



Horizon Europe (HORIZON) - HORIZON-CL5-2024-D3-01-11

AI Testing and Experimentation Facility (TEF) for the energy sector – bringing technology to the market

Project no. 101172705



**Large-Scale Testing and Experimentation Facility (TEF) for Assessing,  
Validating, and Enhancing AI-Powered Next-Generation Energy Solutions**

## **D6.1 - Pilot experiments planning, preparation and M&V plan**

**By R&D Nester, CIEMAT, BER, CEA, CARTIF, REA, SCCB, ICCS and ENGREN**

**December 29th, 2025**

**Work package:** WP6 – EnergyGuard TEF – Pilot experiments and operation

|                        |                                                                  |
|------------------------|------------------------------------------------------------------|
| <b>Authors:</b>        | R&D Nester, CIEMAT, BER, CEA, CARTIF, REA, SCCB, ICCS and ENGREN |
| <b>Status:</b>         | Final                                                            |
| <b>Date:</b>           | 29/12/2025                                                       |
| <b>Version:</b>        | 1.0                                                              |
| <b>Classification:</b> | Public                                                           |

### **Disclaimer:**

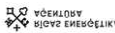
The EnergyGuard project is co-funded by the Horizon Europe Programme of the European Union under grant agreement No. 101172705. This document reflects only authors' views. The EC is not liable for any use that may be done of the information contained therein.

## EnergyGuard Project Profile

Grant Agreement No.: 101172705

|                    |                                                                                                                                             |
|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Acronym:</b>    | EnergyGuard                                                                                                                                 |
| <b>Title:</b>      | Large-Scale Testing and Experimentation Facility (TEF) for Assessing, Validating, and Enhancing AI-Powered Next-Generation Energy Solutions |
| <b>URL:</b>        | <a href="http://www.energy-guard.eu">http://www.energy-guard.eu</a>                                                                         |
| <b>Start Date:</b> | 01/01/2025                                                                                                                                  |
| <b>Duration:</b>   | 36 months                                                                                                                                   |

### Partners

|                                                                                     |                                                                                                                                                      |            |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
|    | EREVNITIKO PANEPISTIMIAKO INSTITOUTO SYSTIMATON EPIKOINONION KAI YPOLOGISTON (ICCS), Decision Support Systems Laboratory, DSSLab <u>Co-ordinator</u> | Greece     |
|    | CENTRO DE INVESTIGACAO EM ENERGIA REN - STATE GRID SA (RDN)                                                                                          | Portugal   |
|    | CENTRO DE INVESTIGACIONES ENERGETICAS MEDIOAMBIENTALES Y TECNOLOGICAS (CIEMAT)                                                                       | Spain      |
|   | COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA)                                                                                 | France     |
|  | FUNDACION CARTIF (CARTIF)                                                                                                                            | Spain      |
|  | RIGA MUNICIPAL AGENCY "RIGA ENERGY AGENCY" (REA)                                                                                                     | Latvia     |
|  | BLUENERGY REVOLUTION SCRL (BER)                                                                                                                      | Italy      |
|  | METASYMBOSE SAS (MS)                                                                                                                                 | France     |
|  | LUXPROVIDE SA (LXP)                                                                                                                                  | Luxembourg |
|  | FUNDINGBOX ACCELERATOR SP ZOO (FBA)                                                                                                                  | Spain      |
|  | FORA FOREST TECHNOLOGIES SLL (FORA)                                                                                                                  | Spain      |
|  | FYLLA ANASTASIA (AF)                                                                                                                                 | Greece     |
|  | ENGREEN SRL (ENGREEN)                                                                                                                                | Italy      |
|  | BUVNICIBAS VALSTS KONTROLES BIROJS (SCCB)                                                                                                            | Latvia     |
|  | HAL SERVICE SPA (HAL)                                                                                                                                | Italy      |

## Document History

| Version | Date       | Author (Partner)                                                                                                                                                                                                                                                                                                   | Remarks          |
|---------|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| 0.1     | 28/08/2025 | Nuno Pinho da Silva (R&D Nester)                                                                                                                                                                                                                                                                                   | Initial Toc      |
| 0.2     | 05/12/2025 | Inoussa Laouali, Frederico Lourenço and Nuno Pinho da Silva (R&D Nester), Félix Bosio (CEA), José L. Hernández and Ismael Lozano (CARTIF), Luca Sità (BER), Alexandros Tzortzis and Theodosios Pountridis (ICCS), Marta Lafuente and Óscar Izquierdo (CIEMAT), Natalja Belska (REA), Francesco Vitellaro (ENGREEN) | Compiled version |
| 0.3     | 12/12/2025 | Luca Sità (BER)<br>Talis Linkaits (REA)                                                                                                                                                                                                                                                                            | Review           |
| 1.0     | 29/12/2025 | Spiros Mouzakis (ICCS)                                                                                                                                                                                                                                                                                             | Final Version    |

## Executive Summary

The EnergyGuard project, co-funded by the Horizon Europe Programme under Grant Agreement No. 101172705, aims to establish a large-scale Testing and Experimentation Facility (TEF) for the assessment, validation, and improvement of AI-powered energy solutions.

With the different TEFs across Europe addressing electricity, heating/cooling and hydrogen energy vectors, the EnergyGuard project's mission is to build a shared space where companies and entrepreneurs can test and improve their AI solutions for multiple energy vectors, ensuring these AI tools are reliable, safe, and useful for the energy sector and the decarbonisation process. Besides properly configured Digital Twins, the EnergyGuard project curated assets include data, models, inference APIs, services, and applications accessible through an AI development testing environment.

The overarching goal of the project is to bridge the gap between emerging AI innovations and their real-world deployment in the energy sector, ensuring that these technologies are deployed in a trustworthy, secure, and ethically compliant manner, fully aligned with European regulations and societal expectations.

This Deliverable "D6.1 – Pilot Experiments Planning, Preparation, and Measurement and Verification (M&V) Plan" presents the planning, preparation, and methodology for the validation of the EnergyGuard Testing and Experimentation Facility (TEF) services through real-life pilot operation experiments. It is the first of a series of three deliverables from the EnergyGuard WP6 "EnergyGuard TEF - Pilot Experiments and Operation" (Figure 0-1).

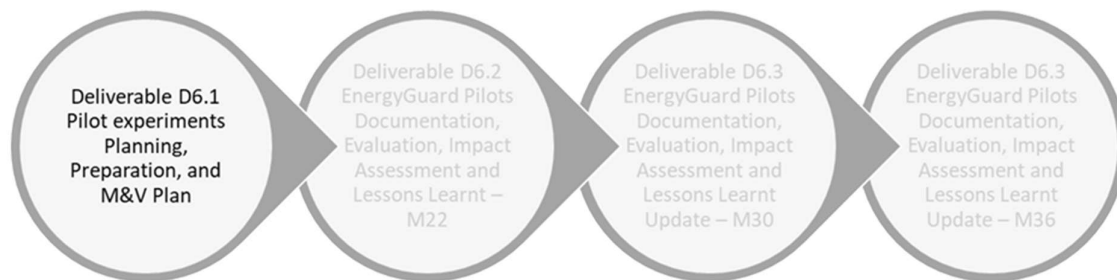


Figure 0-1. Deliverables from the EnergyGuard WP6 "EnergyGuard TEF - Pilot Experiments and Operation"

The work builds on top of the EnergyGuard Deliverable D2.1 "Landscape review analysis, EnergyGuard User requirement and specifications" and it defines the framework for executing, monitoring, and validating the pilot activities that will demonstrate the TEF's capabilities across different segments of the energy system.

The document provides a detailed description of the steps and procedures required for the deployment of the TEF services, outlining how the testing infrastructure will be configured, integrated, and prepared for operational use. It further explains the methodology and workflow of the pilot experiments designed to validate the TEF services under realistic conditions, ensuring that performance evaluations reflect realistic operational environments. The document also identifies what will be measured to validate the TEF services, defining the relevant Key Performance Indicators (KPIs) and establishing clear procedures for how these indicators will be collected, analysed, and interpreted.

Furthermore, the deliverable introduces the Measurement and Verification (M&V) framework, which provides a systematic approach to quantifying and comparing the performance of TEF services across pilots. It includes the definition of baseline conditions and target values, enabling transparent assessment of progress and measurable improvements achieved throughout the validation process.

