Value4Farm

VALUE4FARM

D1.2 Report on demonstrations’ specifications

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Value4Farm

LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
AESI	Agro-Environmental Sustainability Index
AV	Agrivoltaics
BJ	Brown Juice
CAPEX	Capital Expenditures
Cfa	humid subtropical climate
CHP	Combined Heat and Power
CNH	Case New Holland
COS	Characteristic Operating Space
CSTR	Continuously Stirred Tank Reactor
ET	Evapotranspiration
IRRGT	Intercooled, Recuperated and Reheated Gas Turbine
LCA	Life Cycle Assessment
LPC	Leaf Protein Concentrate
MILD	Moderate or Intense Low-oxygen dilution
MPPT	Maximum Power Point Tracking
MT	Minimum Tillage
NT	No Tillage
NUE	Nitrogen Use Efficiency
OPEX	Operating Expenditures
ORC	Organic Rankine Cycle
PAR	Photosynthetic Active Radiation
PSA	Pressure Swing Adsorption
ROI	Return On Investment
ST	Strip Tillage
TEA	Techno-economic analysis

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- Renewable energy
- Agrivoltaics
- Biomethanation
- Crop rotation
- Farm-scale

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EXECUTIVE SUMMARY

Three value chains integrating biomethane production and/or agrivoltaic solutions in three countries (Italy, Belgium and Denmark) are the protagonists of the three demonstration sites of the Value4Farm project (V4F), all with the primary objective of de-fossilising the agricultural sector.

At Università Cattolica del Sacro Cuore (UCSC) and REM Tec in Italy, the partners will demonstrate the best combination of crops with horizontal agrivoltaics and, together with Consorzio Italiano Biogas (CIB), will investigate the compatibility of hybridisation with biomethane production to create an efficient off-grid biomethane plant. It is expected that 100% replacement of current fossil energy use on the farm can be achieved.

At Inagro (INA) in Belgium, a business case for a farm scale biogas unit (up to 30 kW_{el}) will be demonstrated, based on the direct use of the biogas produced to power a tractor, allowing the farmer to potentially achieve a total CO_2 saving of -80% and a total operating cost saving of -40% compared to using a diesel tractor. Next to this, an innovative, high efficiency microturbine will be demonstrated as well.

At Aarhus University (AU) in Denmark, a value chain will be demonstrated to maximise energy production per land area in a sustainable way for large farms (>100 ha, with a corresponding biogas unit of >600 kW_{el}) or cooperatives. The demonstration at AU will be based on vertical photovoltaic technology combined with crop production, a green biorefinery for protein extraction from perennial green crops (and intercrops), and a full-scale biogas plant demonstrating CO_2 valorisation through biomethanation to convert green biorefinery residues into biomethane for use to power a tractor or the natural gas grid. Opportunities for hybridisation will be pursued (e.g. agrivoltaics feeding biogas upgrading, creating an off-grid biomethane plant). Similar as in Italy, the aim is to replace 100% of the farm's current use of fossil fuels, which will reduce the farm's current energy-related CO_2 emissions by 100%. In addition, excess energy can be exported to society without reducing the farm's food production.

In this deliverable (D1.2) each demonstration case will be presented through a comprehensive overview of the concept and objectives, followed by a detailed description of the technologies employed. Where relevant, environmental conditions for the various demonstration sites will be described, illustrating the intricate interplay between environmental factors and their impact on energy production and food systems.

Although the experimental design is outlined in a general way, a detailed description of the experimental protocols will be presented in deliverable D2.3 for the Atlantic demonstration case (agrivoltaics and biomethane production), in D2.4 for the Mediterranean demonstration case (anaerobic digestion and cultivation under agrivoltaic panels), and in D2.5 on how to handle crop residues for biogas production and good use of digestate. In addition, a detailed analysis of the data to be collected in each demonstration case will be presented, providing an essential basis for planning the environmental assessment and techno-economic analysis as part of WP4.

Finally, preliminary mass and energy flows are presented in diagrams and tables for each demonstration value chain. The preliminary flows focus on identifying and mapping the comprehensive inputs and outputs of each unit operation within each value chain, which will be used with upcoming data to determine preliminary mass and energy balances in future project tasks (T3.2 Demonstration in Denmark, T3.3 Demonstration in Italy, and T3.4 Demonstration in Belgium). Furthermore, the diagrams outlining preliminary mass and energy flows also distinguish the most relevant steps in each value chain where

future hotspots will be determined for more detailed life cycle analysis in T4.1 Environmental Assessment. Thus far, the key factors in determining areas for future hotspot assessment include the identification of value chain processes that are either novel to the experimental design of the demonstration site or contain a high potential for environmental impacts. Using collected data from upcoming project tasks T3.2, T3.3, and T3.4, a detailed description of each value chain's mass and energy balance, i.e., the ratios of mass and energy flows within each demonstration value chain, will be found in the upcoming deliverable D4.1 – Sustainability Analysis of the Value Chains.

1. DEMONSTRATION SITE IN ITALY

1.1 Concept of the demonstration case and its objectives

Agrivoltaics and biomethane production are among the most promising technologies for farm-scale renewable energy production. Specifically, the demonstration will i) implement farm-scale agrivoltaic technologies, cultivated with cash crops (e.g. processing tomatoes, potato), in off-grid bio-methane plants (REM); ii) evaluate the scaling-up of agrivoltaic plants on medium/large scale (> 20 ha) to increase the farm's renewable energy production, while maintaining its food/feed and biomethane production potential (UCSC). The data collected during the demonstration will be used to calibrate a simulation platform developed at UCSC and validate its accuracy. The platform will be used to optimise the design and management of agrivoltaic systems, with double-crop systems as proposed by the CIB within BiogasDoneRight®[1]. During the project, several actions of the CIB's flagship initiative FarmingForFuture[2] will be taken; the two main actions concern crop rotation to improve soil fertility and food and feed production per hectare. This will be done through: i) adding winter cover crops to the crop rotation that can be harvested before or after traditional food and feed crops, thus keeping the hectares devoted to food and feed almost at the same level as before, and producing double harvests at the time of year when the land is set aside; ii) introducing nitrogen-fixing plants such as fodder legumes, in rotation with other cereals for market and anaerobic digestion.

The main objective of the demonstration case in Italy is to evaluate two scenarios for the integration of renewable energy on farms. The first scenario consists of the technical-economic evaluation of a farm-scale (1 hectare) agrivoltaic plant to replace the energy needed for the biomethanation process, reducing the demand for electricity from the grid by using the energy produced by an agrivoltaic plant (AV) adjacent to the biogas plant. This specific scenario also evaluates the use of batteries to store the energy produced by the AV and then use it when needed. The second scenario consists of the evaluation of medium-large agrivoltaics (>20 ha) capable of providing the energy needs of the farm and ensuring continuity of production. Specifically, the simulation platform developed by UCSC will be used to define the optimal AV system (e.g. biaxial, vertical, monoaxial) for two farmers associated with the CIB.

Three subsystems (Figure 1) were defined:

1. At REM (**SUBSYSTEM SMALL AGRIVOLTAISM**), cash crops will be studied as part of Scenario 1 (i.e. agrivoltaics on a farm-scale -1 ha- for fulfilling the energy needs of the biomethane plant). In particular, the partners intend to study the behaviour of potatoes and processing tomatoes under the *Agrovoltaico®* 1.0 system[3] by collecting quantitative and qualitative data to understand irrigation, light and nutrient requirements compared to full light. The data collected during the experiment will be used to validate the UCSC simulation platform.

[1] https://www.consorziobiogas.it/wp-content/uploads/2017/05/Biogasdoneright-No-VEC-Web.pdf
[2] https://farmingforfuture.it/?lang=en
[3] https://remtec.energy/agrovoltaico

2. At UCSC (**SUBSYSTEM MEDIUM-LARGE AGRIVOLTAISM**), cash crops (tomato, soybean) will be tested, as well as crops involved in BiogasDoneRight®'s crop rotation protocols for producing feedstock for biomethane production to validate crop performance under agrivoltaics. Around 2 ha will be dedicated to this study at UCSC, and results will be upscaled via a simulation to a medium/large-scale agrivoltaism (> 20 ha) installation as part of Scenario 2. Crop performance (biomass quantity and quality) and crop eco-physiological parameters, as well as crop water and nutrient use efficiency (NUE), will be investigated to understand the impact of agrivoltaics.
3. At two of CIB's associated farms (**SUBSYSTEM FARMLAND**), the updated crop protocol for double cropping for BiogasDoneRight® will be validated at the farm scale against conventional management protocols on the rest of farmland, not under agrivoltaism. The objective is to confirm at farm scale the climate benefits (soil carbon sequestration, greenhouse gas (GHG) emission reduction related crop inputs savings), as well as co-benefits on soil quality and biodiversity, of a set of carbon farming practices under the BiogasDoneRight® protocol and practicalities of advanced agricultural practices (strip tillage, no-tillage, precision farming) to unlock the potential of BiogasDoneRight® to scale.

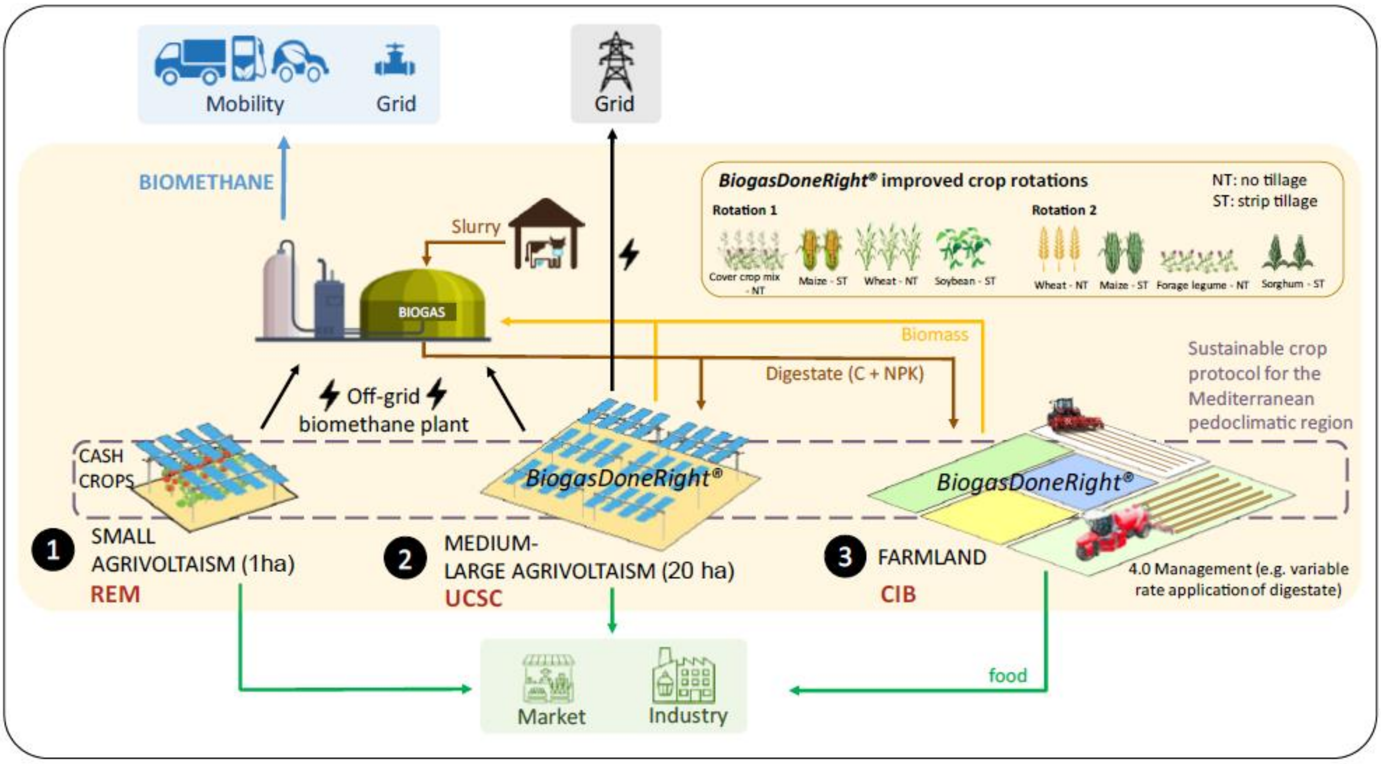

Figure 1: Diagram of the Italian demonstration case

1.2 Description of the demonstration case

The demonstration case in Italy consists of three subsystems. All three subsystems are located in northern Italy, respectively at REM, UCSC and two CIB member farms.

SUBSYSTEM « SMALL AGRIVOLTAISM »

At **REM,** the site in Virgilio (45° 5'40.12"N, 10°47'30.69"E) was established at the end of April 2011. The plant extends over 11,42 hectares, to produce 2,15 MWp (280 Wp polycrystalline modules) with a yearly producible of 1545 kWh/kWp. Since 2019, REM Tec decided to lead some experimentations on various varieties (tomato, pumpkin, potato, wheat, corn, rice, alfalfa, kiwis, apple, vineyard etc.). In this field of activity, a weather station and agronomic sensors were installed to measure climatic and agronomic parameters. The aim of these experiments is to understand how plants evolve under shade. From this data, the goal is to modify the tracking system depending on the crops to provide the right amount of shading and light.

This installation was built with the first version of the monofacial Agrovoltaico® 3D-T1.0 tracker (Figure 2), which consists of a 12-meter-long horizontal tube, which supports 5 rows of wings, each supporting a photovoltaic module, generally made up of 72 cells. The rows of trackers are 12 meters apart from each other. They are connected by a tensile structure to support the cabling and minimize the footprint. The height of the system is approximately 4-4.5m from the ground, allowing traditional agricultural machinery to work below. The rotation that can be allowed is of +/- 50 ° from the horizontal, and +/- 60° from the vertical. Over the years of operation, several crops were grown under the plants, such as wheat, corn, alfalfa, soybeans and rice. Since 2019, REM Tec has also been carrying out experimental research on the Virgilio plant with horticultural crops, such as salad, potatoes, tomatoes, pumpkin, melons, raspberries as well as kiwi and grapes amongst others. The results remain preliminary and until confirmed by several harvests, research continues.

The installed system contains a total of 768 trackers, or 7680 modules (280 Wp modules). Compared to the surface area used by the technology, this provides a coverage rate of 14% (Surface of the modules/surface of the installation). In this specific case, less than one hectare is used and available for the experiments. Today, the system has evolved, to have first 4 secondary axes (technology 2.1, Figure 2 and 3) and now 3 secondary axes with bigger modules (660 Wp and soon 700 Wp) with a size of 1.38m by 2.3 meters that provide a ground coverage ratio of 30% approximately.

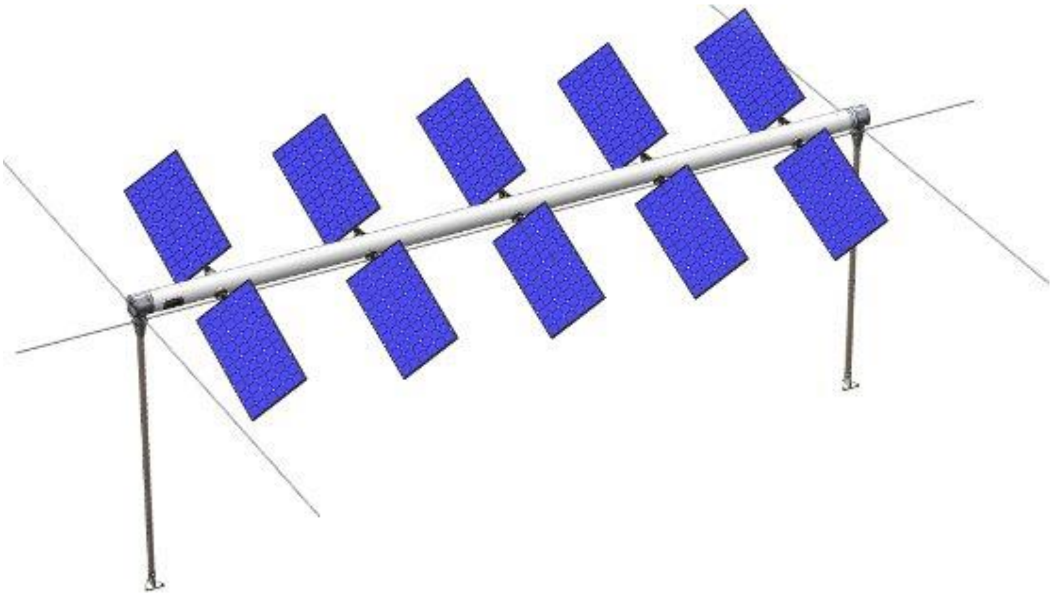

Figure 2: Technology 1.0 developed by REM Tec srl

Figure 3: Technology 1.0 installed in Virigilio (Mantova, Italy)

SUBSYSTEM « MEDIUM-LARGE AGRIVOLTAISM »

At **UCSC** (45°02'16.1 "N 9°43'49.1 "E), a biaxial bifacial plant will be operational from spring 2024, the result of technology developed by REM Tec. The plant covers an area of 0.72 hectares, with a total production capacity of 506.97 kWp (Figure 4 and 5). The installed system comprises a total of 774 modules, each with a power output of 660 Wp (Trina model) and dimensions of 1.38 m by 2.3 m, providing a coverage rate of 33.4 % of the surface area used by the technology.

Starting in spring 2024, various experiments on cash crops and biomass will be conducted at UCSC under the agrivoltaic plant. Meteorological stations and agronomic sensors will be installed to monitor micrometeorological conditions and crop health under shaded conditions, in order to collect data on climatic and agronomic parameters.

The installation was realised with the Agrovoltaico® 3D - T2.1 tracker version, characterised by a 10.5 metre horizontal tube supporting 4 rows of wings, totalling 24 panels per tracker (Figure 6 and 7). Within the plant, there are two sectors with different distances between tracker rows, 15 and 18 metres respectively. Considering the benefits of bifaciality, the installation at UCSC will be able to generate between 1694 and 1740 kWh/kWp.

The 43 installed trackers are connected by a tensile structure, which supports the cabling while minimising the footprint. The height of the system, 5 metres above the ground, enables conventional agricultural machinery to operate below. The permitted rotation is +/- 50° from horizontal and +/- 60° from vertical.

