thorough investigation when assessing the sustainability of a bioenergy value chain. While quantitative data may provide detailed estimates on such factor, measurement and evaluation are often demanding in terms of time and specialized labour or limited by site specificity. Qualitative data may represent a valid alternative to shed light on ways to preserve or increase soil quality. The current section depicts the results of the application of the qualitative indicator related to soil quality performances on the agricultural soils of interest. In particular, the indicator pinpoints presence and frequency of management practices, evaluating these with a scorecard method. With the aim of identifying drawbacks and benefits of certain practices, these are scored according to the effects on soil quality associated to them. By aggregating practices and their scores, it is possible to obtain an overall qualitative indication on the risk level of quality management of the soil in question.

First, presence and frequency of best soil management practices were assessed (Table 65). Of all agronomic practices, exclusively reduced tillage and windbreaks are applied in the case study area. These agronomic practices are beneficial to soil characteristics, for example, by preserving soil aggregation, preventing erosion, and enhancing biological activity. Organic matter addition, crop rotation, continuous cover crop, organic agriculture, and biofertilizer and living organisms' management are not considered. Organic matter addition in this particular case study however is not required since the soils where miscanthus is grown in the UK are not constraint by organic matter content, being organic soils (former peatlands) rather than mineral soils.

Table 68. Presence and frequency of the best soil quality management practices of the case study

	Value	Score
Organic matter addition (e.g. manure, biochar, etc.)	Not applied	0
No-tillage, minimum tillage, reduced tillage	Applied	3
Crop rotation (incl. or excl. fallow, intercropping, etc.)	Not applied	0
Continuous cover crop	Not applied	0
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Windbreaks, shelterbelts, etc.	Applied	1
Biofertilizer and living organisms management	Not applied	0
	SCORE	**4**

Source: results of the FAO's BIKE set of sustainability indicators

Furthermore, Table 66 presents the scores attributed to occurrence and frequency of traditional soil management practices. Considered in the analysis are mechanized land preparation, use and rates of synthesis fertilizers, and monocropping, all coming with detrimental effects on soil characteristics. Deep and surface tillage, and irrigation rates and irrigation systems are not provided.

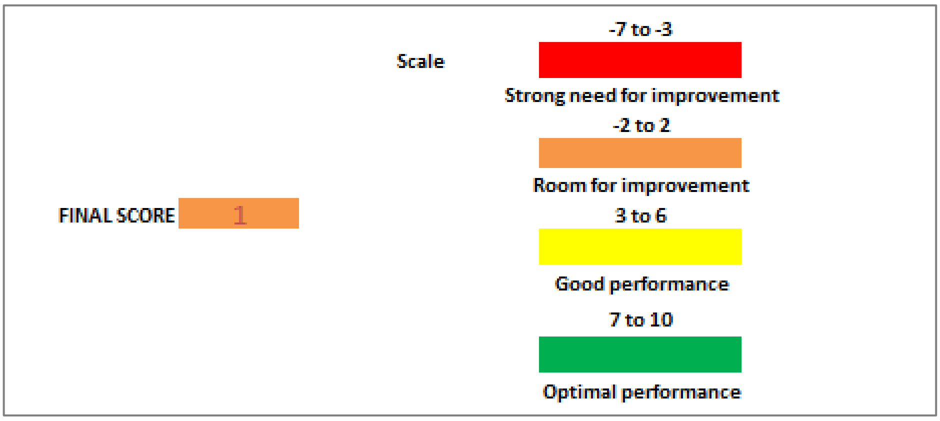
Table 69. Occurrence and frequency of traditional soil management practices

	Value	Score
Mechanized land preparation	Applied	-1
Deep and surface tillage (incl. moldboard plow, ripper, etc.)	Not applied	0
Use and rates of synthesis fertilizers	Applied	-1
Irrigation rates and irrigation systems (e.g. flooding, sprinklers, etc.)	Not applied	0
Monocropping (annual crops only)	Applied	-1
	SCORE	**-3**

Source: results of the FAO's BIKE set of sustainability indicators

The results show significant room of improvement associated to an overall soil management based on no tillage and windbreaks in conjunction with mechanized land preparation, monocropping, and the observed use and rates of synthetic fertilizers. As Figure 24 shows, the indicator scored 1 out of 10. That is, the analysed management of soil quality may benefit from better practices. For instance, a more diverse and complete set of nutrients can be added to the soil by using organic fertilizers instead of synthetic fertilizers. A stronger effort may be done to align soil management to EU's strategic objectives, such as the RED II and the European Green Deal, to be able to improve the environmental friendliness of the bioenergy sector through the production of biomass.

Figure 24. Final score of the soil quality indicator and related scale of credit score



Source: results of the FAO's BIKE set of sustainability indicators

4.2.3 Water Use

The climate in the northwestern England, UK, which includes areas like Manchester, Liverpool, and parts of Lancashire and Cumbria, is characterized as a temperate maritime climate. This means that the region experiences mild temperatures, relatively high humidity, and moderate rainfall throughout the year. The climate is influenced by the warm waters of the North Atlantic Drift, a continuation of the Gulf Stream, which helps to moderate temperatures.

Winters in the northwest are generally mild, with average temperatures ranging from around 2°C to 7°C (36°F to 45°F). Summers are also relatively mild, with average temperatures ranging from around 12°C to 19°C (54°F to 66°F). Rainfall is spread quite evenly throughout the year, with the wettest months typically occurring from October to January[11].

Yorkshire, located to the east of the northwest UK, also experiences a temperate maritime climate, although it can be slightly cooler and drier than the northwest due to its more inland location. The Pennine Mountains, which run through Yorkshire, can have an impact on local weather patterns. Winters in Yorkshire are somewhat colder than in the northwest, with average temperatures ranging from around 1°C to 6°C (34°F to 43°F). Summers are still relatively mild, with average temperatures ranging from around 11°C to 19°C (52°F to 66°F). Like the northwest, Yorkshire receives a moderate amount of rainfall throughout the year, with the wettest months typically occurring in the late autumn and winter.

Table 70. Wfstk Renewable - Renewable water used for feedstock production

Item	Value	Unit
Crop yield	8	ton/ha
Cultivated surface	25 000	ha
Crop ET	900	mm/year
Effective precipitation (Oct-Jun)	1242	mm/year
Crop production	200 000	ton
Annual irrigation requirement	-342	mm/year
Unitary water requirement	9000	m^3/ha
Unitary water requirement	0.225	Km^3/year
Unitary water(Irrigation) requirement	-3420	m^3/ha
Unitary water(Irrigation) requirement	-0.0855	Km^3/year
Tot. water for feedstock production (Wfstk) renewable	**0.1395**	**Km^3/year**

Source: results of the FAO's BIKE set of sustainability indicators

[11] https://www.metoffice.gov.uk/

The production of biomass requires no additional irrigation water in the case study site and it returns yields of around 8 t ha-1 yr-1. As shown in Table 67 below, this translates into a total water requirement of 0.1395 km^3/year to provide water to produce biomass (25 000 ha for 200 000 tonnes/year of Miscanthus).

