



ECOLOOP

www.ecoloop-project.eu

D4.1 AI and Big Data Analytics (IoT ecosystem)

23 September 2025



**Funded by
the European Union**

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. Horizon Europe Grant agreement N° 101118127.

Deliverable details

Title	WP	Version
D4.1 – AI and big data analytics (IoT ecosystem)	4	V0.1

Contractual delivery date	Actual delivery date	Delivery type*	Dissemination **
September 2025 (M24)	September 2025 (M24)	R	PU

* Delivery type: R: Document, report; DEM: Demonstrator, pilot, prototype; DEC: Websites, patent fillings, videos, etc; DMP: Data management plan.

** Dissemination Level: PU - Public; SEN – Sensitive, limited under the conditions of the Grant Agreement.

Author(s)	Organization
Borja Albert Gramaje	ETRA I+D

Version	Date	Person	Action	Status***
V0.1	15/04/2025	Borja Albert Gramaje (ETRA)	Table of contents proposal	Draft
V1.0	15/05/2025	Borja Albert Gramaje (ETRA)	Added explanation about CITRIC and microservices used	Draft
V1.1	02/06/2025	Borja Albert Gramaje (ETRA)	Added pilot site implementation chapter	Draft

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

V1.1	10/06/2025	Borja Albert Gramaje (ETRA) and pilot sites	Added pilot sites implementation	Draft
V1.2	15/07/2025	Borja Albert Gramaje (ETRA)	Updated Inderen pilot site and added Silla biogas specification	Draft
V1.2	04/08/2025	Borja Albert Gramaje (ETRA)	Added acronym tables	Draft
V1.3	05/08/2025	Kevin Rodriguez (INDEREN)	Updated information from Silla (GENIA) site, and Picassent (INDEREN) site	Draft
V1.4	07/08/2025	Ana Fernández (GENIA)	Updated information from Silla (GENIA) site and Spanish biogas pilot	Draft
V1.5	25/08/2025	Kevin Rodríguez (INDEREN), Klemen Kosovinc (SETUP), Jernej Zupančič (IRI UL)	Review	Draft
V1.6	15/09/2025	Denitsa Kuzeva (ALBENA)	Added information from the Bulgarian pilot site	Draft
V1.7	15/09/2025	Kevin Rodríguez (INDEREN)	Added information for Spanish biogas plant	Draft

V1.8	23/09/2025	Borja Albert, Sheila Sánchez (ETRA)	Final Review	Final
------	------------	-------------------------------------	--------------	-------

***Status: Draft, Final, Approved, Submitted (to European Commission).

Keywords

Internet of Things (IoT), sensors, analytics, big data, communication protocol, data, architecture, integration, hardware, decision support system, monitoring, renewable energy sources.



Index

1. INTRODUCTION	11
1.1. Purpose of the document	11
1.2. Scope of the document	11
1.3. Structure of the document	12
2. BIG DATA ANALYTICS FRAMEWORK	13
2.1. Data Integration and Communication Protocols	13
2.1.1. MQTT protocol	13
2.1.2. HTTP protocol	14
2.2. Data Harmonisation and Modelling	15
2.3. System Architecture	17
2.3.1. Support Layer	18
2.3.2. Ingestion Layer	19
2.3.3. Knowledge Layer:	21
2.3.4. Interoperability Layer:	21
2.3.5. Smart Service Layer:	22
2.4. Visualisation and Decision Support	22
3. PILOT SITE IMPLEMENTATION	23
3.1. ES Pilot Site	24
3.1.1. L'Horta Sud	25
3.1.1.1. Renewable Energy Sources	25
3.1.1.1.1. Photovoltaic	25
3.1.1.1.2. Geothermal	27
3.1.1.2. Current Measurements and Monitoring	29
3.1.1.3. Hardware Sensors and Technologies	30
3.1.1.4. Data Ingestion and Integration Approach	32
3.1.2. Silla Biogas plant	34
3.1.2.1. Renewable Energy Sources	35
3.1.2.1.1. Biogas	36
3.1.2.1. Current Measurements and Monitoring	37
3.1.2.1. Hardware Sensors and Technologies	37

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

3.1.2.2. Data Ingestion and Integration Approach	39
3.1.3. Finca Sinyent	39
3.1.3.1. Renewable Energy Sources	39
3.1.3.2. Current Measurements and Monitoring	40
3.1.3.3. Hardware Sensors and Technologies	41
3.1.3.4. Data Ingestion and Integration Approach	42
3.2. SI Pilot Site	43
3.2.1. Biomass Centre Nazarje	44
3.2.2. IC Jablje	44
3.2.2.1. Renewable Energy Sources	45
3.2.2.1.1. Biogas	45
3.2.2.2. Current Measurements and Monitoring	46
3.2.2.3. Hardware Sensors and Technologies	47
3.2.2.4. Data Ingestion and Integration Approach	49
3.3. BG Pilot Site	51
3.3.1. Momchil pilot site	51
3.3.1.1. Renewable Energy Sources	52
3.3.1.1.1. Smart greenhouses and Photovoltaic	52
3.3.1.1.2. Biogas	53
3.3.1.2. Current Measurements and Monitoring	54
3.3.1.3. Hardware Sensors and Technologies	56
3.3.1.4. Data Ingestion and Integration Approach	57
3.4. EE Pilot Site	58
3.4.1. Puhatu pilot site	58
3.4.1.1. Renewable Energy Sources	58
3.4.1.1. Current Measurements and Monitoring	59
3.4.1.2. Hardware Sensors and Technologies	59
3.4.1.3. Data Ingestion and Integration Approach	60
3.4.2. Pindi pilot site	60
3.4.2.1. Renewable Energy Sources	60
3.4.2.2. Current Measurements and Monitoring	61
3.4.2.3. Hardware Sensors and Technologies	61
3.4.2.4. Data Ingestion and Integration Approach	62
3.4.3. Ulila and Tootsi pilot site	62
3.4.3.1. Renewable Energy Sources	62
3.4.3.2. Current Measurements and Monitoring	63
3.4.3.3. Hardware Sensors and Technologies	63
3.4.3.4. Data Ingestion and Integration Approach	64
4. CONCLUSION	64
5. REFERENCES AND ACRONYMS	66

5.1. References	66
5.2. Acronyms	68

List of figures

FIGURE 1: DATA WORKFLOW FROM MQTT TO ECOLOOP.....	14
FIGURE 2: JSON EXAMPLE OF THE ECOLOOP DATA FORMAT.....	17
FIGURE 3: CITRIC MICROSERVICE ECOSYSTEM OVERVIEW	18
FIGURE 4: INDEREN PICASSENT PILOT SITE VIEW.....	26
FIGURE 5: INDEREN GREENHOUSE SOLAR VIEW	27
FIGURE 6: INDEREN PRELIMINARY GEOTHERMAL DESIGN.....	28
FIGURE 7: INDEREN ATMOS- 14 SENSOR.....	31
FIGURE 8: INDEREN ATMOS-14, TEROS-11 AND CONTROL CABINET.....	31
FIGURE 9: HORTA SUD PILOT SITE INTEGRATION DIAGRAM.....	32
FIGURE 10: DSS TOOL DISPLAY INFORMATION FROM THE GREENHOUSE ROOFTOP SOLAR INVERTER	34
FIGURE 11: 3D SPANISH BIOGAS PILOT IN SILLA.	35
FIGURE 12: FLOWMETER AND TEMPERATURE TRANSMIROT AT THE BIOGAS PILOT PLANT IN SPAIN	38
FIGURE 13: SIAR DEVICE	41
FIGURE 14: FINCA SINYENT PILOT SITE INTEGRATION DIAGRAM.....	42
FIGURE 15: DSS TOOL DISPLAYING INFORMATION FROM FINCA SINYENT SIAR DEVICE.....	43
FIGURE 16: JABLJE BIOGAS DIAGRAM WORKFLOW	46

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

FIGURE 17: ETRA SMX DEVICE	48
FIGURE 18: SMX AND SWG100 BIOGAS ANALYSER.....	49
FIGURE 19: JABLJE PILOT SITE INTEGRATION DIAGRAM	50
FIGURE 20: DSS TOOL DISPLAYING INFORMATION FROM SWG100 BIOGAS ANALYZER.....	51
FIGURE 21: PV INSTALLATION IN ALBENA PILOT SITE	53
FIGURE 22: BIOGAS INSTALLATION IN ALBENA PILOT SITE	54
FIGURE 23: MOMCHIL AND ETRA DIAGRAM FOR DATA RETRIEVAL	57

List of tables

TABLE 1: ECOLOOP DATA MODEL ATTRIBUTES	16
TABLE 2: HORTA SUD MEASUREMENTS TABLE	29
TABLE 3: HORTA SUD DEVICES DESCRIPTION TABLE	30
TABLE 4: BIOGAS SILLA MEASUREMENTS TABLE	37
TABLE 5: BIOGAS SILLA DEVICES DESCRIPTION TABLE	38
TABLE 6: FINCA SINYENT MEASUREMENTS TABLE	40
TABLE 7: FINCA SINYENT DEVICES DESCRIPTION TABLE	41
TABLE 8: JABLJE MEASUREMENTS TABLE	47
TABLE 9: JABLJE DEVICES DESCRIPTION TABLE	48
TABLE 10: BIOGAS MOMCHIL MEASUREMENTS TABLE	54

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

TABLE 11: GREENHOUSES MOMCHIL MEASUREMENTS TABLE	55
TABLE 11: ALBENA DEVICES DESCRIPTION TABLE	56
TABLE 12: PUHATU MEASUREMENTS TABLE	59
TABLE 13: PINDI MEASUREMENTS TABLE	61
TABLE 14: ULILA AND TOOTSI MEASUREMENTS TABLE	63
TABLE 15: TABLE OF ACRONYMS.	68

Executive Summary

This deliverable presents the development and implementation of a comprehensive big data analytics framework for the ECOLOOP IoT ecosystem, supporting the project's pillars in energy, agriculture/forestry, and energy community services. The framework is designed to integrate and harmonise data streams from a wide variety of IoT devices and monitoring systems deployed across multiple pilot sites, each representing distinct use cases and operational environments.

For each pilot site, a tailored set of IoT devices and sensors is deployed to capture key parameters relevant to local energy production, agricultural processes, and environmental conditions. These devices include, but are not limited to, sensors for solar irradiance, ambient temperature, relative humidity, air pressure, wind speed and direction, rainfall, soil moisture, and crop health. The collected data is transmitted through standardised protocols and aggregated within the ECOLOOP ecosystem, ensuring interoperability and scalability.

The integration process involves mapping the specific monitoring systems and data requirements of each use case to the broader ECOLOOP data architecture. This enables the seamless flow of information from field devices to centralised analytics platforms, where advanced big data techniques are applied. These analytics support real-time monitoring, predictive maintenance, resource optimisation, and informed decision-making for stakeholders across the energy and agricultural sectors.

By leveraging big data analytics across the entire value chain, the ECOLOOP ecosystem enhances operational efficiency, sustainability, and resilience. The deliverable outlines the methodologies for device integration, data harmonisation, and analytics deployment, providing a replicable model for digital transformation in rural and community-based energy and agricultural systems.

Copyright statement

The work described in this document has been conducted within the ECOLOOP project. This document reflects only the ECOLOOP Consortium view, and the European Union is not responsible for any use that may be made of the information it contains.

This document and its content are the property of the ECOLOOP Consortium. All rights relevant to this document are determined by the applicable laws. Access to this document does not grant any right or license on the document or its contents. This document or its contents are not to be used or treated in any manner inconsistent with the rights or interests of the ECOLOOP

Consortium or the Partners detriment and are not to be disclosed externally without prior written consent from the ECOLOOP Partners.

Each ECOLOOP Partner may use this document in conformity with the ECOLOOP Consortium Grant Agreement provisions.

1. Introduction

1.1. Purpose of the document

The purpose of this document is to describe the design, implementation, and integration of big data analytics within the entire ECOLOOP Internet of Things (IoT) ecosystem, supporting the project's energy, agricultural/forestry, and community service pillars. It details how diverse IoT devices and monitoring systems deployed across multiple pilot sites are connected and harmonised using advanced data integration protocols, including MQTT and REST APIs. The document aims to provide a comprehensive overview of the technical framework, site-specific deployments, and analytics methodologies that enable real-time monitoring, data-driven decision-making, and enhanced operational efficiency throughout the ECOLOOP value chain.

1.2. Scope of the document

The scope of this document encompasses the design, deployment, and operation of a big data analytics framework within the ECOLOOP IoT ecosystem, supporting the integration of diverse IoT devices and monitoring systems across multiple pilot sites. The document covers:

- The technical architecture and protocols enabling seamless data collection, transmission, and harmonisation from distributed sensors and systems.
- The integration strategies for connecting site-specific IoT infrastructures into the unified ECOLOOP ecosystem, ensuring interoperability and scalability.
- The demonstration of these technical solutions in various real-world environments, reflecting different climates, agricultural and forestry practices, and energy systems, as represented by the project's pilot sites in Spain, Estonia, Bulgaria, and Slovenia.

- The support for ECOLOOP's holistic approach, which aims to optimise renewable energy integration, sustainable agricultural protocols, and circular bioeconomy practices, while fostering regional development and environmental sustainability

This document focuses on the technical and operational aspects of IoT data integration and analytics within the ECOLOOP framework.

1.3. Structure of the document

This document is organised into four main chapters:

- **Section 1: Introduction.** Outlines the purpose, scope, and structure of the deliverable, providing essential context for the reader.
- **Section 2: Big Data Analytics Framework.** Describes the overall architecture, data harmonisation and modelling approaches, and the communication protocols (including MQTT and HTTP) that enable integration of diverse IoT devices. It also covers the visualisation tools and decision support mechanisms implemented within the ECOLOOP ecosystem.
- **Section 3: Pilot Site Implementation.** Details the deployment and operation of the big data analytics framework across the project's pilot sites. For each site, it presents the pilot's objectives, renewable energy sources, IoT devices and monitoring systems, integration processes, and analytics outcomes.
- **Section 4: Conclusion.** Concludes the deliverable with a brief overview of all the pilots and the current future work to be done, if present.
- **Section 5: References and Acronyms.** Provides a list of referenced materials and a glossary of acronyms used throughout the document for clarity and ease of understanding.

This structure ensures a logical flow from the general framework to specific real-world applications, supporting both technical and non-technical audiences in understanding the integration and impact of big data analytics within the ECOLOOP IoT ecosystem.

2. Big Data Analytics Framework

The ECOLOOP project is dedicated to optimising the integration of renewable energy sources—such as biogas, biomass, agri-photovoltaics (agri-PV), and geothermal energy—in rural areas, with the goal of reducing carbon footprints, enhancing sustainability, and fostering circular economy practices. Achieving these objectives requires a robust data-driven decision-making platform which is underpinned by a comprehensive Big Data Analytics Framework tailored in this deliverable.

The big data analytics framework will aggregate, process, and analyse substantial volumes of diverse data originating from multiple sources, including renewable energy sources devices (such as solar inverters and biogas analysers) as well as agricultural sensors deployed in crop fields (humidity, temperature, solar radiation, ...). This framework will form the foundational layer for the "Decision Support Tool (DST) for farmers and foresters," which will be detailed and demonstrated in ECOLOOP Deliverable *D4.3. DST for farmers and forester's final version* (M30).