Figure 4: Top view of the agrivoltaic plant at UCSC

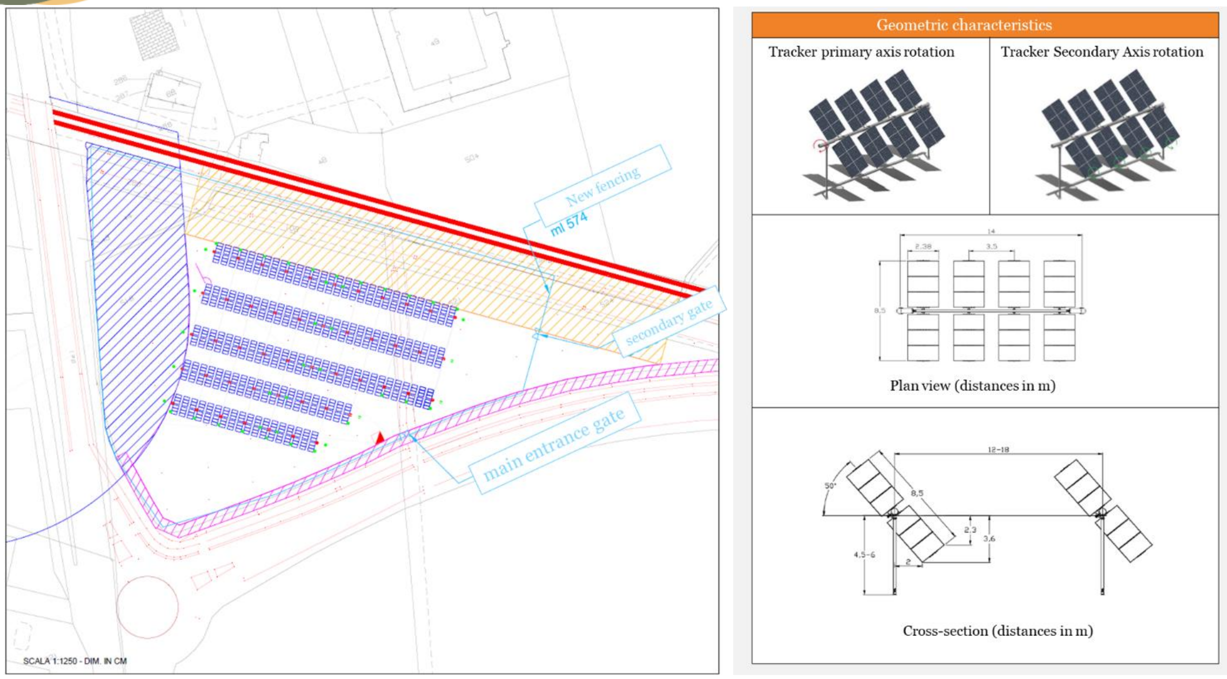

Figure 5: Top view of the agrivoltaic plant at UCSC and tracker Technology 2.1

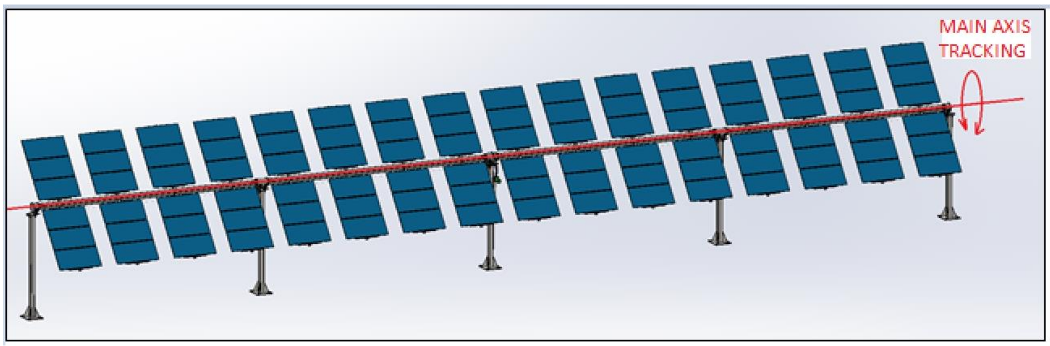

Figure 6: Basic module of 4 trackers in a row (Technology 2.1).

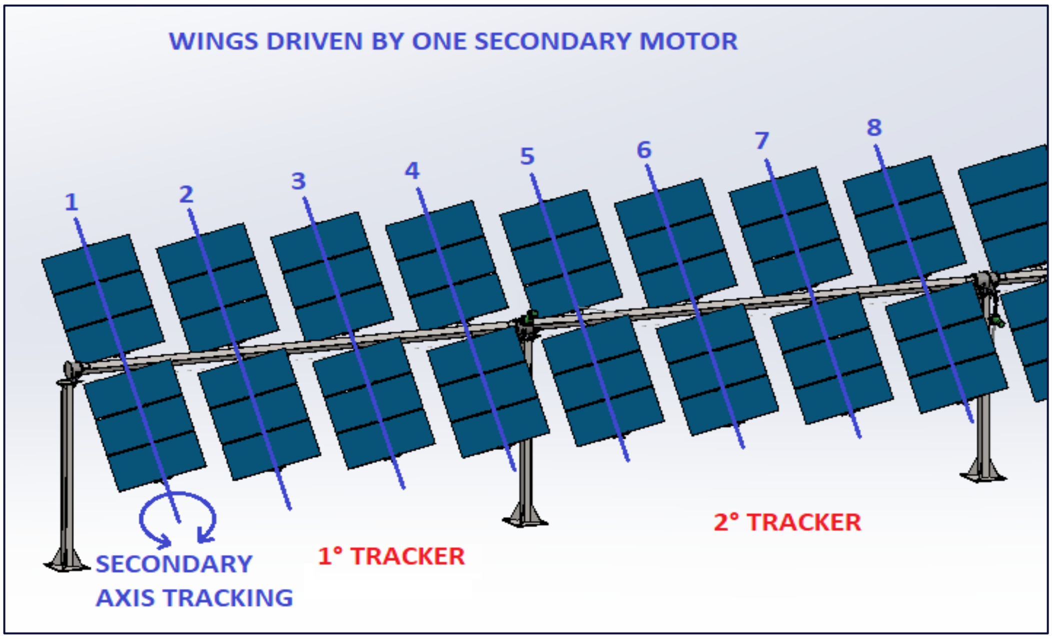

Figure 7: Secondary axis tracking (Example of the 2.1)

SUBSYSTEM « FARMLAND »

At two of **CIB**'s associated farms, a protocol for Nutrient Use Efficient (NUE) double cropping systems (hereinafter *BiomethaneDoneRight® protocol)* will be identified and validated at farm-scale against conventional management protocols (hereinafter baseline) on the rest of farmland not under agrivoltaism.

The objective is to deploy farm-scale practical strategies to improve the NUE (N+P) and circularity (C + NP) and contemporary increase cumulative yearly yield of food and feedstock for biomethane production as well as climate co-benefits (soil carbon sequestration, GHG emission reduction related to crop inputs savings and soil management).

The ambition is to map first the farm-scale baseline NUE in the N input vs. N output diagram and identify the space to target for maximum N output and upper limit for N surplus. The lower and upper limits for NUE (Figure 8) are set by farm-specific Characteristic Operating Space (COS) as proposed by Quemada et al. (2020). The COS is the working space within which the thresholds of a set of indicators are fulfilled, and thus it can be used to indicate the need for improving farm performance and assess the performance of the *BiomethaneDoneRight®* protocols applied in field trials.

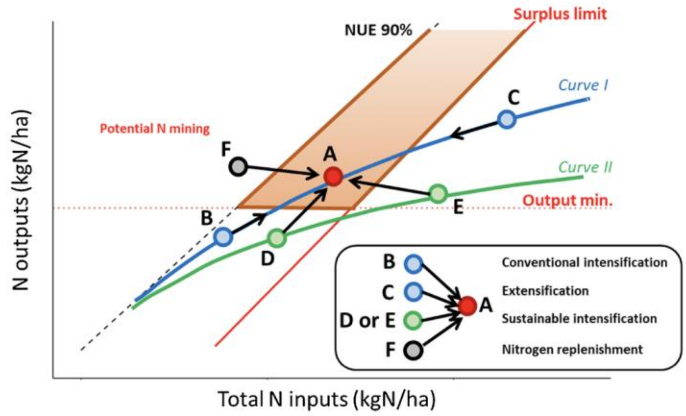

Figure 8: Ideal pathways that any farm could follow to enter the characteristic operating space (Quemada et al., 2020)

Farm-gate mass-balance nutrient balances will be done to calculate a set of NUE and circularity indicators in order to identify the entry points (at crop rotation and soil-nutrients management level) for improving farming performance related to nutrients balance. Three related indicators will be calculated to design and test the *BiomethaneDoneRight®* protocol for double cropping: NUE (farm-gate ratio of N outputs to N inputs), N surplus and N output in agricultural products (Quemada et al. 2020). Circularity indicators (Van Loon et al., 2023) will also be calculated to check the consistency of the current practices in closing and tightening farm-scale C and nutrient loops (e.g. Nutrients fertilization with digestate). Based on the results the *BiomethaneDoneRight®* protocols will be designed.

Three practical strategies will be considered when designing the protocols: 1) improved crop rotations (e.g by adding forage legume and/or cover crop mixture as winter crop); 2) advanced agricultural practices such as minimum/strip tillage to efficiently distribute digestate to all crops into rotation and 3) integration of 4R nutrient stewardships (right rate, right time, right source and right place) into precision farming.

In figure 9 an example how, fertilization plans with digestate can be adopted is reported where red points are moments of digestate distribution with advanced machineries (MT: minimum tillage and ST: strip tillage, NT: No tillage) combined with advanced technologies (VRA: variable rate technologies).

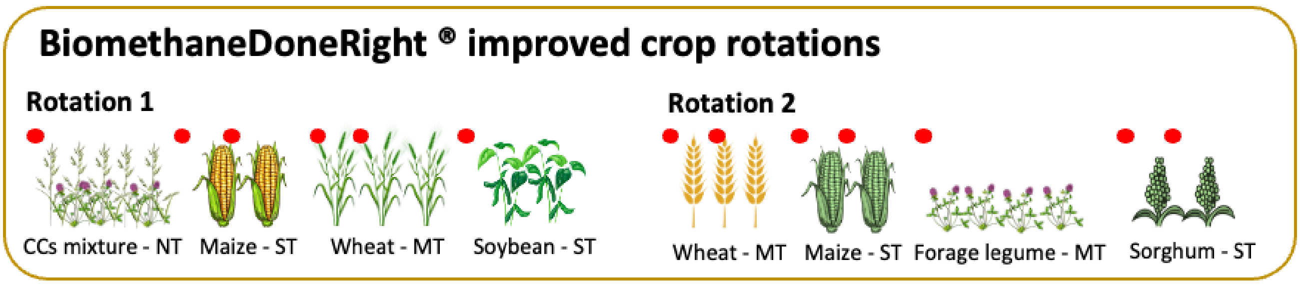

Figure 9: BiomethaneDoneRight® improved crop rotations (NT: no tillage, MT: minimum tillage and ST: strip tillage)

1.2.1 Technical specifications for the renewable energy technologies set-up

This section displays the characteristics of the photovoltaic panels of the agrivoltaic systems studied within the subsystems "SMALL AGRIVOLTAISM" (Table 1 and 2) and "MEDIUM-LARGE AGRIVOLTAISM" (Table 3 and 4).

SUBSYSTEM « SMALL AGRIVOLTAISM »

Table 1: Characteristics of photovoltaic panels used in the 'small agrivoltaism' subsystem at REM

Symbol	Description	Value	Unit of measure	Field additional info
Company	Company name	Shinew	-	string
Code	PV panel code		-	string
BFv	Bifacial module	No	-	boolean
Bff	Reference Bifacial Factor		%	
Wp	Maximum Power (Pmax)	280	W	
Vmp	Maximum Power Voltage	36.27	V	
Imp	Maximum Power Current	7.72	A	
Voc	Open circuit voltage	44.50	V	
Isc	Short circuit current	8.39	A	
STC	Module Efficiency		%	
Tc_Pmax	Temperature coefficient of Pmax	-0.35	%/C	
Tc_Voc	Temperature coefficient of Voc	-0.47	%/C	
Tc_Isc	Short circuit current	unknown	%/C	
NOCT	Nominal operating cell temperature	unknown	°C	
NC	Number of cells	unknown	N	
Rsh	Shunt resistance	unknown	ohm	not always available
Rs	Series resistances	unknown	ohm	not always available
Voltage	Voltage	unknown	V	optional array (25°C curve)
Current	Current	unknown	A	optional array (25°C curve)
Size	Module size: Lmax, Lmin, Thickness	1956*992*50	mm	array

Table 2: General characteristics of the 'small agrivoltaism' subsystem at REM

Features	Value	Unit of measure
Technology	Agrovoltaico®	-
Height above ground	4-4.5	m
Place	Virgilio, Italy	-
Nominal Power	2150.4	kWp
Number of trackers	768	-
Number of modules	7680	-
PV modules type	280	Wp
Specific yield	1545	kWh/kWp
Plant area	11.42	ha

SUBSYSTEM « MEDIUM-LARGE AGRIVOLTAISM »

Table 3: Characteristics of photovoltaic panels used in the « medium-large agrivoltaism « subsystem at UCSC

Symbol	Description	Value	Unit of measure	Field additional info
Company	Company name	Trina Solar	-	string
Code	PV panel code	TSM-DEG21C.20-650	-	string
BFv	Bifacial module	VERO	-	boolean
Bff	Reference Bifacial Factor	70	%	
Wp	Maximum Power (Pmax)	650	W	
Vmp	Maximum Power Voltage	37.7	V	
Imp	Maximum Power Current	17.27	A	
Voc	Open circuit voltage	45.5	V	
Isc	Short circuit current	18.35	A	
STC	Module Efficiency	20.9	%	
Tc_Pmax	Temperature coefficient of Pmax	-0.34	%/C	
Tc_Voc	Temperature coefficient of Voc	-0.25	%/C	
Tc_Isc	Short circuit current	0.05	%/C	
NOCT	Nominal operating cell temperature	43	°C	
NC	Number of cells	132	N	
Rsh	Shunt resistance	unknown.	ohm	not alwais available
Rs	Series resistances	unknown	ohm	not alwais available
Voltage	Voltage	unknown	V	optional array (25°C curve)
Current	Current	unknown	A	optional array (25°C curve)
Size	Module size: Lmax, Lmin, Thickness	2.384; 1.183; 0,033	m	array

Table 4: General and geometric characteristics of the « medium-large agrivoltaism « subsystem plant at UCSC

Symbol	Description	Value	Unit of measure
haz	Height of rotation axis	5	m
hp0	Light below panels (horizontal position)	4.95	m
dss	Distance between supporting elements	10.5	m
Dar	Main axis diameter (max width)	0.25	m
Das	Support axis diameter (max width)	unknown	m
pv_disp	PV panels arrangement	landscape	string
array	Array total width	10.5	m
array_element	Width of an array elemant	3.5	m
N_elements	Number elements per array	3	-
Ne_pv_panels	Number of pv panels per element	6	-
Rows_N	Number of rows	5	-
pitch_d	Distance between arrays	15, 15, 18, 18	m
System management			
N_rot_ax	Number of suntracking axis	2	-
Sun_track_update	Defines the waiting time to update rototation	15	min
	Primary axis tilt angle	(+/-) 55	degrees
	Secondary axis tilt angle	(+/-) 60	degrees

SUBSYSTEM « FARMLAND »

CIB Farm 1

CIB Farm 1 operates as a livestock farm specializing in dairy cattle breeding and dairy production. It places a significant emphasis on organic farming practices and sustainability, which are closely tied to the company's brand identity. The farm is equipped with two biogas plants boasting capacities of 998kW and 999kW, with plans in progress for the conversion of biogas to biomethane. Feedstock for these biogas plants includes agro-industrial by-products, livestock effluents, and energy crops (both 1st and 2nd crops). Approximately 390 hectares of land are cultivated on average, with 87% of the surface area dedicated to double cropping. Additionally, the farm operates a large agrivoltaic power plant.

CIB Farm 2

CIB Farm 2, on the other hand, specializes in pig breeding and follows a more conventional agricultural approach. While still attentive to efficiency and sustainability, it does not prioritize organic farming to the same extent as Farm 1. The farm operates a single biogas plant with a capacity of 635kW and is considering the possibility of converting biogas to biomethane. Similar to Farm 1, the feedstock for this biogas plant includes agro-industrial by-products, livestock effluents, and energy crops (1st and 2nd crops). Cultivation spans approximately 110 hectares of land, with 40% of the area allocated to double cropping.

1.2.2 Environmental condition

Environmental conditions in terms of soil properties and climate can influence agricultural and energy productivity significantly. Soil and climate characteristics are given for each subsystem.

SUBSYSTEM « SMALL AGRIVOLTAISM »

Climate

REM demonstration site is located in Borgo Virgilio (Mantova, Italy, 45°05’40’’N - 10°47’30’’E), in humid subtropical climate (Cfa) by Köppen and Geiger climate classification. According to the ClimatData.org climate model, the area has an average temperature of 13.9 °C. The warmest month of the year is July, with an average temperature of 24.7 °C. January is the coldest month of the year with an average temperature of 3.1 °C. Approximately 931 mm of precipitation occurs annually. The driest month is January, with 50 mm of rainfall. Most precipitation occurs in November, with an average of 103 mm. The total evapotranspiration over the year is approximately 1015 mm, the annual water balance was calculated at - 84 mm The month with the most hours of sunshine per day is June with an average of 12.53 hours of sunshine, similarly in July 12.50 hours. The month with the fewest sunny hours per day is January with an average of 4.81 hours of sunshine per day. For the whole year, there are approximately 3102.45 sunny hours. On average, there are 101.86 hours of sunshine per month.

Soil

The demonstration site is located in the Po River valley, an area dominated by Cambisols and Fluvisols. Soils are developed on quaternary alluvial and glacio-fluvial deposits. Soils have young paedogenetic structure in depth and weakly differentiated profile. Main land capability classes are defined as 1st and 2nd class soils, with local limitations for water excess and clayey texture. Soils are generally fertile, although often poor in organic matter. Water table is usually shallow. The groundwater pollution risk is particularly high in irrigated land.

SUBSYSTEM « MEDIUM-LARGE AGRIVOLTAISM »

Climate

The demonstration site is located in Piacenza in an experimental field owned by UCSC having 45.0377 °N, 9.7298 °E coordinates. According to the Köppen-Geiger classification, the climate in this area is a temperate climate specifically Humid_subtropical_climate “Cfa”, with hot summers. Annual precipitation is relatively well distributed and account in average for 789 mm/year (Figure 10). Most of annual rain falls in autumn and spring leading to a relatively dry period in summer.

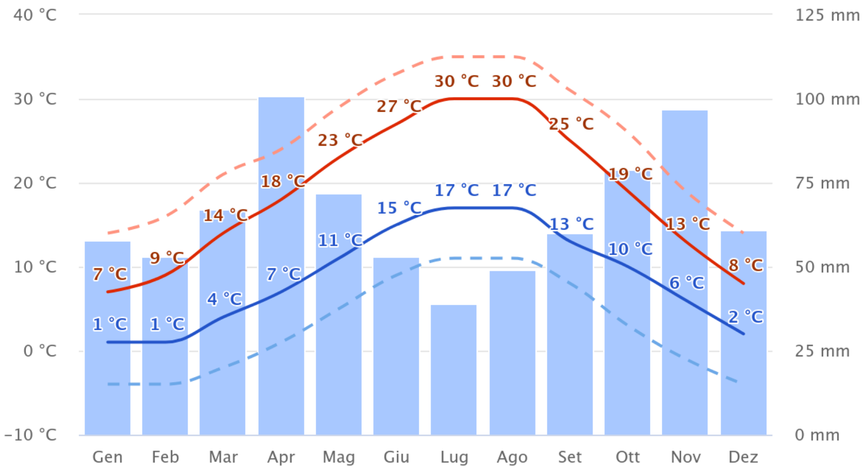

Figure 10: Mean annual precipitation and temperature distribution.