## Table of Contents

|          |                                                                                                                         |           |
|----------|-------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction .....</b>                                                                                               | <b>10</b> |
| 1.1      | Purpose and Scope.....                                                                                                  | 10        |
| 1.2      | Structure of the document.....                                                                                          | 10        |
| <b>2</b> | <b>R&amp;D Nester’s Large-Scale Transmission Grid Testing and Experiment Facility .....</b>                             | <b>13</b> |
| 2.1      | TEF services .....                                                                                                      | 13        |
| 2.2      | Pilot 1 operation and experiments to validate the TEF services .....                                                    | 13        |
| 2.2.1    | Service P1.1: High fidelity Digital Twin of a large-scale electricity grid with high share of renewables.....           | 14        |
| 2.2.2    | Service P1.2: Automatic fault analysis in power systems.....                                                            | 15        |
| 2.2.3    | Service P1.3: Model-free voltage profiles in low voltage electricity grids .....                                        | 16        |
| 2.3      | KPIs to validate the Pilot’s services.....                                                                              | 16        |
| 2.3.1    | KPIs for Service P1.1: High fidelity Digital Twin of a large-scale electricity grid with high share of renewables ..... | 16        |
| 2.3.2    | KPIs for Service P1.2: Automatic fault analysis in power systems .....                                                  | 17        |
| 2.3.3    | KPIs for Service P1.3- Model-free voltage profiles in low voltage electricity grids .....                               | 17        |
| <b>3</b> | <b>CIEMAT’s Renewable Microgrid Testing and Experiment Facility .....</b>                                               | <b>19</b> |
| 3.1      | TEF services .....                                                                                                      | 19        |
| 3.2      | Pilot 2 operation and experiments to validate the TEF services .....                                                    | 20        |
| 3.3      | KPIs to validate the TEF services.....                                                                                  | 21        |
| 3.3.1    | KPIs for Service P2.1: Intelligent Microgrid Management .....                                                           | 21        |
| 3.3.2    | KPIs for Service P2.2: Comparison of AI vs. Human Operator .....                                                        | 22        |
| 3.3.3    | KPIs for Service P2.3: Flexibility through Electrolyser Integration .....                                               | 22        |
| <b>4</b> | <b>BER’s PEM Electrolyzers Hydrogen Testing and Experiment Facility .....</b>                                           | <b>23</b> |
| 4.1      | TEF Services .....                                                                                                      | 23        |
| 4.2      | Pilot 3 Operation and Experiments to Validate the TEF Services .....                                                    | 24        |
| 4.2.1    | Remote Access and Control .....                                                                                         | 24        |
|          | Validation Roadmap .....                                                                                                | 24        |
|          | Validation Experiments .....                                                                                            | 25        |
|          | Data Management and Accessibility.....                                                                                  | 27        |
| 4.3      | KPIs to Validate the TEF Services .....                                                                                 | 27        |
| <b>5</b> | <b>CEA’s H2 Testing and Experiment Facility.....</b>                                                                    | <b>31</b> |

|            |                                                                                                                                                      |           |
|------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>5.1</b> | <b>TEF services .....</b>                                                                                                                            | <b>31</b> |
| <b>5.2</b> | <b>Pilot 4 operation and experiments to validate the TEF services .....</b>                                                                          | <b>32</b> |
| <b>5.3</b> | <b>KPIs to validate the TEF services.....</b>                                                                                                        | <b>34</b> |
| 5.3.1      | KPIs for Service P4.1: AI tool for scenario generation.....                                                                                          | 34        |
| 5.3.2      | KPIs for Service P4.2: MURPHY Digital Twin access for scenario simulation<br>and AI algorithm testing .....                                          | 34        |
| 5.3.3      | KPIs for Service P4.3: Experimental validation of selected scenarios on the<br>physical MURPHY test bench.....                                       | 34        |
| <b>6</b>   | <b>CARTIF's Hydrogen Technology Testing and Experiment<br/>Facility.....</b>                                                                         | <b>35</b> |
| <b>6.1</b> | <b>TEF services .....</b>                                                                                                                            | <b>35</b> |
| <b>6.2</b> | <b>Pilot 5 operation and experiments to validate the TEF services .....</b>                                                                          | <b>36</b> |
| <b>6.3</b> | <b>KPIs to validate the TEF services.....</b>                                                                                                        | <b>37</b> |
| 6.3.1      | KPIs for Service P5.1: Experimental validation and model calibration.....                                                                            | 37        |
| 6.3.2      | KPIs for Service P5.2: AI-based predictive control and optimization.....                                                                             | 37        |
| 6.3.3      | KPIs for Service P5.3 Hybrid energy integration and flexibility analysis .....                                                                       | 39        |
| <b>7</b>   | <b>REA/SCCB's Digital Twin-Assisted and AI-driven Building<br/>Energy Efficiency Decision Support Testing and Experiment<br/>Facility.....</b>       | <b>41</b> |
| <b>7.1</b> | <b>TEF services .....</b>                                                                                                                            | <b>41</b> |
| <b>7.2</b> | <b>Pilot 6 operation and experiments to validate the TEF services .....</b>                                                                          | <b>42</b> |
| <b>7.3</b> | <b>KPIs to validate the TEF services.....</b>                                                                                                        | <b>42</b> |
| 7.3.1      | KPIs for P6.1: EPC Dataset Service.....                                                                                                              | 42        |
| 7.3.2      | KPIs for P6.2: Digital Twin Service .....                                                                                                            | 43        |
| 7.3.3      | KPIs for P6.3: EFI-DSS .....                                                                                                                         | 43        |
| <b>8</b>   | <b>ENGREEN's Enhancing performance of Renewable Energy<br/>Community Facilities through AI experiments Testing and<br/>Experiment Facility .....</b> | <b>45</b> |
| <b>8.1</b> | <b>TEF services .....</b>                                                                                                                            | <b>45</b> |
| <b>8.2</b> | <b>Pilot 7 operation and experiments to validate the TEF services .....</b>                                                                          | <b>47</b> |
| <b>8.3</b> | <b>KPIs to validate the TEF services.....</b>                                                                                                        | <b>48</b> |
| <b>9</b>   | <b>Platform-level assessment KPIs for EnergyGuard TEF .....</b>                                                                                      | <b>51</b> |
| 9.1        | General timeline for pilot evaluation .....                                                                                                          | 51        |
| <b>10</b>  | <b>Summary and Conclusion.....</b>                                                                                                                   | <b>53</b> |
|            | <b>Annex I: References .....</b>                                                                                                                     | <b>55</b> |

## List of Figures

|                                                                                                             |    |
|-------------------------------------------------------------------------------------------------------------|----|
| Figure 0-1. Deliverables from the EnergyGuard WP6 “EnergyGuard TEF - Pilot Experiments and Operation” ..... | 4  |
| Figure 2-1. Workflow for Service P1.1 .....                                                                 | 15 |
| Figure 3-1. CIEMAT’s Renewable Microgrid .....                                                              | 19 |
| Figure 4-1. A set of 2 MOSE electrolyzers with their water treatment unit .....                             | 24 |
| Figure 5-1. CEA TEF workflow .....                                                                          | 33 |
| Figure 6-1. CARTIF’s TEF facilities .....                                                                   | 35 |
| Figure 6-2. Data logger and example of data for CARTIF’s TEF facilities .....                               | 36 |
| Figure 6-3. Baseline calculations for the CARTIF’s TEF KPIs (without and with H2) .....                     | 38 |
| Figure 7-1. REA/SCCB TEF Services Diagram .....                                                             | 41 |
| Figure 9-1. Timeline for the evaluation of pilots and TEF services. ....                                    | 52 |

## List of Tables

|                                                                                                                                    |    |
|------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 2-1. KPIs for service P1.1: High fidelity Digital Twin of a large-scale electricity grid with high share of renewables ..... | 16 |
| Table 2-2. KPIs for service P1.2: Automatic fault analysis in power systems .....                                                  | 17 |
| Table 2-3. KPIs for service P1.3 - Model-free voltage profiles in low voltage electricity grids .....                              | 17 |
| Table 3-1. KPIs for CIEMAT Service P2.1 Intelligent Microgrid Management .....                                                     | 21 |
| Table 3-2. KPIs for CIEMAT Service P2.2: Comparison of AI vs. Human Operator .....                                                 | 22 |
| Table 3-3. KPIs for CIEMAT Service P2.3: Flexibility through Electrolyser Integration .....                                        | 22 |
| Table 4-1. KPIs for PEM Electrolyzers TEF .....                                                                                    | 27 |
| Table 5-1. KPIs for Service P4.1: AI tool for scenario generation .....                                                            | 34 |
| Table 5-2. KPIs for Service P4.2: MURPHY DT access for scenario simulation and AI algorithm testing .....                          | 34 |
| Table 5-3. KPIs for Service P4.3: Experimental validation of selected scenarios on the physical MURPHY test bench .....            | 34 |
| Table 6-1. KPIs for CARTIF’s TEF service P5.1: Experimental validation and model calibration .....                                 | 37 |
| Table 6-2. KPIs for CARTIF’s TEF service P5.2: AI-based predictive control and optimization .....                                  | 37 |
| Table 6-3. KPIs for CARTIF’s TEF service P5.3: Hybrid energy integration and flexibility analysis .....                            | 39 |
| Table 7-1. KPIs for P6.1: EPC Dataset Service .....                                                                                | 42 |
| Table 7-2. KPIs for P6.2: Digital Twin GeoRIGA Service .....                                                                       | 43 |
| Table 7-3. KPIs for P6.3: EFI-DSS .....                                                                                            | 43 |
| Table 9-1. Platform-level KPIs for EnergyGuard TEF .....                                                                           | 51 |

## Acronyms and Abbreviation

|          |                                                             |
|----------|-------------------------------------------------------------|
| AI       | Artificial Intelligence                                     |
| COMTRADE | Common Format for Transient Data Exchange for Power Systems |
| DT       | Digital Twin                                                |
| DERs     | Distributed Energy Resources                                |
| DL       | Deep Learning                                               |
| DSO      | Distribution System Operator                                |
| EFI-DSS  | Energy Efficiency Intelligence – Decision Support System    |
| EU       | European Union                                              |
| HIL      | Hardware-in-the-Loop                                        |
| IED      | Intelligent Electronic Device                               |
| KPI      | Key Performance Indicator                                   |
| LV       | Low Voltage                                                 |
| M&V      | Measurement and Verification                                |
| ML       | Machine Learning                                            |
| PV       | Photovoltaic                                                |
| REC      | Renewable Energy Community                                  |
| RTPSS    | Real-Time Power System Simulation laboratory                |
| TEF      | Testing and Experimentation Facility                        |
| TSO      | Transmission System Operator                                |
| V2G      | Vehicle to Grid                                             |
| WP       | Work Package                                                |

# 1 Introduction

---

## 1.1 Purpose and Scope

Deliverable D6.1 – Pilot Experiments Planning, Preparation, and Measurement and Verification (M&V) Plan

The EnergyGuard project provides access to Digital Twins (DTs) of large-scale electricity networks with high share of renewables [1], microgrids [2], hydrogen systems [3-5], residential buildings [6] and renewable energy communities [7]. The DTs represent facilities with a wide range of elements to cover diverse AI applications to energy systems, wind power and photovoltaic systems, hydropower plant, AEM, PEM and SO electrolyzers, fuel cells, EV charging stations, electric and public buses, and battery storage systems.