Concerning the processing phases, as shown in Table 68, the water used by the value chain to produce 1 ton of feedstock is 1.3 m^3.

Table 71. Wfstk Renewable - Renewable water used for lignocellulosic EtOH production

Item	Value	Unit
Water consumption	1.3	m^3/Nm^3
	0.000260	Km^3/year
EtOH production	40,000	Nm^3/year
LHV EtOH	26.81	MJ/m^3
Total energy output	1,072,400,000	MJ/year
Wbioenergy / Etotal	0.000242	m^3/MJ
	0.242447	l/MJ
Production	**1.3**	**m^3/t feedstock**

Source: results of the FAO's BIKE set of sustainability indicators

4.2.4 Water Quality

The indicator aims to define benefits and challenges associated with traditional or improved water management practices. Using a scorecard method, the indicator evaluates each practice based on its occurrence and frequency, accounting for more beneficial or detrimental effects on water quality attributable to each practice. For instance, processing water treatment has worse results on water quality compared to other practices.

Considered practices include minimum tillage, the employment of organic agriculture, the utilization of conservational buffers, erosion sediment control and wastewater treatment at the feedstock and fuel processing level. In this case, the practices related to organic agriculture, and erosion and sediment control were not applied (Table 69). No tillage and conservation buffers come with the benefits of preventing soil erosion or leaching and consequent loss of nutrients, which may also lead to nutrient pollution of water. Thus, by preserving the quality of water, sustainable practices enhance agricultural productivity and contribute to the protection of the environment. In turn, wastewater may be treated and become an additional resource for agriculture, adding a source of water for crops and strengthening the steadiness of water availability. In addition, treating wastewater allows to recover precious nutrients, including nitrogen, phosphorus, and potassium, crucial for plant health and growth. In doing so, treated bio digestate may be applied to soils and its nutrients recuperated and reused, obtaining a biological alternative to synthetic fertilizers, and improving nutrient management.

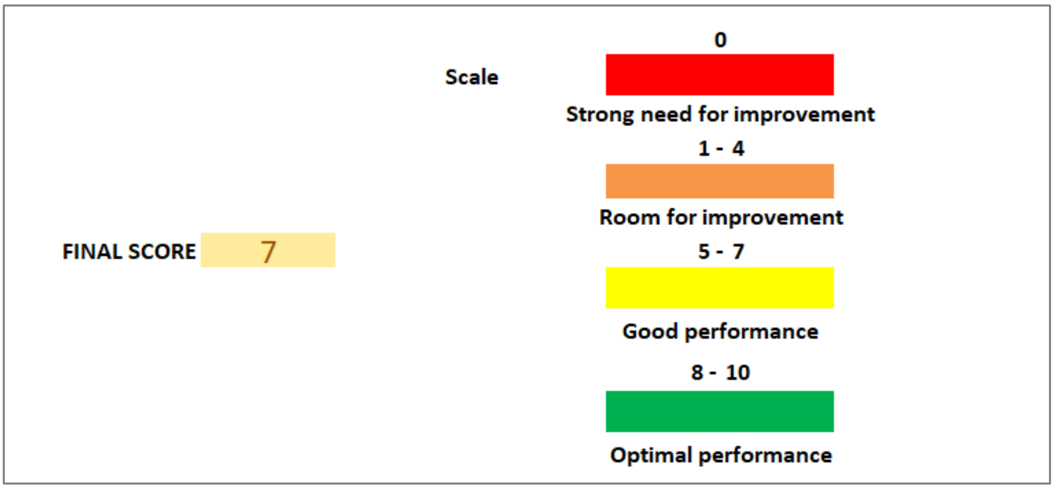
Table 72. Presence and frequency of the best water quality management practices of the UK 2G ethanol case study

	Value	**Score**
No-tillage, minimum tillage, reduced tillage	Applied	3
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Conservation buffers (buffer zones, corridors, etc.)	Applied	1
Erosion and sediment control	Not applied	0
Wastewater treatment of bioenergy processing	Applied	3
	SCORE	**7**

Source: results of the FAO's BIKE set of sustainability indicators

Figure 25 depicts the score of the indicator, namely 7 out of 10. Thus, the indicator returns a good performance of the current management regime concerning water quality, and the potential to reach optimal performance if practices like erosion control techniques would be implemented, for instance.. These favour reuse of wastewater and sustainable use of water, consequentially contributing to the sustainable use of natural resources. Such positive result is along the lines of EU's strategic objective as the ones elicited through RED II and the European Green Deal. The approach provides a way for biomass producers to participate in the development of a more sustainable bioenergy sector, in line with EU policies and strategies.

Figure 25. Final score of the water quality indicator and related scale of credit score for the UK ethanol case study



Source: results of the FAO's BIKE set of sustainability indicators

4.2.5 Biodiversity

Agronomic practices may strongly influence biodiversity. Best practices such as sustainable farming techniques are crucial to manage natural resources sustainably, employing crop diversity, decreasing reliance on chemical inputs and preserving natural habitats. Through such methods, farmers can significantly improve biodiversity in the European Union (EU) towards a diverse and resilient ecosystem. Agronomic best practices foster the proliferation of soil microorganisms while protecting and promoting the health of pollinators and beneficial insects.

Using a scorecard method, the indicator on biodiversity assigns a score to management practices based on their presence and frequency, to give an indication on their beneficial or detrimental effect on biodiversity. For example, some practices may have more detrimental effects on biodiversity compared to others. By aggregating the score given to each employed practice, it is possible to assess the overall risk level associated with biodiversity preservation.