Highest temperatures are reached annually in July and August. Conversely, coldest months are December, January and February. The yearly even Global Horizontal Irradiation account for 1431.78 kWh/m²/year in the plant site (SOLARGIS, 2023).

Soil

According to the USDA texture classification, the experimental field is a silt loam soil. The soil granulometry composition is 21.89% clay, 61.29% silt and 16.82% sand. The organic matter accounts for 2.44% in average and the soil electrical conductivity is 49.47 mS/m.

SUBSYSTEM « FARMLAND »

Climate

The CIB demonstration sites are located in Trescore Cremasco (CIB Farm 1 - 45.4082 °N, 9.6164 °E coordinates) and in Sesto Cremonese (CIB Farm 2 - 45.1852 °N, 9.9162 °E coordinates). According to the Köppen-Geiger classification, the climate in this area is temperate climate specifically Humid subtropical climate "Cfa", with hot summers. Annual precipitation is relatively well distributed and account in average for 789 mm/year (Figure 11). Most of annual rain falls in autumn and spring leading to a relatively dry period in summer.

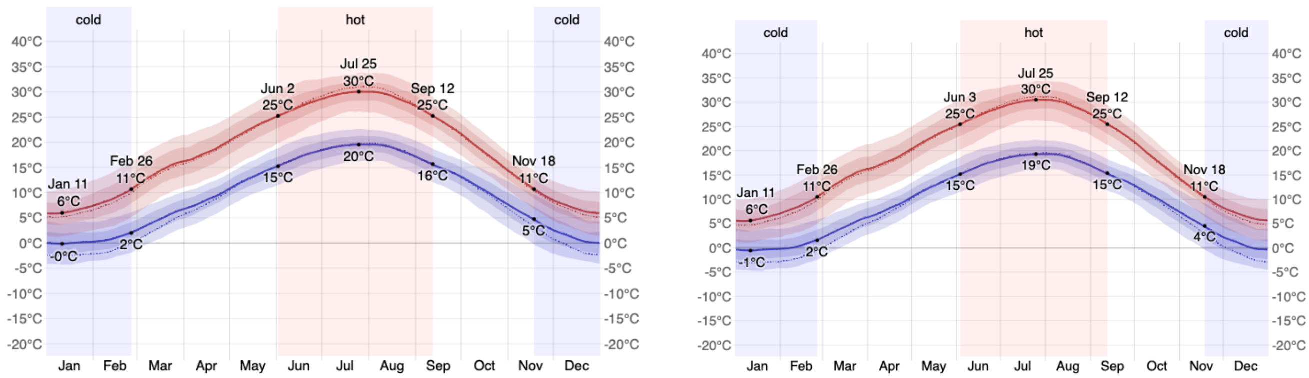

Figure 11: Mean annual precipitation and temperature distribution in CIB Farm 1 (left) and CIB farm 2 (right).

Soil

The soils in CIB farm 1 are loamy soils (19% clay, 38% silt, 43% sand) with an average soil organic matter content of 1.9% and a pH of 7.2. The soils in CIB farm 2 are loamy soils (16% clay, 39% silt, 45% sand) with an average soil organic matter content of 1.8% and a pH of 7.3.

1.2.3 Data collection during the demonstration case

In agrivoltaic (AV) systems, the panels and the movement of the sun generate highly variable shading conditions. This in turn affects the spatial distribution of the direct and diffuse radiation. For most AV systems, however, the variability of radiation available to plants has an easily identifiable pattern along the direction normal to the principal axis of the AV plant layout. For experimental purposes, it is appropriate to identify zones (bands parallel to the main axis) and manage them as experimental treatments.

Crop data

SUBSYSTEM « SMALL AGRIVOLTAISM » and « MEDIUM-LARGE AGRIVOLTAISM »

At **REM** and **UCSC**, using the simulation platform developed by UCSC (Amaducci et al., 2018), the radiation available to crops within the cross-section between the trackers will be estimated to map radiation or shading values. The mapped values will be used to identify 'quasi-homogeneous' shading zones (AV1, AV2, AV3 and AV4, Figure 12 and 13) and to assign an average radiation (or shading) value for the zones of the plant cross-section and characterise the experimental area. For each of the areas delineated within the section, phenological, morphological and productive parameters will be monitored. In particular, the following will be monitored: i) crop phenology expressed in BBCH phase, providing a framework to develop scales for individual crops, ii) crop height, iii) leaf area index (non-destructive), iv) specific leaf area - SLA (destructive), v) number of tubers/fruits/flowers, vi) total biomass production (dry and fresh weight), saleable production, vii) quality parameters (% dry matter, brix ° degree (tomato), pH, protein and fibre content, standard tuber scores (Potato).

Figure 12: Experimental setup of the soybean trial in Monticelli D'Ongina (2021). Different colours represent the different shade depth (SD) levels, and the four SD levels are indicated as follows: AV1 = 27%, AV2 = 16%, AV3 = 9%, and AV4 = 18% (Potenza et al., 2022)

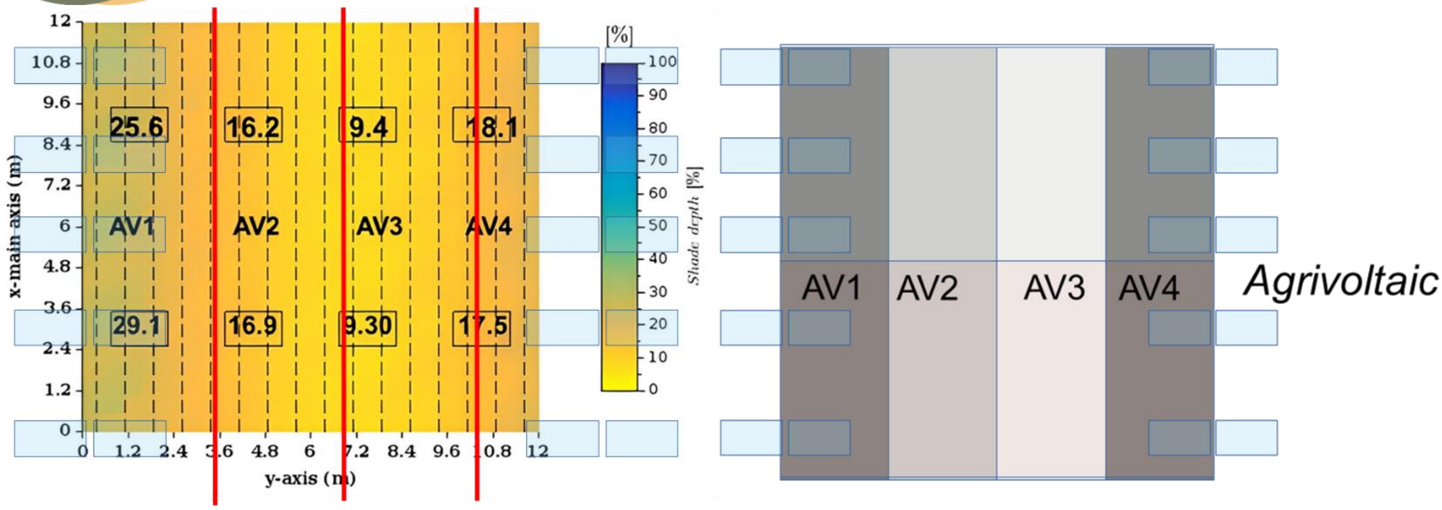

Figure 13: Mapped values of radiation reduction "Shade Depth (%)". The vertical dotted lines represent crop rows, and the boxes represent the positioning and size of the plots

SUBSYSTEM « FARMLAND »

During the adoption of field protocols at two **CIB farms**, encompassing field trials of 5 ha each, the same indicators will be collected at field level. The dataset of inputs/imports and outputs/exports will be improved with a combination of direct field measurements and soil-crop model simulations:

- Crop yield and biomass (hybrid: measurement + modelling)
- Soil C sequestration (hybrid: measurement + modelling)
- Soil nutrients stock changes (measurement)
- Carbon and nutrients inputs (measurement)
- Field N leaching and N_20 emission (modelling)
- N inputs (measurement)
- Gasoline consumption (measurement)
- Carbon footprint of agricultural operations (modelling)

In addition to mass-balance NUE indicators a series of crop N-efficiency parameters will be calculated for each crop at field level and used to calculate AESI, an agro-environmental sustainability index (i.e. product of the dry yield and NUE) proposed by Grillo et al. (2021):

- N use efficiency (NUE; kg kg^{-1}) as the ratio of grain yield to N supply, where N supply is the sum of soil NO_3-N at sowing, mineralized N and N fertilizer.
- N uptake efficiency (NUpE; kg kg^{-1}) as the ratio of total plant N uptake to N supply.
- N utilization efficiency (NUtE; kg kg^{-1}) as the ratio of grain yield to total plant N uptake.

Crop N-efficiency parameters will be calculated to estimate the carry-over effect of “winter legume” on second crops and the overall crop rotation while AESI will be employed to evaluate the agronomic performance of biogas optimized digestate utilisation. Field data collection will facilitate the validation of a series of farm-level adoption scenarios (type of BiomethaneDoneRight® protocol and % farmland under the protocol) generated through soil-crop modelling exercises. This validation process aims to pinpoint scenarios that optimise the trade-off between farm-gate NUE, circularity and AESI. Given the influence of environmental conditions on both agricultural and energy production, it is imperative to monitor weather conditions within the agrivoltaic (AV) system and their impact on agricultural and electricity production. To measure the micro-meteorology in the AV system, different sensors will be placed. In many researches, differences in evapotranspiration (ET) consumption and water consumption have been observed in differently shaded zones. Therefore, identifying critical or representative points within experimental zones is crucial for installing radiation sensors (direct and diffuse) and soil moisture temperature sensors.

To initiate a preliminary energy and mass flow assessment essential for conducting a Life Cycle Assessment (LCA), pertinent data encompassing crop production (Table 5), energy balance, and environmental factors will be gathered during the demonstration phase.

Table 5: Crop Data Collection Inputs and Outputs of Unit Operations in Italian Demonstration Site

Subsystems	Inputs (Unit)	Outputs (Unit)
1. Small Agrivoltaic Farm 2. Medium-large Agrivoltaic Farm 3. Farmland	Amount of Manure (t) Chemical Composition of Manure (%) Amount of Fertilizer (t) Chemical Composition of Fertilizer (%) Amount of Digestate (t) Chemical Composition of Digestate (%) Amount of Irrigation Water (l)	Total Biomass Harvest (t) Amount of Crop Harvest (t) Amount of Biomass Residues Harvest (t)

Environmental data

At REM and UCSC, sensors will be placed for experimentation to monitor environmental conditions with a focus on climatic variables useful for calculating ET. Specifically, a weather station and sensors will be installed to provide data on i) air humidity and temperature (Hygrometer); ii) wind speed (Anemometer) iii) radiation information: PAR (Photosynthetic Active Radiation), global and diffuse radiation; iv) Rainfall (Rain gauge) and v) Humidity and soil temperature. The position of the sensors for monitoring environmental conditions will be decided on the basis of the shading map (Figure 14) generated by the UCSC simulation platform (Amaducci et al., 2018).

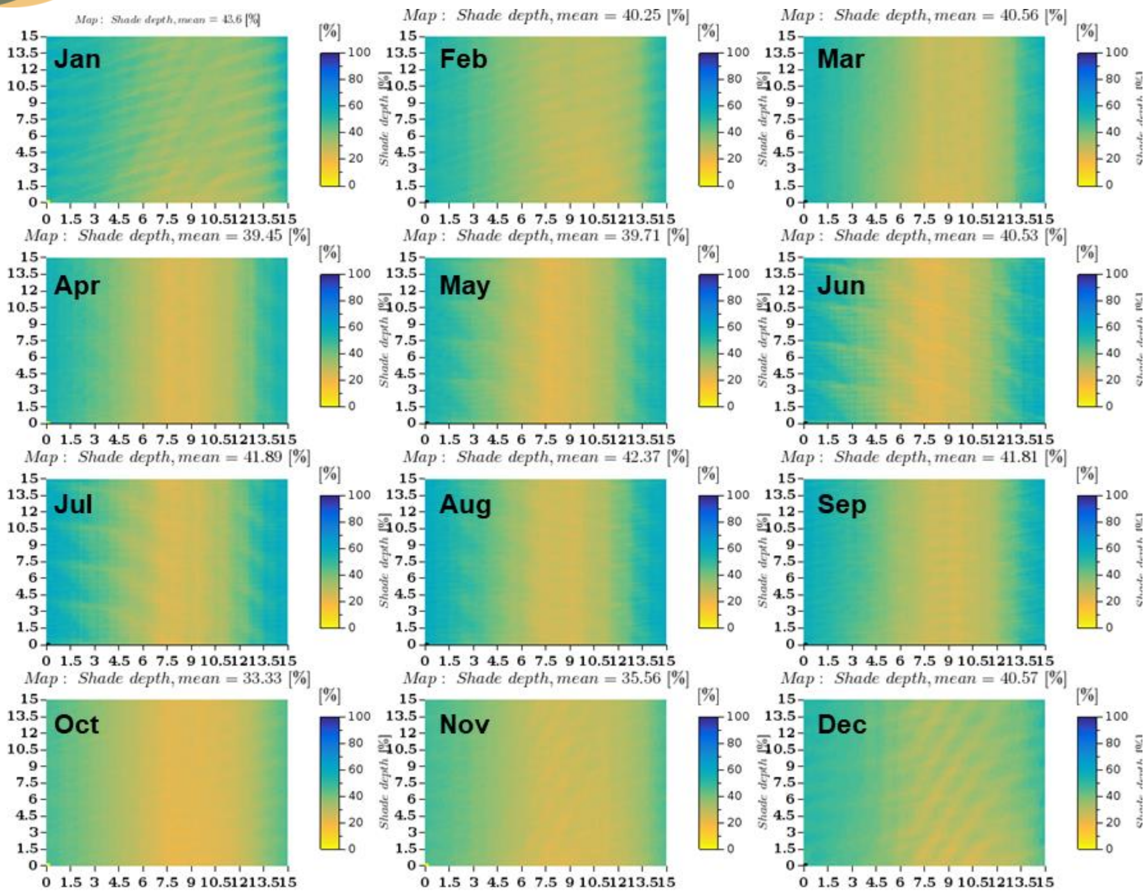

Figure 14: Monthly average 'Shade depth', 15m pitch area. Resolution 0.2m at UCSC

The shade depth variability map below the AV plant will be used to define the location of the sensors for monitoring the microclimate (Figure 15).

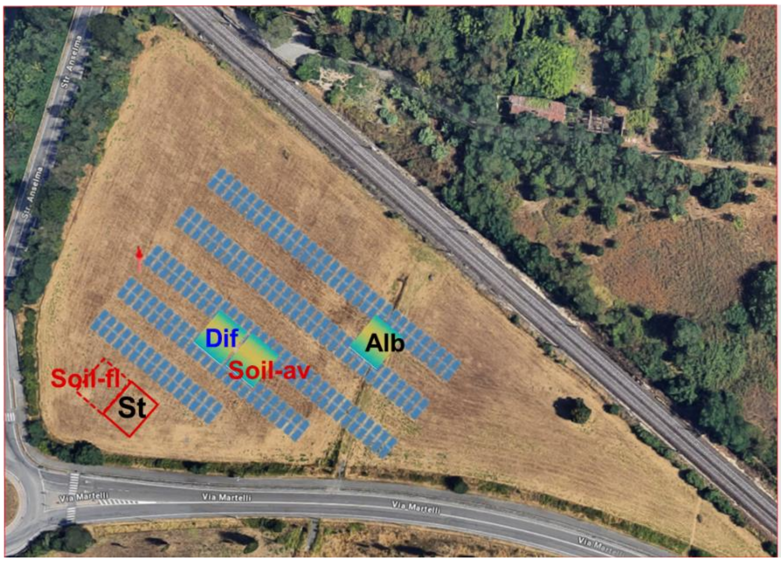

Figure 15: Location of sensors for microclimatic characterisation of the agrivoltaic plant at UCSC

Table 6: Environmental Data Collection Inputs and Outputs of Unit Operations in Italian Demonstration Site

Unit Operation in Value Chain	Inputs (Unit)	Outputs (Unit)
1. Small Agrivoltaic Farm 2. Medium-large Agrivoltaic Farm	Strength of Sunlight Radiation (W/m^2) Amount of rainfall (mm) Amount of rainfall (mm)	
3. Farmland	Strength of Sunlight Radiation (W/m^2) Amount of rainfall (mm)	

Energy data

Energy related data will be collected continuously in order to be able to perform a Techno-Economic Analysis (TEA). An overview of all the energy related inputs and outputs is provided in Table 7. The collection of these data will be necessary to perform the sustainability assessment in WP4.

Table 7: Energy Data Collection Inputs and Outputs of Unit Operations in Italian Demonstration Site

Unit Operation in Value Chain	Inputs (Unit)	Outputs (Unit)
1- Small Agrivoltaic Farm 2- Medium-large Agrivoltaic Farm	Fuel consumed for Mechanical Cultivation (l)	Electricity produced (kWh)
3- Farmland	Fuel consumed for Mechanical Cultivation (l)	Electricity produced (kWh)
Off-grid Biomethane Plant	Amount of Manure (t)	Amount of Biomethane produced (kt)
	Chemical Composition of Manure (%)	Amount of Carbon Dioxide produced (kt)
	Amount of Biomass Residues (t)	Amount of Digestate produced (t)
	Chemical Composition Biomass Residues (%)	
	Electricity consumed (kWh)	Chemical Composition of Digestate produced (%)

Economics data

The TEA will encompass various aspects, incorporating considerations such as CAPEX, OPEX, and ROI. In order to conduct the economic assessments outlined in WP4, EIHP has already conducted a preliminary screening of the necessary data to be collected.