2.1. Data Integration and Communication Protocols

Effective data integration and reliable communication protocols are foundational to the ECOLOOP Big Data Analytics Framework. Given the diversity of data sources—including renewable energy devices and agricultural sensors—seamless data acquisition and transfer are critical for near real-time analytics and informed decision-making. This section outlines the key protocols adopted for secure, scalable, and efficient data exchange within rural energy and agroforestry environments.

2.1.1. MQTT protocol

The Message Queuing Telemetry Transport (*MQTT*) protocol is a lightweight, publish-subscribe messaging protocol ideally suited for resource-constrained devices and low-bandwidth, high-latency networks typical of rural areas [1]. In the ECOLOOP framework, MQTT enables:

- **Efficient Data Collection:** Agricultural sensors and renewable energy devices publish real-time data to a central broker. Depending on the pilot site, this broker will publish the data over MQTT to the ECOLOOP services hosted on the cloud.

- **Low Power Consumption:** MQTT's minimal overhead ensures prolonged device operation, essential for remote field deployments.
- **Scalability:** The protocol supports thousands of devices, allowing for future expansion of sensor networks, without affecting the system performance.
- **Security:** MQTT supports Transport Layer Security (TLS)/ Secure Sockets Layer (SSL) encryption and authentication, protecting sensitive environmental and operational data from unrestricted or undesired access.

By leveraging MQTT, ECOLOOP ensures robust, near real-time integration of heterogeneous data streams, forming the backbone for advanced analytics and responsive decision support. As diagram showcasing a minimal description of how the data flows from the sensor to the ECOLOOP platform can be seen in Figure 1.

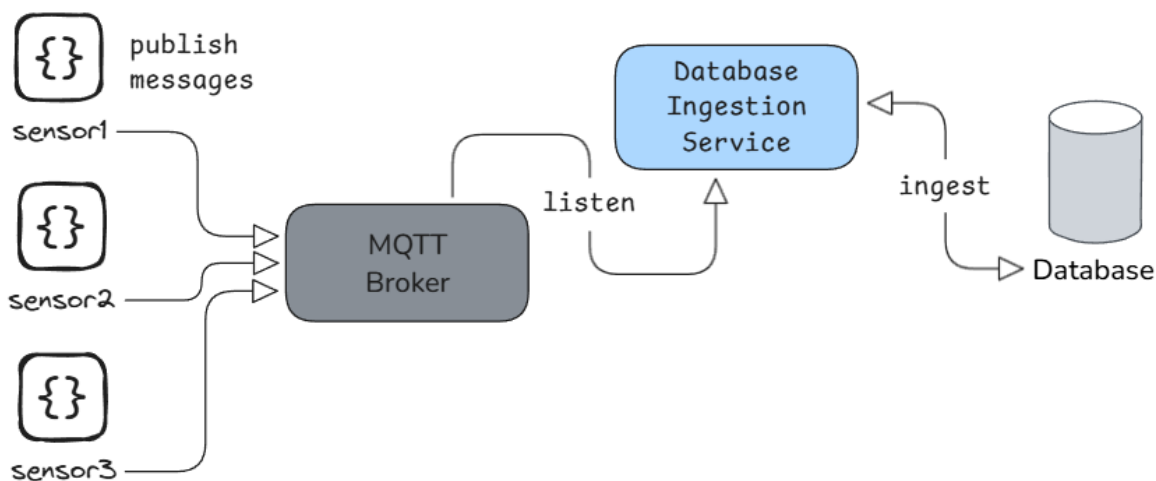


Figure 1: Data workflow from MQTT to ECOLOOP.

2.1.2. HTTP protocol

The Hypertext Transfer Protocol (HTTP) is a widely adopted client-server protocol used for transmitting structured data over the internet [2]. Within the ECOLOOP architecture, HTTP serves several key purposes:

- **Interoperability:** HTTP is universally supported by web services, enabling seamless integration with third-party applications and external data repositories.

- **RESTful APIs:** The framework utilizes RESTful HTTP APIs (Application Program Interfaces) for data ingestion, retrieval, and management, facilitating standardised communication between the big data analytics framework and any web interface, for instance, the DSS [3]. Those APIs enables seamless third-party integration, where ECOLOOP data can be accessed if allowed.
- **Security and Authentication:** HTTPS guarantees secure, encrypted transmission of data, while API keys and OAuth protocols enable controlled access to sensitive resources. The ECOLOOP ecosystem will implement a robust authentication mechanism, issuing access tokens upon successful verification. This process will facilitate comprehensive tracking of user operations and permissions granted. Such an approach significantly enhances security and mitigates potential risks [4].

By combining HTTP with MQTT, ECOLOOP achieves a flexible, hybrid communication infrastructure—balancing the near real-time needs of field devices with the reliability and compatibility required for broader system integration.

2.2. Data Harmonisation and Modelling

Data harmonisation and modelling are needed since the project brings together data from many different sources, each with its formats, structures, and conventions. Without harmonisation, this diversity leads to inconsistencies, errors, and difficulties in integrating and analysing the data effectively. Harmonising and modelling the data ensures accuracy, consistency, and interoperability, making it possible to extract meaningful insights, support reliable analytics, and enable better decision-making across all project components.

There are already well-established data models—such as FIWARE Smart Data Models, which are open-source data models for a diverse variety of sources, such as agrifood, water, energy environment [5]—that provides standardised ways to organise and share information across different domains and systems. For ECOLOOP, a specific data model has been adopted that structures information within the main objectives of the project ensuring consistency and interoperability when integrating the diverse data sources involved, as mentioned above.

The following Table 1 showcases the main attributes that builds the ECOLOOP data model, and an explanation for each one:

Table 1: ECOLOOP Data Model Attributes

Attribute	Description
<code>_id</code>	Unique identifier for the device within the database.
<code>type</code>	Category or technology of the device (e.g., "pv" for photovoltaic).
<code>geometry</code>	Spatial coordinates and geometry type, enabling precise location mapping.
<code>properties</code>	Flexible field for additional device-specific attributes or metadata.
<code>description</code>	Textual description providing additional context about the device.
<code>measurements</code>	Latest real-time values measured by the device (e.g., active power, voltage, current).
<code>measurementsTimestamp</code>	Timestamp of when the latest measurements were captured.
<code>forecasts</code>	Predicted or forecasted values for key measurements.
<code>forecastsTimestamp</code>	Timestamp indicating when the forecast values are valid.
<code>states</code>	Current operational states or flags of the device (e.g., communication status, operating mode).
<code>statesTimestamp</code>	Timestamp of when the current states were last updated.
<code>_expired</code>	Boolean flag indicating whether the device record is outdated or inactive.
<code>_updated</code>	Timestamp of the last modification to the device record.

Below, as shown in Figure 2, there is an example in JSON (JavaScript Object Notation) —a widely adopted, human-readable data format that excels at structuring and exchanging information between diverse systems [6]— that will be used as notation for storing data coming from the pilot sites. This sample demonstrates the typical data structure captured from a solar inverter

deployed at the Spanish pilot site located at *Horta Sud, Picassent*. The format ensures seamless interoperability, making it straightforward for both machines and humans to parse, analyse, integrate and comprehend data from the project.

```
{
  "_id": "PV-04-D1",
  "type": "pv",
  "geometry": {
    "type": "Point",
    "coordinates": [-0.5165110880710488, 39.37516478894509]
  },
  "context": "ecoloop#picassentA#D1#PV-04-D1",
  "iconTree": "material-symbols:solar-power-outline-rounded",
  "label": "PV-04-D1",
  "measurements": {
    "activePower": 0.099,
    "voltage": 562.85,
    "current": 0.179
  },
  "measurementsTimestamp": "2025-06-09T16:56:03.000+02:00",
  "forecasts": {
    "activePower": 0.120,
    "voltage": 563.00,
    "current": 0.180
  },
  "forecastsTimestamp": "2025-06-09T17:00:00.000+02:00",
  "states": {
    "communicationState": "OK",
    "operatingMode": "normal"
  },
  "statesTimestamp": "2025-06-09T16:56:03.000+02:00",
  "_expired": false,
  "_updated": "2025-06-09T16:58:36.988+02:00",
  "description": "MPPT D - Tresbolillo"
}
```

Figure 2: JSON example of the ECOLOOP data format

2.3. System Architecture

The big data analytics framework is composed of a series of interconnected microservices—small, independent software components that each perform a specific task and communicate with one another through well-defined APIs or message brokers [7]—each responsible for a specific function. This architecture is built on ETRA’s CITRIC platform, which was originally developed to address communication requirements in previous H2020 projects, including X-FLEX [8], ASSISTANCE [9] and MATCHUP [10].

CITRIC is built upon the RIVER principles—Reactive, Interoperable, Visible, Elastic, and Resilient—and leverages a microservices architecture with event-driven communication. Its open design allows the ecosystem to broaden its network of services. The event-driven approach ensures reactivity, while interoperability is achieved through the adoption of standard protocols and data-agnostic frameworks. Comprehensive monitoring provides operational visibility. The system’s elasticity enables each service to scale independently, supporting cities of any size, and

its resilience is reinforced through orchestration and monitoring mechanisms that ensure fault tolerance.

CITRIC's microservices distribution adheres to IEC30182:2017 and UNE178104:2017 standards, particularly in its functional layer orientation. Figure 3 illustrates the complete CITRIC architecture, highlighting in red the components utilised in ECOLOOP, which are further described in the next sub-chapters.

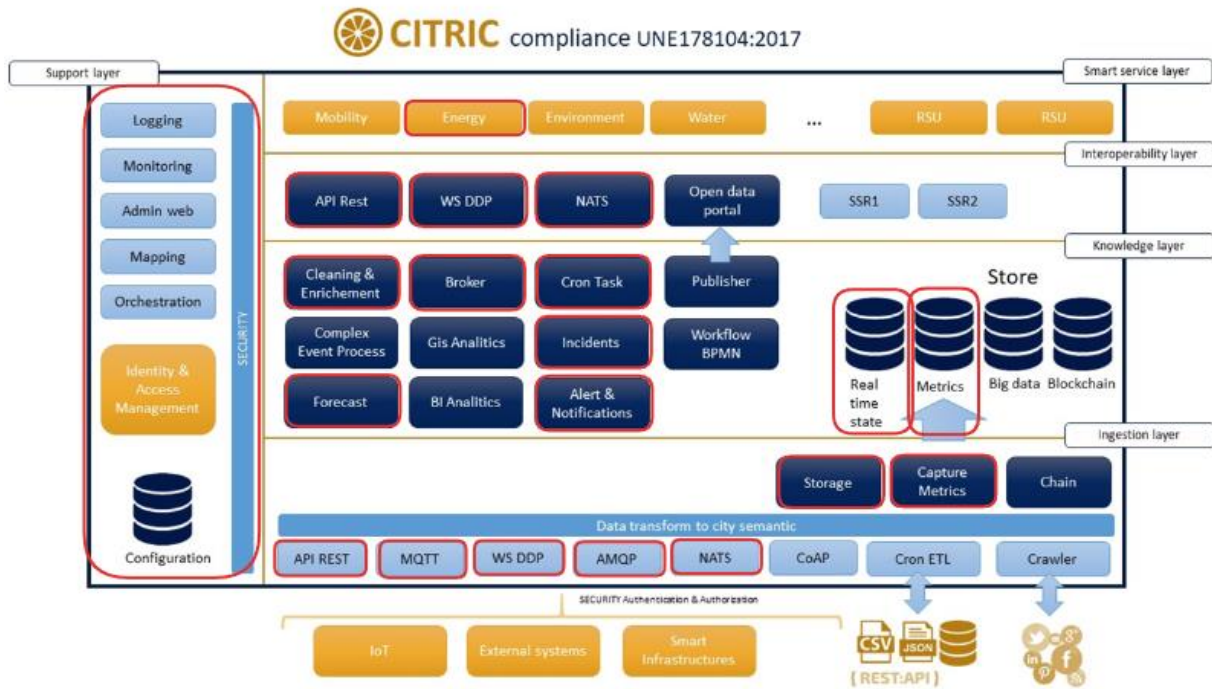


Figure 3: CITRIC microservice ecosystem overview

2.3.1. Support Layer

This layer serves as the backbone of the CITRIC ecosystem, providing a wide range of functionalities and tools to facilitate efficient management and control. It is primarily intended for use by the CITRIC administrators, enabling streamlined oversight and administration of the platform. To support these microservices, the following components are described in detail below.

- **Orchestration:** All components are orchestrated using Kubernetes, an open-source platform designed to automate the deployment, scaling, and management of containerised applications. Kubernetes manages clusters of containers, ensuring high availability, automated rollouts and rollbacks, self-healing, and efficient resource utilisation [11]. This

orchestration enables flexible and monitored deployments. The given deployment operates on Google Cloud Services.

- **Monitoring:** The CITRIC management website provides graphical monitoring of all microservices and real-time data flow across the platform.
- **Logging:** Logging is managed by the orchestrator, with logs securely stored for forensic analysis of errors and alerts.
- **Administration web:** CITRIC offers a multilingual web interface for management and monitoring. The interface displays metrics, mapping, incidents, data, multimedia, and more.
- **Mapping:** A 3D map is integrated into the management interface, allowing users to navigate platform data visually. Supports analytic representations such as aggregations (means, maximums, deviations) and geolocated visualisation of elements.
- **Identification and access management:** CITRIC includes a dedicated component for authentication, authorisation, and user profiling. It supports access control via basic authentication and single sign-on (SSO) protocols with OpenID. OpenID, implemented in Keycloak, is an authentication protocol that allows users to log in using a single account, rather than having to create and manage separate accounts for each service. Keycloak is an open-source platform that centralises authentication and authorisation, offering features like single SSO, support for standard protocols, and user management through an intuitive admin console [12].
- **Configuration:** All configuration data is stored in MongoDB which holds the necessary information for CITRIC's operation. MongoDB, a NoSQL database that stores data in flexible JSON-like documents, is a flexible, document-oriented database that efficiently manages large volumes of structured and unstructured data [13].

2.3.2. Ingestion Layer

The data ingestion layer forms the foundation that allows ECOLOOP partners and devices to submit data to CITRIC. Acting as a bridge between project tools and CITRIC, this layer enables seamless data publishing within the ecosystem. A set of dedicated microservices has been developed to support these functions, as detailed below.

- **API REST:** CITRIC offers a secure and robust HTTPS REST API, implemented with Express, featuring rate limiting to protect against potential attacks and abuse. The API enables flexible data ingestion and enforces authorisation, granting each authenticated user access

only to specific datasets as permitted. This approach ensures both strong security and precise control over data access within the platform.