Table 73. Presence and frequency of the best biodiversity management practices

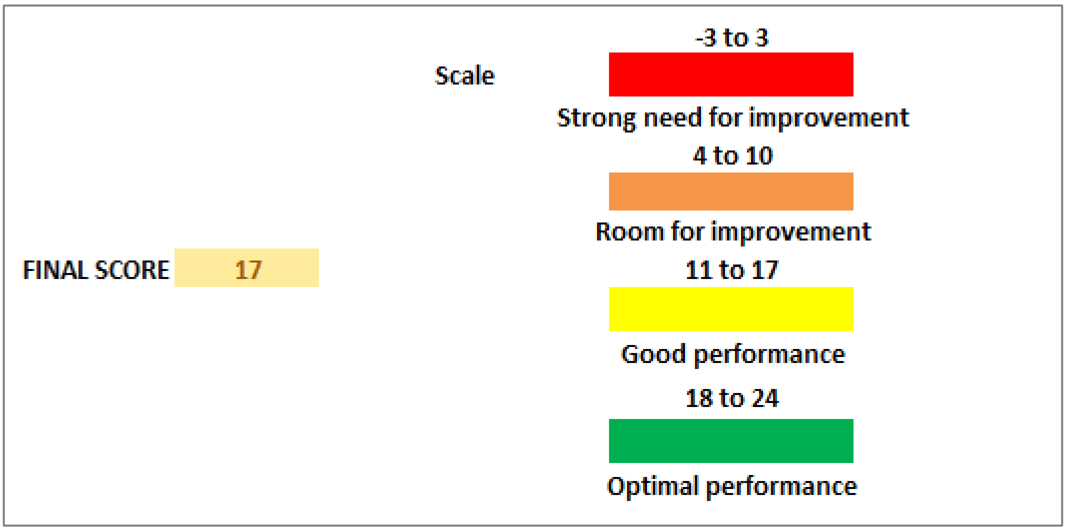
	Value	Score
Invasive alien species	Applied	-3
No-tillage, minimum tillage, reduced tillage	Applied	3
Crop rotation (incl. or excl. fallow, intercropping, etc.)	Not applied	0
Continuous cover crop	Not applied	0
Organic agriculture (incl. IPM, INM, biological pest control, etc.)	Not applied	0
Windbreaks, shelterbelts, etc.	Applied	1
Biofertilizer and living organisms' management	Not applied	0
Conservation buffers (buffer zones, corridors, etc.)	Applied	1
No shrubs removal	Applied	2
Use 1 ha every 100 ha for planting legumes/cereals for wildlife	Applied	2
Pollinators management (bees, Bumblebees, etc..)	Not applied	0
Avoiding open field burning	Applied	1
Agroforestry (multi-layers of canopy, etc..)	Not applied	0
Report and protect nest	Not applied	0
Ensure that species are not collected	Applied	3
Cooperation with environmental or nature protection organizations	Applied	2
Promote awareness campaigns on biodiversity conservation in agriculture	Applied	2
Erosion and sediment control	Not applied	0
Wastewater treatment of bioenergy processing	Applied	3

Source: results of the FAO's BIKE set of sustainability indicators

Table 70 shows the score of applied management practices. These consist in: No tillage; windbreaks; conservation buffers; not removing shrubs; planting legumes or cereals on 1 ha every 100 ha; avoiding open field burning; ensuring no collection of species; cooperating with environmental or nature protection organizations; promoting awareness campaigns on biodiversity conservation in agriculture; wastewater treatment of bioenergy processing; and using invasive alien species. All but the latter practice has positive effects on biodiversity, with invasive alien species increasing the risk associated with biodiversity preservation.

Aggregating the score given to each applied practice shows an overall good performance, with a final score of 17 out of 24 (Figure 26). That is, the applied management practices have positive implications on biodiversity preservation, even though alien species were included in the computation. The application of several best agronomic practices demonstrates the potential to contributing to the conservation of biodiversity and represent a way for farmers to contribute to the resilience and variety of the ecosystem in the European Union (EU).

Figure 26. Final score of the biodiversity indicator and related scale of credit score



Source: results of the FAO's BIKE set of sustainability indicators

4.2.6 Jobs in the bioenergy sector

The target area, comprising 21 municipalities, has a total population of 3 056 200 inhabitants. The working population, which includes both men and women in the age group of 20 to 64, accounts for 75.5 percent, resulting in an unemployment rate of 24.5 percent. Within the area, permanent jobs constitute 67.6 percent of employment, while temporary jobs make up 32.9 percent. The majority of jobs in the region are of a permanent nature. Advanced bioenergy value chains offer the potential to generate employment across various sectors. This includes job opportunities in the agriculture sector for feedstock production, in the industrial sector for feedstock processing, and in accessory sectors like biomass transport and induced jobs related to the production of inputs and machinery, among others. As provided in Table 27, in the target scenario the lignocellulosic ethanol value chain would employ both skilled and unskilled workers. In total, the project would generate around 1 393 skilled and 82 unskilled job positions per year also considering the transport phases, with an increase in the target area of around 0.096 and 0.010 percent, respectively.

Figure 27. Results of the job indicator for jobs for the UK ethanol case study

	Skilled positions		Unskilled positions	
Feedstock production phase	**Hours/year**	**Days/year**	**Hours/year**	**Days/year**
Land preparation	25,000	3,125	7,500	938
Land cultivation	25,000	3,125	75,000	9,375
Harvesting	25,000	3,125	75,000	9,375
Fuel production phase				
Pretreatment	0	0	0	0
Hydrolysis	0	0	0	0
Fermentation	0	0	0	0
Distillation	0	0	0	0
Aggregated workers (Alternatively)	2,592,000	324,000	0	0
Transport of biomass				
Drivers/loaders	6,667	833		
Transport of fuel				
Drivers/loaders	1,667	208		
TOTAL SKILLED JOB POSITION	1,393			
TOTAL UNSKILLED JOB POSITION	82			
Total population, men and women, age group 20-64		2,307,431		
Low skilled persons, age group 20-64		856,749		
Skilled persons, age group 20-64		1,450,682		
increased position in the target area				
INCREASE IN TOTAL SKILLED JOB POSITION		0.096		
INCREASE IN TOTAL UNSKILLED JOB POSITION		0.010		

Source: results of the FAO's BIKE set of sustainability indicators

4.2.7. Energy access

In the scope of this assessment, it's important to underscore the concept of the energy access indicator, which holds particular relevance in developing countries where inadequate energy access remains a significant challenge. This indicator serves as a metric to quantify the extent to which populations in these regions have reliable and sufficient energy sources, addressing the critical issue of energy scarcity that often prevails.

However, it's important to note that the primary focus of this assessment lies in the enhanced capacity for energy production, particularly in comparison to traditional fossil fuels. This analysis pertains to a specific context that differs from the typical energy access challenges faced by developing countries. Consequently, the measurement of the energy access indicator was not included in this evaluation. Rather, increased emphasis was placed on appraising the potential of the investment scenario within the framework of EU standards and regulations, specifically concerning renewable energy pricing and economic viability.

4.2.8 Productivity

Marginal lands, often unproductive for traditional crops due to factors like poor soil, drainage issues, and harsh climates, can sustain a scalable production by cultivating the right crop with the correct set of practices. Perennial crops like miscanthus can thrive on such lands, making use of previously unsuitable resources. This boosts land productivity, generating revenue from previously neglected areas. Miscanthus, requiring minimal inputs, boasts high biomass yield potential. Its use as a biomass feedstock for energy is on the rise due to its favourable traits. Particularly, the Miscanthus x giganteus genotype, a clone-based hybrid, excels in photosynthesis, biomass yield, and climate tolerance. This makes it a prime candidate for lignocellulosic feedstock production in the UK.