This deliverable D6.1 “Pilot Experiments Planning, Preparation, and Measurement and Verification (M&V) Plan” is the first of three deliverables from the EnergyGuard project’s Work Package 6 “EnergyGuard-TEF Pilot Experiments and Operation”. The next deliverables are the intermediary and final version of “EnergyGuard Pilots Documentation, Evaluation, Impact Assessment and Lessons Learnt”, depicting the pilots’ implementation, evaluating their operation and their impact, as well as producing clear and actionable lessons to support the development of the exploitation strategy of the EnergyGuard TEF beyond the project duration.

This work builds upon Deliverable D2.1 “Landscape review analysis, EnergyGuard User requirement and specifications” [8]. The purpose of this document is to define the planning, technical preparation, and methodological approach that will guide the execution of pilot operation experiments within Work Package 6 (WP6). It defines the overall strategy, procedures, and methodologies that will guide the validation of the EnergyGuard Testing and Experimentation Facility (TEF) services.

The document outlines the steps and procedures required to deploy the TEF services, including their configuration, integration, and testing within real-life operational environments. It further defines the procedures for conducting the pilot experiments that will validate the TEF’s capabilities, ensuring that all activities are performed in a consistent and replicable manner across the different pilot sites. The Key Performance Indicators provide the baseline to assess the performance of each TEF and the tools that are tested in the pilots. Furthermore, platform-level KPIs and the general timeline for pilot evaluation define the general evaluation framework of the EnergyGuard pilots and TEF services.

The scope of this deliverable therefore encompasses both the technical planning and the validation methodology of all EnergyGuard TEF facilities. It ensures coherence across the project’s various experimental activities, supporting the ultimate objective of EnergyGuard to demonstrate and validate AI-driven energy solutions that are robust, secure, and compliant with European standards and societal values.

## 1.2 Structure of the document

The document is organized into nine main parts:

- Section 1 introduces the purpose, scope, and structure of the deliverable.
- Section 2 presents the Digital Twin of the Large-Scale Transmission Grid Testing Facility, detailing its services, pilot operation procedures, and key performance indicators (KPIs).

- Section 3 describes the Renewable Microgrid Testing Facility, including its services, pilot execution steps, and validation approach.
- Section 4 focuses on the PEM Electrolysers Hydrogen Testing Facility, outlining its services, validation roadmap, and experimental activities.
- Section 5 covers CEA's Hydrogen Testing Facility, explaining its pilot operation process, KPIs for each service and experimental activities.
- Section 6 describes CARTIF's Hydrogen Technology Testing Facility, describing the experiments and key performance indicators used for validation.
- Section 7 presents the Riga's multi-apartment residential buildings Testing Facility including its operational methodology and KPIs.
- Section 8 describes the Antrodoco Renewable Energy Community Testing Facility, outlining its services, validation roadmap, and experimental activities.
- Section 9 provides a summary and conclusion, highlighting the overall planning, validation framework, and next steps for the execution phase.
- Section 10 presents the Platform-level assessment KPIs for EnergyGuard TEF



## 2 R&D Nester’s Large-Scale Transmission Grid Testing and Experiment Facility

---

### 2.1 TEF services

R&D Nester’s Testing and Experimentation Facility (TEF) provides an advanced and interoperable environment for testing, assessing, and validating AI-based and data-driven solutions dedicated to the operation and optimisation of power transmission systems. The core of this facility is the Digital Twin (DT) of a large-scale Transmission Grid with high shares of renewables, inspired by the Portuguese Transmission Network, designed to accurately replicate its electrical, operational, and control dynamics. This Digital Twin serves as a comprehensive digital replica of the physical grid, capable of reproducing both steady-state and transient behaviours under diverse operating conditions, including network contingencies, renewable variability, and demand fluctuations.

The DT operates within the R&D Nester’s Real-Time Power System Simulation (RTPSS) laboratory, using a combination of simulated and real-world data, integrating historical datasets and live operational data streams provided by the Portuguese national Transmission System Operator (TSO). Its architecture combines electrical, communication, and control layers, enabling multi-domain analysis of the grid’s performance and stability. This layered structure supports in-depth studies on system reliability, flexibility, and interoperability, as well as the validation of advanced optimisation methods and digital control services under realistic conditions

Through EnergyGuard’s infrastructure, the TEF provides secure access for developers and researchers to deploy and validate grid-related services such as operational forecasting, voltage and power-flow analysis, network optimisation, and automated fault analysis. The facility also supports Hardware-in-the-Loop (HIL) configurations, allowing the seamless integration of physical Intelligent Electronic Devices (IEDs) and protection relays with the virtual grid model. This setup enables realistic and reproducible testing of algorithms, control strategies, and digital tools.

In particular, two AI-based tools will be tested in this TEF: the ICCS’s DeepTSF will be included in the grid validation of the market results during operational planning and the R&D Nester’s tool for Circuit Breaker’s fault analysis will be tested to automatic fault analysis in power systems. A third service will be tested in this Pilot using the EnergyGuard’s infrastructure, testing the R&D Nester’s tool to estimate model-free voltage profiles in low voltage grids in the CIEMAT’s Renewable Microgrid Testing Facility (Section 0).

Overall, the Digital Twin of the Large-Scale Transmission Grid TEF serves as a reference infrastructure within the EnergyGuard ecosystem, providing a reliable testbed for evaluating and benchmarking digital solutions that enhance the performance, efficiency, and resilience of transmission networks with a high share of renewable energy. It plays a pivotal role in demonstrating how advanced analytics and AI-enabled services can support the evolution of a secure, flexible, and sustainable European power system.

### 2.2 Pilot 1 operation and experiments to validate the TEF services

Pilot 1 “**Testing, Evaluating and Validating AI Solutions to Support the Operation of Smart Grids**” aims to showcase the capability of the EnergyGuard TEF in enabling the deployment of reliable,

secure and trustworthy AI solutions for smart grid operations. It illustrates how the integration of high-fidelity digital modelling, advanced simulation tools, and real operational data can significantly enhance the testing, assessment, and validation of intelligent energy applications under realistic transmission system conditions.

The pilot leverages the Digital Twin of the large-scale transmission grid with high-shares of renewables to establish an experimental framework where AI-driven services and analytical tools can be tested under controlled yet realistic operating conditions. By combining simulation-based experiments with live data streams, the pilot enables an in-depth evaluation of AI solutions addressing grid optimisation, fault detection, voltage regulation, and predictive maintenance.

The pilot operation will consist of a series of structured experiments aimed at validating the technical performance, scalability, and interoperability of the Digital Twin and associated EnergyGuard services. The key experimental activities include two distinct experiments, each targeting a specific analytics service developed within the EnergyGuard framework. Furthermore, the pilot also includes the testing of the AI-based model-free voltage profile in low voltage electricity grids in the CIEMAT's TEF (Section 0). Therefore, the pilot will deliver three services, detailed below.

#### **2.2.1 Service P1.1: High fidelity Digital Twin of a large-scale electricity grid with high share of renewables**

Service-P1.1 aims to integrate a Digital Twin (DT) of the large-scale Transmission Grid into the EnergyGuard testing sandbox, providing a secure and realistic environment for developing and validating AI-driven solutions in large electricity networks with high shares of renewables. The objective is to enable EnergyGuard users to evaluate and validate intelligent services and algorithms under operationally realistic conditions while maintaining full data protection and system integrity. This involves the establishment of secure interfaces to access up-to-date grid data, namely renewable generation and consumption. Dedicated data ingestion and processing pipelines will be developed to ensure reliable and continuous data flow from the EnergyGuard Data Services Layer into the Digital Twin environment and vice-versa. The DT incorporates advanced simulation modules capable of reproducing power flows, renewable energy integration, and dynamic system responses, allowing the accurate replication of grid behaviour under varying operational conditions.

A key element of this workflow is the DeepTSF forecasting module, which generates short-term renewable generation and load forecasts that feed directly into the Transmission Network Digital Twin. The DeepTSF workflow automates the complete data-driven modelling process, from data ingestion and pre-processing to model training and evaluation. Figure 2-1 illustrates this integration.

As presented in Figure 2-1, the EnergyGuard Data Services Layer collects anonymised up-to-date operational data from the DT of the large-scale transmission grid (Transmission Grid DT). This data is transferred to the DeepTSF workflow, where it undergoes pre-processing before being used for model training. The trained DeepTSF models will produce one-week-ahead forecasts of renewable generation and load, which are injected into the Transmission Network DT. The DT then performs grid analyses based on these inputs and market data to understand if the day-ahead market results do not produce grid constraints given the renewable and load forecasting. Hence, this pilot's experiment will evaluate the integration of the DT for large-scale transmission grids with high shares of renewables and the integration with a third-party AI-based tool through the EnergyGuard's sandbox.