- **MQTT:** CITRIC supports data ingestion from lightweight IoT devices using the MQTT protocol, a standard for efficient, low-overhead messaging. RabbitMQ is used as the MQTT ingestion service, ensuring reliable and scalable message handling within the platform.
- **AMQP:** Advanced Message Queuing Protocol (AMQP) with CITRIC enables direct data ingestion via the AMQP protocol, where data is received through queues, processed by microservices, and stored within the platform. RabbitMQ provides AMQP support, ensuring reliable and scalable message handling.
- **WS DDP:** CITRIC enables platform connectivity through WebSocket's (WS). The protocol over WS is implemented by Distributed Data Protocol (DDP) — a client-server protocol developed by Meteor to support real-time data synchronization and efficient mass data ingestion — developed for efficient mass data ingestion [14].
- **NATS:** CITRIC uses **NATS** as its message broker, functioning as an enterprise service bus (ESB) for microservices communication. NATS is a lightweight, high-performance messaging system that enables services to interact via secure, access-controlled topics, allowing direct and efficient access to storage microservices [15].
- **Transform:** All ingestion processes undergo a transformation step to normalise data before storage. Those transformations schemas are pre-configured for each source and tailored per deployment. For ECOLOOP all the diverse data coming from the diverse data sources, will be transformed into the standardised data model explained in the previous chapter.
- **Security:** Every ingestion process is authenticated and authorised at the microservice level. The authorisation is managed per credential (token or user/password) with three security levels: read, write, and public attributes only.
- **Storage:** A dedicated microservice manages data storage and modifications in CITRIC, handling near real-time database operations with MongoDB. MongoDB's flexible, document-oriented design allows efficient storage and rapid updates, making it well-suited for microservices.
- **Metrics:** A dedicated microservice extracts data to generate KPIs for each modelled data type and stores time-series information in a database such as **InfluxDB**. InfluxDB is a high-performance, purpose-built time series database designed for efficiently storing, querying, and analysing large volumes of time-stamped data [16].

2.3.3. Knowledge Layer:

Most of the data provided by the ECOLOOP project consists of raw information, which on its own offers limited value for achieving the project's objectives. The knowledge layer is designed to enrich this data, transforming it into actionable insights that can be displayed and shared with customers and stakeholders through the Decision Support Tool (to be detailed in ECOLOOP D4.3). Below is a brief description of each component that forms the knowledge layer:

- **Cleaning & Enrichment:** The Cleaning & Enrichment process uses Extract, Transform and Load (ETL) batch operations to cleanse and enhance data in the big data repository. This ensures that downstream analytics are based on high-quality, reliable, and enriched information.
- **Forecast:** A dedicated microservice generates machine learning models on stored data collections, leveraging the XGBoost library for efficient model training and time series prediction [17]. It seamlessly integrates with the CITRIC ecosystem through NATS messaging and offers a REST API, enabling external applications to access predictions and interact with the models securely and efficiently.
- **Broker:** CITRIC's microservices architecture relies on NATS, a robust, scalable, and fault-tolerant messaging broker. NATS ensures reliable, organised, and redundant communication across the service network, supporting high availability and resilience [15].
- **Incidents:** CITRIC monitors operational incidents within the installation and features an advanced notification system to ensure prompt response. Alerts can be sent through multiple channels, including Telegram, Email, and external web services, or by triggering automated workflow processes. This multi-channel approach ensures that incidents are quickly communicated to the right stakeholders and that appropriate actions can be initiated for effective incident management.
- **Alert and Notifications:** CITRIC offers comprehensive event alerting and reporting, integrating with channels such as Telegram, Email, external web services, and automated workflow processes. This ensures timely notifications and effective event management, similar to its incident notification system.

2.3.4. Interoperability Layer:

This layer primarily facilitates data exchange between ECOLOOP tools and third-party applications that need to work with data from various devices installed at pilot sites. It ensures

secure and efficient interoperability by leveraging a set of standardised tools and protocols, including RESTful APIs, WebSocket's, MQTT, AMQP, and the NATS messaging broker. Robust authentication and authorisation mechanisms are also implemented to control access, making the data exchange process reliable, scalable, and compatible with diverse external systems.:

- **API REST:** CITRIC exposes a dedicated segment of its REST API for Create, Read, Update and Delete (CRUD) operations, enabling secure and efficient data management. This API allows partner back-end services and third-party applications to interact seamlessly with the platform, supporting integration and collaboration within the ECOLOOP project.
- **WS DDP:** Customers can interact with the platform using WebSocket's via the DDP protocol, primarily through front-end applications. WebSocket's enable real-time, bidirectional communication, making them the only method for seamless two-way interaction with external systems [14].
- **MQTT:** MQTT can be used as a data exchange mechanism for partners who prefer subscribing to near real-time data updates. Its lightweight publish/subscribe model makes integration easy and ensures efficient, timely delivery of data streams. [1]

2.3.5. Smart Service Layer:

Any vertical service or application can utilise the platform and its services. These external agents are typically organised by their domain expertise, such as Energy within ECOLOOP, which determines the specific types of data, like entities and metrics, that each application can access and use. This domain-based organisation ensures that each service interacts with the most relevant data for its specialised needs.

2.4. Visualisation and Decision Support

The Visualisation and Decision Support component is a key element within the ECOLOOP platform, designed to empower stakeholders with actionable insights derived from the diverse data collected across all pilot sites. In alignment with ECOLOOP's objectives, this chapter outlines the main features and scope of this component, providing a high-level overview without delving into technical specifics, as further details will be presented in the upcoming Deliverable 4.3.

- **Transforming Data into Insights:** The platform will convert raw and enriched data into clear, intuitive visualisations, supporting informed decision-making for all ECOLOOP partners and stakeholders.

- **Comprehensive Data Access:** Users will be able to access and explore data from each pilot site, ensuring transparency and enabling comparative analysis across different domains and locations.
- **Support for Strategic Decisions:** The decision support tools will facilitate the identification of trends, anomalies, and key performance indicators (KPIs), aiding in the evaluation of project outcomes and the optimisation of operational strategies.
- **Export Options:** The system will support the export of visualisations, enabling stakeholders to share findings and support collaborative decision-making.
- **Interactive Dashboards:** Dashboards will provide real-time and historical views of critical project metrics, tailored to the needs of different user groups.

As part of this deliverable, representative screenshots will be included in the following section to showcase the successful retrieval and visualisation of data from each pilot site. These examples will demonstrate the platform's ability to aggregate, display, and make accessible the information collected throughout the ECOLOOP ecosystem.

3. Pilot Site Implementation

The ECOLOOP project demonstrates its innovative solutions through four pilot sites located in **Spain, Slovenia, Estonia, and Bulgaria**. These sites were selected to represent a diverse range of agricultural and forestry conditions, climates, crop types, management techniques, and socio-economic contexts. Each pilot site serves as a real-world testbed for integrating and validating renewable energy technologies and sustainable practices.

These countries collectively cover a wide spectrum of environmental and operational scenarios, ensuring that ECOLOOP's solutions are robust, scalable, and adaptable to different rural realities.

For each pilot site, the following information has been included:

- **Pilot Information:** Each site's unique context, objectives, and operational environment are described in detail, providing insight into the specific challenges and opportunities addressed by the project.
- **Current Measurements and Monitoring:** A dedicated chapter which outlines the key parameters being measured at each site. This includes, but is not limited to:
 - Energy production and consumption

- Soil health and biodiversity indicators
- Efficiency of Renewable Energy Sources.
- **Hardware Sensors and Technologies:** The technical assets deployed at each pilot site are thoroughly explained. This encompasses:
 - Type of sensors (smart meters, biogas analysers, environmental sensors, etc.)
 - Renewable Energy Sources technologies (solar inverters, solar batteries, etc.)
 - Data acquisition systems and communication gateways (PLCs, dataloggers, etc.)
- **Data Ingestion and Integration Approach:** The process for collecting, transmitting, and integrating data from each site into the ECOLOOP IoT ecosystem has been detailed. This includes the use of standardised protocols (such as MQTT, AMQP, RESTful APIs, and WebSocket's), security measures, and data quality assurance steps.

This structured approach ensures that the technical implementation, monitoring, and integration strategies for each pilot site are transparent, reproducible, and tailored to the ECOLOOP objectives, setting a strong foundation for future replication and scale-up across Europe

3.1. ES Pilot Site

The Spanish pilot demonstration of ECOLOOP is distributed across several strategic sites in the Valencia region, each contributing uniquely to the project's goals of renewable energy integration and sustainable agriculture.

In Picassent (L'Horta Sud), the project integrates Agri-PV systems with geothermal energy to create a sustainable energy community that supports crop production and stabilises agricultural environments.

At Finca Sinyent in Polinyà del Xúquer, biofertilizers from biogas digestate are tested on various crops within an experimental farm equipped with advanced irrigation and monitoring systems, including the SiAR (Agroclimatic Information System for Irrigation) sensing system. The site also functions as a living lab in collaboration with the Universitat Politècnica de València (UPV), providing a real-world environment for testing and demonstrating innovative agricultural technologies and practices.

In Silla, a biogas plant pilot processes local agricultural biowaste using an anaerobic digester, producing biogas that is upgraded to biomethane for sustainable transport through innovative membrane technology.

Each of these sites is further detailed in the following sections, with full technical background and implementation information available in Deliverable D2.1. [18]

3.1.1. L'Horta Sud

The L'Horta Sud pilot site in Valencia, led by INDEREN, integrates photovoltaic (PV) and geothermal energy systems within a productive agricultural area to create a sustainable energy community. PV panels supply renewable electricity for farm operations, while geothermal systems provide heating and cooling for agricultural structures.

Real-time monitoring and data collection feed into the ECOLOOP IoT ecosystem, enabling efficient resource management and supporting the site as a scalable model for sustainable agriculture.

3.1.1.1. Renewable Energy Sources

The L'Horta Sud pilot site employs a combination of renewable energy technologies to support sustainable agricultural operations. Together, these renewable energy sources (RES), described hereinafter, enable the L'Horta Sud pilot site to operate as a sustainable energy community, integrating modern energy solutions with traditional agricultural practices.

3.1.1.1.1. Photovoltaic

The project integrates photovoltaic technology with agricultural use through an agrivoltaic system, combining solar energy generation with productive land use. Elevated photovoltaic structures allow for crops to grow underneath, optimising both energy and agricultural outputs in a shared space.

This dual-use approach contributes to energy self-sufficiency while promoting sustainable farming practices, particularly relevant in rural or peri-urban environments.



Figure 4: Inderen picassent pilot site view

- **Picassent Solar Energy Community**

The Picassent Solar Energy Community features an agrivoltaic installation composed of 2,848 bifacial solar panels, model *Jinko Solar Tiger Pro 72HC-BDVP*, each with a capacity of 535 Wp, reaching a total installed peak power of 1,523 kWp. The modules are mounted on *Zimmermann ZAEW2-VT-2P* elevated structures, with a maximum height of 6.235 meters, enabling simultaneous energy generation and agricultural activity underneath. The system includes 10 *Sungrow SG125CX-P2* inverters, each rated at 125 kW, and is supported by an energy storage system composed of *Endurance Motive ST160* batteries providing a total of 644 kWh.

- **Greenhouse Rooftop Solar System**

The greenhouse features an off-grid three-phase solar installation with 18 kW nominal power, a photovoltaic field of 40 kWp, and 53.6 kWh of battery storage. The configuration uses AC-coupled architecture, where daytime consumption is directly supplied via a *SMA STP CORE1* grid-tied inverter, improving efficiency and extending battery life by minimizing charge/discharge cycles. Power is stabilized by a three-phase inverter-charger cluster made up of 3 SMA Sunny Island 8.0H units (48V, 6 kW each). The system's battery is composed of four *CEGASA eBick 280 Pro* modules, each with 13.4 kWh, forming a 53.6 kWh lithium-LFP bank with a nominal current of 525 A, integrated with a BMS and protection interface.

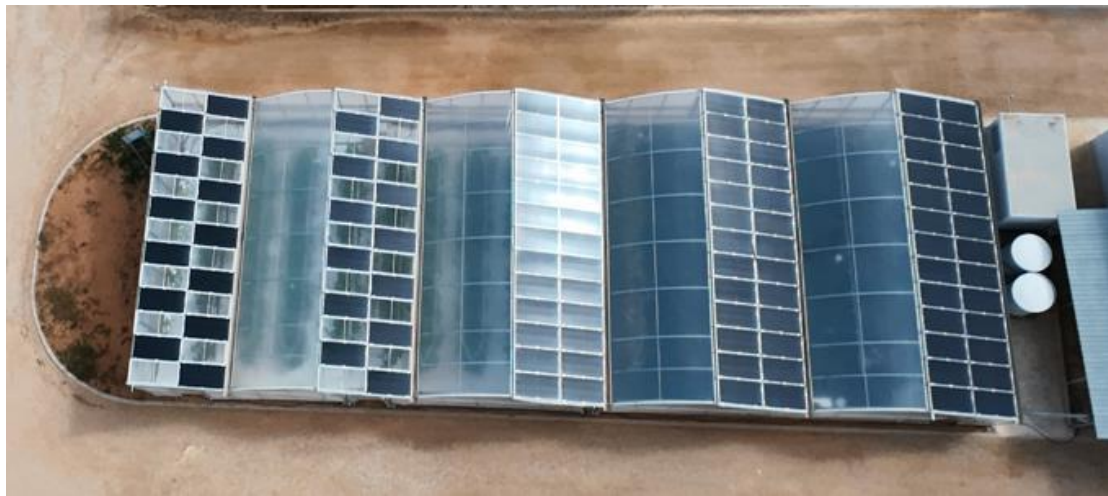


Figure 5: Inderen greenhouse solar view

The system includes a 20 kVA backup diesel generator, programmed for automatic start based on battery state of charge (SOC) levels, power demand, or weekly maintenance cycles, ensuring continuous operation during extended low-sunlight periods or system maintenance.

3.1.1.1.2. Geothermal

Geothermal energy is a renewable, clean, and reliable thermal energy source that harnesses the Earth's subsurface heat to provide heating, cooling, and domestic hot water (DHW). At the Horta Sud pilot site, a hybrid system will combine photovoltaic generation with shallow geothermal energy to meet the site's diverse energy demands, especially in agricultural applications.

A closed-loop geothermal system will be deployed at the beginning of 2026, using five vertical boreholes, each 125 meters deep, connected to a high-efficiency *ENERTRES TERRA SW Twin heat pump*. The system has an installed thermal capacity of 30 kW, designed to cover a total estimated demand of 101.52 W/m^2 across the site.

This setup will supply:

- Heating and cooling for Agri-PV infrastructure
- Thermal regulation for mushroom cultivation facilities
- Climate control in fruit storage chambers or cold rooms
- Hot water for toilets, offices, and laboratories

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

The geothermal loop includes a PT100 probe system, a 4-way manifold, and an inertia tank of 5,000 litres for thermal storage and buffering. An intelligent Navigator 2.0 controller manages the entire system and integrates it with the solar generation infrastructure, ensuring energy efficiency and smart operation through a centralised interface.

An active hydraulic cooling unit and modular drive system support variable temperature control depending on seasonal and operational needs. This design ensures year-round temperature stability, improves crop yields (especially for temperature-sensitive products like mushrooms), and reduces energy costs by leveraging local, renewable resources.



Figure 6: Inderen preliminary geothermal design

The geothermal installation at the Picassent pilot site has not yet been deployed, as its final design depends on the completion of the photovoltaic infrastructure and agricultural layout. The energy community with PV panels is pending grid connection approval with Iberdrola, which may require minor modifications in the distribution and power output of the arrays. These adjustments could involve terrain movement, directly affecting the feasible locations for the vertical boreholes.

The boreholes, each 125 m deep in a closed-loop configuration, are essential to provide the geothermal system with access to the stable subsurface temperature required for efficient heat exchange. Their correct positioning is critical to ensure thermal performance, hydraulic

balancing, and to prevent any interference with PV foundations or root systems of the crops grown beneath the panels.