According to the work done by Imperial College in the context of the BIKE project (Imperial College, 2023), annual production costs (operative and fixed) for miscanthus production in UK are 491.55 EUR per ha of cultivated marginal land, or some 75.6 EUR per tonne considering a yield of 6.5 tonnes per hectare (Table 6).

Figure 28. Miscanthus cultivation characteristics

Item	Value	Unit
Crop type	Miscanthus	[-]
Crop yield	6.5 – 9.0	t/ha
Crop production cost	491.55	€/ha
Crop production cost at 6.5 t/ha	75.62	€/t
Crop production cost at 9.0 t/ha	54.62	€/t

Source: https://www.bike-biofuels.eu/wp-content/uploads/2023/07/BIKE_D.2.3_ICL_1.0.pdf

Based on the assessed production costs and considering a market price of 80 EUR/t as proposed by Panoutsu in 2020 (Panoutsu 2020), the projected revenues from cultivating and selling miscanthus in the UK appear insufficient to warrant its cultivation. Therefore, achieving profitability for miscanthus hinges upon three key factors: firstly, the establishment of higher market prices; secondly, the implementation of substantial support mechanisms such as subsidies to bolster miscanthus production; and thirdly, crop yield increase. This latter point is especially linked to the development of clones and hybrids strains that can be better adapted to the specific site where the perennial crop will be cultivated. The more likely scenario however, is the one that leads farmers to increase the market price on the local market for their biomass, to at least EUR 100/t in order to have a minimum net revenue margin (25%) over the production costs. Marginal lands cultivation is governed by peculiar conditions when compared to agricultural activities on traditional arable land. The condition of marginality in the specific case study is represented by low productivity factors of the pedoclimatic combination found, but also by the geographical isolation of these lands with respect to the markets. Productivity and profitability of agricultural activities that could take place on these lands are therefore two intertwined aspects. A productivity of 6.5 t/ha and a market price of the biomass around 100 EUR/t against a production cost of 75.6 EUR/t would hardly justify investing in agricultural activities in remote areas for smallholder farmers. Based on the results of this indicator then, the enabling factor for the miscanthus supply chain would be the opportunity for large scale developers (>1 000 ha each) to engage in biomass production with specific contracts with the ethanol plant.

4.2.9 Investment

This indicator is based on a financial analysis, where a standard CBA approach is applied to demonstrate net profits. The analysis is done to compute the investment's financial performance indicators and is carried out to assess the potential investment's profitability. Information on CAPEX and OPEX for the selected investments was collected from specific literature and the outcomes of the FORBIO project[12], which assessed the financial characteristics of two investments centred around the establishment of a 40 000 t/yr cellulosic ethanol industry. Table 72 shows CAPEX and OPEX for the investment. CAPEX represent the investment required to design, construct, and commission the bioenergy plant and include the buildings, platforms, facilities, equipment, pipelines, and everything else with a lifetime greater than one year. A Bank loan covering 50 percent of CAPEX is assumed with the following features: constant interest rate (7 percent), duration (10 years), grace period (3 years), loan repayment plan (constant instalments) (Table 71).

Table 74. Loan structure UK case study

Equity private financing	**-75 000 000.00**		
Loan	**-75 000 000.00**	**50%**	of initial investment
Constant interest rate	**5%**		
Duration of loan (years)	10		
Grace period (year)	3		
Loan repayment plan	Constant instalments		

Source: results of the FAO's BIKE set of sustainability indicators

The OPEX that were considered for this analysis were: feedstock expenditures and salaries for feedstock transport, salaries and inputs for feedstock processing into fuel, plant processing miscellaneous. (Table 72).

Table 75. CAPEX and OPEX considered for the 2G ethanol plant in UK

Item	Value	Unit
Investment cost (CAPEX)	172 500 000	€
Operating expenditures (OPEX)		
Inputs	14 950 000	€/year
Salaries	1 495 000	€/year
Miscellaneous	2 300 000	€/year
Feedstock (including transport)	20 000 000	€/year
Lifespan investment	25	years

[12] Welcome | Forbio (forbio-project.eu)

In general, considering an asset depreciation of some 6.9 million per year for the 2G ethanol plant, a price paid for the feedstock of EUR 100/t, and the other discussed operational expenses, the total annual OPEX would be some 45 645 000 EUR. According to data provided by the Imperial College (IC, 2022), the European price for ethanol for 2023 is around 1 027 EUR/tonne. At EU market prices, sales of ethanol from a 40 000 t/year biorefinery would generate some 41 080 000 EUR/year in the UK. In addition to ethanol production, the surplus electricity produced in the hypothetical biorefinery could reach some 104 GWh of electricity per year.

It is crucial to underline the importance of this production of surplus electricity sold to the grid in the economic feasibility of cellulosic ethanol , as the price per unit of electricity generated is as much of a key aspect in evaluating the economics of a 2G ethanol biorefinery as the price paid per ton of ethanol. In fact, at the current price of electricity for large scale biomass-fueled power plants in UK 2023 of 380 EUR/MWh (IC, 2022), revenues from the 2G ethanol plant in Northwest England for the generation of the surplus of electricity would amount to EUR 39 489 600 EUR per year. Electricity prices in 2022 have been driven by the global energy situation, in turn caused by the war in Ukraine and related embargo on Russian products, including energy products. This is important to notice for any long-term assessments which are expected to have lower average electricity prices and thus lower overall revenues attributable to the co-products of the cellulosic ethanol plant. Total revenues for a 40 000 t/year biorefinery at 2023 market conditions would then be EUR 82 289 600 per year. Considering a 15 percent inflation in CAPEX and OPEX and a loan with a constant interest repaid within a maximum of 10 years at a 5 percent interest rate, the analysis yielded positive results with an Internal Rate of Return (IRR) of 37% and a high positive Net Present Value (NPV). The payback period is calculated to be 3 years from the loan agreement (Figure 29).

Figure 29 shows the results of the financial CBA. Net Present Value (NPV) and Internal Rate of Return (IRR) were calculated. The analyses showed positive results, particularly when a 50 percent capital loan is applied.