Preliminary Mass and Energy Flows

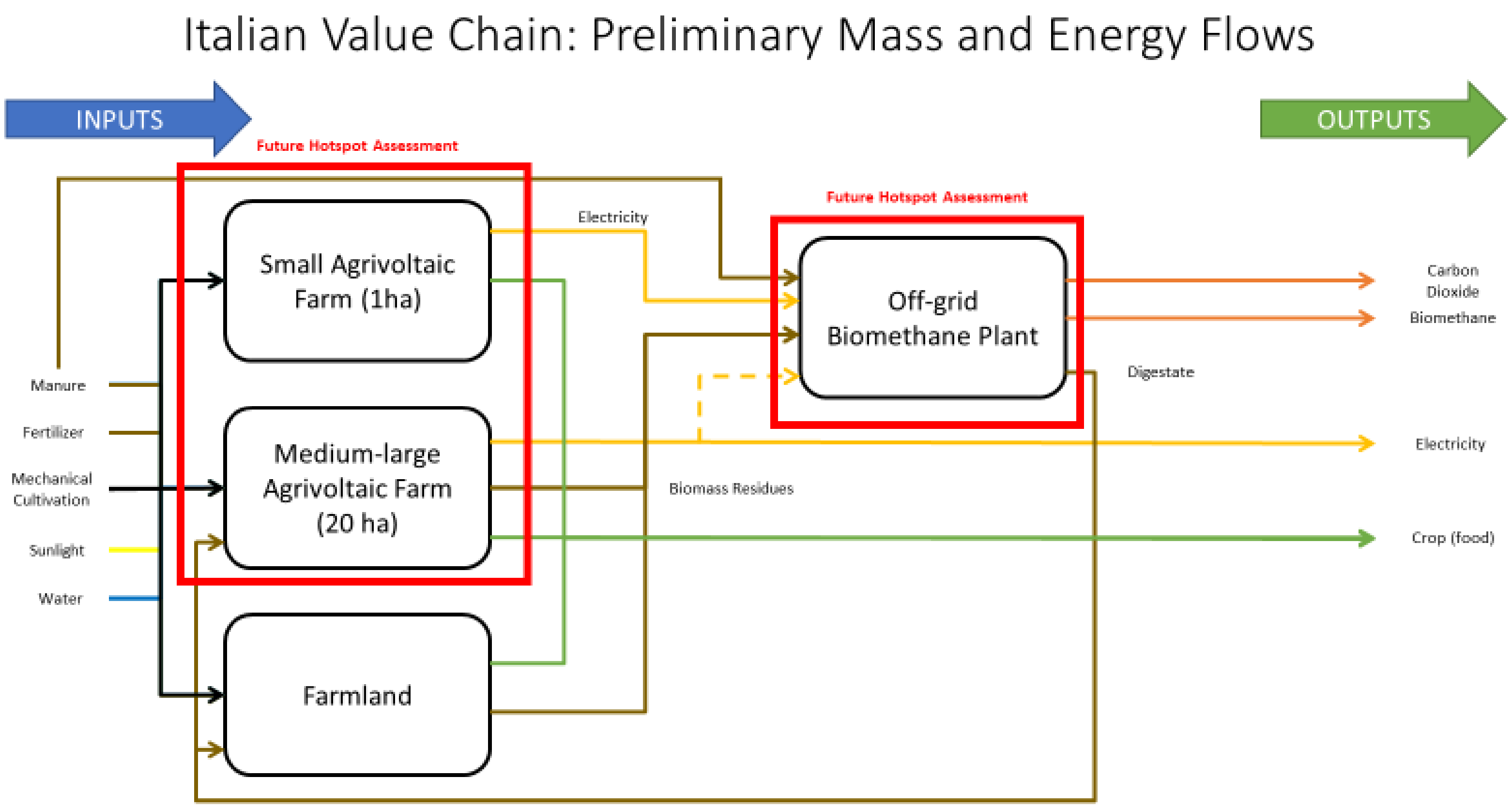

Figure 16: Preliminary Mass and Energy Flows of the Italian Value Chain

Table 8: Inputs and Outputs of Unit Operations in Italian Demonstration Site

Unit Operation in Value Chain	Inputs	Outputs
1. Small Agrivoltaic Farm	Fertiliser Mechanical Cultivation Sunlight Water Manure	Crop (food) Electricity
2. Medium-large Agrivoltaic Farm	Fertiliser Mechanical Cultivation Sunlight Water Manure	Crop (food) Electricity Biomass Residues
3. Farmland	Fertiliser Mechanical Cultivation Sunlight Water Manure	Crop (food) Biomass Residues
Off-grid Biomethane Plant	Electricity Biomass Residues Manure	Biomethane Carbon Dioxide Digestate

2. DEMONSTRATION SITE IN BELGIUM

2.1 Concept of the demonstration case and its objectives

The Belgian demonstration will be carried out by INA on its own experimental facility, shown in Figure 17. The set-up consists of a farm-scale plug-and-play biogas installation, suitable for on-farm renewable energy production by valorising agroresidues. This installation will be the heart of the Belgian Value4Farm demonstration, focussing on putting resources to their best use by proposing reliable business cases for anaerobic digestion (AD) on the farm level.

Figure 17: Farm-scale AD plant at INA for research and demonstration purposes

In Flanders, there is a specific category for AD on farm level, which is called small-scale AD or pocket digestion. The boundaries are that the installations have to work with their own input streams (e.g. manure and/or residual streams of crops), a maximum amount of input material of 5,000 tonnes per year and a maximal power of 200 kW_{el}. To this end, INA will propose sustainable biogas valorisation, focusing on efficient electricity and heat production via an innovative microturbine, and mobility solutions by powering a biogas tractor with biomethane obtained via a.o. in situ biomethanation. A schematic overview of INAs demonstration and the different value chains is shown in Figure 18.

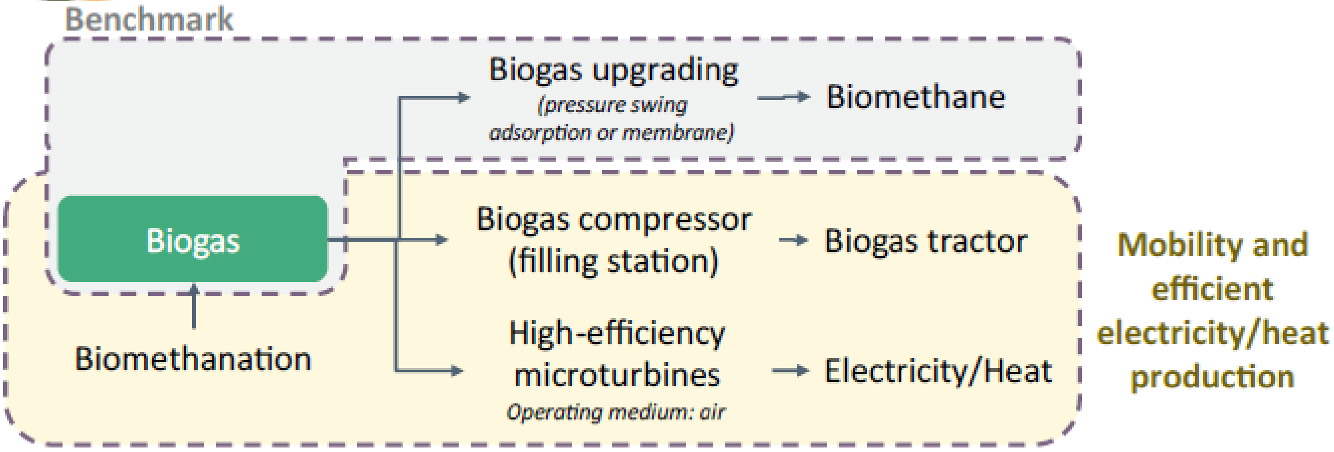

Figure 18: Value chain to be demonstrated at INA (Belgium)

2.2 Description of the demonstration case

Description of AD pilot plant

The small-scale plug-and-play biogas installation of INA is a classical Continuously Stirred Tank Reactor (CSTR) with a total volume of 200 m³ and a nominal volume of 150 m³. The installation can be operated at mesophilic (± 40°C) or thermophilic (± 50-60°C) temperatures. The biomass is being mixed by a Peters Fermento Mixer (15 kW), adjustable in height and width. The installation is equipped with a Combined Heat and Power (CHP) unit of 31 kW_{el}, where the biogas is producing renewable energy in the form of electricity and heat. Prior to burning the biogas in the CHP unit, water vapour and sulphur are removed from the biogas by a condensation step and biological desulphurization, respectively. This is the standard way of how a farm scale AD plant is being operated.

The reactor can be fed with liquid agroresidues (such as pig slurry), as well as dry agroresidues (such as crop residues). Liquid agroresidues are being stored in two silage tanks and being pumped into the reactor, while solid agroresidues are being fed to the reactor via a Trioliet screw press (Figure 19). To date (beginning of 2024), the feed fully consists of crop residues such as chicory roots and leaves, maize silage, rotten potatoes, grass, … However, it must be noted that most of the farm scale AD plants in Belgium are operated at mesophilic temperatures only and are not equipped to process solid biomass with a dry matter content of more than 15%. Most of the farm scale AD plants are part of dairy farms and fed with daily-fresh cattle manure only.

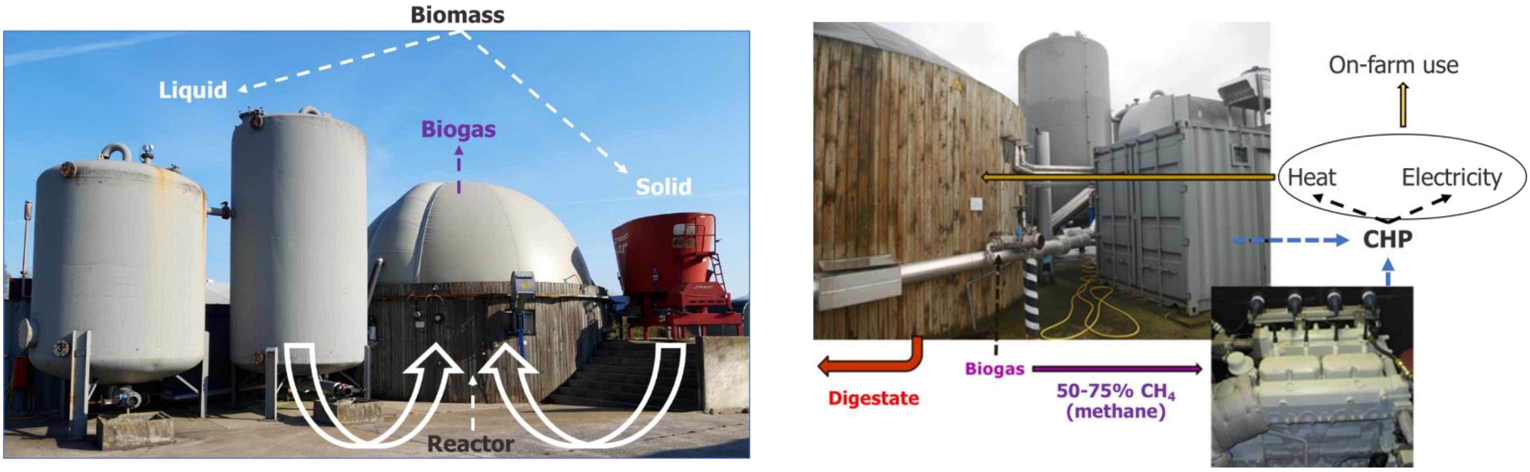

Figure 19: Working principle of a standard farm scale AD plant

High-efficiency microturbine

An intercooled, recuperated and reheated gas turbine (IRRGT, Figure 20) cycle will be exploited in a novel two stage microturbine being developed by MITIS. The microturbine (Micro-20) will generate 20 kW of clean electricity with 40-44 kW of heat. For this range of electric power, electric efficiency of the system reaches 30%. As a second step, Micro-20 will employ cycle modifications by adding a complimentary system to the microturbine to enhance its electrical yield. This is envisaged by adding an Organic Rankine Cycle (ORC) to generate electricity by utilizing the heat generated by the microturbine. In other case, a humidifier can be added in the cycle that demonstrates the potential of increasing the electrical yield of the cycle and/or decreasing the fuel input and maximum turbine inlet temperature for the fixed electrical power output. Any of the employed technology, hence, enhances the electrical efficiency.

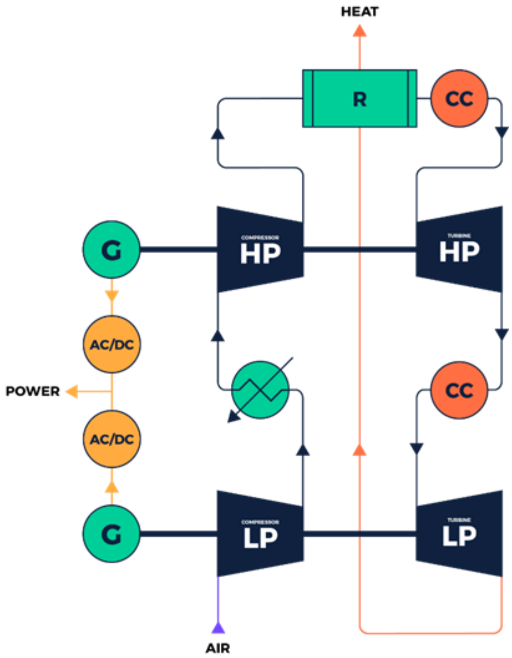

Figure 20: IRRGT Cycle of Micro-20

MITIS' microturbines employ the following novel aspects:

1. The combustor uses the flameless combustion technology (known as moderate or intense low-oxygen dilution, (MILD)) to reach extremely low emission levels, as well as allow fuel flexibility. MILD combustion inhibits the formation of NOx and soot, thanks to the strong dilution of the fuel/oxidiser mixture, which leads to the reduction of the O_2 level in the reaction region and a homogeneous as well as distributed reaction zone.
2. The recuperator is a patented design inspired from the microchannel compact heat exchanger.
3. The turbogenerator assembly operates on foil aerodynamic bearings to avoid any usage of oil that increases the maintenance interval, reduces complexity by avoiding complicated and failure prone lubrication hydraulic systems and does not require any specific cooling.
4. The electric generator system uses a permanent magnet, which is in the front of the compressor in a very compact design, avoiding the requirement for a complex mechanical coupling between the compressor-turbine shaft and the generator, and hence also reducing the number of bearings.
5. The micro-20 microturbine implements the intercooled regenerative reheat gas turbine cycle with two separated stages based on the same shaft architecture, which can rotate at different speeds and offers a wide range of part-load capability.

Biogas tractor

A methane-powered tractor has been developed by Case New Holland (CNH). When certain standards are met (e.g. >85% CH_4 content), it can also run on biogas. Though this technology has already been developed and promises benefits in terms of cost and carbon footprint reductions, there seems to be no real uptake by the market. For instance, there is no gas tractor in operation in Belgium to date. While the methane tractor is developed mostly for use with natural gas, the combination with a biogas plant is very promising. However, it can be observed that there are a very limited amount of small-scale biogas plants in Belgium (i.e. with a typical range between 10 and 30-40 kW_{el} capacity). The same applies to other European countries. All of these biogas plants work with a combined heat and power unit (CHP), and the produced electricity is partly used on site and partly injected into the grid. The heat is mainly used for heating the digester and the rest (dependent on the time of the year and biogas plant) can be used on-farm. However, it can be noticed that less and less small-scale installations are being built. In the first place because of the difficulty nowadays to obtain permits in nitrogen intensive regions such as Flanders, but also because a CHP might not be the most profitable business case for biogas valorisation on a small-scale when not able to fully valorise the heat.

Therefore, Value4Farm will assess a simple and novel business case for small-scale biogas plants to encourage their installation via the use of biogas as fuel for on-site mobility needs. It is estimated that an installation which has now a 20 kW_{el} CHP unit delivers enough biogas to run a methane-powered tractor through a whole year. To this end, several novelties will be pursued such as biogas upgrading on farm scale. Technologies for biogas purification already exist but are aimed at big plants and for grid quality biomethane, while grid quality is not necessary for a methane powered tractor. For reaching the minimum required methane content for running the biogas tractor (> 85%) without having to go all the way to pure biomethane, in-situ biomethanation will be installed at INA, and benchmarked with two other upgrading solutions. The interest is that there is no big investment for the upgrading technology in this case, yet instead there is the H_2 injecting infrastructure and the operational cost involved. Additional benefits are the extra fuel/biomethane created, as well as the low heat amount needed to heat up the reactor because biomethanation is an exothermic process. This value chain will be benchmarked in terms of efficiency and costs with the traditional biomethane route, yet investigating partial upgrading to achieve the minimum requirement of 85% of methane, using both Pressure Swing Adsorption (PSA) and membrane biogas upgrading techniques. These two technologies will be installed at INA as part of the SBO Biogas-MAMBO project[3].

The tractor demonstration will be using a market available biogas filling station and tractor, rented respectively from Basgas and CNH. The use of biogas in a methane tractor will allow the defossilisation of transport fuel, save on energy costs and allow the farmer to be more independent by producing own transport fuel. The legal aspects related to the usage of (partially) upgraded biomethane as tractor fuel will be investigated in the project, with particular emphasis on the implication on guarantees of the methane tractor, taxes, reductions/emission rights for avoided CO_2 emissions, and investigating if a tractor like this can drive on public roads or only on own fields. It should be noted that this value chain is in line with the context encountered in Flanders concerning biogas, i.e., biogas valorisation through a CHP. Up

[3] https://inagro.be/projecten/biogas-mambo

to date, there is no small-scale installation producing biomethane yet. Hence, there is until now no usage of biomethane as transport fuel in Flanders.

Nutrient recovery out of digestate

Digestate is an interesting product containing valuable nutrients. Therefore, it is important to bring these nutrients to a maximal use. In Flanders, there is already a widespread use of digestate and quite a lot of work has been done on good practice to use it. This will not be demonstrated in detail, but a handbook of good practices for digestate use will be provided via D2.5.