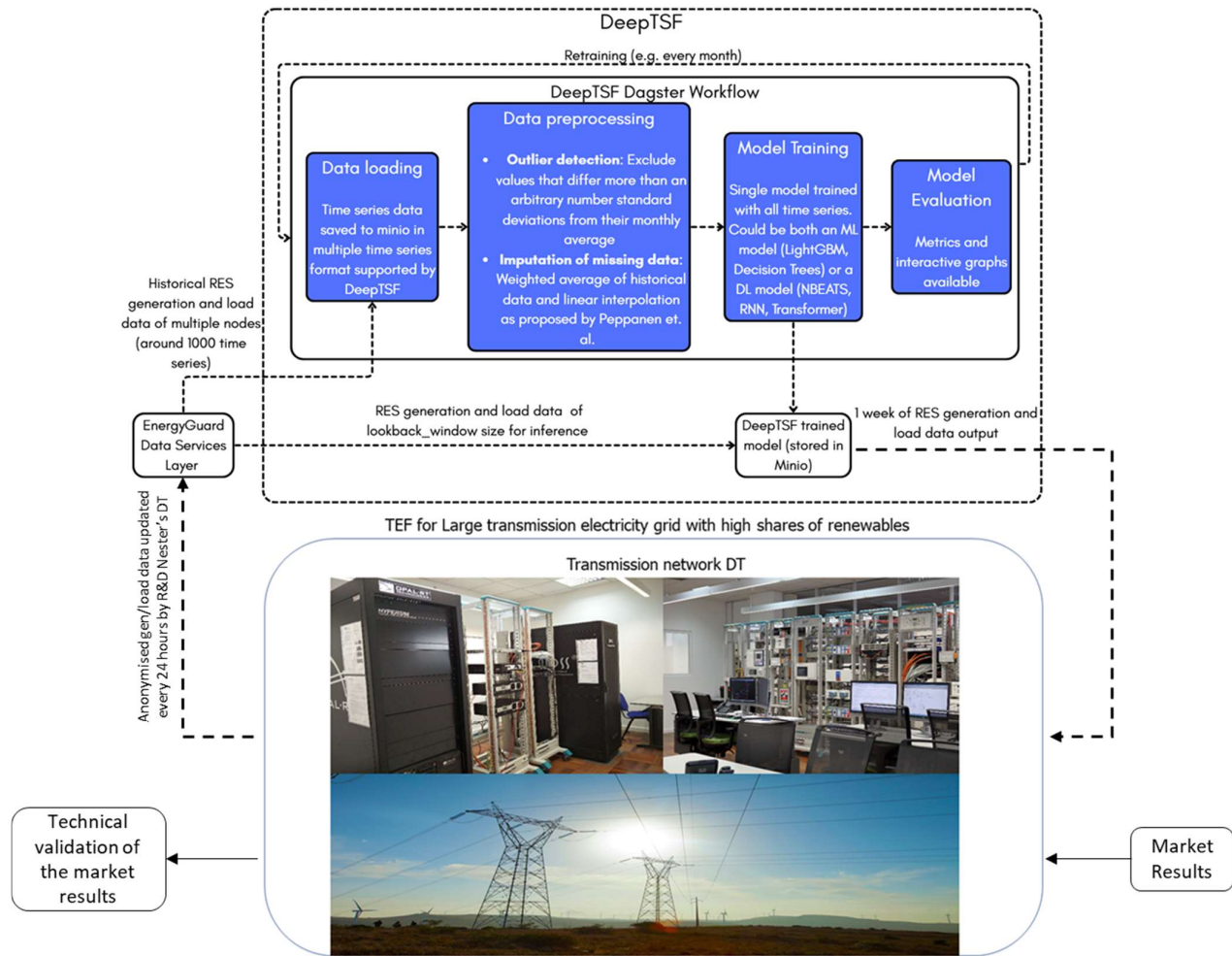


Figure 2-1. Workflow for Service P1.1

Continuous ingestion of operational data from the TSO ensures that the DT remains synchronised with real grid conditions, providing a living digital representation of the system. By harnessing diverse data streams and simulation capabilities, Service P1.1 enables the creation and validation of AI and data-driven models that support enhanced grid management. These AI-based tools may range from identifying usage patterns across the transmission network, forecasting potential disruptions such as overloads or imbalances, or recommend proactive operational actions to improve overall efficiency, reliability, and resilience.

### 2.2.2 Service P1.2: Automatic fault analysis in power systems

Service-P1.2 focuses on the development and validation of an AI-driven service for automatic fault analysis in power transmission systems. The service leverages advanced signal processing techniques and AI tools to detect and classify faults while also quantifying critical event statistics such as detection time, short-circuit current etc. It is designed to automatically process COMTRADE (COMMON format for TRANsient Data Exchange) files generated by Intelligent Electronic Devices (IEDs), including protective relays, and provide incident reports within seconds. Data pipelines will be established to ingest and process these files automatically, while signal processing algorithms and AI tools will be configured to detect, classify, and quantify power system faults. The system will be integrated with the Large-scale

transmission grid TEF, where physical IEDs are connected to the DT providing Hardware-in-the-Loop (HIL) simulations to replicate fault events and provide a realistic testing environment. The pilot experiments will consist of fault event simulations using the transmission network DT. IEDs will generate COMTRADE files in response to HIL-simulated transient fault conditions. These files will be automatically ingested by the tool for automatic fault analysis in power systems, which will process them to detect, classify the faults and produce incident reports. Experiments will be performed under different types of disturbances and operating conditions, allowing the service's performance to be compared against the actual ground-truth data. This setup enables a detailed assessment of the service's performance in conditions that closely replicate real-world power system disturbances, ensuring fast, accurate, and reliable fault detection and analysis.

### 2.2.3 Service P1.3: Model-free voltage profiles in low voltage electricity grids

Service-P1.3 seeks to estimate voltage profiles of low-voltage (LV) networks, addressing the challenge of limited or unavailable detailed grid models and the computational intensity of traditional simulations. By leveraging high-resolution net load data and consumption/generation metrics at each node, the service will enable real-time voltage estimation without relying on power flows requiring grid models that may not be available for low voltage grids. This approach enhances operational efficiency and supports smarter grid management through scalable, data-driven analytics. It will be tested and validated using the CIEMAT's Renewable Microgrid TEF within the EnergyGuard AI development sandbox.

## 2.3 KPIs to validate the Pilot's services

### 2.3.1 KPIs for Service P1.1: High fidelity Digital Twin of a large-scale electricity grid with high share of renewables

Table 2-1. KPIs for service P1.1: High fidelity Digital Twin of a large-scale electricity grid with high share of renewables

| KPI name                             | KPI description                                                                | KPI validation                                                                                                                                                                                                                                                                                                                                                 | KPI baseline                                    | KPI target values |
|--------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|-------------------|
| <b>Execution time of simulations</b> | Time required by the DT to process input data and generate simulation results. | The fidelity of the DT will be validated by comparing simulation results such as voltage, power flows with actual data. Data integration will be assessed by monitoring ingestion rates, latency, and error-free synchronization between data streams and the DT. Execution time will be recorded during simulation runs under different operating conditions. | Simulations requiring several minutes to hours. | <3 minutes        |

### 2.3.2 KPIs for Service P1.2: Automatic fault analysis in power systems

Table 2-2. KPIs for service P1.2: Automatic fault analysis in power systems

| KPI name                             | KPI description                                                                          | KPI validation                                                | KPI baseline                            | KPI target values                                                  |
|--------------------------------------|------------------------------------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------|--------------------------------------------------------------------|
| <b>Fault classification accuracy</b> | Measures how accurately the AI service identifies the type and characteristics of faults | Comparison of AI classifications with ground-truth fault data | 80%                                     | ≥90%                                                               |
| <b>Incident reporting speed</b>      | Time required to generate and deliver a complete incident report after a fault event     | Monitoring report generation during HIL test runs             | Reports available after several minutes | Incident reports generated within ≤ 60 seconds of fault occurrence |

### 2.3.3 KPIs for Service P1.3- Model-free voltage profiles in low voltage electricity grids

Table 2-3. KPIs for service P1.3 - Model-free voltage profiles in low voltage electricity grids

| KPI name                                        | KPI description                                                                                                          | KPI validation                                                                | KPI baseline | KPI target values |
|-------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|--------------|-------------------|
| <b>Phase and feeder identification accuracy</b> | Measures how accurately the algorithm identifies the phase and feeder of all grid “clients” (consumption and generation) | using CEDER’s microgrid data, identify load and generation phases and feeders | 80%          | 85%               |



### 3 CIEMAT's Renewable Microgrid Testing and Experiment Facility

---

#### 3.1 TEF services

The CIEMAT TEF, located at the Centro de Desarrollo de Energías Renovables (CEDER-CIEMAT) in Soria (Spain), provides an advanced environment for testing and validating AI-based energy management and flexibility services under real microgrid operating conditions. The facility integrates a variety of Distributed Energy Resources (DERs), including photovoltaic (PV), wind and mini-hydraulic generation, electrochemical storage, electric vehicle charging stations with V2G capability, and flexible thermal loads, all managed through a centralized control and monitoring platform.



Figure 3-1. CIEMAT's Renewable Microgrid.

Within EnergyGuard, CIEMAT participates in Pilot 2 – Microgrid Intelligent Operation, offering a set of TEF services focused on the intelligent management and optimization of hybrid microgrids through the application of predictive and AI-based algorithms.

The first service (Service V) is the *intelligent management of hybrid microgrids* using predictive algorithms. This includes the development and validation of renewable generation and consumption forecasting models, initially tested in a Digital Twin environment that replicates the real CEDER microgrid. Once validated, these models are implemented in the physical infrastructure to optimize the coordination of PV, wind, and hydraulic resources together with storage systems and EV flexibility. The

service aims to enhance the operational efficiency and resilience of the microgrid, maximizing renewable integration while minimizing curtailment and ensuring supply reliability.