Figure 29. Investment analysis of lignocellulosic EtOH production in UK using low i-LUC feedstock

Year	0	1	2	3	4	5	6	7	8	9	from 10 to 20
General											
Annual production of Ethanol (Tonnes)	0.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00
Annual production of Electricity (MWh)	0.00	103,920.00	103,920.00	103,920.00	103,920.00	103,920.00	103,920.00	103,920.00	103,920.00	103,920.00	103,920.00
EtOH price (EUR/tonne)		1,070.00	1,070.00	1,070.00	1,070.00	1,070.00	1,070.00	1,070.00	1,070.00	1,070.00	1,070.00
Feed in tariff (EUR/MWh)		380.00	380.00	380.00	380.00	380.00	380.00	380.00	380.00	380.00	380.00
- Asset depreciation		-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00	-6,900,000.00
Cash Flow											
+ Sale of ethanol + electricity	0.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00	82,289,600.00
- O&M cost + labour cost + feedstock costs		-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00	-38,745,000.00
Operating Cash Flow	**0.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**
- Investments	-172,500,000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
- Loan annuity	0	0	0	0	-12,280,060	-12,280,060	-12,280,060	-12,280,060	-12,280,060	-12,280,060	0
Total Cash Flow	**-172,500,000.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**
Cumulative Cash Flow	-172,500,000.00	-135,855,400.00	-99,210,800.00	-62,566,200.00	-25,921,600.00	10,723,000.00	47,367,600.00	84,012,200.00	120,656,800.00	157,301,400.00	560,392,000.00
Payback Year	0.00	0.00	0.00	0.00	0.00	Payback	0.00	0.00	0.00	0.00	0.00
TCF (to shareholders)	**-86,250,000.00**	**36,644,600.00**	**36,644,600.00**	**36,644,600.00**	**24,364,540.39**	**24,364,540.39**	**24,364,540.39**	**24,364,540.39**	**24,364,540.39**	**24,364,540.39**	**36,644,600.00**
CCF (to shareholder)	-86,250,000.00	-49,605,400.00	-12,960,800.00	23,683,800.00	48,048,340.39	72,412,880.78	96,777,421.17	121,141,961.56	145,506,501.95	169,871,042.34	523,841,403.90
Payback Year	0.00	0.00	0.00	Payback	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Loan and capital structure											
Equity private financing	**-86,250,000.00**										
Loan	**-86,250,000.00**	**50%**	of initial investment								
Constant interest rate	**7%**										
Duration of loan (years)	10										
Grace period (year)	3										
Loan repayment plan	Constant installments										
Loan outstanding (BoP)	**86,250,000**	**86,250,000**	**86,250,000**	**86,250,000**	**86,250,000**	**80,007,440**	**73,327,902**	**66,180,795**	**58,533,391**	**50,350,669**	**0**
- Interests		0	0	0	6,037,500	5,600,521	5,132,953	4,632,656	4,097,337	3,524,547	0
- Capital repaid		0	0	0	6,242,560	6,679,539	7,147,106	7,647,404	8,182,722	8,755,513	0
Loan outstanding (EoP)	**86,250,000**	**86,250,000**	**86,250,000**	**86,250,000**	**80,007,440**	**73,327,902**	**66,180,795**	**58,533,391**	**50,350,669**	**41,595,156**	**0**
Project profitability											
Project IRR	**21%**										
Project IRR shareholders	**37%**										
Project NPV	**270,640,679.16**										
Project NPV shareholders	**274,772,119.06**										
Project payback (years)	**5.00**										
Project payback (years) Shareholders	**3.00**										

Source: results of the FAO's BIKE set of sustainability indicators

The positive outcomes of the cost-benefit analysis are primarily attributed to the remarkably high selling prices of the final products, namely ethanol and electricity, during this particular historical period vis a vis the low market price paid for the feedstock (see productivity indicator). This situation is intricately linked to the prevalent geopolitical and energy instability witnessed in recent months. It is imperative to recognize the persistent fluctuations in these prices as an integral aspect of investment analyses. This metric serves as an initial reference point, subject to the continuous market variations, and should thus be regarded as a benchmark for reference and a basis for future discussions rather than a definitive outcome of a purely financial profitability analysis.

To align our analysis with the prevailing standards of the European Union, a novel investment scenario has been formulated. This scenario considers a fundamental aspect specific to EU member countries: the imposition of a ceiling on renewable electricity prices. As per EU regulations, the maximum allowable price for renewable electricity stands at EUR 180 per megawatt-hour (MWh)[13]. This pivotal factor underscores the unique economic landscape within which our investment evaluation will transpire, reflecting the EU's commitment to sustainable and affordable energy solutions. A comparison between the current and novel scenario was done as presented in Table 73.

Table 76. Comparison between investment scenarios (current vs novel) for the UK 2G ethanol case study

Item	Unit	Current scenario Price UK 2023	Novel Scenario EU price cap
Electricity price	€/MWh	380	180
Annual electricity production	GWh/yr	103.9	103.9
Annual sale of electricity	€/yr	39 489 600	18 705 600
Total cash flow	€/yr	36 644 600	15 860 600
Project IRR	%	21	7
Project IRR shareholders	%	37	9
Project NPV	€	270 640 679	23 960 127
Project NPV shareholders	€	274 772 119	28 091 566
Project payback	years	5	11
Project payback Shareholders	years	3	14

Source: results of the FAO's BIKE set of sustainability indicators

Upon introducing this innovative scenario while maintaining consistent parameters for all financial variables, the outcomes of this analysis yielded positive results in terms of investment

[13] https://www.consilium.europa.eu/en/press/press-releases/2022/09/30/council-agrees-on-emergency-measures-to-reduce-energy-prices/

profitability. Notably, the NPV and IRR indicators both indicate a favourable stance for the investment. This signifies that the projected cash flows, discounted at an appropriate rate, not only cover the initial investment but also yield a surplus, emphasizing the feasibility and attractiveness of the endeavour. As anticipated, one key aspect that has been influenced by the EU's capped renewable electricity prices is the payback period. In alignment with expectations, the payback period has extended, implying that the time required to recoup the initial investment has lengthened. This effect can be attributed to the restricted revenue potential resulting from the price cap. Nevertheless, the positive NPV and IRR underscore the investment's capacity to generate value over its lifespan, further highlighting its potential to align with sustainable energy objectives while adhering to the EU's regulatory framework.

4.2.10 Net Energy Balance

This indicator assesses the variation in energy inputs needed for biomass production, transportation to the biorefinery/bioenergy plant, processing into advanced biofuel, and eventual distribution of the fuel. Table 74 reports the energy inputs associated to lignocellulosic ethanol production and transport across the value chain, including feedstock production, biomass transport, biomass processing, product transport. The total input energy is 3 541 715 150 MJ.