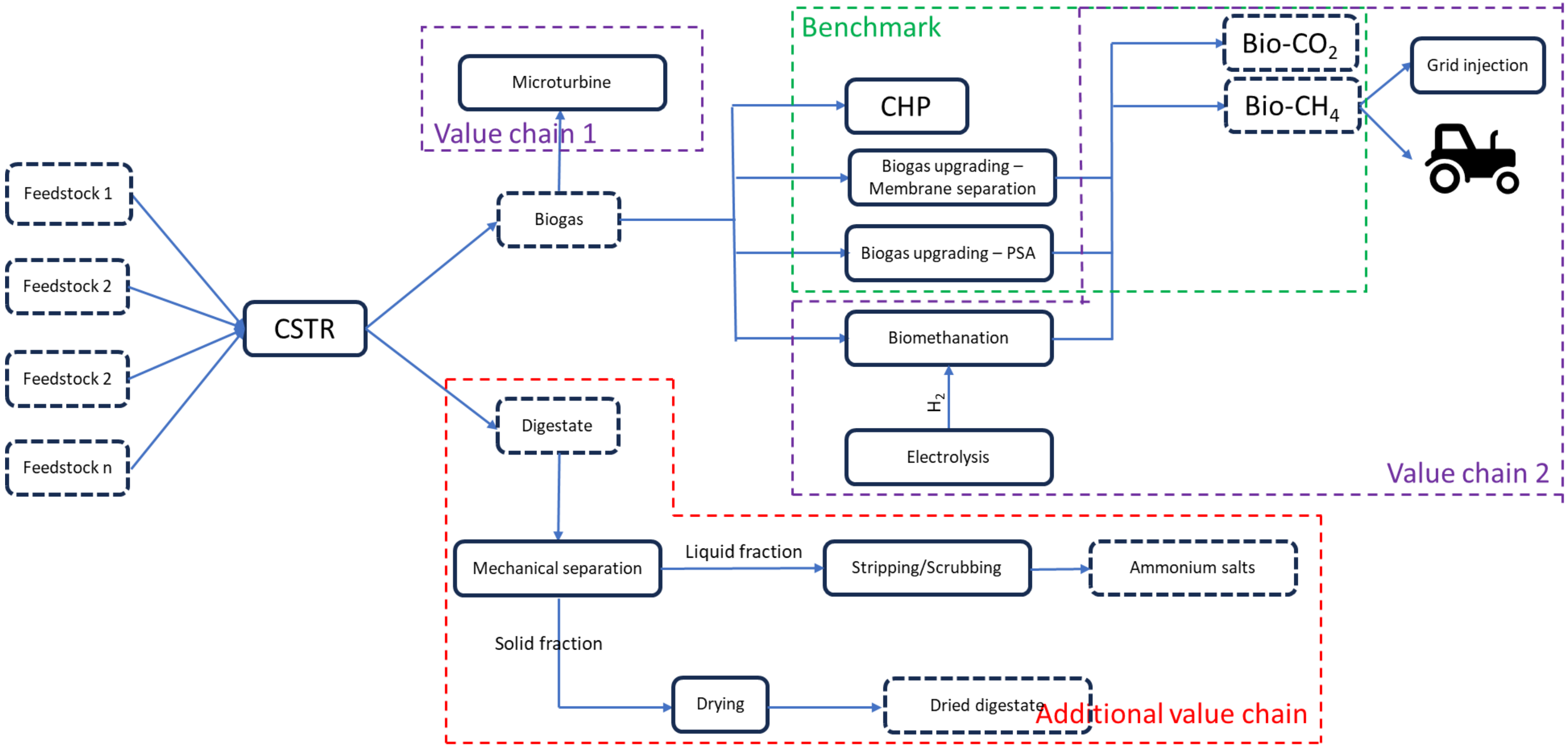

Figure 21: Schematic overview of the demonstration in Belgium

2.2.1 Technical specifications for the renewable energy technologies set-up

The specifications of the microturbine are mentioned in the table below.

Table 9: Microturbine specifications

Electrical performance	
Electrical power output	20 kWe[4]
Electrical efficiency	>30 %
Voltage	110-220-380-400 VAC[5]
Frequency	50 Hz - 60 Hz
Exhaust	
Thermal power output	44 kWth[6]
Exhaust mass flow	140 g/s
NOx emissions	< 10 ppmvd (6.6 mg/kWh)[7]
CO emissions	< 10 ppmv (8.2 mg/kWh)[5]
Fuel characteristics	
Gaseous fuel	Biogas[6]
Fuel flow (Biogas, 17 MJ/Nm³)[8]	5.4 g/s
Operating conditions	
Ambient air pressure	Atmospheric
Inlet air temperature	-20°C to +35°C
Service interval (operating hours)	12,000 hours

[4] ISO conditions are defined as: 15 °C (59 °F), 60% relative humidity, and 101.325 kPa (14.696 psia) (standard sea level pressure).
[5] The microturbine is connected to its own DC 380 V microgrid which can be connected to any solar inverter for bidirectional grid connection to produce 110V-220-380-400V AC.
[6] Maximum exhaust gas temperature is 270°C which can be exploited for various purposes such as hot water production, steam generation or other cycle power supply (Organic Rankine Cycle, ad(b)sorption heat pump). Heat output based on a 70/90 water temperature flow.
[7] Emissions estimation based on simulated data and experiments at ISO conditions.
[8] The microturbine is compatible with biogas (min 60% CH_4, max 6% H_20, H_2S < 5000 ppm, CO_2 bal.)

INA will invest in a biogas compressor for the integration of several pilots. The compressor has the following specifications (Table 10):

Table 10: Compressor specifications

Characteristics	value		
Noise level (dB)	75±3		
Gas composition	50-60% CH_4, 40-50% CO_2		
Gas humidity	Dry		
Max H_2S content	300 ppm in flow; 800 ppm in peak		
Inlet pressure min-max (barg)	0.01-0.15		
Delivery pressure min-max (barg)	2-12		
Duty cycle (%)	50-100		
Flow rate min-max (m^3/min)	0.2-0.6		
Starter specification	Inverter		
Electric supply (Vac)	400		
Frequency (Hz)	50		
Phases	3		
Rotational speed (rpm)	1200-1800		
Nominal power (kW)	5.5		
Performance			
Inlet pressure (bara)	1.1		
Outlet pressure (barg)	12		
Rotational speed (rpm)	1200	1500	1800
Flow rate (m^3/min)	0.42	0.51	0.60
Power consumption at shaft (kW)	3.5	4.5	5.6

Furthermore, INA will invest in a small scale reactor (1.5-2 m^3) for the in situ biomethanation and get in touch with Basgas and CNH for the implementation of the gas filling station and biogas tractor. All necessary investments/adaptations to the biogas plant will be ATEX certified to guarantee process safety.

2.2.2 Environmental condition

Since the Belgian Value4Farm demonstration is focusing on technological innovations only and not to crop growing, including information on the soil and climate is not of relevance.

2.2.3 Data collection during the demonstration case

During the demonstration phase, the type of data that will be collected are mainly related to technical data and economic data. Crop data and meteorological data will not be assessed since this is not part of the Belgian demonstration.

Technical data

Following data are continuously being collected from the AD plant:

- Biogas flow (m^3/h)
- Biogas composition (% CH_4, % CO_2)
- Temperature (°C)
- Pressure (bar)
- H_2S content (ppm)
- Relative humidity (%)
- Visual observations (e.g. foam formation)
- Analysis of feedstock
- Analysis of digestate (pH, nutrient content, DM, OM, FOS/TAC …)

Next to this, following data will be collected during the demonstration:

- Upgrading performance
    - CH_4 content
    - Impact of H_2S and H_2O on upgrading performance
    - H_2 injection rate for biomethanation
    - Gas/liquid transfer of H_2
- Performance of microturbine
    - Compressor and turbine pressure ratios
    - Fuel flow rates to individual combustors
    - Optimum speeds of the individual turbo
    - Electrical efficiency
    - Overall thermal efficiency
- Performance of biogas tractor
    - Running hours
    - Max power
    - Practicability
    - Gas filling performance

Energy data

Energy related data will be collected continuously in order to be able to perform a TEA:

- Gross energy production out of biogas
- Net energy production out of biogas
- Energy needed for biogas upgrading
- Electric and thermal efficiency of microturbine

An overview of all the energy related inputs and outputs is provided in Table 11. The collection of these data will be necessary to perform the sustainability assessment in WP4.

Table 11: Energy Data Collection Inputs and Outputs of Unit Operations in Belgian Demonstration Site

Unit Operation in Value Chain	Inputs (Unit)	Outputs (Unit)
Continuous stirred-tank reactor (CSTR)	Electricity consumed (kWh) Amount of Biomass feedstock (t) Chemical Composition of Biomass feedstock (kg/t)	Amount of Biogas produced (m^3/t) Chemical Composition of Biogas produced (%) Amount of Digestate produced (kt) Chemical Composition of Digestate produced (kg/t)
Microturbine	Amount of Biogas (m^3) Chemical Composition of Biogas produced (%)	Heat produced (J) Electricity produced (kWh)
Combined Heat and Power (CHP) Unit	Amount of Biogas (m^3) Chemical Composition of Biogas produced (%)	Heat produced (J) Electricity produced (kWh)
Biogas Upgrading - Membrane Separation	Electricity consumed (kWh) Amount of Biogas (m^3) Chemical Composition of Biogas (%)	Amount of Biomethane produced (m^3) Amount of Carbon Dioxide produced (kt)
Biogass Upgrading - PSA	Electricity consumed (kWh) Amount of Biogas (m^3) Chemical Composition of Biogas (%)	Amount of Biomethane produced (m^3) Amount of Carbon Dioxide produced (kt)
Biomethanation	Electricity consumed (kWh) Amount of Biogas (m^3) Chemical Composition of Biogas (%) Hydrogen (kt)	Amount of Biomethane produced (m^3) Amount of Carbon Dioxide produced (kt)
Electrolysis	Amount of Water (l) Electricity consumed (kWh)	Amount of H_2 produced (t)

Economics data

To perform the economic assessments in WP4, a preliminary screening of the data that need to be collected was already performed. A TEA will be performed of several aspects, including information on the CAPEX, OPEX, ROI for several type of farms. This will be done for at least following aspects:

- Biogas upgrading to biomethane via PSA and membrane filtration, as part of the Biogas-MAMBO project
- Biogas upgrading via in situ biomethanation (H_2 injection)
- Microturbine for efficient electricity and heat production
- On-farm mobility solutions for tractors

Preliminary Mass and Energy Flows

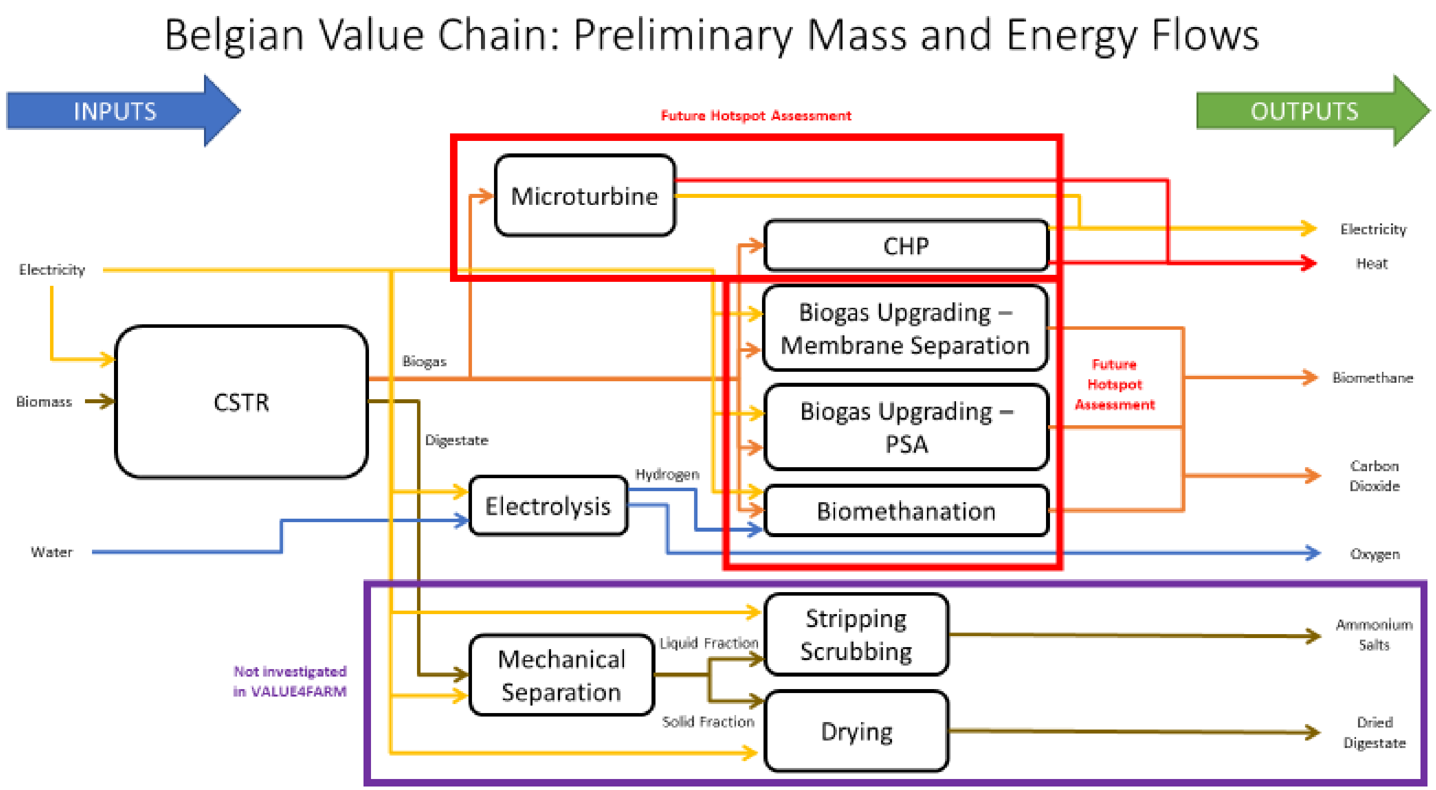

Figure 22: Preliminary Mass and Energy Flows of Belgian Value Chain

Table 12: Inputs and Outputs of Unit Operations in Belgian Demonstration Site

Unit Operation in Value Chain	Inputs	Outputs
Continuous stirred-tank reactor (CSTR)	Biomass (manure and/or crop residues) Energy (electricity for pumping/mixing and heat for heating up the reactor)	Biogas Digestate
Microturbine	Biogas	Electricity Heat
Combined Heat and Power (CHP) Unit	Biogas	Electricity Heat
Biogas Upgrading - Membrane Separation	Biogas Electricity	Biomethane Carbon Dioxide
Biogas Upgrading (PSA)	Biogas Electricity	Biomethane Carbon Dioxide
Biomethanation	Biogas Electricity Hydrogen	Biomethane Carbon Dioxide
Electrolysis	Water Electricity	Hydrogen Oxygen

3. DEMONSTRATION SITE IN DENMARK

3.1 Concept of the demonstration case and its objectives

The aim of the Danish experimental and demonstration setup at AU is to investigate the potential of coupling primary production of food and feed with renewable energy production e.g., electricity and biofuels. This is based on the idea of 'solar sharing' (Sekiyama & Nagashima, 2019; Trommsdorff et al., 2022). The system setup and its specifications should be comprehensively assessed from a holistic and circular perspective. However, for the purpose of the Value4Farm, they will be elaborated on by examining three subsystems:

- SUBSYSTEM 1: Agrivoltaics
  - Vertical photovoltaic panels + 'control'
  - Conventional tilted photovoltaic panels + 'control'
- SUBSYSTEM 2: On-site green biorefinery
- SUBSYSTEM 3: Biogas reactor and biomethanation
  - Thermophilic anaerobic digestion
  - In-situ biomethanation technology

SUBSYSTEM 1: Agrivoltaics

The agrivoltaics subsystem setup is situated at the research station Foulumgård close to the AU Viborg campus (N 56°29'35.577"; E 9°33'40.266") and integrates a combination of vertical and conventional tilted bifacial solar panels. This system is designed with a spacing of 11 m between the vertical panels and 12 m between the tilted panels. Each panel strip spans a length of 23 m. Biodiversity strips at the base of the vertical photovoltaic panels are incorporated as these areas cannot be managed with machinery. Each plot within the vertical photovoltaic system is about 240 m^2, and for each crop there are 3 subplots ('strips'). However, as more biomass for the biorefinery will be needed, an additional share of 60 ha of experimental farmland may be used. Furthermore, 400 ha for animal feed production and the derived manure, can be considered as (nutrient) inputs to the crops in the agrivoltaic system or for additional biomass input to the subsequent anaerobic digester facility (subsystem 3).

The deliberate panel spacing accommodates the planting of three rows of crops, facilitating the analysis of the impact of panel distance on microclimate, crop growth, development and quality. Additionally, the crop plots extend beyond the solar panels by 23 m, enabling it to be used as "control" to evaluate the panels' effects on crops. In addition, the setup of the demonstration also allows for the comparison between the vertical bifacial system and the 'classical' tilted bifacial solar system with regards to crop productivity, PV-efficiency and other indicators.

The region in which the demonstration site is located experiences strong westward winds throughout the growing season, hence the application of natural (woody) shelterbelts are widely used in the traditional farmland. One of the (original) key objectives of the agrivoltaic demonstration is to investigate the effectiveness of using vertical photovoltaic panels arranged in a north-south direction as wind shelter.

Detailed meteorological and microclimatic parameters are continuously collected between the panels and for the overall site, through installed flexible stations with weather sensors. In total, 6 'nests' of sensors, entailing air temperature, relative humidity, photosynthetic radiation, precipitation, wind speed, wind direction, leaf wetness, and soil moisture.

SUBSYSTEM 2: On-site green biorefinery

The on-site green biorefinery is located in AU Viborg, right next to the research station Foulumgård, and is thus in close connection with the field operations and transport is limited (<1 km). The facility is a pilot/demonstration scale research and development platform for processing of nature-wet leafy biomass, with a flexible process configuration able to produce a variety of product-streams. In the basic setup the product streams include protein concentrates with a crude protein content of 50-60%, fibrous press cake of varying moisture and nutrient content, and a liquid residue rich in soluble carbohydrates, nutrients and other small soluble plant constituents. The facility was inaugurated in 2019 and has since then been used in several national and international research and development projects (including the Green Valleys Interreg project[9] and the GO-GRASS EU H2020 project[10]). The facility is gathering considerable data on the up-scaling of green biorefinery technology, producing products for applications tests, and due to the developments in the R&D projects the facility is constantly advancing.

SUBSYSTEM 3: Biogas reactor and biomethanation

The demonstration case for subsystem 3, focused on biogas reactor and biomethanation technologies, represents a pioneering effort to advance sustainable energy production within the agricultural sector. At its core, the concept revolves around the innovative approach of *in-situ* methanation, where the biological conversion of CO_2 to methane occurs concurrently with traditional biogas production in existing anaerobic digesters. This process, partly developed at AU, harnesses the natural microbiome of anaerobic digesters to convert internally produced CO_2 to methane using exogenously added hydrogen, resulting in biogas with an enriched methane content and higher calorific value.

The objectives of this demonstration case are multifaceted. Firstly, it aims to validate the performance and robustness of *in-situ* methanation technology, particularly when utilising different feedstocks, such as a mixture of manure and pelleted straw, along with residue biomasses from green biorefinery (ideally originating from subsystem 1, the agrivoltaics). By investigating the influence of biomass composition on fermentation processes and overall process performance, the case seeks to optimise the efficiency and effectiveness of biomethanation processes.

Moreover, the demonstration case of subsystem 3, serves as a platform for showcasing the synergistic potential of coupling agrivoltaics with biomethanation. By integrating on-farm agrivoltaics to produce electricity and biomaterial inputs, the case explores the feasibility and viability of interconnected value-chains within sustainable energy systems. This coupling is not only expected to enhance the performance of *in-situ* methanation processes but also contribute to the maturation of renewable energy technologies at a farm and regional scale. For instance, it will be investigated if the energy-intensive biomethanation

[9] https://greenvalleys.eu/
[10] https://www.go-grass.eu/

technology can be synchronised with peak electricity production from the agrivoltaic system (subsystem 1).