Moreover, as crops will be cultivated under the PV structures, it is essential to first finalize the PV connection works and define the plantation layout to avoid interferences. Once these dependencies are resolved, the precise siting and drilling of the boreholes, along with the installation of the geothermal probes and associated infrastructure, can be carried out without risk of rework or incompatibility.

3.1.1.2. Current Measurements and Monitoring

The *L'Horta Sud* pilot site employs a comprehensive monitoring system to track key environmental, energy, and operational parameters essential for sustainable agricultural management. This section outlines the main measurements performed at the site, along with their respective units, followed by a summary of the IoT devices deployed for data acquisition presented in Table 2.

Table 2: Horta Sud measurements table

Measure	Unit
Temperature	degC
Relative Humidity	%
Flow rate heat transfer	<i>L/min or m³/h</i>
Pressure sensor	<i>bar</i>
Inlet/outlet temperature	<i>degC</i>
Subsoil Temperature	<i>degC</i>
Electrical consumption	<i>kWh or Wh</i>
Generated power (Total production)	<i>Wh or kWh</i>

Battery charge status	<i>%</i>
Charging power	<i>kWh</i>
Total consumption	<i>kWh</i>
Direct consumption	<i>kWh</i>

3.1.1.3. Hardware Sensors and Technologies

The *L'Horta Sud* pilot site employs a variety of IoT devices to facilitate accurate, real-time monitoring and control of both agricultural and energy systems. The following table provides a detailed overview of each device used, including the device model, the specific parameters it measures, and its application within the pilot site. Given that sensors are deployed to monitor crop fields as well as the two renewable energy sources (photovoltaic and geothermal), Table 3 includes a dedicated column specifying each device's usage context, and the given protocol.

Table 3: Horta Sud devices description table

Device	Measures	Scope	Protocol
ATMOS-14	<i>Temperature and relative humidity</i>	CROP	DDI serial or SDI-12 communication
SP-110-SS	<i>Solar Radiation (pyranometer)</i>	CROP	USB SDI-12 Modbus
TEROS-11	<i>Soil Humidity and Soil Temperature</i>	CROP	SDI-12
RAIN-O-MATIC 0.2MM	<i>Pluviometry</i>	CROP	Reed switch

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

3S-MT-PT100	<i>Photovoltaic Temperature Sensor</i>	PHOTOVOLTAIC	Modbus RTU Analogic output
CR310	<i>Datalogger</i>	AGROVOLTAIC	ETHERNET
SIEMENS PCL 1500 SJ7/SE7	<i>Controller PLC</i>	GENERAL	MQTT through EWON



Figure 7: Inderen ATMOS- 14 sensor



Figure 8: Inderen ATMOS-14, TEROS-11 and Control Cabinet.

After obtaining this information, an approach was taken to obtain the data from the diverse systems already present in the pilot site.

3.1.1.4. Data Ingestion and Integration Approach

At the L'Horta Sud pilot site, data from a range of IoT devices—including weather stations, soil and energy sensors, and geothermal system monitors—is collected and aggregated by local gateways. These gateways preprocess and securely transmit the data using standardised protocols to the CITRIC ecosystem, which serves as the central integration platform. Within CITRIC, data is ingested, enriched, and made available through APIs for real-time access, analytics, and visualisation, ensuring seamless integration of all field and energy information into the ECOLOOP IoT environment.

However, the installation of crop-specific sensors is still pending. These devices, which will provide detailed information on soil and plant conditions, have not yet been deployed and are scheduled for future installation. Similarly, the geothermal plant at the site is not yet fully operational, and its integration into the system will proceed once installation and commissioning are complete by December 2025. This phased approach ensures that as each new component comes online, it will be seamlessly incorporated into the existing data ingestion and integration framework.

The following diagram (Figure 9) illustrates the end-to-end data ingestion and integration workflow for L'Horta Sud.

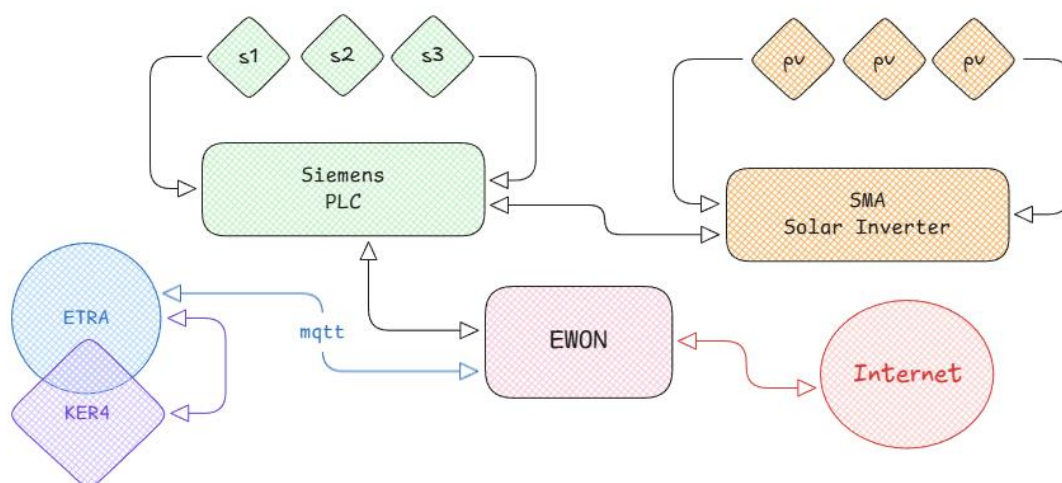


Figure 9: Horta Sud pilot site integration diagram

The system architecture at the L'Horta Sud pilot site is designed for seamless, real-time integration of operational and energy data into the ECOLOOP IoT platform. Field sensors and PV devices are connected to a central Siemens Programmable Logic Controller (PLC), which serves as the main aggregator for all real-time data streams across the site, including inputs from the

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

SMA solar inverter. This setup ensures that both process and energy generation data are collected centrally for efficient management and control.

The Siemens PLC communicates directly with an Ewon gateway, which acts as a secure interface between the on-site infrastructure and external digital networks. The Ewon gateway handles protocol conversion and secure data transmission, forwarding all aggregated data using the MQTT protocol. This data is then delivered to the CITRIC ecosystem, where it is ingested, stored, and made accessible for advanced analytics, visualisation, and decision support.

Within the CITRIC ecosystem, specialised microservices manage all incoming data streams from the L'Horta Sud pilot site. These microservices are responsible for:

- **Storing:** Efficiently persisting both raw and processed data, supporting time-series and event-based models.
- **Adapting:** Standardising and normalising data formats, converting device-specific payloads into a unified structure based on the ECOLOOP data model.
- **Transforming:** Processing and enriching data as needed, including unit conversion, aggregation, validation, and extraction of key metrics.

This architecture is inherently reliable, scalable, and secure, supporting both local operational control and remote digital services. By centralising data collection through the PLC and leveraging the Ewon gateway for secure transmission, the L'Horta Sud pilot site ensures that all relevant field and energy information is efficiently integrated into the broader ECOLOOP platform, enabling comprehensive monitoring and informed decision-making.

As proof that the given proposed architecture is fully operational and tested, the following Figure 10 showcases data coming in from the **Greenhouse Rooftop Solar System**

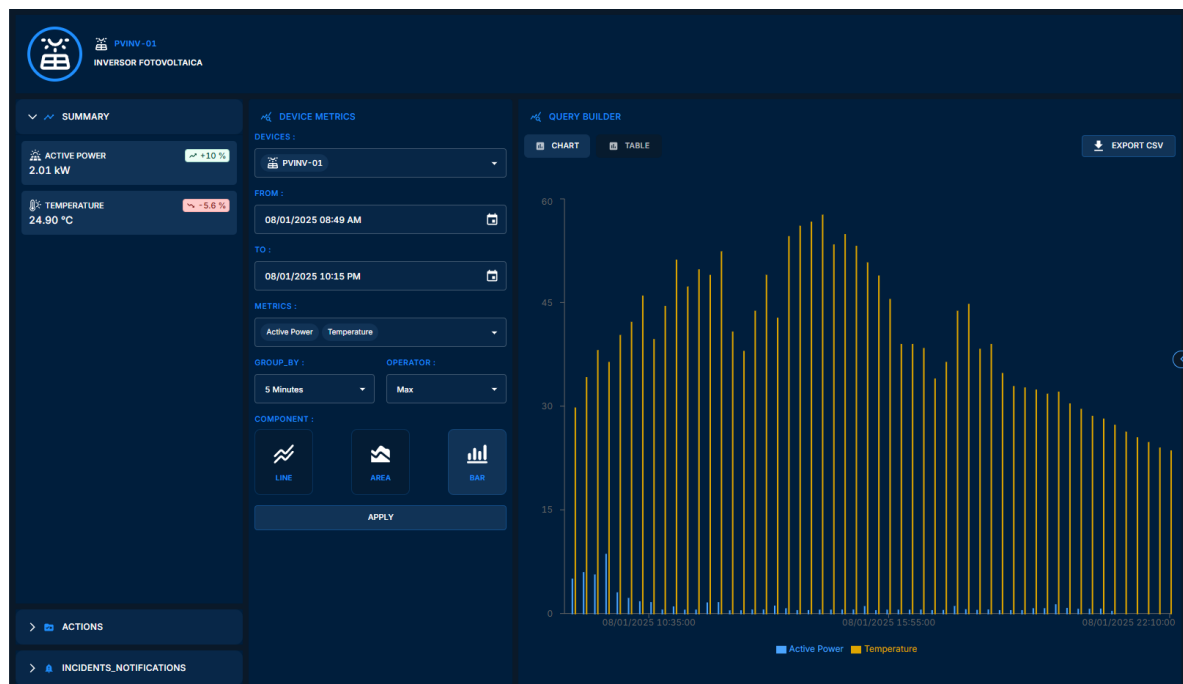


Figure 10: DSS tool display information from the Greenhouse Rooftop solar inverter

Importantly, for the pending geothermal installation, the current architecture is designed to be adaptable and resilient. Once the geothermal system is completed and brought online, it can be integrated into the existing framework without major issues or inconveniences. The modular and scalable nature of the system ensures that new data sources, such as the geothermal installation, can be incorporated smoothly, maintaining the integrity and performance of the overall data ingestion and integration process.

Moreover, this technical approach might be changed during the course of the project, if newer additions or technical equipment is installed at the pilot site. Nevertheless, any changes will be reflected into the *D4.3 Decision support tool for farmers and forester's final version*.

3.1.2. Silla Biogas plant

A biogas pilot plant (Figure 11) led by GENIA will be developed in Silla (Valencia), processing 2-3 tons of agricultural waste daily to produce 9-10 Nm³ of biogas per hour. This biogas will be validated to upgrade to vehicle-grade biomethane using innovative hydrophobic membrane technology, adaptable to rural anaerobic digestion facilities. This membrane offers a modular solution for biogas upgrading, adaptable to a wide range of biogas fluxes and especially appealing for anaerobic digestion facilities in rural areas. This solution will be cost-efficient and adaptable to the local conditions in the region of Horta Sud in the region of Valencia (Spain).

The biogas plant will be based on a modular and compact design devoted to managing agricultural waste. The plant will include an anaerobic digester where local agricultural biowaste will be treated. The capacity of the digester will be between 100-120 m³ (before final design), with hydraulic agitation (by pumping, not agitators), external heating system and a gasometer for storage of 30 m³ capacity. The equipment for pre-treatment is a pulper (pulping), a mechanical hydrolysis. By pulping in the presence of water, water enters the cells and promotes further digestion. The maximum operating capacity will be 2-Tn/h (material will arrive, be pulped and stored). To validate the biogas technology under relevant environment with a pilot plant of 50-100 l/h working capacity.

In the frame of the pilot a nutrients recovery system will be implemented in the biogas pilot site for biofertilizers production. Furthermore, the project will explore benefits of the produced digestate during the anaerobic digestion of agroforestry wastes able to replace mineral fertilizers. The system will optimize the anaerobic digestion phase to maximize both biogas and digestate production.

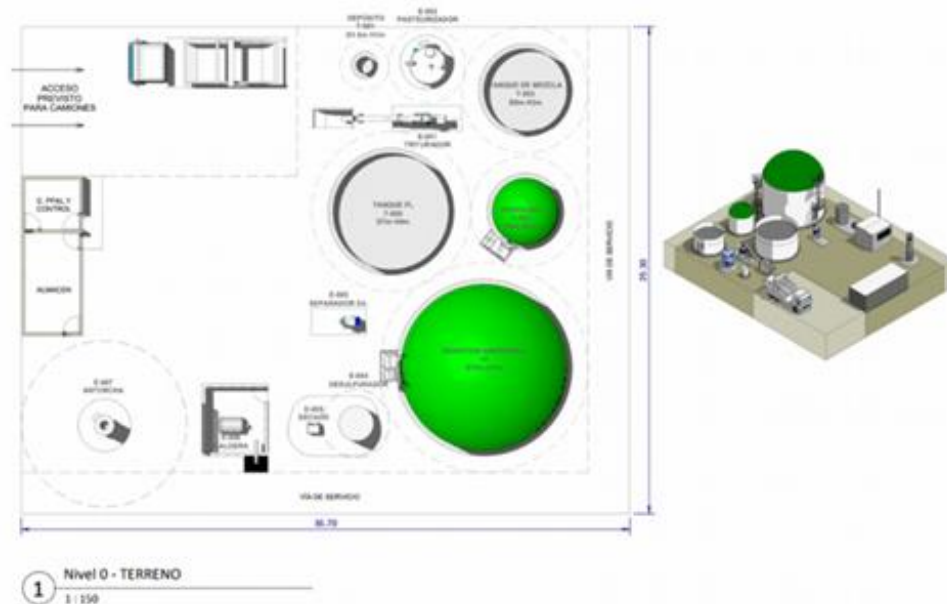


Figure 11: 3D Spanish Biogas Pilot in Silla.

3.1.2.1. Renewable Energy Sources

As the pilot's name states, the unique RES present in this area is biogas. Biogas production, led by GENIA, will be employed as a source of energy in the context of ECOLOOP project.

3.1.2.1.1. Biogas

Biogas is a RES produced by the anaerobic digestion of organic matter—such as agricultural waste, food scraps, and manure—by microorganisms in an oxygen-free environment. The resulting gas primarily consists of methane (CH₄) and carbon dioxide (CO₂) and can be used to generate heat, electricity, or as a vehicle fuel. In parallel, the process produces digestate, a nutrient-rich byproduct suitable for use as a fertilizer.

At the Silla pilot site, a biogas plant is being developed to process approximately 2.95 tons of agroforestry waste per day, primarily including onions, potatoes, citrus fruit, and persimmons. The process begins with the reception of these organic materials in a hopper that incorporates a horizontal grinder and screw conveyor, where the substrate is pre-treated and homogenised.

Once prepared, the substrate is diluted and pumped into a closed digestion tank with a total volume of 100 cubic meters. This tank is thermally insulated and equipped with an internal heating system and hydraulic agitation to maintain optimal conditions for anaerobic digestion. In this oxygen-free environment, microbial activity breaks down the organic matter, generating biogas composed mainly of methane and carbon dioxide.