Table 77. Energy inputs of the lignocellulosic EtOH value chain in UK

MECHANIZATION	**Diesel consumption**	
Land preparation (Year 1 only) + harvesting	Kg DIESEL yr-1	31 500
	TOTAL YEARLY DIESEL CONSUMPTION (MJ)	1 354 815
Agricultural inputs		
Amount of fertilization (chemical) N	Kg yr-1	2 500 000
Amount of fertilization (chemical) P	Kg yr-1	375 000
Amount of fertilization (chemical) K	Kg yr-1	3 750 000
Amount of applied pesticides	Kg yr-1	0
Amount of organic fertilizers	Kg yr-1	0
	TOTAL YEARLY INPUTS CONSUMPTION (MJ)	206 656 250
Transport: Biomass transport	Km	25
Total FSTK production (tot ha*yield)	tonnes	200 000
	TOTAL YEARLY DIESEL CONSUMPTION (MJ)	4 050 000
Feedstock processing into fuel	**MJ**	34 085
Energy from enzymes (embedded)	**MJ**	3 328 000 000
Transport: Fuel transport	Km	50
Total fuel produced	tonnes	40 000
	TOTAL YEARLY DIESEL CONSUMPTION (MJ)	1 620 000

Source: results of the FAO's BIKE set of sustainability indicators

Table 75 shows the energy output of the value chain, for a total 1 446 512 000 MJ. This output involves the ethanol (40 000 tonnes per year) and the electricity (103.9 GWh per yesr) produced by the plant.

Table 78. Energy outputs of the lignocellulosic EtOH value chain in UK

Total biofuel produced	**MJ**	1 072 400 000
Co-products (electricity)	GWh	103.9
	MJ	374 112 000

Source: results of the FAO's BIKE set of sustainability indicators

Table 76 presents the net energy ratio (EO/EI or TFO/TFI), which represents the relationship between the energy output associated with the advanced biofuel and the energy input required for its production. In this particular case study, the final EO/EI ratio is 0.4.

Table 79. Energy outputs of the lignocellulosic EtOH value chain in UK

FEEDSTOCK PRODUCTION		TFI	1,040
	MJ/tfeedstock	TFO	17,450
	Net Energy Value	TFO-TFI	16,410
	Net Energy Ratio	TFO/TFI	17
FEEDSTOCK TRANSPORT and PROCESSING INTO FUEL		TFI	20
	MJ/tfeedstock	TFO	7,233
	Net Energy Value	TFO-TFI	- 9 428
	Net Energy Ratio	TFO/TFI	0.43
ENERGY EFFICIENCY OF INTERNAL COMBUSTION ENGINES			
	MJ/tfeedstock		
	Net Energy Value	TFO-TFI	1,803
	Net Energy Ratio	TFO/TFI	0.25
LIFECYCLE ENERGY EFFICIENCY OF THE STUDIED VALUE CHAINS			
	Net Energy Ratio	TFO/TFI	0.4

Source: results of the FAO's BIKE set of sustainability indicators

The culmination of our analysis reveals a noteworthy final Energy Output to Energy Input (EO/EI) ratio of 0.4. This outcome can be attributed to a significant factor—the substantial energy input necessitated by the production of enzymes, a pivotal component in the renewable energy generation process. The energy-intensive nature of enzyme production has consequently driven up the energy input side of the ratio, impacting the overall balance between energy generated and energy expended. It's important to recognize that the ratio's value of 0.4, as derived from a study conducted in 2014 (Feni, 2014) and referenced in an officially reviewed scientific paper, might potentially be outdated due to the dynamic nature of technological advancements in the renewable energy sector. It is plausible that subsequent years have witnessed substantial progress in the efficiency and energy requirements of enzyme production processes. Such technological developments could feasibly lead to a reduction in the energy input required, thus influencing the EO/EI ratio positively. While the 2014 analysis provides a foundational understanding, it is imperative to consider the evolving landscape of renewable energy technologies and their potential impact on the EO/EI ratio. Continued research and updated data would allow for a more accurate assessment of the current relationship between energy output and input in the context of enzyme-based renewable energy production.

4.2.11 Infrastructure

The examination of the transportation infrastructure for biomass and biofuels complements the information discussed in other indicators, providing a comprehensive perspective on the target area's characteristics from this standpoint. This indicator involves the user evaluating distances between production areas and a hypothetical biorefinery location, according to the primary assumption of the target scenario. Using GIS tools, actual distances between production sites and the collection point are then calculated. Moreover, this indicator measures the time required for collecting and delivering biomass to the biorefinery's entrance.

The average yearly transport time of the biomass was determined by considering the average loading capacity of the vehicles (such as tractors, trucks, and rails) used at each stage of transportation (from the field to the road, road to biorefinery gate, etc.). Additionally, the average speed permitted on the specific road type in kilometres per hour and the averaged actual distance between the different production sites and the collection site were taken into account during the calculation process.

In this case study, the 200 000 tonnes of feedstock are transported from the fields to the biorefinery (25 km distance) by trucks with a loading capacity of 30 tonnes, and an average speed of 50 km/h, for a total amount of hours of 6 667 hours annually. As for the cellulosic ethanol transport from production site to various distribution sites (gas stations, etc.), the transportation is carried out by trucks with a capacity of 30 tonnes and an average speed of 80 km/h, totalling 1 677 hours. The total amount of hours associated to transport is thus 8 333 hours. This time value was used in the sustainability analysis for calculating transportation emissions, job positions created, and other related factors. Table 77 reports the result of the assessment.

Table 80. Results of the assessment of the Infrastructure indicator for UK 2G ethanol case study

	Distance [km]	Total produced feedstock [ton]	Vehicle type	Loading capacity [ton]	Average vehicle speed [Km/h]	Hrs
Feedstock transport	25	200 000	Truck	30	50	6 667
Fuel transport	50	40 000	Truck	30	80	1 667
					TOTAL HOURS	**8 333**