The second service (Service VI) focuses on the *comparison between conventional and AI-optimized operational strategies*. By applying advanced control algorithms, the TEF enables the evaluation of economic and technical benefits obtained when replacing rule-based or human-supervised operation with AI-driven decision-making. This comparison supports the quantification of economic savings, reduction in operating costs, improved energy balance, and enhanced flexibility, providing robust evidence of the added value of AI in distributed energy systems.

Finally, the third service (Service VII) involves the *integration of a 7 kW PEM electrolyser* as a controllable and flexible load within the microgrid. Although this equipment is primarily associated with Pilot 4 – Hydrogen System Optimization, its coupling with the CEDER microgrid provides an additional flexibility service, allowing the absorption of renewable energy surpluses, production of green hydrogen, and contribution to grid stability. This multi-pilot integration reinforces the microgrid's role as a living laboratory for flexibility, sector coupling, and decarbonization.

Through these services, the CIEMAT TEF contributes to the EnergyGuard ecosystem by providing a realistic, safe, and instrumented testbed where AI developers, researchers, and innovators can validate algorithms and control strategies for advanced energy management applications.

### 3.2 Pilot 2 operation and experiments to validate the TEF services

CIEMAT's activities are framed within Pilot 2 – Microgrid Intelligent Operation, which focuses on validating advanced management strategies for hybrid microgrids with a high penetration of renewable energy sources. This pilot is implemented at the CEDER-CIEMAT facilities in Lobia (Soria, Spain), where a unique experimental microgrid integrates distributed renewable generation (solar PV, wind and small hydro), several storage systems (batteries, V2G-enabled electric vehicles) and controllable loads. In addition, flexible hydrogen technologies, such as a 7 kW PEM electrolyser, are available to absorb renewable surpluses and enhance system stability.

The operation of Pilot 2 is structured in successive stages to ensure both the robustness of the results and safe deployment in a real environment. In the first stage, a Digital Twin of the microgrid is used to replicate the physical infrastructure and model the dynamics of renewable generation, demand, and storage. In this phase, advanced prediction and control algorithms are virtually tested to assess their ability to improve renewable integration and anticipate demand fluctuations. This approach enables researchers to explore different operating scenarios, including critical or stress conditions, without jeopardising the stability of the real system.

Once validated in the digital environment, the algorithms are implemented in the real microgrid operation through their integration into the Supervisory Control and Data Acquisition (SCADA) system of the CEDER facility. In this phase, CIEMAT deploys predictive control strategies that enable a direct comparison between conventional operation (baseline scenario, based on operator decisions and fixed rules) and intelligent operation (optimised scenario, supported by AI and advanced optimisation

algorithms). The experiments include both normal operating conditions and controlled stress tests, such as disconnection of generation units, sudden demand increases, or grid disturbances.

The main experiments to be performed within Pilot 2 include:

- Renewable integration tests: quantifying the increase in renewable energy absorbed by the system under optimised operation compared to conventional operation.
- Resilience experiments: applying controlled perturbations to the system (e.g., intentional variations in generation or load) and measuring recovery time and stability under different control strategies.
- Economic performance analysis: monitoring operational expenditures (OPEX) in both baseline and optimised scenarios to evaluate cost reduction potential.
- Flexibility demonstrations: integrating the PEM electrolyser as a controllable load to absorb renewable surpluses, thus reducing curtailment and providing additional flexibility to the microgrid.

All experiments are systematically monitored using real-time data acquisition systems, ensuring full traceability and reliability of the results. The combination of Digital Twin validation and real-life experimental deployment guarantees that the services offered by CIEMAT in Pilot 2 are tested under safe, realistic, and reproducible conditions, providing solid evidence of their technical and economic impact.

### 3.3 KPIs to validate the TEF services

The validation of CIEMAT's services is based on a set of Key Performance Indicators (KPIs) selected to quantify the technical, economic, and environmental impact of the advanced control strategies tested in Pilot 2.

These KPIs focus on renewable integration, system resilience, operating cost reduction, and flexibility enabled by hydrogen technologies.

#### 3.3.1 KPIs for Service P2.1: Intelligent Microgrid Management

Table 3-1. KPIs for CIEMAT Service P2.1 Intelligent Microgrid Management

| KPI name                                 | KPI description                                                                                                     | KPI validation                                                                                      | KPI baseline                  | KPI target values                                    |
|------------------------------------------|---------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-------------------------------|------------------------------------------------------|
| <b>Renewable Energy Integration Rate</b> | Share of renewable energy generation that is consumed or stored within the microgrid without curtailment.           | Continuous monitoring; comparison between baseline (conventional) and optimised AI-based operation. | 90–92% renewable integration. | ≥ 98% renewable integration; negligible curtailment. |
| <b>Operational Resilience</b>            | Average recovery time of the microgrid after a disturbance (e.g. load spike, generation loss, network fluctuation). | Stress-test experiments in both the Digital Twin and the physical microgrid; recovery times.        | > 5 minutes recovery time.    | ≤ 3–4 minutes recovery time.                         |

### 3.3.2 KPIs for Service P2.2: Comparison of AI vs. Human Operator

Table 3-2. KPIs for CIEMAT Service P2.2: Comparison of AI vs. Human Operator

| KPI name                                               | KPI description                                                                                                       | KPI validation                                                                                                    | KPI baseline                               | KPI target values      |
|--------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------------------------------------|------------------------|
| <b>Operational Expenditure Reduction (OPEX Saving)</b> | Percentage reduction in operational costs achieved through AI-based optimisation compared to operator-led management. | Economic analysis of energy balance, operational logs, and electricity bills in baseline vs. optimised scenarios. | Current OPEX under operator-led operation. | 10–20% OPEX reduction. |

### 3.3.3 KPIs for Service P2.3: Flexibility through Electrolyser Integration

Table 3-3. KPIs for CIEMAT Service P2.3: Flexibility through Electrolyser Integration

| KPI name                                                               | KPI description                                                                                | KPI validation                                   | KPI baseline                                              | KPI target values                                               |
|------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------------|
| <b>Reduction of Renewable Curtailment via Electrolyser Flexibility</b> | Share of renewable surplus energy absorbed by the PEM electrolyser instead of being curtailed. | Monitoring of data and hydrogen production logs. | 5–10% renewable curtailment under conventional operation. | Curtailment reduced by 5–10% via flexible hydrogen consumption. |

## 4 BER's PEM Electrolyzers Hydrogen Testing and Experiment Facility

---

### 4.1 TEF Services

BER will manufacture and install 2 of its MOSE (MODular Smart Electrolyzer) PEM electrolyzers: the first will be our standard 7kW unit that will be delivered and integrated into CEDER's microgrid facility; the second will be the first version of our 14kW design and will be installed in our testing facility. Both electrolyzers are based on the same BOP and are equipped with an internal regenerative dryer, allowing the production of dry, 99.999% purity, hydrogen gas.

BER's electrolyzers are equipped with an advanced data acquisition and logging system that records all process values at 0.1s resolution. This high-frequency data collection capability makes the systems particularly suitable for training and validating AI models for predictive maintenance, performance optimization, and energy management.

BER will provide daily batch uploads of all process values from the units to the Energy Guard's Data Lake, along with an internal database of process values acquired during the validation of our first two 7kW units. The data will include:

- **Operational parameters:** Current, voltage, power consumption, hydrogen production rate, system pressure, temperature sensors across multiple points
- **Environmental conditions:** Ambient temperature
- **Regenerative dryer performance:** Profile, electrical consumption during regeneration, column availability status
- **System status indicators:** Operating mode, fault conditions, uptime metrics
- **Water management:** Water consumption, water quality parameters, tank levels

This comprehensive dataset will enable external developers using the EnergyGuard platform to develop and validate AI models addressing:

1. **Predictive maintenance models:** Early detection of component degradation, prediction of regeneration column saturation, forecasting of maintenance needs
2. **Performance optimization models:** Real-time efficiency optimization considering environmental conditions, hydrogen production forecasting under variable renewable energy input, energy consumption minimization strategies
3. **Operational strategy models:** Optimal start-up sequences, load-following algorithms for renewable energy integration, regeneration scheduling optimization



Figure 4-1. A set of 2 MOSE electrolyzers with their water treatment unit.

## 4.2 Pilot 3 Operation and Experiments to Validate the TEF Services

### 4.2.1 Remote Access and Control

BER will provide a VPN connection with which the TEF's users can reach the electrolyzers' MODBUS control interface and operate the devices. Alternatively, we can provide a custom REST API to operate the electrolyzers, but it needs to be developed based on specific requirements defined by the EnergyGuard platform architecture.

For the 14kW unit at BER's HQ, due to operational constraints of our testing facility, we require the units to be operated only during our business opening hours (MON-FRI, 9-17), and in accordance with our testing needs. A booking system from the TEF's user interface is required to coordinate access and avoid conflicts with internal testing activities.

For the 7kW unit at CEDER, operational procedures and access constraints will be defined in coordination with CEDER's facility management team.

### Validation Roadmap

The validation of this TEF will follow a structured approach:

1. **Realization of the electrolyzer units:** Manufacturing and quality testing of both 7kW and 14kW units

2. **Installation and commissioning of the units:** Physical installation at BER and CEDER facilities, followed by functional testing and safety validation
3. **Data exchange validation:** Verification of daily batch data uploads from electrolyzers to the Energy Guard Data Lake, including data integrity and completeness
4. **Remote control validation:** Testing of command execution, response times, and fail-safe mechanisms through the Energy Guard platform
5. **Experimental validation campaigns:** Execution of the validation experiments described below

### Validation Experiments

The following experimental campaigns will be conducted to generate high-quality datasets for AI model development and to validate the TEF's capability to support diverse research objectives:

#### Experiment 1: Dynamic Characterization - Start-up Performance

**Objective:** Characterize the electrolyzer's thermal and operational dynamics from cold start to full capacity as a function of ambient temperature.