After the main digestion phase, the material flows into a secondary post-digestion tank with agitation, where residual biodegradation continues and the digestate stabilises. From there, a solid-liquid separation unit divides the digestate into two fractions: the solid portion, which can be used as compost or soil amendment, and the liquid portion, which is stored in a buffer tank for reuse or safe discharge.

The biogas produced is collected in a double-membrane gas holder equipped with a blower system to maintain pressure. If gas cannot be used on-site, it is safely burned in an enclosed flare system. To ensure a stable digestion temperature, a low-temperature boiler supplies hot water to the digester via a closed-loop recirculation circuit.

The plant includes an integrated instrumentation and control system to ensure proper operation and process stability. Flow meters are installed to measure both the input of substrates and the biogas output. Temperature probes (PT-100) monitor the thermal conditions within the digesters and heating circuits. Pressure sensors and manometers track system performance, while radar level sensors and buoy-type level switches provide accurate monitoring of fluid levels. Valves—including gate valves, butterfly valves, ball valves, and check valves—are strategically distributed for both manual and automated flow control.

3.1.2.1. Current Measurements and Monitoring

The following attributes in Table 4 will be measured. Nevertheless, the **current measurement and monitoring system for the biogas pilot is under design review**, and the final instrumentation setup may vary depending on engineering developments and project needs. Any possible modifications will be presented in further deliverables as *D4.3. Decision support tool* and *D6.2. Demonstration activities results*.

Table 4: Biogas Silla measurements table

Measure	Unit
Digestate temperature	degC
Biogas pressure	mbar/bar
Biogas flow	Nm ³ /h
Substrate flow	Nm ³ /h
Water flow (thermal circuit)	m ³ /h
Water temperature (in/out)	degC
Digestate level (digester)	% or m
Substrate weight	Kg/t

3.1.2.1. Hardware Sensors and Technologies

The following list includes the **required sensors** for the anaerobic digestion pilot plant. However, the **current measurement and monitoring system for the biogas pilot is under design review**, and the final instrumentation setup may vary depending on engineering developments and project needs. Any modifications to the sensors and biogas technologies will be presented in further deliverables as D4.3 and D6.2.

Table 5: Biogas Silla devices description table

Device	Measures	Scope	Protocol
SIMATIC ET 200 SP	PLC/ Datalogger	GENERAL	Ethernet RJ45 RS-232/485
Promag W 400, 5W4C50	Flowmeter	BIOGAS	RJ45 Ethernet
Cerabar M PMP51	Pressure Transmitter	BIOGAS	4-20 mA <i>with</i> HART
iTHERM ModuLine TM131	Temperature	BIOGAS	4-20 mA <i>with</i> HART
Liquifloat T FTS20 NAMUR PP/PV	Float-type point level	BIOGAS	NAMUR
Promag P 100	Electromagnetic flowmeter	BIOGAS	4-20 mA Modbus RS485



Figure 12: Flowmeter and temperature transmirot at the biogas pilot plant in Spain

3.1.2.2. Data Ingestion and Integration Approach

At the Silla Biogas pilot site, data from a range of IoT devices—including process instrumentation equipment, the control cabinet with equipment protection, and the control PLC with the SCADA process control system monitors—is collected and aggregated by local gateways. The SCADA system is connected via Ethernet to a router solution that securely transmits the processed data to the ECOLOOP ecosystem using MQTT as the standardized communication protocol.

One option under consideration is the use of an EWON industrial router, which provides VPN-based secure remote connectivity and native support for MQTT. However, given that this is a pilot I+D installation (not a full-scale industrial plant with high criticality), alternative solutions are also being evaluated, such as the use of conventional routers or simpler industrial-grade routers without licensing requirements, to simplify deployment and reduce costs while maintaining reliable communication.

These gateways preprocess and securely transmit the data using standardized protocols to the ecosystem, which serves as the central integration platform. Within SCADA, data is ingested, enriched, and made available through APIs for real-time access, analytics, and visualization, ensuring seamless integration of all field and biogas information into the ECOLOOP IoT environment.

However, the installation of biogas-specific sensors is still pending. These devices—which will provide detailed information about biogas pressure and flow, composition, water flow, water temperature, pH, and digestate level—have not yet been deployed and are scheduled for future installation. The site is not yet fully operational, and its integration into the system will proceed once installation and commissioning are complete by December 2025.

3.1.3. Finca Sinyent

Finca Sinyent is an experimental agricultural farm located in Polinyà del Xúquer, Valencia, Spain. Managed by AVA-ASAJA, its primary role is to serve as a testing ground for innovative agricultural practices, products, and technologies. The farm spans approximately 30 hectares, divided into 1-hectare plots to facilitate controlled experiments and comparative studies.

3.1.3.1. Renewable Energy Sources

Finca Sinyent, does not currently have its on-site RES such as solar panels, wind turbines, or geothermal installations. Instead, the pilot focuses on the application and testing of products derived from renewable energy processes. Notably, biofertilizers produced from biogas

digestate—originating from anaerobic digestion of agricultural waste—are evaluated on the farm for their agronomic and environmental benefits. These activities allow the site to contribute to the circular economy and sustainable agriculture, even though the farm itself is not generating renewable energy directly.

3.1.3.2. Current Measurements and Monitoring

Finca Sinyent hosts a Living Lab (LL) coordinated by the UPV, where stakeholders such as farmers, researchers, and local communities collaborate to test and co-create innovative bioproducts and sustainable agricultural practices. Additionally, AVA-ASAJA measures a comprehensive set of meteorological and environmental parameters—including pePMon (potential evapotranspiration), etPMon (actual evapotranspiration), temperature, humidity, wind speed, wind direction, radiation, and rain—to support research, optimize irrigation, and enhance the scientific activities of the LL.

Table 6: Finca Sinyent measurements table

Measure	Unit
pePMon	-
etPMon	-
temperature	degC
humidity	%
windSpeed	m/s
windDirection	deg
radiation	MJ/m2
rain	mm

3.1.3.3. Hardware Sensors and Technologies

The pilot site is equipped with a SiAR weather station. This station provides official, real-time climate data that is essential for managing irrigation and crop scheduling efficiently. Figure 13 shows the related device. The integration of the SIAR weather station ensures that decisions regarding water use and crop management are based on accurate, up-to-date meteorological information.



Figure 13: SiAR device

Furthermore, the pilot site has indicated the possibility of augmenting the existing monitoring network with additional sensors for enhanced data collection and extra-monitoring capabilities. Should these new sensors be installed and successfully integrated with the current infrastructure, the implementation process, as well as the results and benefits of their deployment, will be documented in deliverable *D4.3 DST for farmers and forester's final version*.

Table 7: Finca Sinyent devices description table

Device	Measures	Scope	Protocol
SiAR weather station	<i>A weather station measuring diverse weather parameters</i>	GENERAL	HTTP through the SiAR cloud.

3.1.3.4. Data Ingestion and Integration Approach

The system architecture is designed to ensure seamless and reliable integration of both meteorological and experimental data into the ECOLOOP platform. This setup enables real-time data acquisition and supports advanced analytics and decision-making for sustainable agriculture.

Meteorological data is sourced from the SiAR weather station, which is part of the Spanish government's official network [19]. Instead of connecting field sensors directly to the farm's infrastructure, all relevant weather measurements—such as temperature, humidity, wind speed, wind direction, radiation, and rain—are collected and stored centrally in the SiAR cloud. To integrate this data into the ECOLOOP platform, a dedicated microservice developed by ETRA securely reads and extracts the latest meteorological information from the SiAR cloud. This microservice is responsible for retrieving, standardising, and forwarding the weather data in a format compatible with the ECOLOOP data model, ensuring that all climate information is available for further analysis and visualisation within the platform.

In parallel, the LL generates experimental and participatory data, often structured in CSV (Comma Separated Values) files. To facilitate the integration of these datasets, a specialised ingestion module has been implemented within the ECOLOOP Decision Support Tool. This module allows users to upload CSV files containing results from LL activities directly into the system. The ingestion module interprets and maps the CSV columns to the appropriate ECOLOOP data structures, making the data readily available for analysis, visualisation, and decision support.

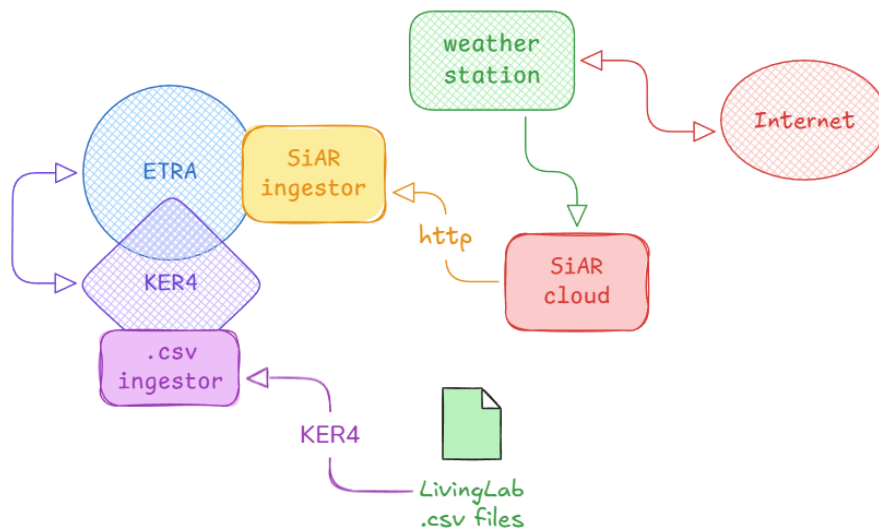


Figure 14: Finca Sinyent pilot site integration diagram

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

Both the SiAR weather data and Living Lab experimental **datasets are harmonised and ingested** into the ECOLOOP platform through modular microservices. This architecture is designed to **be secure, reliable, and scalable**, allowing for the addition of new data sources or experimental modules as needed. All data transmission and storage follow **secure protocols**, maintaining the integrity and confidentiality of the information collected.

As proof that the given proposed architecture is fully operational and tested, the following Figure 15 showcases data coming in from the SiAR device where weather data can be displayed.

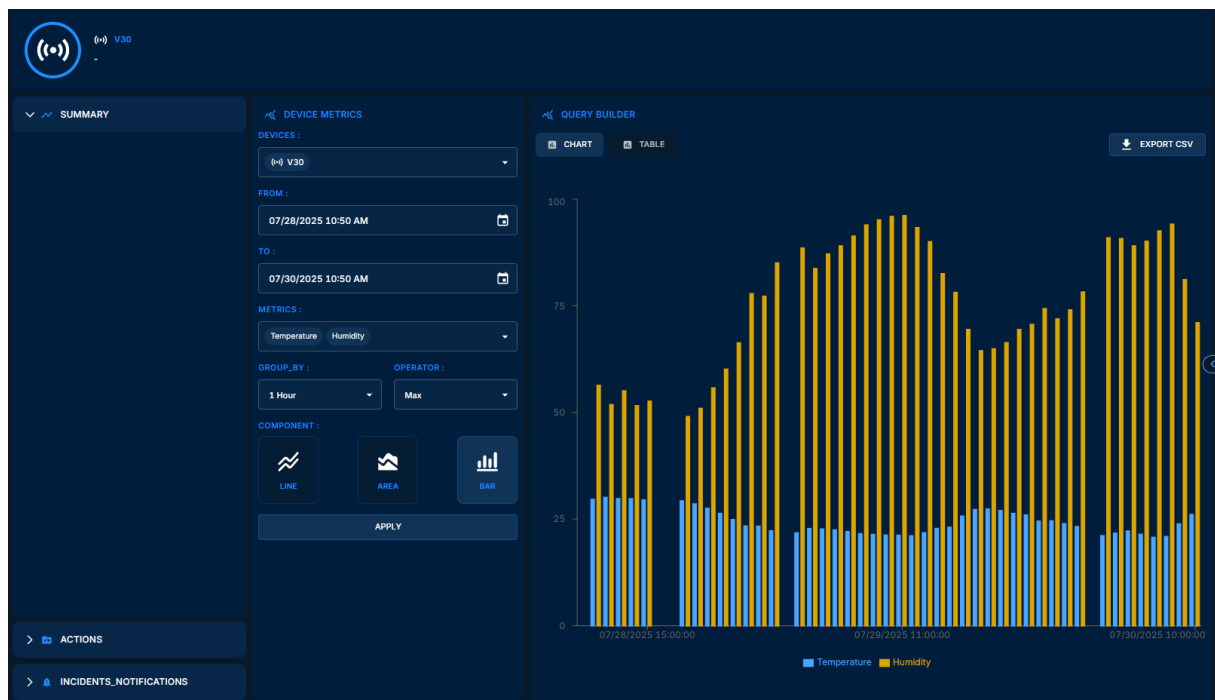


Figure 15: DSS tool displaying information from Finca Sinyent SiAR device

3.2. SI Pilot Site

The Slovenian pilot site within the ECOLOOP project is a multifaceted demonstration area focused on optimising renewable energy integration and advancing sustainable practices in both agriculture and forestry. It is primarily composed of two key locations: the Biomass Centre Nazarje and the Infrastructure Center Jablje (IC Jablje), each offering distinct but complementary innovations.

At Biomass Centre Nazarje, wood waste is processed into woody biomass for heat and power generation using modular Combined Heat and Power (CHP) units, wood chip boilers, and a wood gasifier, all managed by a central automated control system.

IC Jablje, managed by the Agricultural Institute of Slovenia, operates a modular micro biogas plant that digests organic waste to produce biogas for on-site electricity and heat. Upgrades are underway for biomethane production and refuelling stations for agricultural machinery.

Both locations are equipped with advanced monitoring and automation, enabling efficient energy production, storage, and use. The pilot site follows a circular approach while also exploring innovative business models and policy frameworks to support renewable energy adoption and rural development.

Each of these sites will be further detailed in dedicated chapters, with full technical background and implementation information available in Deliverable *D2.1. Pilot site analysis and use cases, requirements and KPIs definition*. [18]

3.2.1. Biomass Centre Nazarje

The Biomass Centre Nazarje is a central component of the Slovenian pilot site within the ECOLOOP project. It is dedicated to processing wood waste into woody biomass, which is then used for the generation of heat and power. The facility is equipped with modular CHP units, wood chip boilers, and a wood gasifier, all managed by a centralised, automated control system. This infrastructure enables the efficient conversion of wood residues into electricity, thermal energy, and products such as pellets and briquettes. The centre is also planning future upgrades, including additional CHP capacity, photovoltaic panels, battery storage, and electric vehicle charging stations, further reinforcing its role as a renewable energy hub.

Although being an official pilot site within the ECOLOOP project, it is important to note that its operational data is **not currently planned for integration** into the ECOLOOP IoT ecosystem or the DST. According to recent communication from the site's representatives, the centre already has its **own comprehensive monitoring systems** in place and does not manage or control crop production—one of the primary focuses of the DST. As such, the DST is considered **more relevant for the other part of the Slovenian pilot** (IC Jablje, managed by KIS), where agricultural machinery and biogas operations are directly aligned with the DST's intended use.

3.2.2. IC Jablje

IC Jablje, part of the Slovenian pilot site in the ECOLOOP project, is a modular micro biogas plant managed by the Agricultural Institute of Slovenia (KIS). The facility is designed for the anaerobic digestion of organic agricultural waste, producing biogas that is utilised on-site for electricity and heat generation. The plant features a compact anaerobic digester, biogas holder, and a cogeneration unit, enabling efficient conversion of organic residues into renewable energy.