Technically, the setup of subsystem 3 comprises two full-scale anaerobic digesters for processing raw biomasses, along with pilot-scale plants for Power-to-X technologies, including biomethanation. Additionally, the facility hosts research infrastructure for environmental impact assessment, such as a biofilter for odorous waste air treatment. Lab-scale experiments conducted alongside the main activities will provide valuable insights into the combined effects of adding green biomasses and exogenous hydrogen, further refining the understanding and implementation of *in-situ* methanation processes. Overall, the demonstration case underscores a holistic approach to advancing sustainable energy production, integrating cutting-edge technologies with agricultural practices to drive innovation and environmental mitigation.

3.2 Detailed Investigation

Across the three subsystems

The vertical agrivoltaic demonstration site at AU facilitates the comprehensive investigation of how the integration of vertical photovoltaic panels influences crop yields and other ecosystem services while producing electricity and subsequently feed and biofuel. This demonstration site seeks to contribute substantive insights to the evolving discourse on sustainable land-use and agricultural practices. It will do so, through the lens of agroecological mechanisms responsible for crop production and quality, such as soil and nutrient management, as well as microclimate modulation by photovoltaic panels. Subsequently, crop and biomass material from the agrivoltaic system (subsystem 1), will be used by on-site project partners to collaboratively assess whole-system performance, such as the sustainable use of crops for both food, feed and traditional and renewable energy applications as well as solar electricity production.

Within the agricultural component, this includes studying not only the yields of grains (i.e. wheat) but also of straw, contributing to the overall energy (biomass, electricity, and heat) production per hectare. In addition, the yield and quality of the grass crop will be assessed to determine its potential as input to the biorefinery to derive a protein source for food and feed. Furthermore, the demonstration will be used to investigate optimal crop rotation protocols, tailored for the Atlantic pedoclimatic region with crops of regional economic importance. This will involve an emphasis on optimising primary crop production and quality as well as strategic nutrient and residue management, for instance, assessing the fixation and capture of nutrients in the soil, such as nitrogen. The integration of different crops, including nitrogen-fixing crops, and cover crops, contributes to nutrient cycling within the system. This will be investigated through detailed agronomic monitoring of inputs and outputs - for instance, by installing lysimeters to monitor leaching and keeping records of nutrient balances such as manure and crop residues. Hence, whole-system trade-offs and win-wins can be assessed, including how to increase carbon capture and production of renewable energy at farm-level, while keeping efficient and sustainable food production on the same piece of land.

SUBSYSTEM 1: Agrivoltaics

The inclusion of flexible placement of meteorological and microclimatic sensors between the panels and across the entire site allows for the evaluation of spatial and temporal variability in microclimatic conditions. Different microenvironments are created within the agrivoltaic system due to factors such as shading from panels, wind patterns, and varying degrees of sunlight. By collecting data from multiple points, it can be analysed how these microclimates differ across the system. For instance, recording of humidity and precipitation patterns can contribute to the assessment of water use efficiency, or how the agrivoltaic system may influence humidity patterns in general. Moreover, sensors measuring leaf wetness in combination with soil moisture sensors can provide insights into the water status of crops and soil - which is relevant for assessing conditions conducive to diseases or water availability for crops. These parameters are crucial for evaluating the overall health and resilience of the agrivoltaic system. Sensors measuring wind speed and direction can become essential for evaluating the potential benefits of wind protection provided by the photovoltaic panels. The nature of continuous data collection allows for the analysis of temporal dynamics in microclimatic conditions. In this way it can be assessed how microclimates change throughout the day, across seasons, and in relation to overall weather events (i.e. drought). This temporal perspective is crucial for understanding the dynamic nature of microclimates in the agrivoltaic system.

The demonstration site at AU integrates various components to facilitate a comprehensive assessment through a semi-linked circular system ('closed loop'), emphasising optimal and sustainable land-use through energy production, crop production, residue and nutrient management, biodiversity, and resilience.

Figure 23: Aerial photo of experimental fields

SUBSYSTEM 2: On-site green biorefinery

A green biorefinery for extracting protein out of the perennial crops (i.e. grass clover) and catch crops from the agrivoltaics system (subsystem 1), will be an integrated part of the Danish demonstration site. Within the project it will be assessed and quantified how to optimise a balanced energy production and consumption between the photovoltaic panels of the agrivoltaics system, the green biorefinery, the anaerobic digester and the biomethanation process. The overall energy and protein production efficiencies per hectare will be translated into recommendations for the best implementation of such a system in the regional socio-ecological context.

Green biorefinery is seen as a driver to a much-needed change of land use which has the potential to reduce nutrient losses, while increasing carbon sequestration and biodiversity, by incentivising the cultivation of perennial grasslands. Within the project scope of the Danish demonstration site, around 4-8 ton of fresh weight green biomass will be processed at each test round to assess the yield and quality of different optimised crop mixtures. Two of the three main outputs will be of interest: i) The fiber press-cake, will be used in a subsequent anaerobic digester to generate biomethane; ii) The brown juice will be used as an easily converted substrate for the production of even more biomethane, and through anaerobic digestion the nutrients are made readily available as sustainable and circular biofertilisers (nitrogen, phosphorus, potassium) for the primary biomass production (agrovoltaics, subsystem 1). Overall, when both residual side streams are used for bioenergy, it is even more important to extract as much protein from the crops as possible, as protein has more value in feed, compared to input for the anaerobic digester. In the project, AU will work on increasing the yield of protein in the protein concentrate by increased physical treatment and evaluate the effect of this optimised process on biomethane yields of the fiber press-cake. This will be done by exploring and testing additional mechanical and physical processing of the biomass before and during the wet fractionation step where the raw material is separated into a press cake fiber and a green juice. It is the aim that more severe treatment of the biomass will result in more biomass constituents including protein, separating into the green juice and also ending up in the protein concentrate.

SUBSYSTEM 3: Biogas reactor and biomethanation

As an alternative to separate and costly *ex situ* methanation technologies (chemical or biological), the technology developed at AU is based on *in situ* methanation, where biological methanation of H_2 occurs concurrently with conventional biogas production in existing biogas reactors. Biological *in situ* methanation exploits the natural microbiome of anaerobic digesters to convert CO_2 produced from fermentations of organic matter in the biogas reactor, to methane using exogenously added hydrogen. Injection of H_2 to existing biogas reactors consequently leads to methanation of the internally produced CO_2 in the biogas reactor and the production of a biogas which is enriched in methane and therefore has a higher calorific value, compared to biogas produced without the addition of hydrogen.

Current feedstocks tested at pilot-scale have been limited to a mixture of manure (primary from cattle) mixed with pelleted straw. However, the addition of other feedstocks from green biorefinery, which contains high concentration of different sugars, are expected to potentially influence fermentation processes and overall process performance. This effect will depend on dose and composition of the biomasses. *In situ* methanation using different feedstocks is therefore a natural next step in validating the performance and robustness of the *in situ* methanation process, since the composition of biomass is known to influence both the physical transfer of H_2 to the microorganisms, as well as the biological processes affected by the addition of H_2.

The Danish demonstration site will in close collaboration and semi-connected product chains, demonstrate how *in situ* biomethanation processes perform when H_2 (and biomass) is derived using on-farm agrivoltaics - to produce electricity and biomaterial inputs. The coupling of agrivoltaics and biomethanation is of high relevance for the maturation of the in-situ methanation technology.

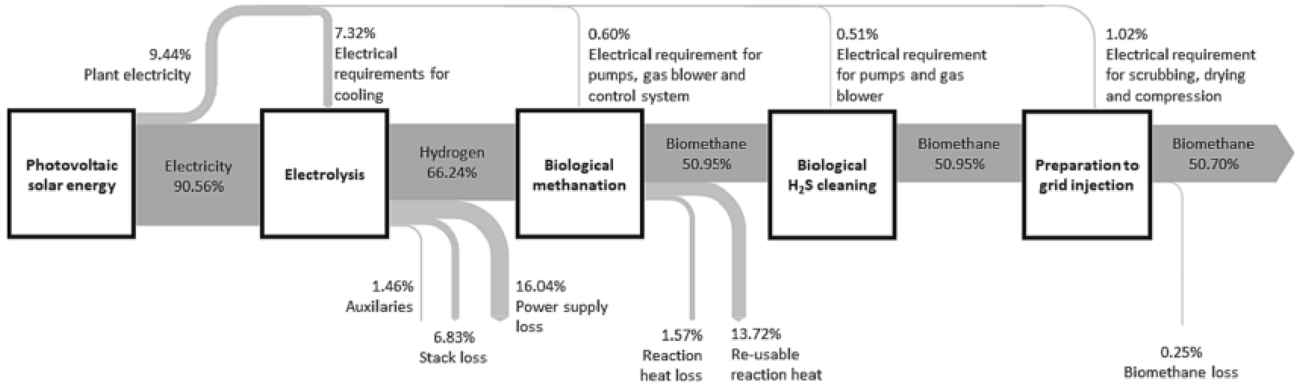

Figure 24: Sankey Diagram showing the energy balance of energy conversion from photovoltaic electricity production to biomethane of natural gas quality through use of ex situ biomethanation (Sieborg et al., 2024)

The effects of fluctuating production patterns of electrolysis-derived hydrogen, has previously been studied for *ex situ* methanation reactors by the AU researchers (Sieborg et al., 2024). The production patterns were here modelled based on photovoltaic production from the California Flats solar production facility. Based on the case of California Flats, an analysis of the energy input in the form of electricity and its conversion to biomethane of natural gas quality, was carried out. A similar analysis is expected from the *in situ* methanation technology employed in the Value4Farm project, however, reaching (lower) concentrations of methane applicable to on-farm use.

3.3 Diagram

Across the three subsystems

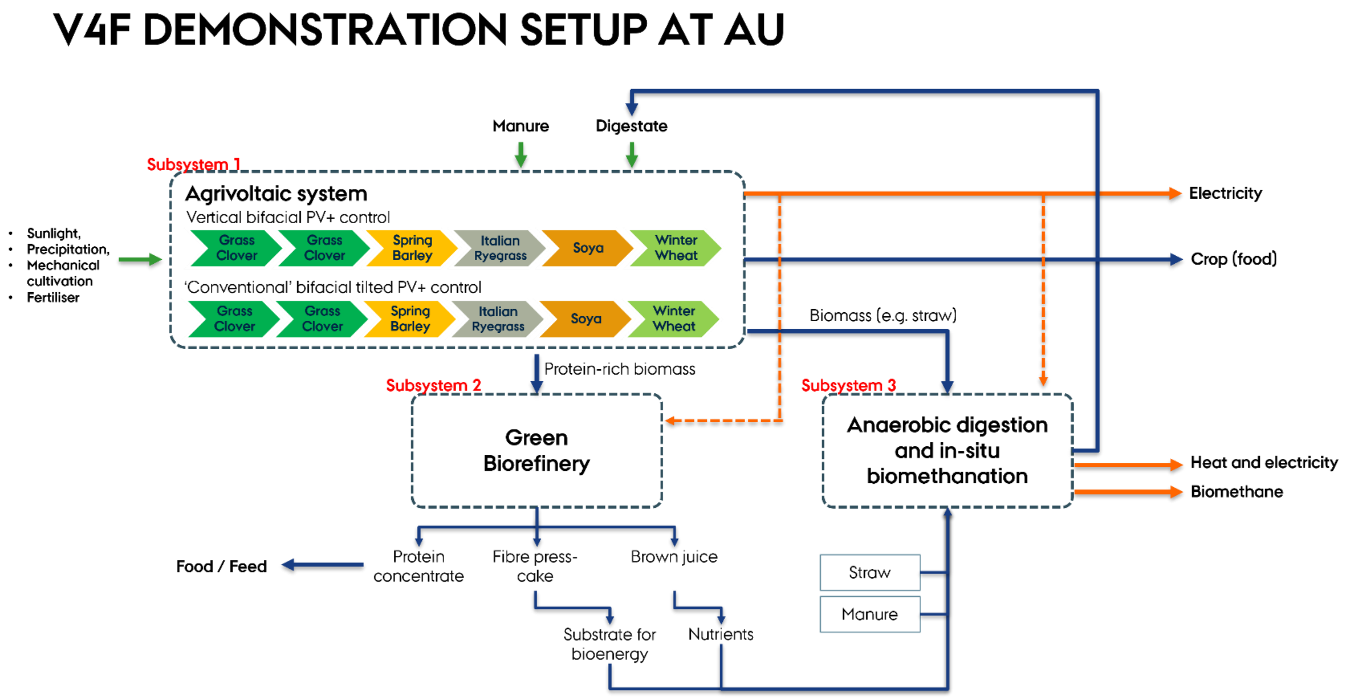

Figure 25: Diagram of the Danish demonstration case

3.4 Description of the demonstration case

3.4.1 Technical specifications for the renewable energy technologies set-up

Technical set-up of SUBSYSTEM 1: Agrivoltaics

The demonstration site comprises an 88.8 kW solar photovoltaic system, which was installed in on the 16th September 2022. In total 160 bifacial photovoltaic silicon panels (Jolywood JW-HD144N) of each 555 W are used for the system. From the 88.8 kW system, 44.4 kW corresponds to a configuration in which the panels are tilted facing south ('traditional system'), and 44.4 kW corresponds to a vertical setup where the backside of photovoltaic panels faces eastward, and the front side is facing westward.

Each system consists of four photovoltaic strings, which contain 20 series-connected panels. In the tilted setup, the photovoltaic panels are placed in portrait orientation while they are in landscape configuration in the vertical setup. Furthermore, two inverters (SUN2000-40KTL) are used, one for each system. Each inverter has eight inputs of which four are maximum power point tracking (MPPT) inputs, which are utilised for each system input. Overall, four inverter inputs are used, and each inverter input has a single series-connected photovoltaic string consisting of 20 series-connected panels. Therefore, 80 photovoltaic panels are connected to each inverter for a fair comparison.

Furthermore, the electricity produced by the system will be used by Aarhus University (AU) campus in Foulum, about 1.6 km away, which proved to be a challenge to supply electricity for that long of a distance from the system.

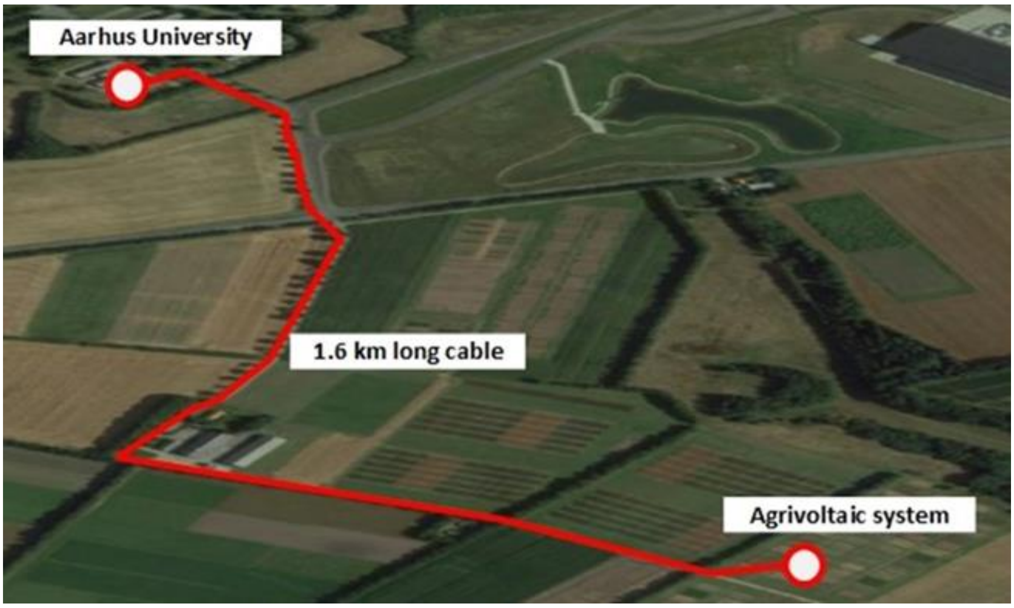

Figure 26: Location of the agrivoltaic system and load (Aarhus University, Foulum, Denmark) to system

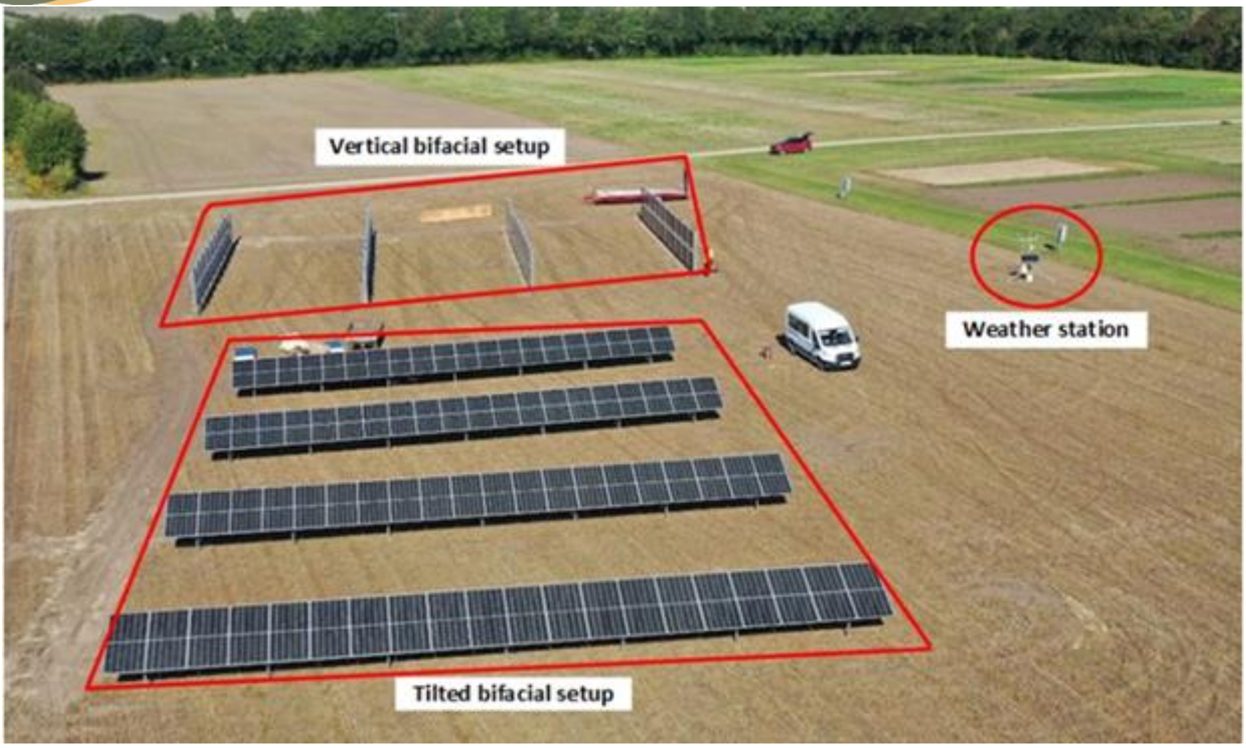

Figure 27: Photo of Agrivoltaic systems and weather station.