**Description:** This experiment will measure the time required for the system to reach 100% operational capacity from a cold start under different ambient temperature conditions. The focus will be on understanding how environmental conditions affect warm-up time, energy consumption during start-up, and the system's readiness for hydrogen production.

##### Methodology:

- Conduct cold starts at various ambient temperatures (ranging from 5°C to 35°C)
- Repeat experiments at different times of day and seasons to capture variation

Expected outputs: Dataset suitable for developing models that predict optimal start-up timing based on ambient conditions, and for calculating the true energy cost of intermittent operation.

#### Experiment 2: Renewable Energy Integration - Solar Profile Following

**Objective:** Evaluate hydrogen production capability and system efficiency when following typical renewable power generation profiles across different seasons.

**Description:** The electrolyzer will be operated following realistic renewable power generation curves representing different seasons and weather conditions. This experiment aims to quantify daily hydrogen production as a function of the input power profile and to understand efficiency variations under dynamic load conditions.

##### Methodology:

- Implement pre-recorded solar generation profiles from different seasons (winter, spring, summer, autumn) and weather conditions (clear sky, partially cloudy, variable)
- Operate the electrolyzer to follow these power profiles, simulating direct renewable energy coupling
- Compare performance across different seasonal profiles

**Expected outputs:** Datasets enabling the development of hydrogen production forecasting models for solar-coupled systems, and optimization algorithms for load-following operation.

### Experiment 3: Regeneration Cycle Characterization

**Objective:** Establish the relationship between operating conditions and regenerative dryer cycling frequency, duration, and impact on system efficiency.

**Description:** Since the integrated regenerative dryer consumes both hydrogen and electrical energy during regeneration cycles, understanding the factors influencing regeneration frequency and duration is critical for overall system efficiency optimization. This experiment will systematically vary operating conditions and monitor regeneration behavior.

**Methodology:**

- Operate the system under different combinations of:
  - Ambient temperature (5°C to 35°C)
  - Production rate setpoints (partial load vs. full load)
  - Continuous operation vs. intermittent operation patterns
- Record regeneration cycle frequency (cycles per day/month)
- Measure electrical consumption per regeneration cycle
- Monitor dryer column saturation indicators and regeneration effectiveness
- Track the impact of regeneration cycles on overall system efficiency

**Expected outputs:** Models for predicting regeneration requirements based on environmental and operational conditions, enabling proactive efficiency optimization and maintenance scheduling.

### Experiment 4: Stack Voltage Degradation Monitoring

**Objective:** Establish baseline degradation rates and develop predictive models for stack voltage evolution over time under various operating conditions.

**Description:** Long-term monitoring of stack voltage and performance to detect early signs of degradation and predict maintenance needs. This experiment leverages continuous data collection to identify degradation patterns and their correlation with operating conditions.

**Methodology:**

- Continuous monitoring of stack voltage throughout the validation period
- Correlation analysis between voltage drift and:
  - Operating hours and load cycles
  - Average operating current density
  - Number and duration of start-stop cycles
  - Regeneration cycle frequency
  - Ambient temperature variations
- Statistical analysis to establish baseline degradation rates

**Expected outputs:** Predictive maintenance models capable of forecasting component degradation and optimizing operating strategies to extend system lifetime.

### Experiment 5: Water Consumption Analysis

**Objective:** Characterize water consumption patterns under different operating conditions and develop optimization strategies for water management.

**Description:** Systematic monitoring of water consumption in relation to hydrogen production, environmental conditions, and system efficiency. This data is valuable for both operational optimization and for facilities planning hydrogen production deployment.

#### Methodology:

- Monitor water consumption rate vs. hydrogen production rate under varying conditions
- Evaluate the impact of ambient conditions on overall water efficiency
- Track water quality parameters and their effect on system performance

**Expected outputs:** Water consumption forecasting models and water management optimization strategies.

#### Data Management and Accessibility

All experimental data will be recorded locally on the electrolyzer systems and uploaded daily to the Energy Guard Data Lake with appropriate metadata tagging, including:

- Experiment identification and phase
- Operating conditions and setpoints
- Environmental parameters
- Timestamps synchronized across all sensors

The data will be made accessible to EnergyGuard platform users through CARTIF's FTP server.

### 4.3 KPIs to Validate the TEF Services

The validation of the PEM Electrolyzers TEF will be assessed through the following Key Performance Indicators:

Table 4-1. KPIs for PEM Electrolyzers TEF

| KPI name                        | KPI description                                                                                                                                | KPI validation                                                                                                                                                                    | KPI baseline                                      | KPI target values                                            |
|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|--------------------------------------------------------------|
| <b>Data Upload Completeness</b> | Percentage of scheduled daily data uploads successfully completed and ingested into the Energy Guard Data Lake without data loss or corruption | Automated monitoring of daily batch uploads. Cross-reference between data volume expected (based on operating hours and sampling rate) and data volume received in the Data Lake. | Industrial standard for batch data transfers: 99% | ≥ 99.5% successful daily uploads over the validation period. |

|                                              |                                                                                                                               |                                                                                                                                                                                                                                                              |                                             |                                                                                                                                                                                                                                                                                                                              |
|----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Historical Data Volume and Diversity</b>  | Total volume of operational data made available to the platform and coverage of diverse operating conditions.                 | Query Data Lake for total hours of operational data, number of distinct experimental conditions covered, and representation of the full operational envelope (temperature range, load range, etc.)                                                           | 0 hours at project start                    | <p>Minimum 500 hours of operational data from the two new units</p> <p>Complete dataset from validation of first two 7kW units</p> <p>Coverage of all five planned experimental campaigns</p> <p>Operating data spanning ambient temperatures from 5°C to 35°C</p> <p>Load variations from 20% to 100% of rated capacity</p> |
| <b>Remote Command Execution Success Rate</b> | Percentage of remote commands successfully executed by the electrolyzer systems when issued through the Energy Guard platform | Track all remote commands (start, stop, setpoint changes, mode changes) and verify successful execution through system status feedback.                                                                                                                      | Local control interface: 100% success rate  | ≥ 98% success rate for remote commands                                                                                                                                                                                                                                                                                       |
| <b>Control Interface Availability</b>        | Percentage of scheduled access time during which the remote-control interface is available and functional.                    | Monitoring of VPN connection status and MODBUS/API interface responsiveness during scheduled operating hours. Log successful and failed connection attempts.                                                                                                 | 99.5% (industrial control systems standard) | ≥ 99.5% availability during scheduled operating hours                                                                                                                                                                                                                                                                        |
| <b>Experimental Campaign Completion</b>      | Percentage of planned experimental conditions successfully executed across all five validation experiments.                   | Checklist-based tracking of all planned experiments covering the range of environmental conditions (temperature, humidity, seasonal variations) and operational scenarios (start-up, solar profile following, various loads, regeneration characterization). | 0% at project start                         | ≥ 95% of planned experimental conditions completed with valid data                                                                                                                                                                                                                                                           |
| <b>AI Model Development Success</b>          | Demonstration of successful AI model development for key use cases                                                            | Develop baseline models using training datasets, validate on held-out test data. Calculate prediction accuracy for:                                                                                                                                          | No existing models                          | Regeneration frequency prediction: ± 10% error ( $R^2 \geq 0.85$ )                                                                                                                                                                                                                                                           |

|                                                   |                                                                                                                      |                                                                                                                                                                            |                                                                 |                                                                                                                                                                                         |
|---------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                   | using TEF data, measured by prediction accuracy of developed models.                                                 | Regeneration cycle frequency and efficiency impact<br>Start-up energy consumption and time-to-capacity<br>Performance under renewable profile operation<br>Fault detection |                                                                 | Start-up energy prediction: $\pm 10\%$ error ( $R^2 \geq 0.80$ )<br>Daily hydrogen production forecasting: $\pm 10\%$ error ( $R^2 \geq 0.80$ )<br>Fault detection accuracy $\geq 90\%$ |
| <b>Platform Integration Documentation Quality</b> | Completeness and usability of documentation for data formats, API usage, control procedures, and safety constraints. | Documentation coverage checklist and user satisfaction surveys from external developers.                                                                                   | Standard documentation requirements for research infrastructure | 100% of data fields, API endpoints, and safety constraints documented<br>User satisfaction rating $\geq 4.0/5.0$ on documentation clarity and completeness                              |



## 5 CEA's H2 Testing and Experiment Facility

---

### 5.1 TEF services

The CEA Hydrogen testing facility is part of the Energyguard's pilot 3, related to the prognostic of electrolyzers.

The CEA facility includes the MURPHY module dedicated to the experimental testing of Solid Oxide stacks at high temperature ( $\sim[650:800]^{\circ}\text{C}$ ). It comprises four reversible stacks and all associated Balance of Plant (BoP) systems required for operation in either electrolysis or fuel cell mode. This home-made test bench was built to maximize the system efficiency and to study the impact of control strategies on it, as on the system behaviour and health management. Full access to the automation program and team expertise allows the implementation of new control strategies and features, their test and validation by detailed results analysis thanks to a high level of instrumentation.

As the project focuses on the electrolysis mode, fuel cell operations will not be included in the scope of the proposed services.

The nominal module power consumption required for the electrolysis reaction is about 10kW, corresponding to a H2 production of about 3.3 Nm<sup>3</sup>/h ( $\sim 7\text{kg/day}$ ). An efficiency of 79%LHV has been reached at the complete system scale.