IC Jablje serves as a demonstration site for sustainable waste management and renewable energy integration in agriculture. It showcases the potential for circular bioeconomy solutions by transforming organic waste into valuable energy and biofertilizer products, while also supporting the transition to renewable fuels in farming operations.

3.2.2.1. Renewable Energy Sources

IC Jablje features a modular micro biogas plant as its primary renewable energy source. This facility processes organic agricultural waste through anaerobic digestion, producing biogas that is used on-site for both electricity and heat generation. The plant is equipped with an anaerobic digester, a biogas holder, and a cogeneration unit, enabling efficient conversion of organic residues into renewable energy.

3.2.2.1.1. Biogas

The plant is equipped with a single anaerobic digester and an energetic container that houses systems for substrate processing, biogas cleaning and upgrading, and a CHP unit with a capacity of 7 kWe. Additional features include thermal energy storage, a control and monitoring system, a biogas holder integrated into the container, and a dosing system with a milling unit for pre-processing solid biomass. A modular biomethane upgrading system, based on Pressure Swing Adsorption (PSA), is also being implemented to upgrade biogas to biomethane quality.

The produced biogas primarily powers the CHP unit, providing energy for the farm, with surplus electricity exported to the grid. The digestate remaining after the anaerobic process is reused as an organic fertilizer, closing the nutrient loop. Future developments at KIS Jablje include the use of upgraded biomethane as a renewable fuel for agricultural machinery, further promoting sustainability and circularity in farming operations (Figure 16).

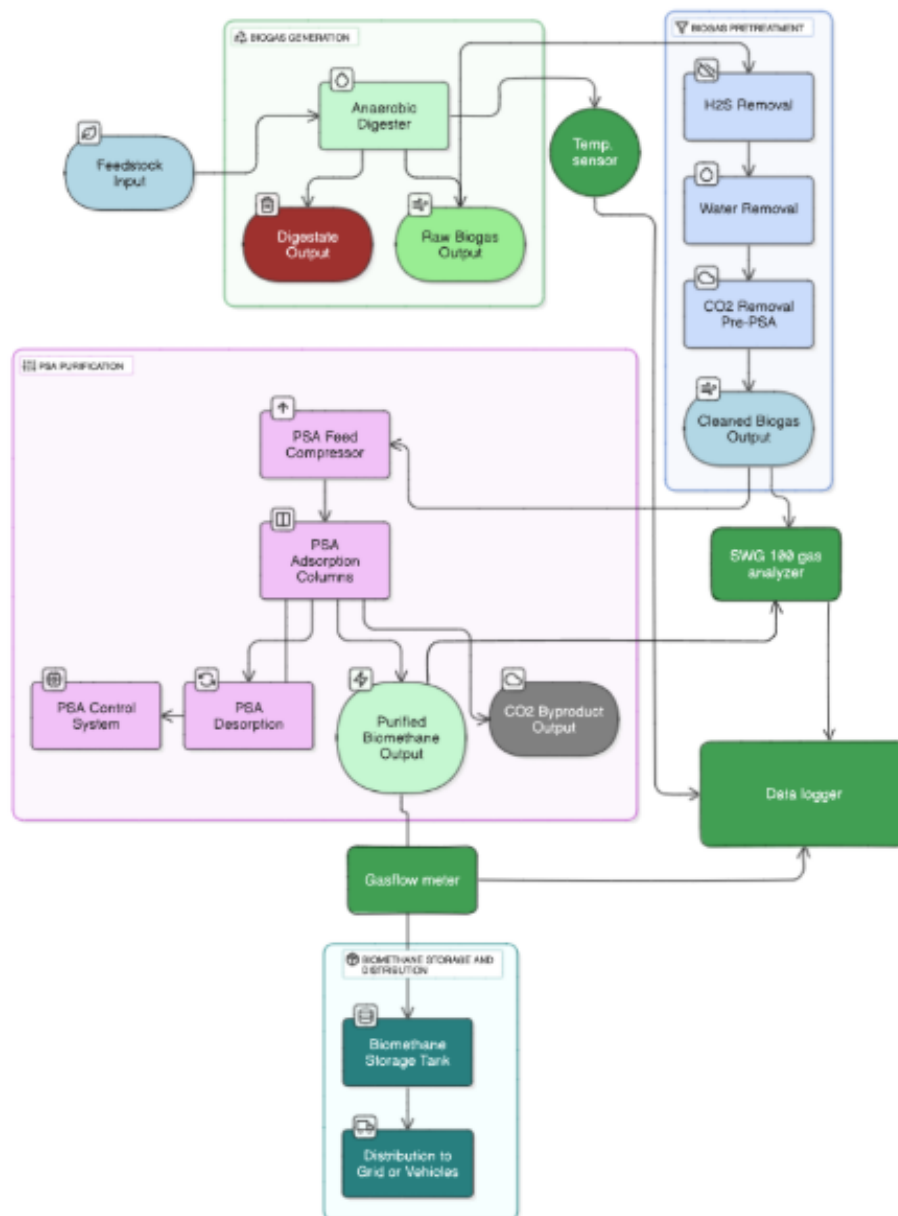


Figure 16: Jablje biogas diagram workflow

3.2.2.2. Current Measurements and Monitoring

The plant's control and monitoring system oversees input substrate processing, biogas cleaning and upgrading, and dosing of solid biomass with a milling unit for pre-processing. Continuous monitoring is supported by the SWG100 biogas analyser, which measures key gas attributes such as methane, carbon dioxide, oxygen, hydrogen sulphide, temperature, and humidity, ensuring optimal process performance and safety.

Table 8: Jablje measurements table

Measure	Unit
Biogas production	<i>m3/day</i>
Biogas composition	-
CH₄	%
O₂	%
H₂S	<i>ppm</i>
H₂	<i>ppm</i>
Balance N₂	%
Temperature (in digester)	<i>degC</i>
Biomethane production/consumption	<i>m3/day</i>

3.2.2.3. Hardware Sensors and Technologies

A dedicated set of hardware sensors and technologies has been integrated at the IC Jablje biogas plant to enable comprehensive monitoring and control of the facility's processes. These devices are essential for ensuring efficient operation, process optimisation, and maintaining high standards of safety and environmental compliance.

Table 9: Jablje devices description table

Device	Measures	Scope	Protocol
SWG100	<i>Biogas analyzer</i>	BIOGAS	ModbusRTU
PT100	<i>Temperature inside digester</i>	BIOGAS	-
QuantumX MX840B	<i>Datalogger for sensors. Retrieves data from sensors connected to it</i>	GENERAL	Ethernet, CAN Bus, Profibus
ETRA SMX	<i>Device for capturing data, to forward to ECOLOOP IoT ecosystem</i>	GENERAL	MQTT, HTTP.

A key element of this setup is the **Smart Extended Meter (SMX) device** shipped by ETRA (Figure 17). The SMX is a versatile board designed to connect with the plant's various hardware sensors and equipment, enabling seamless data acquisition from all critical process points. The SMX board forwards the collected data directly to the ECOLOOP cloud platform, ensuring that all operational and environmental parameters are continuously available for analysis and decision support.

The board has a serial port where multiple devices in the same bus can be interconnected, and configured for the SMX to read the data and post it to the IoT ecosystem. The board for usefulness has integrated a VPN connection, where from any part of the world, access to the device is possible, making it possible to adjust or reprogram the reading mechanism if needed.



Figure 17: Etra SMX device

Additionally, the SMX device provides remote access capabilities for ETRA. This feature allows ETRA's technical team to retrieve data and perform system debugging remotely, streamlining maintenance and troubleshooting processes and minimising downtime.

3.2.2.4. Data Ingestion and Integration Approach

At the IC Jablje biogas plant, the data architecture has been carefully designed to fulfil KIS's request for dual data storage: all monitoring and operational data are made available both in the central ECOLOOP IoT cloud and locally at the plant. To achieve this, KIS has set up a dedicated on-site computer to serve as a local data repository, ensuring that all critical process and sensor data are securely stored and easily accessible within the facility. Communications were held between ETRA and KIS technicians to make the proposed architecture fully operational.

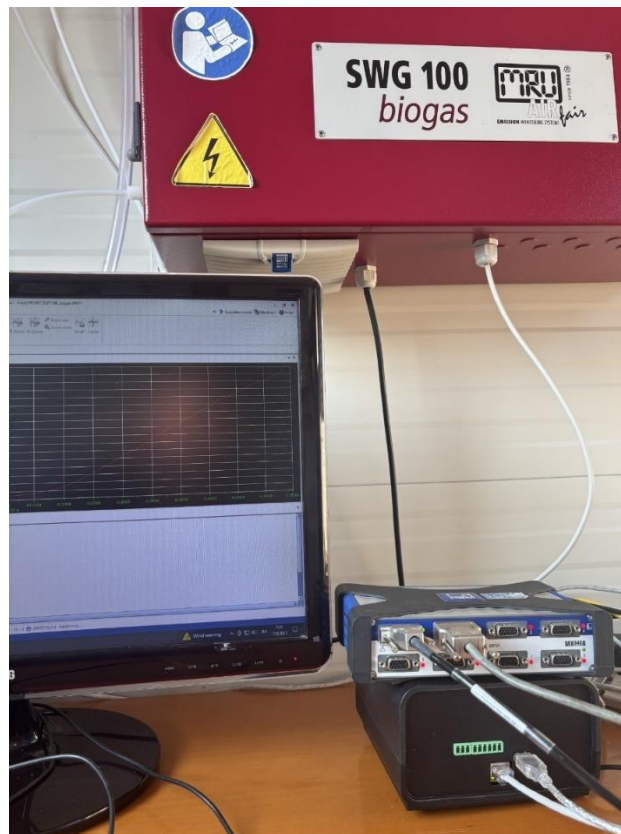


Figure 18: SMX and SWG100 biogas analyser

For biogas analyser data, ETRA's SMX device plays a central role. The SMX board reads information from the SWG100 biogas analyser using the Modbus RTU protocol, collecting real-time data on key gas quality metrics. Meanwhile, KIS uses the QuantumX datalogger to acquire data from various plant sensors, such as those monitoring temperature, pressure, and flow. The

QuantumX datalogger stores this sensor data directly on the KIS server, ensuring that all readings are available locally. All this setup can be seen in Figure 18.

To synchronize and exchange data between systems, a Mosquitto MQTT server has been deployed locally on the KIS infrastructure. This MQTT broker acts as a real-time data hub, enabling seamless communication between devices. The QuantumX datalogger forwards selected sensor data to the SMX device via the local Mosquitto MQTT server, ensuring that the SMX has access to all relevant process information for further integration and cloud transmission. Conversely, the SMX device not only sends biogas analyser data to the ECOLOOP IoT cloud but also publishes this data to the local Mosquitto MQTT server, allowing KIS to store all SWG100 biogas analyser data locally as well.

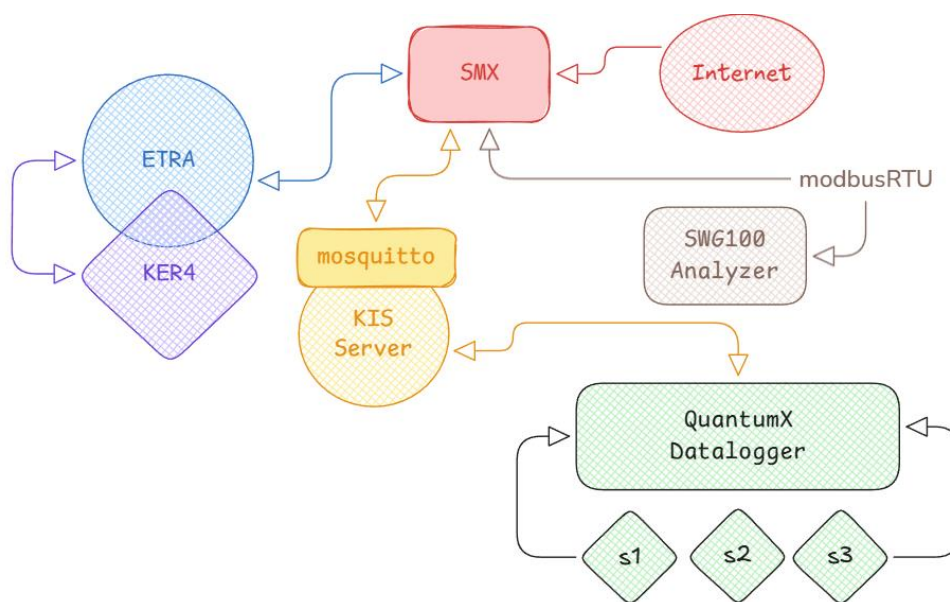


Figure 19: Jablje pilot site integration diagram

This setup ensures data redundancy and operational flexibility: all essential data is available both locally and, in the cloud, minimising the risk of data loss and allowing KIS to analyse and archive process data on-site, regardless of cloud connectivity. The local MQTT broker guarantees fast and reliable data exchange between devices, and the SMX device provides remote access for ETRA's technical team to retrieve data and perform system debugging, streamlining maintenance and minimising downtime. This architecture gives KIS full control and access to its operational data while supporting advanced analytics, monitoring, and decision support within the broader ECOLOOP ecosystem.

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

As proof that the given proposed architecture is fully operational and tested, the following Figure 20 shows data coming in from the SWG100 biogas analyser that the SMX is responsible for retrieving and forwarding data.

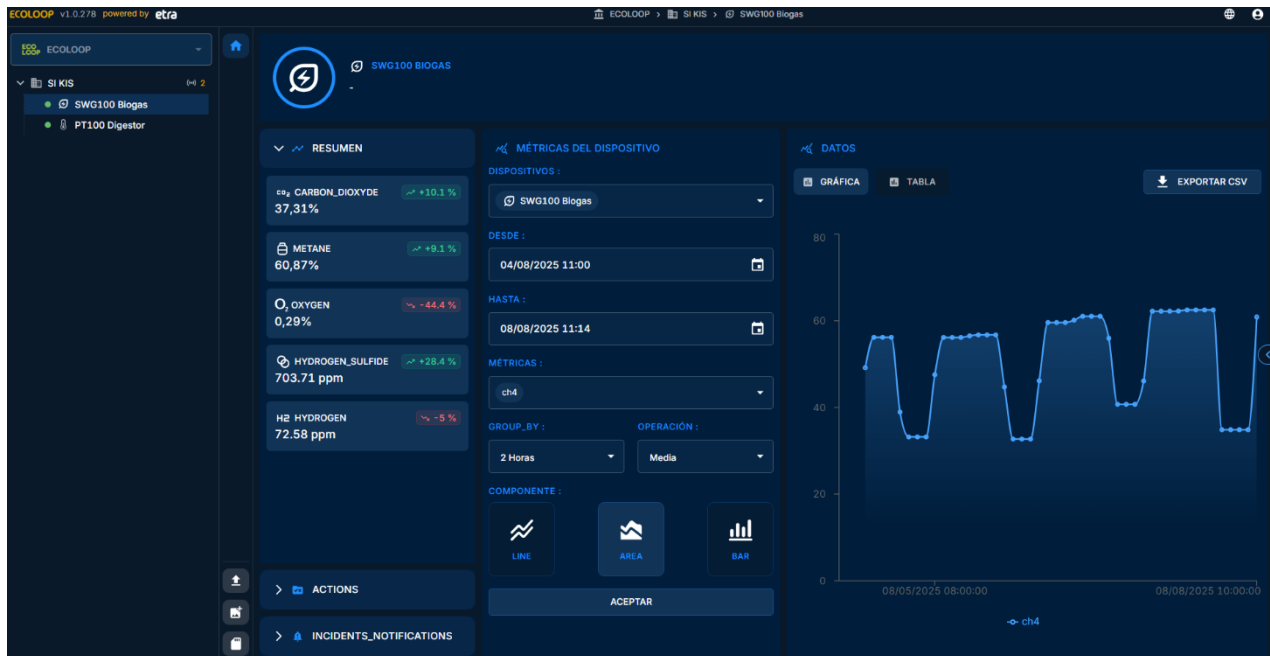


Figure 20: DSS tool displaying information from SWG100 biogas analyzer

3.3. BG Pilot Site

The Bulgarian pilot site of the ECOLOOP project, located in Momchil area near Balchik in the Dobrich region and led by ALBENA, demonstrates how renewable energy and circular economy practices can be integrated into agriculture. The site features smart greenhouses equipped with photovoltaic (PV) panels that supply renewable electricity for crop cultivation and greenhouse operations, reducing grid dependence and CO₂ emissions. An operational biogas plant processes agricultural and organic waste to generate electricity and heat, with thermal energy used for greenhouse heating and digestate applied as biofertilizer to close nutrient loops.