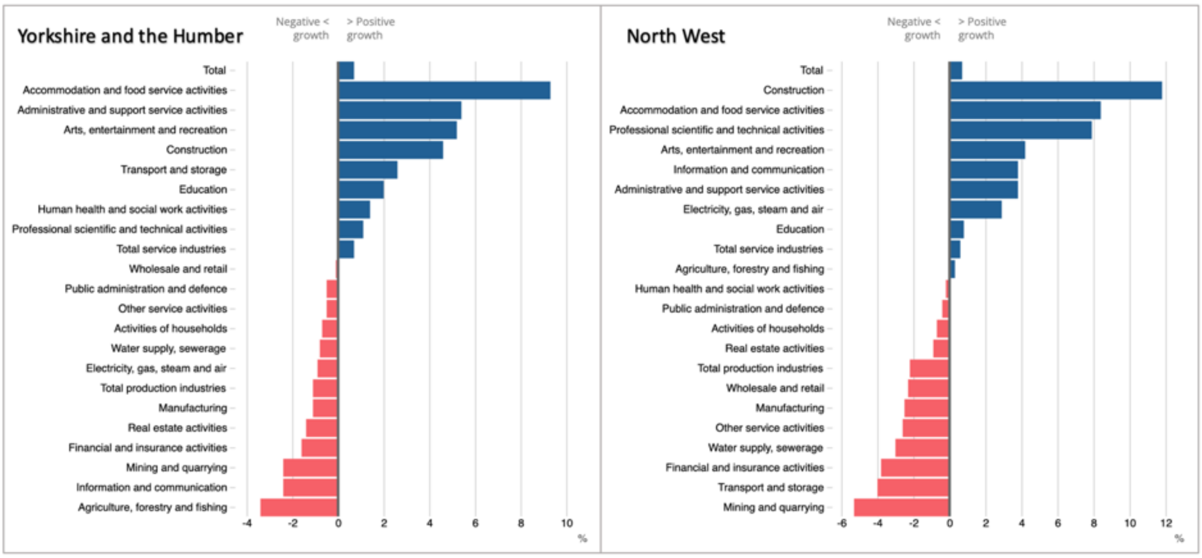
Source: results of the FAO's BIKE set of sustainability indicators

4.2.12 Gross Value Added

This indicator evaluates the impact of a specific bioenergy value chain on the GDP (Gross Domestic Product). In the UK case study, the GDP contribution is attributed to the sales of bioethanol and excess electricity.

As per the 2022 report from the UK Government (HM Treasury, 2022), the United Kingdom is currently grappling with a period of heightened inflation. This situation is illustrated in Figure 30, where the agriculture and energy sectors in Yorkshire exhibited a notably negative growth trend in 2022. The Northwest also experienced modestly positive trends. To address the issue of soaring energy costs, the government has undertaken significant measures through its 2022 Growth Plan. This plan aims to implement substantial interventions within the energy market, targeting cost reduction and bolstering resilience over the long term. The surge in UK energy prices is intricately tied to global market dynamics, having been a primary contributor to the nation's inflationary pressures over the past year. The supply of gas to Europe has further dwindled since spring, following the embargo on Russian products, including natural gas. This situation has triggered price hikes in the global liquefied natural gas market, with Europe and Asia competing to secure supplies ahead of winter, thus driving up UK prices.

Figure 30. Seasonally adjusted quarter on quarter GDP growth for Quarter 1 (Jan to Mar) 2022



Source:https://www.ons.gov.uk/economy/grossdomesticproductgdp/bulletins/gdpukregionsandcountries/januarytomarch2022

In response, the government of the UK (as well as virtually all EU-27 governments) unveiled an extensive support package designed to alleviate the strain of escalating energy costs on households and businesses across the country. A novel Energy Supply Taskforce has been established with the purpose of negotiating long-term agreements with key gas producers. Additionally, collaboration with electricity generators is underway to reform the antiquated market structure, where gas currently dictates electricity prices. The government's intent is to transition to a system wherein electricity prices more accurately reflect the UK's domestic, cost-effective, and low-carbon energy sources, consequently reducing consumer bills.

The successful measures should stabilize gas and electricity prices, bolster supply security, and reduce future energy price crises. The government's path involves tax cuts, public sector streamlining, and promoting a dynamic private sector. By fostering investment, easing capital flow barriers, creating skilled job opportunities, and expediting infrastructure projects, the UK aims for prosperity.

In this context, a cellulosic ethanol plant diversifies energy sources, aligning with the government's goal to reduce fossil fuel reliance and stabilize energy costs. By producing ethanol sustainably from non-food plant materials, like miscanthus, the plant mitigates global energy market impact on the UK's costs. This mirrors the government's vision for a sustainable and diversified energy landscape.

Considering an Ethanol market price of 1 070 €/ton, and a market price for the electricity (co-product of the value chain) of 380 €/MWh, and that the Gross Domestic Product of the target area is 82 249 M€, the assessment of this indicator holds the results shown in Table 78. The project would have a modest impact (0.0003%) on the target area GDP generating an annual Gross Value Added (GVA) of some 25.13 million EUR.

Table 81. Contribution to target area GDP of the proposed lignocellulosic EtOH value chain

SALES of advanced biofuel	42,800,000
SALES of additional services (Electricity)	39,489,600
Variable operating expenses	-57,152,000
GVA	25,137,600
Contribution to GDP	0.0003%

Source: results of the FAO’s BIKE set of sustainability indicators

4.2.13 Capacity

The contribution of the production from the case study to reaching the capacity of using bioenergy of a country is measured in this indicator. Due to the increasing fuel efficiency of vehicles, consequence of emission reduction policy at the EU-level, petrol consumption is expected to decrease over time. This indicator calculate the contribution of the potential 2G ethanol production on the ethanol consumption considering the E10 mandate in UK and by basing its analysis on 2023 petrol consumption.

As of 2023, in the target area, the consumption of ethanol for transport amounts to around 61 500 tonnes per year, while in the Northwest and Yorkshire it is 234 600 tonnes per year. In England, UK and in the EU the use of ethanol for transport is currently about 910 686, 1 075 677 and 6 250 532 tonnes per year, respectively.

According to these figures, the additional production of 40 000 tonnes per year of lignocellulosic ethanol would replace around 65 percent of the petrol consumption in the target area, 17 percent in the Northwest and Yorkshire, 4.3 and 3.7 percent in England and UK, and finally considering a common E10 mandate around 0.64 percent in the EU.

Table 82. Summary of the impacts on the capacity of using lignocellulosic EtOH the target area fleet, in the North-West and York Shire fleet, in the England fleet, in the UK fleet, and in the European fleet

Baseline	**Unit**	**Target area**	**NW + YS**	**England**	**UK**	**EU**
Current Petrol use	t	615 220	2 346 000	9 106 863	10 756 774	62 505 324
Current bioenergy capacity (E10)	t	61 522	234 600	910 686	1 075 677	6 250 532
Target biofuel production	t	40 000	40 000	40 000	40 000	40 000
Capacity ratio TARGET	**Share**	65.02	17.05	4.39	3.72	0.64