The strong coupling between multiple physical domains (electrochemistry, thermofluidic, thermomechanical...) and the operation at high temperature makes the system behaviour highly complex to model and control. In addition, the use of rare materials, complex designs and sensitivity to operation parameters such as the pressure or gas composition led to high costs and limited robustness of stacks. Altogether, these factors create significant challenges in identifying optimal operating strategies to maximize stack lifetime performances. A Digital Twin (DT) approach is therefore pertinent to simulate and assess these strategies safely and efficiently.

CEA has developed a complete multi-physics dynamical model of MURPHY module. This model includes the same components than the real system, the same control logics and gives access to the same variables. This DT is used to test and validate new control strategies to de-risk their implementation on the real system. It can also be used for sensitivity analysis on overall efficiency.

The services provided by CEA's TEF are mainly oriented toward scenario testing and validation. A scenario represents a time-dependent profile defining the setpoint values to the system's control variables. This approach enables the assessment of system performance under realistic operating conditions. The main variables considered are the following:

- The current to apply on the stacks (directly linked to the H2 production rate)
- The stacks voltage required
- The stacks operating temperature
- The steam flowrate

Some of these variables are directly linked and cannot be controlled independently at each operation step. A complete description of the main high level control strategies will be provided to the user to understand the overall operation philosophy.

- Service #1: AI tool for scenario generation  
**CEA** will develop a data-driven tool aimed at defining operational scenarios consistent with given performance constraints and maximizing system efficiency and lifetime. As no direct modifications of the code deployed on the real Programmable Logic Controller (PLC) is allowable by external users, the use of input scenarios is required to control the system.
- Service #2: MURPHY Digital Twin access for scenario simulation and AI algorithm testing  
CEA provides the Digital Twin (DT) of the system for the Energyguard TEF. It will give access to users to a high-fidelity dynamic model of a solid oxide electrolysis system in order to generate data from input scenario to feed and test their AI-based algorithms developments (c.f. service #1) without the strong constraints of the real test-bench availability, the high risk and cost of real stacks operation or the CEA's severe internal security rules.
- Service #3: Experimental validation of selected scenarios on the physical MURPHY test bench  
The CEA facility MURPHY module could be used to validate selected scenarios under some conditions. The deployment of the scenario will be carried out subject to the availability of 4 stacks as well as a time slot compatible with the laboratory constraints. The scenario must have passed an operational validation via the DT (service #2).

## 5.2 Pilot 4 operation and experiments to validate the TEF services

The following picture describes the steps and procedures that will be used to validate the CEA TEF services:

The first step depends on the availability of a scenario to test. If the TEF user provides a scenario with the right format, the service #2 can be directly used. Otherwise, the TEF user can provide its requirements to the service #1 to automatically generate a compatible scenario before using the service #2. Depending on the results obtained by running the scenario with the system's DT, adaptations could be necessary on the inputs to fulfil the KPIs before obtaining a numerical validation. This validation ends the steps on the Energyguard TEF environment.

After that, depending on the real system availability and the technical feasibility, the proposed scenario could be executed. A detailed analysis is provided to end the process.

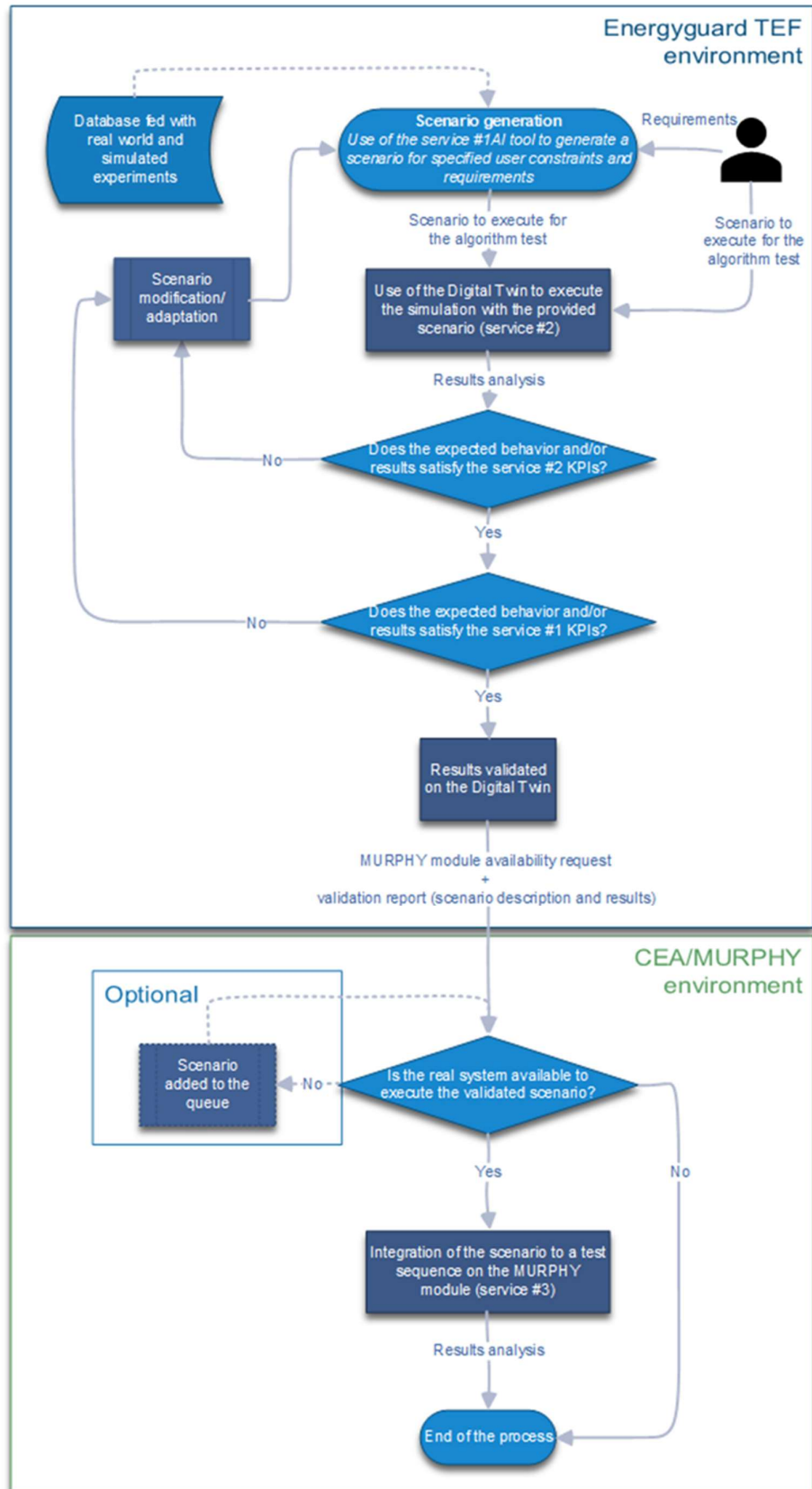


Figure 5-1. CEA TEF workflow

### 5.3 KPIs to validate the TEF services

#### 5.3.1 KPIs for Service P4.1: AI tool for scenario generation

Table 5-1. KPIs for Service P4.1: AI tool for scenario generation

| KPI name                      | KPI description                                                                          | KPI validation                             | KPI baseline                              | KPI target values  |
|-------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------|-------------------------------------------|--------------------|
| <b>Creation of a scenario</b> | The AI tool is able to create a scenario with the constraints and requirements provided. | Scenario generation.                       | Scenario available                        | Scenario available |
| <b>Tool performance</b>       | The AI tool is able to create a scenario in a reasonable time.                           | Time measured for the scenario generation. | NA (the tool doesn't exist at the moment) | <1 hour            |

#### 5.3.2 KPIs for Service P4.2: MURPHY Digital Twin access for scenario simulation and AI algorithm testing

Table 5-2. KPIs for Service P4.2: MURPHY DT access for scenario simulation and AI algorithm testing

| KPI name                                                         | KPI description                                                                                                       | KPI validation                                                                                                                                                                                     | KPI baseline                     | KPI target values                                        |
|------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|----------------------------------------------------------|
| <b>Completion of the scenario execution on the DT</b>            | Validation of the good execution of the simulation based on the sent scenario.                                        | Positive analysis of the log file obtained by the model.                                                                                                                                           | Simulation completed             | Simulation completed                                     |
| <b>Limits respected on the critical parameters and variables</b> | Respect of the system safety and functional limitations.                                                              | The scenario does not make the critical parameters and variables exceed their limits values, especially the cells voltage.                                                                         | Values inside the validity range | Values inside the validity range, no overtaking accepted |
| <b>Performances' degradation reduction</b>                       | The proposed AI-based scenario allows a quantified improvement of the stacks' performances degradation over the time. | Comparison between the degradation rate obtained with expert rules strategies. As the performance degradation is compensated by the temperature, the criteria should be the measured in °C/khours. | Expert rules scenario value      | >5%                                                      |

#### 5.3.3 KPIs for Service P4.3: Experimental validation of selected scenarios on the physical MURPHY test bench

Table 5-3. KPIs for Service P4.3: Experimental validation of selected scenarios on the physical MURPHY test bench

| KPI name                            | KPI description                                                                                           | KPI validation                                                                                                                | KPI baseline | KPI target values |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|--------------|-------------------|
| <b>Availability of the facility</b> | Secure a minimal availability of the real facility to test AI -based scenarios against expert rules ones. | The test facility is available to run a sequence with an expert rules' scenario followed by an AI-based one.                  | 1 sequence   | 1 sequence        |
| <b>Digital Twin validity</b>        | The experimental results are conformed to those obtained with the service #2.                             | Results comparisons on different topics: performances' degradation reduction, system efficiency, critical variables' limit... | <5%          | <5%               |

## 6 CARTIF's Hydrogen Technology Testing and Experiment Facility

### 6.1 TEF services

CARTIF's Hydrogen Testing Facility, located in Valladolid (Spain), is designed to enable the development, integration and validation of AI-driven control strategies and hybrid energy management approaches combining hydrogen, electricity and heat. The facility is based on an electrolyser with a production capacity of up to 500 NI/h (equivalent to 1.08 kg H<sub>2</sub> per day) and nominal energy consumption of 2.0–3.0 kW, operating at pressures up to 35 bar. It also incorporates a PEM (Proton-Exchange Membrane) fuel cell (2 kW nominal power, 48-cell stack) that enables cogeneration applications, with an operational efficiency of around 40%, a fast start-up time (<30 s), and flexible load response.