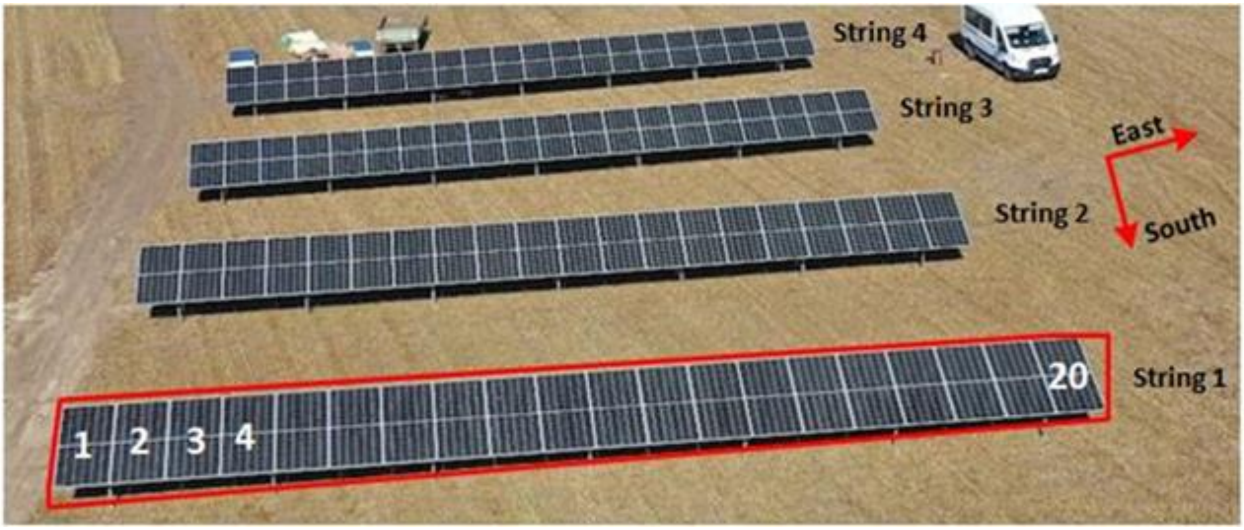

Figure 28: Detail of the Tilted bifacial setup.

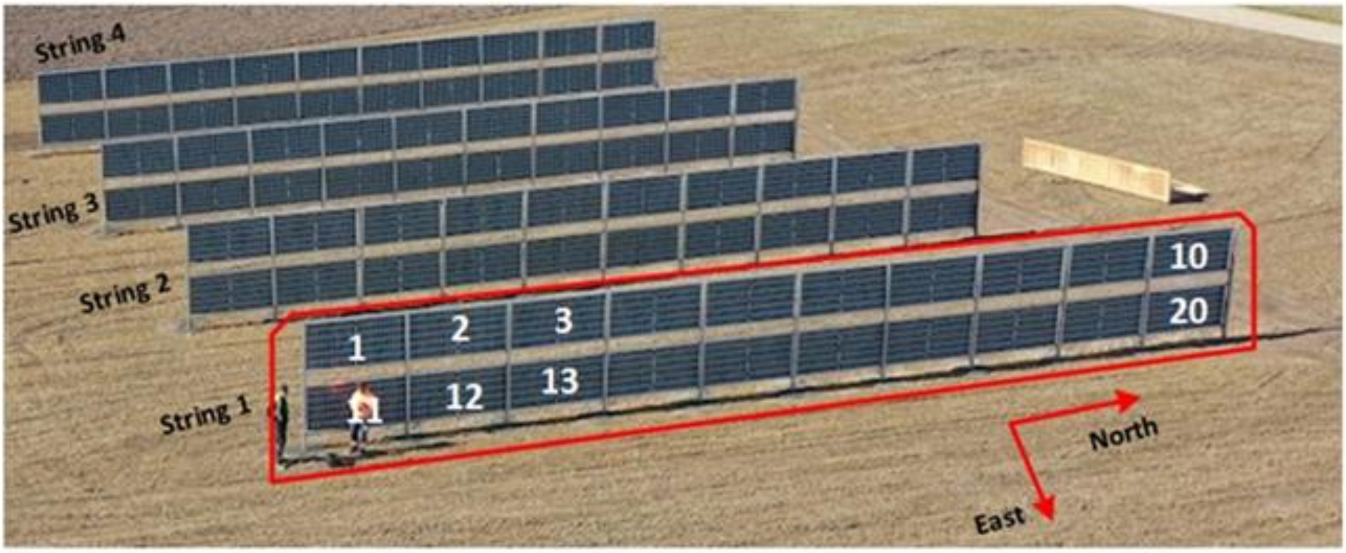

Figure 29: Vertical bifacial setup.

Figure 30: Inverters in field.

Table 13: Rating of the photovoltaic panel (JW-HD144N)

Characteristics	
Model number	JW-HD144N
Rated power (P_{max})	555 W
Open circuit voltage (V_{oc})	50.40 V
Short circuit current (I_{sc})	13.93 A
Maximum power voltage (V_{mpp})	42.20 V
Maximum power current (I_{max})	13.16 A

Table 14: Design details of the agrivoltaic system

Characterics	
Geographical location	Foulum, Denmark (56.4966° N, 9.5843° E)
PV system	88.80 kW (44.4 kW each system)
PV panel	JW-HD144N (555 W)
Inverter	SUN2000-40KTL
Number of PV panels, string	20
Number of inverters	2 (1 for each system)
Number of inputs used per inverter	4
Number of PV panels per inverter	80
Total Strings, park	8
Number of PV panels, park	160
Number of arrays per Inverter input	1
PV panel orientation	Portrait (tilted setup), landscape (vertical setup)

Selection, establishment and evaluation of crops

Through a previous research project (HyPErFarm (www.hyperfarm.eu) running till ultimo 2022, the following suitable crops were identified: Blue lupine (sown in spring, sowing density 119 kg/ha), winter wheat (WHEAT MIX 221 variety mixture comprising the varieties Heerup, Rembrandt and Kvium, sowing density 197 kg/ha), and grass-clover (FORAGEMAX 49 mixture comprising five grassland species, sowing density 35 kg/ha). Each crop will be grown between the solar panels continuing the crop rotation from the HyPErFarm project (Figure 31). Apart from blue lupine, these crops are common practice in Denmark, and allow for meaningful comparison in the EU at large. The blue lupine is selected to investigate whether it is possible to cultivate a protein-rich seed legume for direct human consumption. The grass-clover is selected because of its ideal ability for multiple harvests a year which can allow the investigation of (inter)seasonal effects of the panels. In addition, the harvests of the grass-clover can be further processed in our on-site biorefinery and upgraded into a protein concentrate to feed monogastric animals and possibly humans.

The crop parcels within and outside the solar panels will be divided into three 1.5 m wide strips (subplots) to allow the study of the potential gradient effect of the photovoltaic panels. Combining data from the micrometeorological stations, lysimeters, and soil moisture sensors will provide a comprehensive assessment of spatiotemporal dynamics in microclimates of the agrivoltaic systems. It will be evaluated whether an additional sampling of destructive plant material can be used in combination with non-destructive measurement techniques to quantify biomass developments across the season. The obvious limitation to this approach is the lack of real replicates.

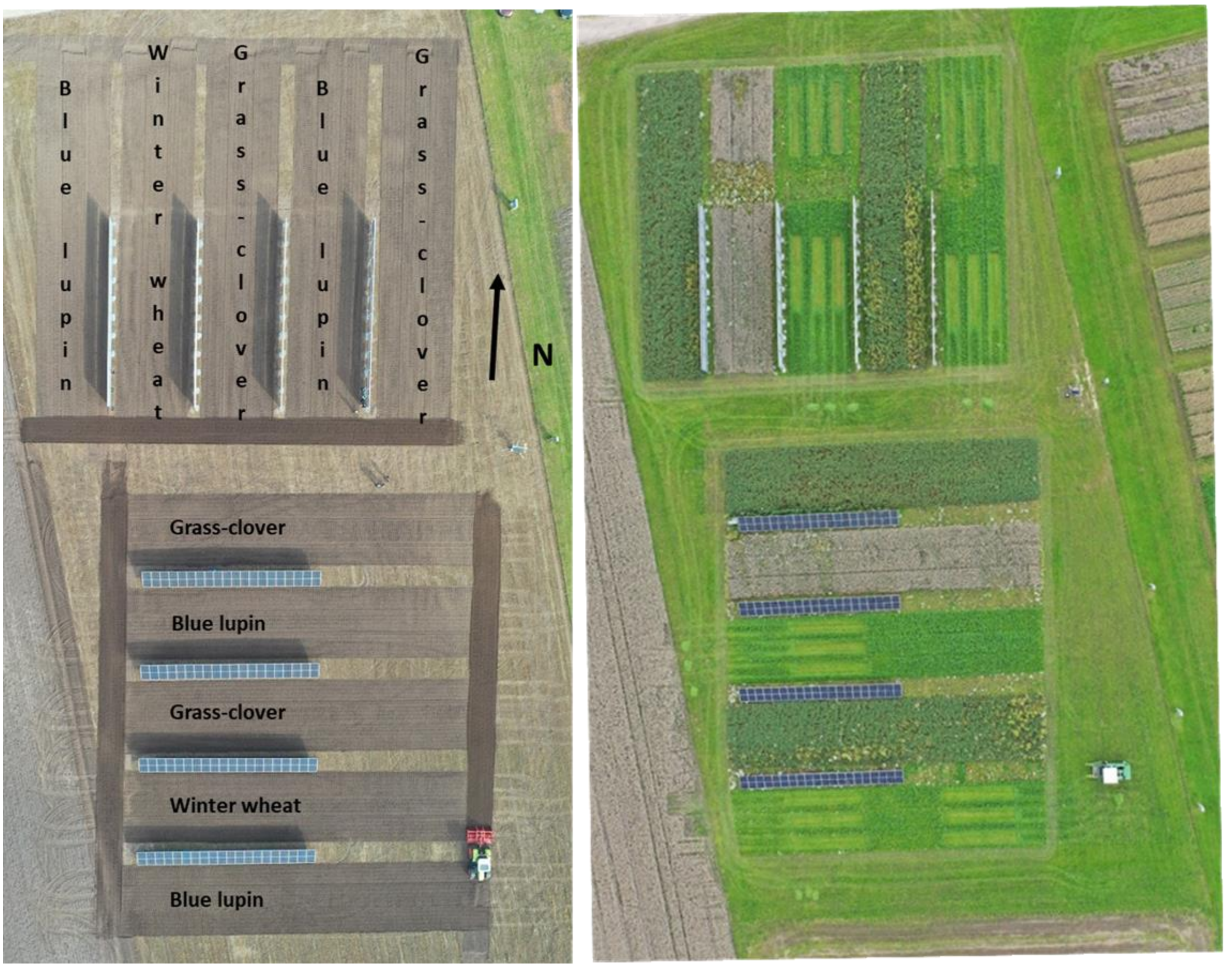

Figure 31: Placement of crops continuing the crop rotation from the HyPErFarm project.

Technical set-up of SUBSYSTEM 2: On-site green biorefinery

The demonstration-scale platform is a flexible and modular set-up of industrially scalable unit operations, utilities, and a fully integrated PLC control and data collection system. It is designed to make optimization, test, and experiments easy to perform, while still capable of producing bulk amounts of products for further application tests. The basic process relies on the processing of fresh green biomass with a maximum input capacity of 10 tonnes of wet biomass per hour, however normally the operational capacity is kept around 3-6 tonnes per hour to have the flow of biomass streams run continuously and efficient through the entire process.

Figure 32: Fully integrated PLC control and data collection system

In the base case green biorefinery, represented in the flow diagram on Figure 25, the harvested crop is initially macerated to increase the biomass surface area and disrupt the plant cells, which guarantees that the components are pressed out of the biomass more effectively. This can be done by different setups and machinery but with a default operation using a stationary cutter with a theoretical length of 4-5 cm. The next step is a wet fractionation employing a mechanical pressing using a CirTech P25 Twin-screw press. The fiber pulp fraction, also referred to as press cake, is rich in lignocellulosic materials and suitable to replace the use of other types of silage for ruminant feeding. However, in Value4Farm the press cake will be used for bioenergy production through anaerobic digestion and in-situ biomethanation. The filtered green juice is processed further for protein precipitation. This procedure can be performed using thermal coagulation at temperatures ranging from 60 to 95 °C, acid treatment at pH 3-5, and lactic acid fermentation for decreasing pH and protein precipitation. In Value4Farm the precipitation will be done through heat coagulation. This has been found to be the best method for the current Leaf Protein Concentrate (LPC) for feed concentrates due to efficient separation and resulting in high protein content in the LPC. The heat treatment is done in Alfa Laval WideGap 100 gasketed plate heat exchanger in two stages to minimize energy use. In the first stage, the juice is heated to 65 °C by harnessing the heat generated from the residual BJ itself. Subsequently, added heat is applied to raise the temperature to 85 °C. The resulting precipitated solid is then separated from the BJ using a GEA CF 4000 Decanter Centrifuge. This separation process yields a solid protein-rich fraction of the LPC and a liquid residue (BJ). The LPC is further dried in a vacuum dryer, with temperatures reaching a maximum of 60 °C. This drying process achieves a dry matter concentration of 95%. The final product, the dried LPC, is intended for commercialization as monogastric feed substituting soy concentrates.

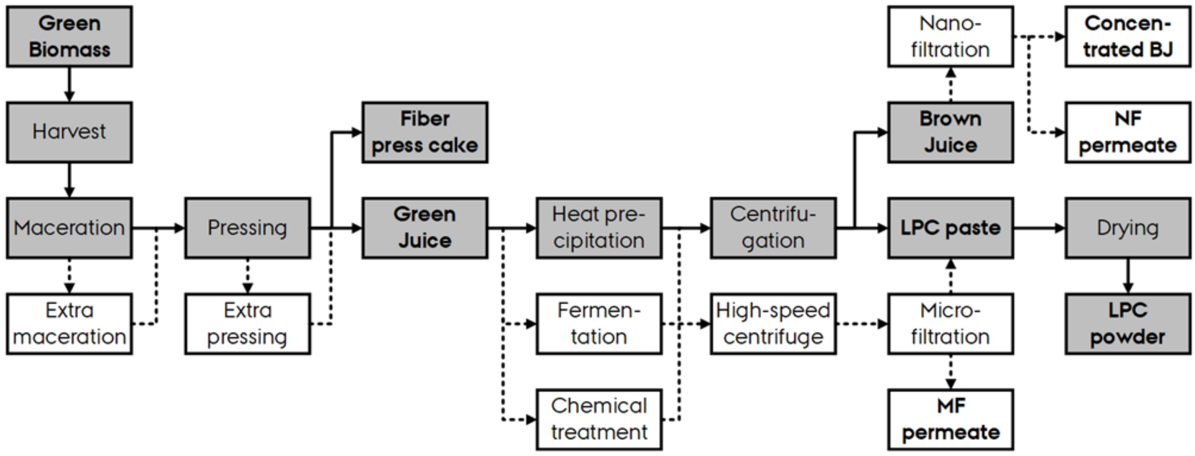

Figure 33: Integrated green biorefinery demonstration plant. Grey boxes represent the base case and white boxes represent alternative process units under development. Process fractions are highlighted in bold.

Technical set-up of SUBSYSTEM 3: Biogas reactor and biomethanation

The AU demonstration site for biogas and biomethanation consists of two full-scale anaerobic digesters. Raw biomasses are fed into the thermophilic primary anaerobic digester (1200 m^3) where they are degassed. Digestate processed in the primary digester is subsequently transferred to the secondary digester (3500 m^3) to increase the methane yield from the applied biomasses. The biomasses for the biogas plant are comprised of agricultural biomasses - primarily slurry from pig and cattle - and solid biomasses including straw and ensilaged grass.

In connection with the plant, several Power-to-X pilot-scale plants for producing methane, methanol and ammonia are deployed. One of these is a 30 m^3 pilot-scale reactor for *in situ* biomethanation.

In addition to Power-to-X technologies, the plant also hosts a full-scale research biofilter for treatment of odorous waste air originating from the plant, to enable research on the environmental impacts of biogas production.

A main part of the Value4Farm activities on biogas production and biomethanation on residues from green biorefinery will be conducted at lab-scale in the laboratories at the biogas plant. Here, batch-scale biogas reactors will be employed for studying the combined effects of adding green biomasses to biogas reactors and the subsequent effects of adding exogenous hydrogen. Based on the batch scale experiments, the effect of adding green biomasses in conjunction with the continuous addition of hydrogen will be studied in the *in situ* methanation pilot-reactor. The hydrogen will be supplied as pressurized hydrogen from a nearby storage facility.

Figure 34: Aarhus University Biogas and Power-to-X facility located at AU Campus Viborg.

4.2.2 Environmental condition

The agrivoltaics subsystem setup is situated at the research station Foulumgård adjacent to the AU Viborg campus (N 56°29'35.577"; E 9°33'40.266").

Climate

The Danish demonstration site is placed in Foulum (56°30′ N, 9°35′ E) in Tjele municipality in Mid-Jutland Region. According to the Köppen-Geiger classification, the climate is this region is described as temperate oceanic (Cfb). Average annual perception sum is 740 mm. The region is characterised by relatively even distribution of perception during the year, typical for oceanic climate. Most of the rain falls between May and October. The highest monthly perception sums are recorded between June and August, up to 80 mm, the smallest in period of February, March and April, of about 50 mm. (Climatdata.org 2023). Average annual temperature in Foulum is 7.8 °C. In Tjele region, the warmest months are July and August with average daily temperatures of 16,8 °C and 16,4 °C respectively, when the coldest months are January and February, both with temperature of 1.3 °C. Potential evapotranspiration is about 600 mm year^{-1} (Manevski et al., 2018), making climatic water balance of +140 mm year^{-1}, indicating high risk of nutrient leaching in this location.

Soil

In Foulum, dominating soil type is sandy loam, with texture of 78.2% sand, 10.7% silt, and 8.0% clay. Solid depth is about 25 cm, water table depth was not specified, crops are mostly rain fed. Soil organic matter content is 3,1% (Manevski et al 2018).

Biodiversity

According to Inaturalist (2023), 6,905 observations were made in the Tjele commune by 316 observers. In total 1,694 species of living organisms were found, including 575 species of plants, 715 species of insects and 147 species of vertebrates.

4.2.3 Data collection during the demonstration case

SUBSYSTEM 1: Agrivoltaics

In the comprehensive investigation of the agrivoltaics system (subsystem 1), an extensive array of input and output variables will be systematically collected to facilitate a thorough comparison and analysis of its performance. The input variables within the cropping component encompass essential factors such as manure input, fertilizer input, and mechanical cultivation practices. These inputs are integral components of the agronomic management strategies employed within the system, contributing to the overall health and productivity of the associated crops.

On the output side, the cropping component is assessed through various variables including crop yield, crop productivity, crop efficiency, and crop quality. These parameters offer a holistic understanding of the overall performance of the crops grown within the agrivoltaics system. Additionally, the electricity generation component is evaluated using variables such as DC side string current and voltage as well as AC side string current and voltage. This provides insights into the efficiency and electrical performance of the photovoltaic panels integrated into the system.