Each of these sites will be further detailed in dedicated chapters, with full technical background and implementation information available in Deliverable D2.1. [18]

3.3.1. Momchil pilot site

This pilot site exemplifies the practical integration of renewable energy and circular economy solutions in agriculture. Led by the company ALBENA, the site features smart greenhouses that

have been refurbished and equipped with PV panels installed on greenhouse roofs. The PV system is oriented to make shadow in the afternoon so it lowers the air temperature and reduces water irrigation needs, providing renewable electricity for crop production and greenhouse operations such as heating and climate control.

The operational biogas plant at the site processes food waste, manure, and corn silage to produce electricity and heat, with thermal energy used to maintain optimal greenhouse conditions and digestate reused as biofertilizer. The electricity generated is used on-site for both the greenhouse complex reducing external grid dependence. The ALBENA site collaborates with academic partners to analyse local waste streams and test new energy crops, supporting the development of digital decision support tools for local farmers.

3.3.1.1. Renewable Energy Sources

It integrates two main renewable energy sources: PV and biogas. The site features smart greenhouses and agricultural buildings equipped with PV panels, which generate renewable electricity to power crop cultivation and greenhouse operations, reducing reliance on the grid and lowering carbon emissions. Additionally, an operational biogas plant processes agricultural and organic waste, including food waste, manure, and corn silage, to produce both electricity and thermal energy. The thermal energy from the biogas plant is used for greenhouse heating, and the resulting digestate is applied as biofertilizer, supporting a circular approach to resource use and energy production in agriculture.

3.3.1.1.1. Smart greenhouses and Photovoltaic

The system features a modular design, enabling phased expansion based on annual budget availability. This approach was chosen specifically to avoid mechanically integrating materials with different thermal expansion coefficients—a common source of material fatigue and leakage at connection points, as confirmed by empirical evidence. By keeping the PV system structurally separate, the risk of differential thermal stresses and associated maintenance issues is minimised.

The photovoltaic modules were installed at a fixed tilt angle of 22°, optimised for the site's geographic latitude. To allow partial transmission of sunlight into the greenhouse, intentional gaps were left between the modules. This design ensures that a portion of diffuse solar radiation reaches the greenhouse interior, supporting plant growth. To further optimise light conditions, the PV modules are designed to be repositionable, allowing adjustments after evaluating plant growth following the first or second harvest cycle (Figure 21).

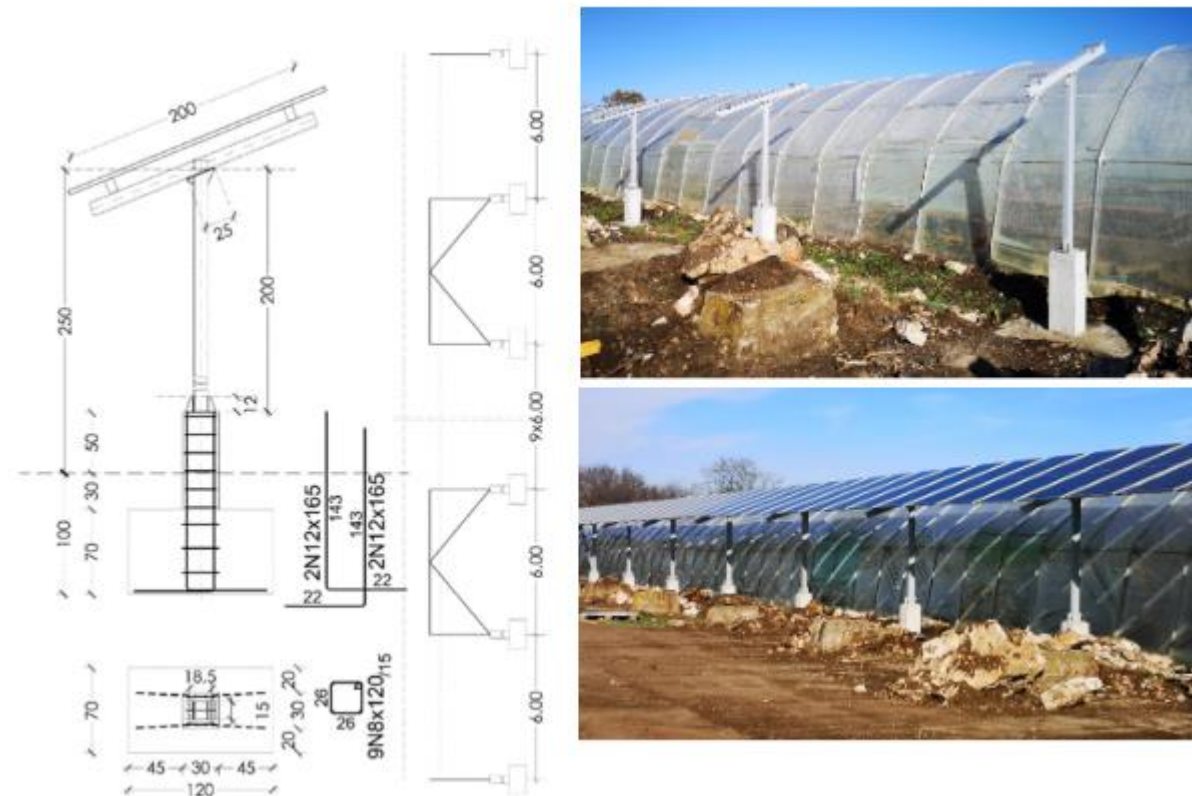


Figure 21: PV installation in Albena pilot site

The electrical energy generated by the PV modules is used to power essential greenhouse systems, including electric motors for ventilation and window actuation. In the absence of an energy storage system, the generated electricity also operates irrigation pumps. This setup creates a synergy, as irrigation demand typically peaks during periods of maximum solar radiation, aligning energy generation with agricultural water needs.

3.3.1.1.2. Biogas

Biogas power plant produces 1 MWeI and 1 MWth energy with input of 55 tons/day maize silage. In summer, the plant reduces the input maize silage to 20 tons/day and uses additionally 30 tons of bio waste from restaurants. The Hygienization of the bio waste substrate uses thermal energy from the CHP. Additionally, cucumbers and tomatoes waste from greenhouses will be used as raw materials which will then influence the quality of biogas – mainly the content of methane and sulfur.

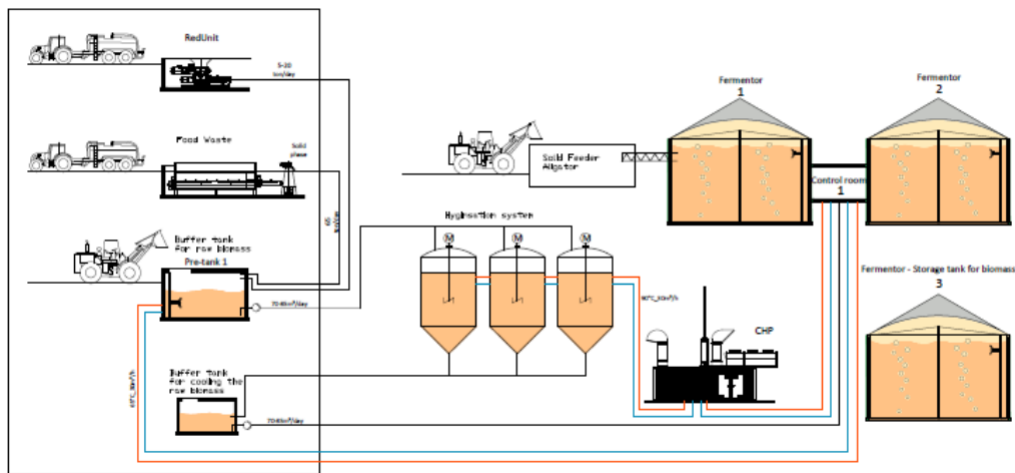


Figure 22: Biogas installation in Albena pilot site

3.3.1.2. Current Measurements and Monitoring

Albena operates a biogas power plant which was built in 2013. The measurements are carried out with sensors that deliver data into the local Biogas-SCADA system, which doesn't provide the ability to export data for further analysis. The most important measurements, which are required to optimize the input materials are the following: weight of the imported materials, performance of the mixers, gas pressure in each of the fermenters, substrate temperature, gas storage capacity in each of the fermenters, CH₄ and H₂S content in the biogas, and biogas flow to the CHP.

Table 10: Biogas Momchil measurements table

Measure	Unit
Imported material weight	Tons
Temperature of substrate	degC
Pressure of biogas in each fermenter	mbar
Mixers' performance	Minutes per hour
Biogas flow	Nm ³ /h

Water flow (thermal circuit)	m^3/h
Water temperature (in/out)	$degC$
Gas availability level	%
CH₄ and H₂S content in the biogas	$ppmol$

For the greenhouses, the following measurements are captured:

Table 11: Greenhouses Momchil measurements table

Measure	Unit
Internal Air Temperature	$degC$
External Air Temperature	$degC$
Internal Air Humidity	%
Soil Temperature	$degC$
Soil Humidity	%
Water flow (thermal circuit)	m^3/h
Water temperature (in/out)	$degC$
Water quantities for irrigation	m^3

3.3.1.3. Hardware Sensors and Technologies

A dedicated set of hardware sensors and technologies has been integrated at the Bulgarian plant to enable comprehensive monitoring and control of the facility's processes. These devices are essential for ensuring efficient operation, process optimisation, and maintaining high standards of safety and environmental compliance.

Table 12: Albena devices description table

Device	Measures	Scope	Protocol
Huawei SUN2000-30KTL-M3	<i>Data related to PV installation. Is a Solar Inverter</i>	PHOTOVOLTAIC	Modbus TCP, MQTT
JA Solar 550Wp	<i>Nothing, just PV panels with 30kWp power</i>	PHOTOVOLTAIC	-
Schneider Electric PLC M251	<i>Main processing unit</i>	GREENHOUSE	MQTT
Soil Temperature and Humidity Sensor	<i>Soil Temperature, Humidity/moisture of the the soil by conductivity</i>	GREENHOUSE	4-20mA, then MQTT
Indoor air Humidity and Air Temperature sensor (TM1SHTCC4)	<i>Temperature from -40 – 60°C; rel. Humidity from 0% - 100%</i>	GREENHOUSE	4-20mA, then MQTT
Awite Gas Analysis systems	<i>Methane, Carbon Dioxide, Carbon Monoxide, Oxygen, Hydrogen Sulfide</i>	BIOGAS	ProfiNet, then MQTT
Resistance Temperature Detector (RTD) Adafruit	<i>Change of resistance (100 Ω = 0°C), which is the temperature of the substrate</i>	GREENHOUSE	-

3.3.1.4. Data Ingestion and Integration Approach

Measurements are being obtained directly from the PLC's M251 that control the biogas processes to analyse their change when we alter the input raw materials. For this, significant reorganization of the existing communications infrastructure was made so that an additional computer with upgraded Movicon software [20].

Movicon software allows a direct network connection using Ethernet, allowing a data exporting to different providers in this case ETRA technical partner to feed their system with the data being measured at the pilot site. The protocol chosen is MQTT, protocol that is implemented in Movicon, that will feed and forward our data to ETRA's cloud.

For allowing that MQTT data forwarding mechanism, a custom service that receives the data captured by the pilot site is implemented. This service will act as an Extract, Transform, Load (ETL) mechanism, that will transform the incoming raw data into the ECOLOOP data model.

Following Figure 23 represents a brief diagram explaining the data retrieval process, where them Movicon software and mentioned ETRA's services will be in charge of feeding the data into the system. This approach ensures between both ends, a full data availability and resilience.

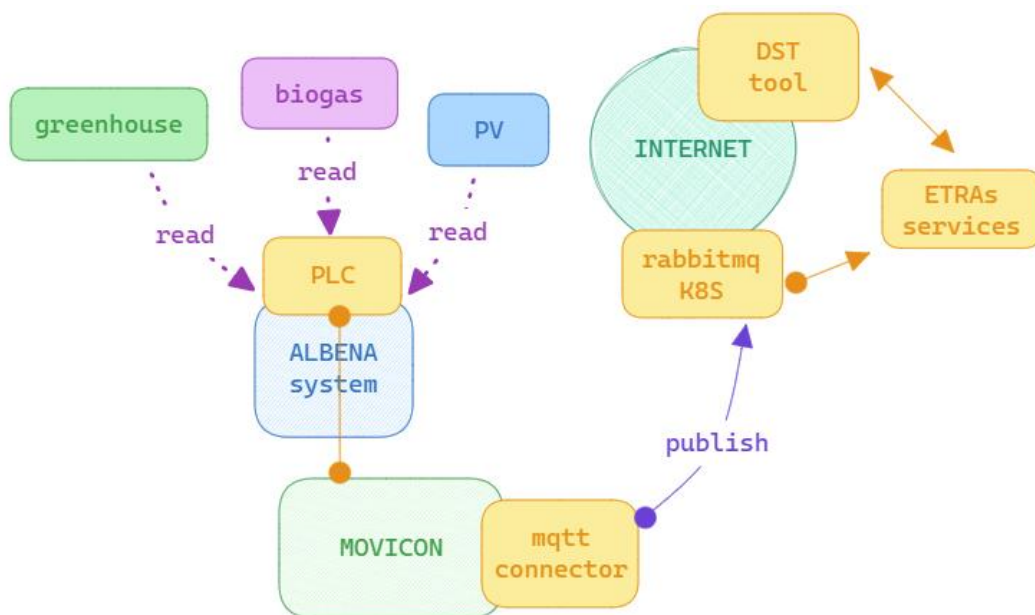


Figure 23: Momchil and ETRA diagram for data retrieval

3.4. EE Pilot Site

The Estonian pilot of the ECOLOOP project is focused on a network of 70 short-rotation forest plantations, strategically located at key sites such as *Puhatu*, *Pindi*, *Ulila*, and *Tootsi*. These sites were chosen for their varied soil types and land-use histories, mainly involving abandoned agricultural land and organic soils like cutaway peatlands. Fast-growing deciduous species—particularly *hybrid aspen*, *black alder*, and *silver birch*—are cultivated to explore their potential for carbon sequestration, biodiversity improvement, and compatibility with biorefinery processes, while also reducing reliance on spruce monocultures vulnerable to climate change.