Source: results of the FAO's BIKE set of sustainability indicators

4.3 Conclusions

This case study is based entirely on secondary data, including the identification of suitable land for the production of low ILUC feedstock. As a consequence, the authors had to make a number of assumptions, being impossible to verify data on the ground. On the other hand, however, this exercise highlighted to potential to carry out a pre-feasibility study of sustainable potential with the use of existing tools, some of which already designed in the context of previous H2020 projects. In total, the reference target area used for the assessment of the sustainability of the selected bioenergy value chain has a surface of 1 760 000 ha of which about 30 000 ha would be necessary for the production of miscanthus, the selected feedstock for this case study. Miscanthus cultivation, through high yielding clones, is characterized by elevated input use efficiency, which is alone an important determinant of sustainability of a bioenergy value chain. After planting, this perennial grass does not require heavy inputs and over its lifetime this translates into positive impacts on several environmental indicators, including the GHG profile of the biofuel produced (72 percent emission reduction when compared to petrol) and especially on biodiversity conservation potential. Perennial grasses are a sensible choice for any marginal land reclamation activity and this assessment confirmed such claim. In the specific set of conditions tested in this case study, water quality aspects have been particularly considered, by including a series of best practices. Considered practices include minimum tillage, the employment of organic agriculture, the utilization of conservational buffers, erosion sediment control and wastewater treatment at the feedstock and fuel processing level. The indicator shows the effects of the presence of these practices with a positive result and only marginal room for improvement for both water quality and biodiversity conservation. The bare lands where miscanthus would be planted could also benefit for additional layers of a canopy that can host macro and microfauna with increased value compared to the neighbouring areas, and the peculiar distribution of the territory of some 30 000 ha of perennial tall grasses in a landscape dominated by mosses and bare land, would constitute an important biodiversity corridor and increase the mosaic of the landscape. The low mechanization characteristics of the value chain, if on the one hand limit the impacts on soil, water and biodiversity, on the other hand return poor results in terms of job creation since only harvesting and biomass transport would require substantial workforce. However, these field operations and above all activities at the processing stages, would lead to few but all highly qualified and skilled job positions. The economics of the value chain show positive conditions for investing in cellulosic ethanol as of 2023, but this is largely due to the existing energy price situation in the UK and in Europe. Shall such conditions remain unchanged over time (especially the price cap for renewable electricity at EUR 180 MWh), a marked sustainable potential for this value chain could be confirmed. Although production costs are higher on marginal lands, and thus net revenues for farmers might not be sustainable if compared to biomass market prices, the profitability of investing in cellulosic ethanol and crucially, in electricity generation from biomass, would justify not only the investment on the industrial phases of processing miscanthus into ethanol, but also the acquisition and cultivation of the land necessary for the supply. The economies of scale identified, the marginality and distance from major markets of the lands selected for this case study, coupled with the low requirements in terms of labour for miscanthus, would most likely impede smallholders from embarking autonomously in the production of such feedstock. Conversely instead, this value chain poses the conditions only for large Agri holdings and industrial developers to manage the entire value chain by renting the land and carrying out all necessary production activities. Risks associated with such approach are not negligible but difficult to evaluate in the context of this report.

The potential positive impacts on environmental indicators as well as the need to further detail a sound roadmap for the deployment of a cellulosic ethanol value chain in the UK require further analysis and possibly primary data collection, field trials and stakeholder consultations and additional studies are recommended.

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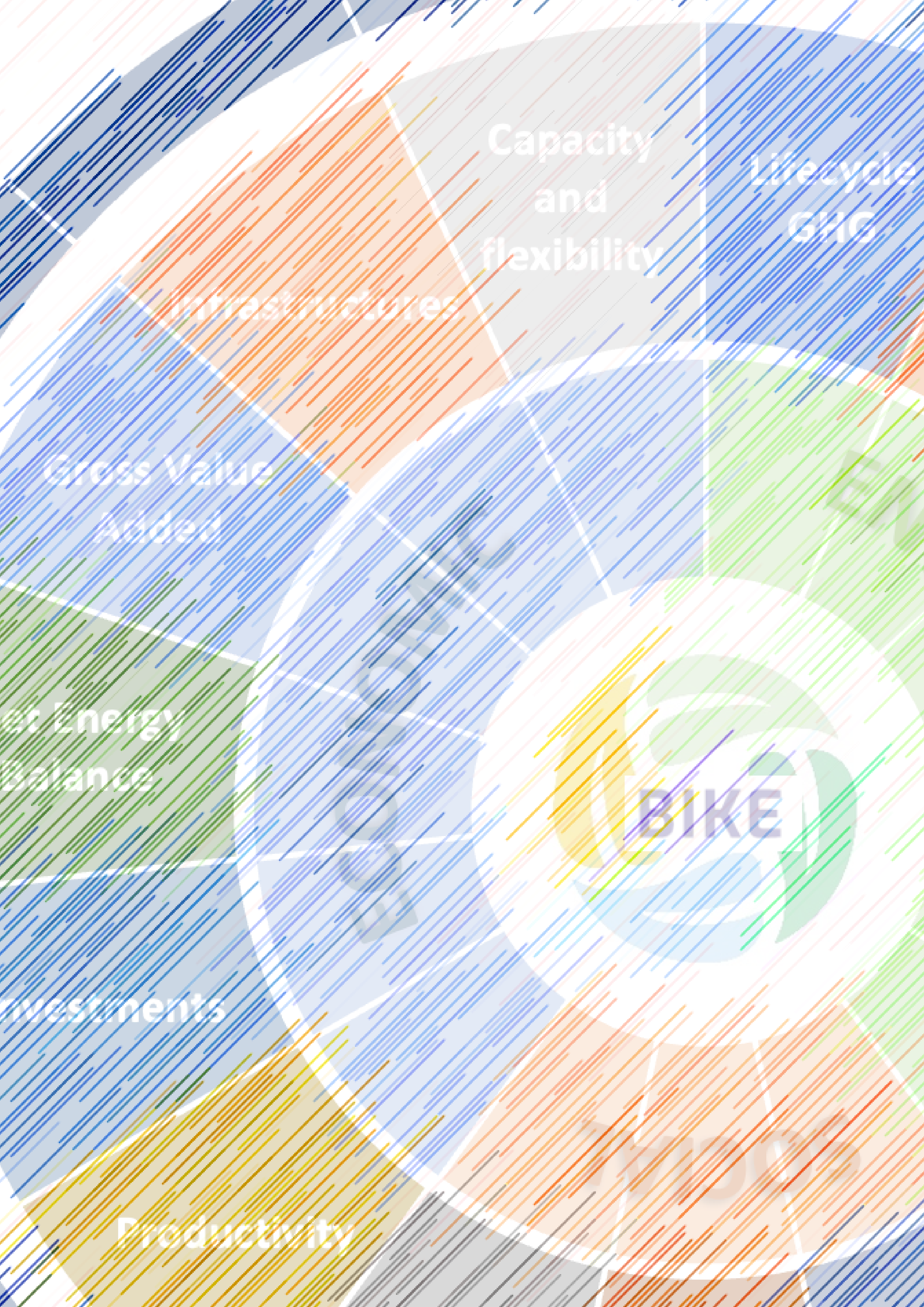
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