In tandem with the cropping and energy components, inherent pedoclimatic parameters and variables play a crucial role in characterising the environmental conditions. Soil-related factors, including physical attributes like soil type, moisture levels and loss processes such as leaching (NO_3), provide insights into the soil health and nutrient dynamics. Meteorological variables, ranging from irradiance and temperature to wind speed and precipitation, offer a comprehensive overview of the atmospheric conditions influencing the agrivoltaics system. This intricate dataset ensures a robust foundation for investigating, comparing, and analysing the multifaceted performances of subsystem 1 within the research framework.

Table 15: Crop, agronomic and electric data collected during the demonstration

Variable/parameter	Variable type	How and when we intent to measure/record/evaluate
Crop yield	AGRONOMIC	Crop yield will be assessed at harvest via wet and dry yield evaluation. Depending on the crop (e.g. wheat vs. grass clover). Yields will be evaluated through the growing season. Samples will be separated into straw and grains (via standard procedures) and both plant parts will be oven dried at 60 degrees Celsius until constant weight.
Crop quality	AGRONOMIC	Depending on the crop quality assessment will be evaluated on harvested products.
Crop productivity	AGRONOMIC	Depending on the crop (e.g. wheat vs. grass clover) productivity will be evaluated through the growing season destructive and non-destructive measures.
Crop phenology and physiology	AGRONOMIC	Record dates of key events such as emergence, flowering, fruiting, and maturity. Specific leaf area, leaf area index, etc. Visual assessments of crop performances.
Leaf temperature	AGRONOMIC	Leaf temperature was measured using the LI-600 light meter (LI-COR, Lincoln, NE, USA).
Fertiliser input	AGRONOMY	The type, amount and timing of fertilisers will be recorded.
Manure input	AGRONOMY	The type, quality, amount and timing of manure applied will be recorded.
Mechanical cultivation	AGRONOMY	The type of intervention, tool, process and timing will be recorded.
Pesticide use	AGRONOMY	The type, amount and timing of potential pesticide applications will be recorded.
Vegetation indices	AGRONOMIC	NDVI will be measured using the Polypen (Photon Systems Instruments, spol. s r.o., Drásov, Czech Republic).
Drought stress	AGRONOMIC	Drone-based thermal and multispectral images throughout key times during growing season.
DC side string current and voltage	ELECTRIC POWER	Huawei Smart logger will be used to get the data from the Huawei inverters. Both inverters are connected to a smart logger that send data to the Huawei portal and the data will be accessed real-time from a Fusion solar and Enspire software.
AC side string current and voltage	ELECTRIC POWER	
Soil texture	SOIL	Using a standard methodology to assess the granulometric fraction by sieving, sedimentation and particle centrifugation.
Soil moisture	SOIL	
Leaching losses (NO3)	SOIL	Active (pump) lysimeters (suction cup) will be installed at designated locations throughout the agrivoltaic site (within and outside panels) to record real-time nitrate leaching.
Soil nutrients		Flame atomic absorption spectrometry (FAAS), atomic absorption spectrometry method with amalgamation technique, flame atomic emission spectrometry (FAES), flow analysis method with spectrophotometric detection (CFA), high-temperature combustion with detection (TC), and inductively

		coupled plasma excitation atomic emission spectrometry method (ICP-OES) will be used for the determination of selected soil macronutrients.
Soil pH		Potentiometric determination of pH in H_2O and in KCl
Irradiance	MICROCLIMATIC	Global horizontal irradiance (GHI) is measured via a pyranometer sensor, which is used to measure the irradiance (W/m2).
Diffuse radiation	MICROCLIMATIC	Diffused horizontal irradiance (DHI) is measured using another pyranometer, a shadow ring/band is used to prevent direct radiation from reaching it. Therefore, the shaded pyranometer will only measure diffuse radiation.
Reflected solar radiation (albedo)	MICROCLIMATIC	Albedometer will be used to measure reflected solar radiation (W/m2).
Photosynthetic active radiation (PAR)	MICROCLIMATIC	Quantum/photosynthetically active radiation (PAR) sensors will be used to measure within a range of 400-700 nm. The PAR sensor will share the information of the irradiances, which will help the crop to perform the process of photosynthesis.
Temperature	MICROCLIMATIC	Ambient temperature will be measured using thermocouple sensors.
Wind speed	MICROCLIMATIC	Wind speed and wind direction will be measured using anemometers. Measurement of wind speed in m/s and wind direction in degrees.
Wind direction	MICROCLIMATIC	
Air humidity	MICROCLIMATIC	Air humidity and dew point will be measured using thermohygrometers. Hygrometers will be used to measure the humidity or amount of water vapor in the air.
Dew point	MICROCLIMATIC	
Precipitation	MICROCLIMATIC	Tipping bucket (measuring rainfall).
Data loggers	MICROCLIMATIC	Campbell scientific data logger is used, which is storing data from the above-mentioned sensors. The data will be sent to the cloud and accessed remotely through a modem equipped with a SIM-card.

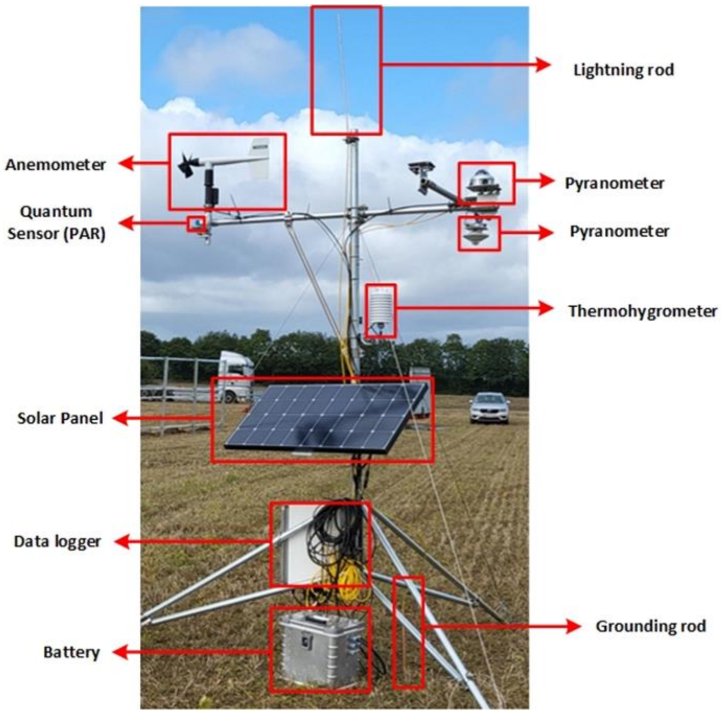

Figure 35: Movable weather station for micrometeorological data mounted on the ground

SUBSYSTEM 2: On-site green biorefinery

In the on-site green biorefinery (subsystem 2) a multitude of comprehensive data will be collected to investigate, compare, and analyse performances.

The work in Value4Farm will focus on gathering data for the new feedstocks produced in subsystem 1, optimize the protein yields towards the LPC product and deliver suitable samples of press cake fibre and brown juice to subsystem 3. From these activities mass and energy balances will be collected and established.

Energy consumption measurements in the demonstration platform aim to assess the energy requirements of various stages within the process. The collected data are categorized into three key areas: infeed and wet fractionation, heat treatment and protein separation, and protein drying. The infeed area encompasses the electrical energy consumed by the maceration and wet fractionation equipment, conveyor belts, and pumps involved in biomass handling. The heat treatment zone accounts for the heat energy used in the heat exchanger for protein coagulation, along with the electrical energy consumed by the decanter centrifuge and respective pumps. Protein drying includes the assessment of both heat and electrical energies spent in the vacuum drier during the drying process. By categorizing and analyzing the energy consumption in these distinct areas, a comprehensive understanding of the energy requirements throughout the demonstration platform is obtained, enabling future optimization and efficiency-enhancing measures.

Table 16: Energy data collected during the demonstration case

Variable/parameter	Variable type	How and when we intent to measure/record/evaluate
Energy inputs	Electricity (kWh) Heat (kWh)	The energy consumption is divided into three groups: 1) Infeed and wet fractionation, 2) Heat treatment and LPC separation, 3) LPC drying.
Biomass input	Kg of wet weight, dry matter, crude protein, carbon and inorganics	The input biomass is (at least) measured in terms of total mass, dry matter crude protein, carbon and inorganics.
Product yielded output	Kg of wet weight, dry matter, crude protein, carbon and inorganics	The output product streams are (at least) measured in terms of total mass, dry matter crude protein, carbon and inorganics. This is done for both LPC, press cake fiber and brown juice
Process parameters measured during processing	pH, Temperature, pressure, flow, etc.	

SUBSYSTEM 3: Biogas reactor and biomethanation

In the biogas reactor (subsystem 3) a multitude of comprehensive data will be collected to investigate, compare, and analyse performances.

Initial experiments will be performed at laboratory scale, investigating the effect of utilizing residues from the on-site green biorefinery in anaerobic digestion. Anaerobic digestion consists of a wide array of microbial processes, including hydrolysis of polymers, fermentations of monomers and acids, and methanation of acetic acid, CO_2 and H_2. Addition of biomasses with high concentrations of sugars and other labile organic compounds is expected to impact the fermentation processes upstream of the methanation process. Baseline data will therefore be produced through experiments where green biomasses are added to batch scale bioreactors to hereby establish a dose-response correlation.

These data will be supplemented with investigation on effects of adding hydrogen (H_2) to the lab-scale bioreactors. Addition of exogenous H_2 will here potentially disturb the balance of the fermentation processes and cause reactor failure. The combination of green refinery biomasses and exogenous H_2 addition will therefore be performed at lab scale before further upscaling.

Based on laboratory experiments, a selected diet of biomasses will be fed to the 30 m^3 pilot-scale anaerobic digester and the process and operational conditions monitored.

Table 17: Process data collected during the demonstration case

Variable/parameter	Variable type	How and when we intent to measure/record/evaluate
Biomass input and composition	PROCESS PARAMETER	Primary parameters include analysis of dry weight, volatile solids and total nitrogen content.
Hydrogen input	PROCESS PARAMETER	Volume of hydrogen will be controlled via mass-flow controllers
Biogas/Biomethane output (CH_4, CO_2, H_2)	PROCESS PARAMETER	Gas chromatographic analysis of outlet gas and volumetric analysis of outlet gas to calculate gas mass balances.
Process parameters and internal reactor conditions (pH, Volatile Fatty Acids)	PROCESS PARAMETER	Digestate content of volatile fatty acids (VFA's) will be analyzed trough gas chromatographic analyses assay along with regular measurements of digestate pH.

Table 18: Crop Data Collection Inputs and Outputs of Unit Operations in Danish Demonstration Site

Unit Operation in Value Chain	Inputs (Unit)	Outputs (Unit)
Agrivoltaic System Green Biorefinery Anaerobic Digestion Biomethanation	Amount of Manure (t) Chemical Composition of Manure (%) Amount of Fertilizer (t) Chemical Composition of Fertilizer (%) Amount of Digestate (t) Chemical Composition of Digestate (%) Amount of Irrigation Water (l)	Total Biomass Harvest (t) Amount of Crop Harvest (t) Amount of Biomass Residues Harvest (t)

Environmental data

Table 19: Environmental Data Collection Inputs and Outputs of Unit Operations in Danish Demonstration Site

Unit Operation in Value Chain	Inputs (Unit)	Outputs (Unit)
Agrivoltaic System	Solar Radiation (W/m^2) Precipitation (mm) Fertiliser (t) Composition of Fertilizer (%) Digestate (t) Composition of Digestate (%) Mechanical cultivation (kWh)	Crop yield, biomass (t/ha) Crop yield, grain (t/ha) Electricity (kWh) Nitrate leaching (kg/ha)
Green Biorefinery	Crop yield, biomass (t/ha) Energy (kWh)	Crude protein (kg) Brown juice (l) Fibre residue (kg)
Anaerobic Digestion Biomethanation	Energy (kWh) Straw (t) Crop yield biomass (t) Manure (t) Biorefinery residues (t) Composition of crop biomass, manure, residues (%) Hydrogen input (m^3)	Biogas and Biomethane output (m^3) Heat energy output (kWh)

Energy data

Energy related data will be collected for the purposes of a TEA. An overview of all the energy related inputs and outputs is provided in Table 20. The collection of these data will be necessary to perform the sustainability assessment in WP4.

Table 20: Energy Data Collection Inputs and Outputs of Unit Operations in Danish Demonstration Site

Unit Operation in Value Chain	Inputs (Unit)	Outputs (Unit)
Agrivoltaic System	Fuel consumed for Mechanical Cultivation (l)	Electricity produced (kWh)
Green Biorefinery	Amount of Digestate (t) Chemical Composition of Digestate (%) Electricity consumed (kWh)	Amount of Protein Concentrate (t) Chemical Composition of Protein Concentrate (%) Amount of Fibre Press Cake (t) Chemical Composition of Fibre Press Cake (%) Amount of Brown Juice (t) Chemical Composition of Brown Juice (%)
Anaerobic Digestion	Amount of Manure (t) Chemical Composition of Manure (%) Amount of Biomass Residues (t) Chemical Composition of Biomass Residues (%) Amount of Substrate (t) Chemical Composition of Substrate (%) Amount of Nutrients (t) Chemical Composition of Nutrients (%) Electricity consumed (kWh)	Amount of Biogas produced (kt) Chemical Composition of Biogas produced (%) Amount of Digestate (t) Chemical Composition of Digestate (%)
Biomethanation	Amount of Biogas (kt) Chemical Composition of Biogas (%) Electricity consumed (kWh)	Amount of Biomethane produced (kt) Amount of Carbon Dioxide produced (kt) Heat produced (J)

Preliminary Mass and Energy Flows

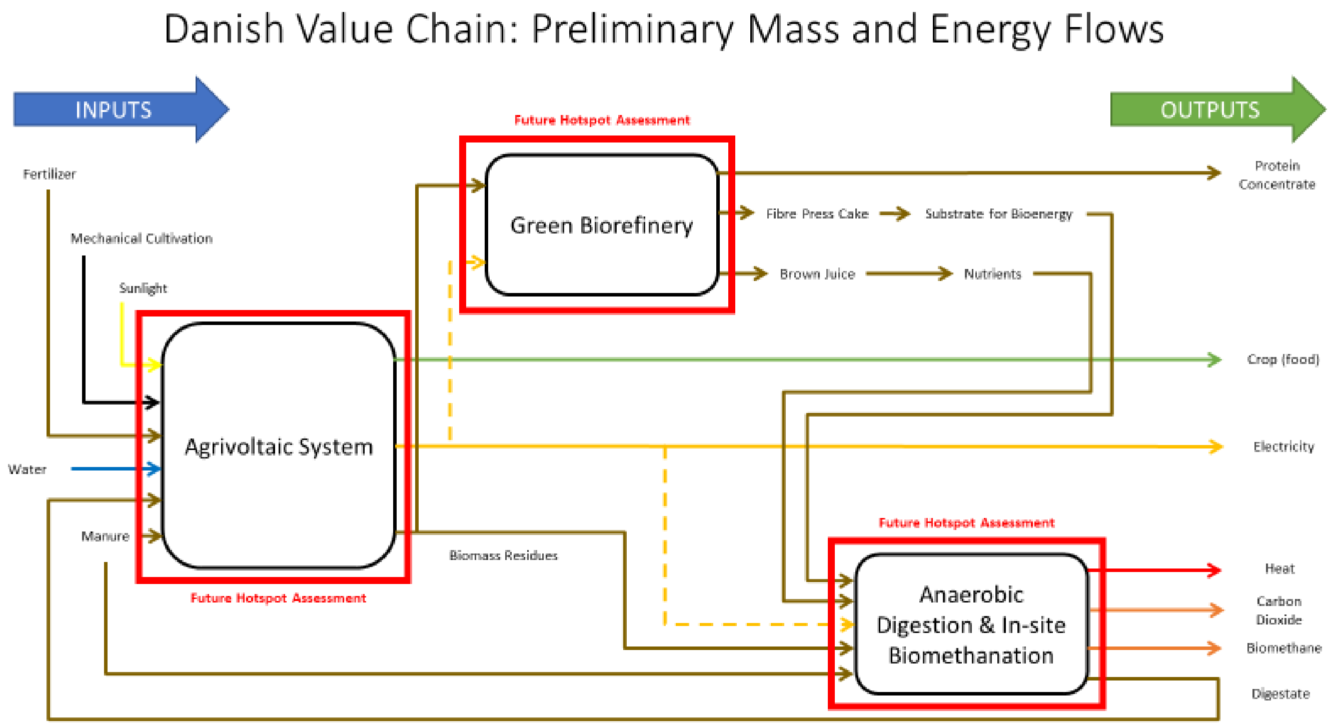

Figure 8: Preliminary Mass and Energy Flows of Danish Value Chain

Table 21: Inputs and Outputs of Unit Operations in Danish Demonstration Site

Unit Operation in Value Chain	Inputs	Outputs
Agrivoltaic System	Fertiliser Mechanical Cultivation Sunlight Water Manure	Crop (food) Electricity Biomass Residues
Green Biorefinery	Electricity Biomass Residues	Protein Concentrate Fibre Press Cake Brown Juice Substrate for Bioenergy Nutrients
Anaerobic Digestion	Electricity Biomass Residues Manure Nutrients Substrate for Bioenergy	Biogas Digestate
Biomethanation	Electricity Biogas	Biomethane Carbon Dioxide

4. CONCLUSIONS

The demonstration sites in Italy, Belgium and Denmark together represent a concerted effort to introduce innovative agricultural practices and promote renewable energy technologies. Each demonstration site, adapted to its regional context, demonstrates innovative solutions to promote sustainability, resilience and circularity in the agricultural sector. Deliverable D1.2 lists the technical specifications of the three demonstration sites.

In Italy, the focus on agro-photovoltaics demonstrates the potential of integrating solar energy production with agricultural activities, maximising land use efficiency and resource utilisation. Exploiting advanced agro-photovoltaic systems and monitoring techniques, the Italian demonstration site proposes an interesting link between solar energy - agricultural production and biomethane production.

Meanwhile, the Belgian demonstration highlights the importance of on-farm renewable energy production through anaerobic digestion, emphasising the valorisation of agroresidues for biogas production. Through the integration of high-efficiency micro-turbines and biogas tractors, the project offers viable solutions for decentralised energy generation and on-site mobility, paving the way for a more self-sufficient and environmentally friendly agricultural sector.

In Denmark, the emphasis on 'solar sharing' exemplifies a holistic approach to coupling primary food and feed production with renewable energy generation. Through the integration of agri-voltaic technologies, green biorefineries and biomethanation, the project explores interconnected value chains that promote sustainable land use, energy production and agricultural resilience. Exploiting synergies between solar energy production, biomass processing and biogas generation, the project aims to catalyse transformational changes in agricultural and energy systems, driving towards a more sustainable and equitable future.

Value4Farm

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