The pilot is closely integrated with FIBE's flagship biorefinery which uses Sunburst® technology to process low-grade woody biomass into renewable biomaterials such as lignin, bio-sugars, and specialty cellulose. This contributes to the circular bioeconomy and supports EU decarbonization strategies across sectors like construction, cosmetics, and packaging.

In addition, the pilot underpins the development of a web-based carbon calculator, which uses field data from the plantation sites to estimate CO₂ sequestration, potential carbon credit revenues, and overall climate impacts.

Each of these sites is further detailed in dedicated chapters, with full technical background and implementation information available in Deliverable D2.1. [18] The upcoming Deliverable D4.2 will explain the carbon calculator tool.

3.4.1. Puhatu pilot site

Puhatu serves as one of the primary sites within the Estonian ECOLOOP pilot, distinguished by its extensive areas of cutaway peatlands. Here, afforestation efforts are focused on reintroducing deciduous species—mainly hybrid aspen and silver birch—on organic soils that have historically suffered degradation from peat extraction. The project activities at Puhatu emphasise long-term monitoring of tree growth, biodiversity, and soil recovery, offering key data to model the carbon sequestration potential in similar landscapes across Estonia.

3.4.1.1. Renewable Energy Sources

The Puhatu pilot site does not feature RES technologies as part of its operations. Its primary activities revolve around experimental approaches to afforestation, focusing on the restoration of cutaway peatlands through the planting of fast-growing deciduous tree species like silver birch and hybrid aspen. All efforts at Puhatu are directed towards studying plantation growth, biodiversity dynamics, and soil recovery under these organic soil conditions.

3.4.1.1. Current Measurements and Monitoring

These are the empirical attributes collected by the technician, providing practical, observable data relevant to the specific use case. This set of attributes ensures that the evaluation is based on factual evidence directly obtained from the member's activity and context.

Table 13: Puhatu measurements table

Measure	Unit
PH_{KCL}	-
N	%
P	mg/kg
K	mg/kg
Ca	mg/kg
Mg	mg/kg
Corg	%

3.4.1.2. Hardware Sensors and Technologies

Puhatu does not involve the use or testing of any sensor-based technologies or on-site hardware installations. All data collected within this site originates from manual field observations that assess plantation growth, species performance, and basic environmental variables. This information is processed offline and subsequently imported into project systems using structured formats such as CSV files or Excel spreadsheets. There is no IoT infrastructure, wireless telemetry, or automated monitoring systems foreseen or required at Puhatu, as the pilot's objectives are strictly focused on evaluating ecological restoration methods, particularly reforestation of cutaway peatlands with deciduous species.

3.4.1.3. Data Ingestion and Integration Approach

At the Puhatu site, data management follows a fully manual and offline process, with no in-field sensor systems or real-time data acquisition technologies deployed. Data related to afforestation trials, soil assessments, plantation growth, and species performance are recorded through direct field observation and subsequently transferred to standardised digital formats (primarily Excel and CSV files). These datasets serve as the input for the ECOLOOP data infrastructure rather than being collected from automated sources.

To support this workflow, ETRA has developed a custom CSV/Excel file importer integrated into the DST. This importer enables structured empirical data from Puhatu to be uploaded into the ECOLOOP IoT ecosystem efficiently, while ensuring compatibility with downstream analytics and platform services.

Through this functionality, all relevant observations can be systematically processed and made available to the broader ECOLOOP digital framework, despite the absence of direct sensor instrumentation.

3.4.2. Pindi pilot site

At Pindi, the pilot implements advanced site-based trials for wood ash recycling. This location, also characterised by its organic soils and history of land abandonment, is an important testbed for assessing the effects of applying nutrient-rich wood ash as a biofertilizer. Such trials help to address both productivity challenges and climate mitigation goals, as wood ash application can enhance tree growth while also promoting carbon retention in soils. Pindi's data are used to refine protocols for large-scale afforestation and provide empirical results for both ecological improvement and circular bioeconomy models in forestry.

3.4.2.1. Renewable Energy Sources

The Pindi pilot site does not incorporate any RES technologies within its activities. The site's main focus is on experimental trials related to sustainable afforestation and soil enhancement, notably wood ash recycling for abandoned peatland restoration and productivity improvement. No solar panels, wind turbines, biogas units, or similar RES infrastructure have been installed or tested at this location.

3.4.2.2. Current Measurements and Monitoring

These are the empirical attributes collected by the technician, providing practical, observable data relevant to the specific use case. This set of attributes ensures that the evaluation is based on factual evidence directly obtained from the member's activity and context.

Table 14: Pindi measurements table

Measure	Unit
PH_{KCL}	-
N	%
P	mg/kg
K	mg/kg
Ca	mg/kg
Mg	mg/kg
Corg	%

3.4.2.3. Hardware Sensors and Technologies

Pindi does not involve the deployment of any physical sensor systems or automated monitoring hardware. All data collection at this location is based on in-field empirical methods, such as manual observation, sampling, and recording by forestry researchers. The experimental focus is on validating the use of wood ash as a soil amendment to enhance the productivity of plantations established on organic soils.

As such, all measured parameters—such as tree growth rates, soil properties, and treatment effects—are gathered manually and subsequently processed offline. Data will be provided in standardised digital formats, including Excel spreadsheets and CSV files, for analysis and

integration into project-level platforms. No IoT-based monitoring, real-time telemetry, or hardware-assisted data acquisition systems are required or planned for implementation at this site.

3.4.2.4. Data Ingestion and Integration Approach

ETRA has developed a custom CSV and Excel file importer, which is embedded within the DST. This importer serves as the primary interface for feeding locally gathered, manually recorded data into the broader ECOLOOP IoT ecosystem.

All data generated at Pindi—including site observations, tree growth metrics, soil analyses, and results from wood ash recycling trials—are documented using conventional field protocols and stored in standardised formats as described in previous chapters. The DST's importer tool is designed to accept these CSV or Excel files directly, performing data validation and formatting as they are ingested. This ensures compatibility with downstream analytics and facilitates automated integration into ECOLOOP's data infrastructure.

By leveraging the custom importer, the Pindi pilot site is able to efficiently contribute high-quality, structured empirical datasets without deploying additional sensor hardware or requiring real-time telemetry. The approach guarantees that all essential data relevant to silvicultural and ecological innovation at Pindi are systematically incorporated into the ECOLOOP IoT ecosystem, setting a reproducible model for digital data exchange across the project's forestry pilots.

3.4.3. Ulila and Tootsi pilot site

Ulila and Tootsi contribute to the Estonian pilot through the implementation of bio stimulants applications and diverse afforestation models on degraded lands with mixed soil conditions. These sites test innovative combinations of bio-based growth enhancers and mineral fertilizers under different climate and soil scenarios to optimise tree performance and soil health. Ulila, in particular, is used for longitudinal studies on forest plantation productivity, while Tootsi emphasises the adaptation of forestry practices to peatland restoration and the integration of digital monitoring.

3.4.3.1. Renewable Energy Sources

Both pilot sites do not include RES technologies among its testbed infrastructure. The focus is on afforestation and soil improvement, specifically on the restoration of degraded peatlands through the plantation of fast-growing deciduous trees. The experimental activities are dedicated to evaluating different combinations of bio-based growth enhancers and mineral fertilizers with the aim of improving tree growth and soil quality under organic soil conditions.

3.4.3.2. Current Measurements and Monitoring

These are the empirical attributes collected by the technician, providing practical, observable data relevant to the specific use case. This set of attributes ensures that the evaluation is based on factual evidence directly obtained from the member's activity and context.

Table 15: Ulila and Tootsi measurements table

Measure	Unit
PH_{KCL}	-
N	%
P	mg/kg
K	mg/kg
Ca	mg/kg
Mg	mg/kg
Corg	%

3.4.3.3. Hardware Sensors and Technologies

At Ulila, all data on biostimulants application and plantation performance are manually collected and later processed into digital formats, with no use of in-field sensors or automated data logging. Similarly, at Tootsi, monitoring of soil enhancement treatments and afforestation outcomes is conducted entirely through direct observation and manual sampling, without the involvement of any electronic sensing or telemetry equipment.

3.4.3.4. Data Ingestion and Integration Approach

At the Ulila and Tootsi pilot sites, data management relies entirely on empirical fieldwork, with no installation of sensor networks or real-time monitoring hardware. Researchers collect all relevant data—such as tree growth metrics, soil properties, and results from bio stimulants and soil enhancement trials—through manual observation, sampling, and documentation during scheduled site visits. This information is then transferred into standardised digital formats, predominantly Excel spreadsheets and CSV files.

To facilitate seamless integration of these datasets into the ECOLOOP project's digital infrastructure, ETRA has developed a custom CSV/Excel file importer as part of the Decision Support Tool (DST). This importer validates, formats, and directly uploads data files from Ulila and Tootsi, ensuring data compatibility and enabling streamlined processing for project analytics and reporting. The approach enables both pilot sites to contribute high-quality, structured empirical data to the ECOLOOP IoT ecosystem, while maintaining a workflow free of automated hardware or sensor-based data acquisition.

4. Conclusion

This deliverable presents the design and deployment of a robust big data analytics framework within the ECOLOOP IoT ecosystem, supporting energy, agriculture, forestry, and community service pillars. The architecture integrates heterogeneous IoT devices and monitoring systems across diverse pilot sites in Spain, Slovenia, Bulgaria, and Estonia, using standardised protocols such as MQTT and HTTP.

The platform facilitates real-time data collection, harmonisation, and analytics, laying the foundation for the upcoming Decision Support Tool that will empower stakeholders with data-driven insights to optimise renewable energy use, sustainable agriculture, and circular bioeconomy practices.

The modular microservices-based system, built on ETRA's CITRIC platform, demonstrates scalability, resilience, and interoperability, capable of accommodating varying site-specific operational contexts. The pilot site implementations validate the system architecture's flexibility to collect and manage environmental, energy, and agricultural data reliably, supporting efficient decision-making and regional sustainability goals.

However, certain limitations arose during the implementation phase. At the Silla biogas plant pilot site, installation of sensor devices was delayed due to the impacts of the La DANA floods. Consequently, the proposed architecture for this site has yet to undergo testing or validation, and

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

it is expected that future iterations of the system may incorporate necessary architectural adjustments once the installation is complete. Similarly, the Bulgarian pilot site is experiencing significant IT infrastructure restructuring, including network overhauls and SCADA system maintenance, which affect the integration of renewable energy and greenhouse monitoring systems. These ongoing upgrades, while essential for long-term system performance, have temporarily postponed full operational integration and testing.

These challenges highlight the dynamic nature of deploying advanced IoT and analytics solutions in real-world rural and industrial environments, emphasising the need for adaptable designs and iterative development. Despite these obstacles, the ECOLOOP big data analytics framework sets a solid precedent for replicable and scalable digital transformation in rural energy and agricultural systems.

It's worth noting that future changes and updates regarding the devices and sensors installation and integration will be reflected in further deliverables D4.3. *DST for farmers and forester's final version* (M30) and D6.2. *Demonstration activities results* (M48).

5. References and acronyms

5.1. References

- [1] “MQTT,” [Online]. Available: <https://mqtt.org/>.
- [2] Mozilla, “MDN,” [Online]. Available: <https://developer.mozilla.org/en-US/docs/Web/HTTP/Guides/Overview>.
- [3] R. Hat, “Red Hat,” 8 May 2020. [Online]. Available: <https://www.redhat.com/en/topics/api/what-is-a-rest-api>.
- [4] “SailPoint,” 9 February 2025. [Online]. Available: <https://www.sailpoint.com/identity-library/access-token>.
- [5] FIWARE, “FIWARE,” [Online]. Available: <https://www.fiware.org/smart-data-models/>.
- [6] JSON, “JSON,” [Online]. Available: <https://www.json.org/json-en.html>.
- [7] C. Richardson, “Microservices.io,” [Online]. Available: <https://microservices.io/>.
- [8] X-FLEX, [Online]. Available: <https://xflexproject.eu/>.
- [9] assistance, [Online]. Available: <https://assistance-project.eu/>.
- [10] MATCHUP, [Online]. Available: <https://www.matchup-project.eu/>.
- [11] kubernetes, “kubernetes,” [Online]. Available: <https://kubernetes.io/docs/concepts/overview/>.
- [12] KEYCLOAK, “KEYCLOAK,” [Online]. Available: <https://www.keycloak.org/>.

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

- [13] MongoDB, [Online]. Available: <https://www.mongodb.com/>.
- [14] Meteor, "Github," [Online]. Available: <https://github.com/meteor/meteor/blob/devel/packages/ddp/DDP.md>.
- [15] NATS, "NATS," [Online]. Available: <https://nats.io/>.
- [16] InfluxData, "InfluxData," [Online]. Available: <https://www.influxdata.com/>.
- [17] XGBoost, "XGBoost," [Online]. Available: <https://xgboost.readthedocs.io/en/stable/>.
- [18] G. A. B. J. D. G.-C. K. R. Klemen Peter Kosovinc, "Deliverable 2.1 Pilot site analysis and use cases, requirements and KPIs definition," [Online]. Available: https://ecolooop-project.eu/wp-content/uploads/2025/03/ECOLOOP_D2.1.pdf.
- [19] [Online]. Available: <https://servicio.mapa.gob.es/websiar/>.
- [20] Movicon | Emerson, "Movicon | Emerson," [Online]. Available: <https://www.emerson.com/en-es/automation/control-and-safety-systems/movicon>.
- [21] Opentunity Grant Agreement. EC, 2022.
- [22] "WebGL," [Online]. Available: <https://get.webgl.org/>.
- [23] MRU GmbH, "MRU GmbH," [Online]. Available: https://www.mru.si/wp-content/uploads/2023/05/9512EN_USER_MANUAL_SWG100-BIOGAS.pdf.

5.2. Acronyms

Table 16: Table of acronyms.

Acronym	Description
Agri-PV	Agri-photovoltaics
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
CHP	Combined Heat Power
CRUD	Create, Read, Update and Delete
DDP	Distributed Data Protocol
DHW	Domestic Hot Water
DST	Decision Support Tool
ESB	Enterprise Service Bus
ETL	Extract, Transform and Load
etPMon	Actual evapotranspiration
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
JSON	JavaScript Object Notation
KIS	Agricultural Institute of Slovenia
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt-hour
LL	Living Lab
MQTT	Message Queuing Telemetry Transport
pePMon	potential evapotranspiration
PLC	Programmable Logic Controller
PSA	Pressure Swing Adsorption
PSA	Pressure Swing Adsorption
PV	Photovoltaic
RES	Renewable Energy Sources

Deliverable 4.1: AI and Big Data Analytics (IoT ecosystem)

RIVER	Reactive, Interoperable, Visible, Elastic and Resilient
SiAR	Agroclimatic Information System for Irrigation
SMX	Smart Extended Meter
SOC	State of Charge
SSL	Secure Sockets Layer
SSO	Single Sign On
TLS	Transport Layer Security
UPV	Universitat Politècnica de València
WS	WebSocket