The installation is complemented by a metal hydride storage system with a capacity of 1.6 kg H<sub>2</sub> (18,000 NI), operating under 30–45 bar, with water-based cooling at 15–25°C to ensure stable thermal conditions. This configuration allows safe and reversible hydrogen storage for testing charging/discharging cycles and for coupling with renewable generation profiles.

In addition, CARTIF's facility (Figure 6-1) integrates electrical and thermal storage subsystems that enable hybrid operation and multi-energy coupling. The battery storage system (25.6 V nominal voltage, 2.56 kWh capacity) and DC/DC converters (up to 1 kW–1.5 kW, 94% efficiency) allow flexible electric interface management and testing of control algorithms. The thermal section, equipped with a 4.4 kW heat pump, 2.5 kW electrical heater, and 300L thermal tank, supports cogeneration validation and energy balance assessment under dynamic operating conditions.



Figure 6-1. CARTIF's TEF facilities

The facility also includes an advanced data acquisition and control system based on PLCs and Node-RED (Figure 6-2), communicating with all main components (electrolyser, fuel cell, hydride tank, batteries, and heat pump). It allows real-time monitoring of parameters such as temperature, pressure, flow, current, and voltage, as well as the implementation of AI-based predictive and adaptive control

strategies. The system can reproduce variable generation and demand profiles, enabling the study of renewable integration, load shifting, and storage optimization at building and microgrid scales.

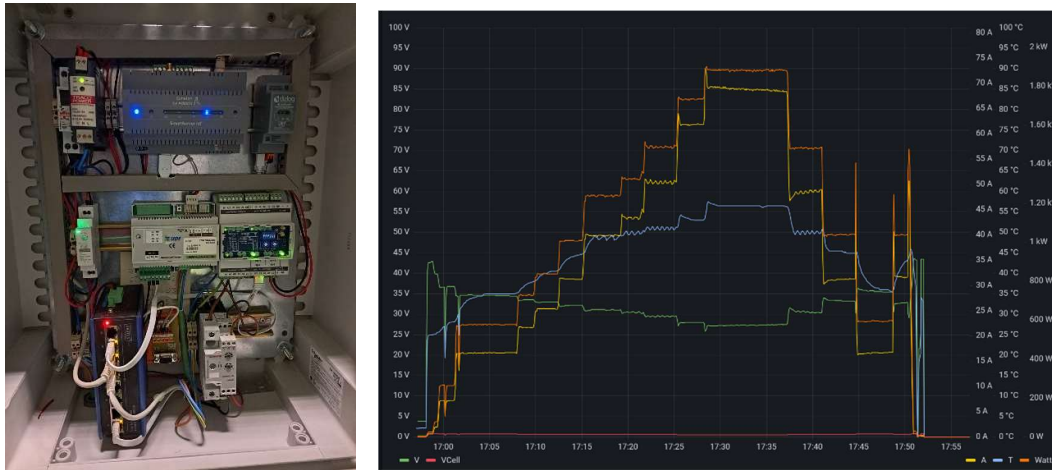


Figure 6-2. Data logger and example of data for CARTIF's TEF facilities

This facility provides a unique environment to evaluate energy flexibility strategies, hybrid storage integration, and intelligent management of hydrogen systems in low-power applications such as tertiary and residential buildings. Experimental results can be extrapolated to larger installations, supporting the design, scaling, and control optimization of future multi-MW systems.

## 6.2 Pilot 5 operation and experiments to validate the TEF services

As part of the pilot, a set of experiments will be carried out to characterise the real behaviour of the plant's main equipment, mainly focused on the electrolyser, the fuel cell and the hydrogen batteries. By running different scenarios, the outcome will allow to compare the responses with those expected from the theoretical models previously developed. The purpose of these tests is twofold: on the one hand, to characterise the different elements of the TEF by identifying operational limitations, response delays or inefficiencies that theoretical models do not always capture and subsequently incorporate them into these models; and on the other hand, to generate a solid experimental database that will allow for the adjustment of model parameters and the validation of their performance under real operating conditions.

The tests will focus on the key processes of production, conversion and energy storage. Specific operating setpoints will be applied to each subsystem in order to observe response times, stability during start-up phases, losses associated with charge and discharge cycles, and the accuracy of monitored variables under different operating regimes. The comparative analysis between the results observed in the TEF and those projected in simulation will serve to calibrate the models and ensure that they are adequately adapted to the complexity of the plant.

To run the experiments, the operation will cover a variety of dynamic load profiles reproducing renewable generation variability and building demand patterns. Tests will include start-up and shut-down sequences, partial-load operation, efficiency under variable pressure and temperature, and cycle durability of the hydrogen storage subsystem. In this sense, energy balance will be obtained to analyse the capabilities and capacities for renewable production and demand coverage.

The TEF will operate under supervised control via the PLC-based data acquisition system, enabling high-frequency monitoring of temperature, voltage, current, pressure, flow, and efficiency indicators. These datasets will populate the AI-driven Digital Twin environment, allowing real-time comparison between measured and simulated values. Deviations will be analysed to refine predictive models, particularly in transient regimes such as electrolyser ramp-up, fuel cell switching, and hydride tank charge/discharge transitions.

### 6.3 KPIs to validate the TEF services

The validation of the TEF services will rely on a comprehensive set of KPIs designed to assess the effectiveness, reliability, and scalability of the CARTIF Hydrogen Testing Facility in supporting AI-enabled experimentation. These KPIs will quantify the facility's ability to (i) reproduce realistic operating conditions for hydrogen production, storage, and conversion; (ii) validate Digital Twin and AI-based control models; and (iii) ensure replicability of results across other TEFs and use cases.

#### 6.3.1 KPIs for Service P5.1: Experimental validation and model calibration

Table 6-1. KPIs for CARTIF's TEF service P5.1: Experimental validation and model calibration

| KPI name                             | KPI description                                                                                       | KPI validation                                           | KPI baseline           | KPI target values                              |
|--------------------------------------|-------------------------------------------------------------------------------------------------------|----------------------------------------------------------|------------------------|------------------------------------------------|
| <b>Model accuracy index</b>          | Quantifies deviation between simulated and experimental variables (e.g., temperature, current, flow). | Statistical comparison of time-series data (RMSE, MAPE). | ±10% average deviation | < ±5% deviation across all monitored variables |
| <b>System response time</b>          | Time required for electrolyser and fuel cell to reach steady-state after a new setpoint.              | Dynamic response tests under load step changes.          | > 60s average          | < 30s for 90% of test cases                    |
| <b>Operational data completeness</b> | Proportion of data successfully recorded, processed, and integrated in the AI Data Lake.              | Automated logging validation through PLC/Node-RED.       | 85% completeness       | ≥ 95% completeness                             |

#### 6.3.2 KPIs for Service P5.2: AI-based predictive control and optimization

Table 6-2. KPIs for CARTIF's TEF service P5.2: AI-based predictive control and optimization

| KPI name                                        | KPI description                                                               | KPI validation                                                | KPI baseline | KPI target values |
|-------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------|--------------|-------------------|
| <b>Prediction accuracy of AI models</b>         | Measures forecasting error for energy demand and hydrogen production.         | AI model validation (MAE, R <sup>2</sup> ).                   | MAE = 0.15   | MAE ≤ 0.05        |
| <b>Energy cost reduction through AI control</b> | Quantifies reduction in energy consumption due to AI optimization strategies. | Comparison between baseline control and AI control scenarios. | 0%           | ≥ 10% reduction   |
| <b>Renewable energy utilization rate</b>        | Ratio of renewable input energy used in hydrogen production.                  | Energy balance analysis.                                      | 70%          | ≥ 90%             |
| <b>Ratio H2 stored energy vs renewable</b>      | Ratio of energy stored in the H2 system versus the renewable input energy.    | Energy balance analysis.                                      | n.a.         | > 65%             |

|                                                 |                                                                              |                                               |      |       |
|-------------------------------------------------|------------------------------------------------------------------------------|-----------------------------------------------|------|-------|
| <b>Ratio battery stored energy vs renewable</b> | Ratio of energy stored in the batteries versus the renewable input energy.   | Energy balance analysis.                      | n.a. | > 30% |
| <b>Ratio H2 cell energy vs energy demand</b>    | Ratio of energy generated by the H2 cell versus the energy that is demanded. | Energy balance analysis.                      | n.a. | < 30% |
| <b>Net consumed energy</b>                      | Energy that is used from the grid.                                           | Energy balance analysis.                      | n.a. | < 30% |
| <b>Hydrogen storage cycle efficiency</b>        | Ratio between energy recovered and energy input per cycle.                   | Experimental test of charge/discharge cycles. | 80%  | ≥ 90% |

Related to the KPIs and baseline calculation, Figure 6-3 includes some experiments carried out prior EnergyGuard project and provides the overview of the performance of the operative paraments when using or not the H2.

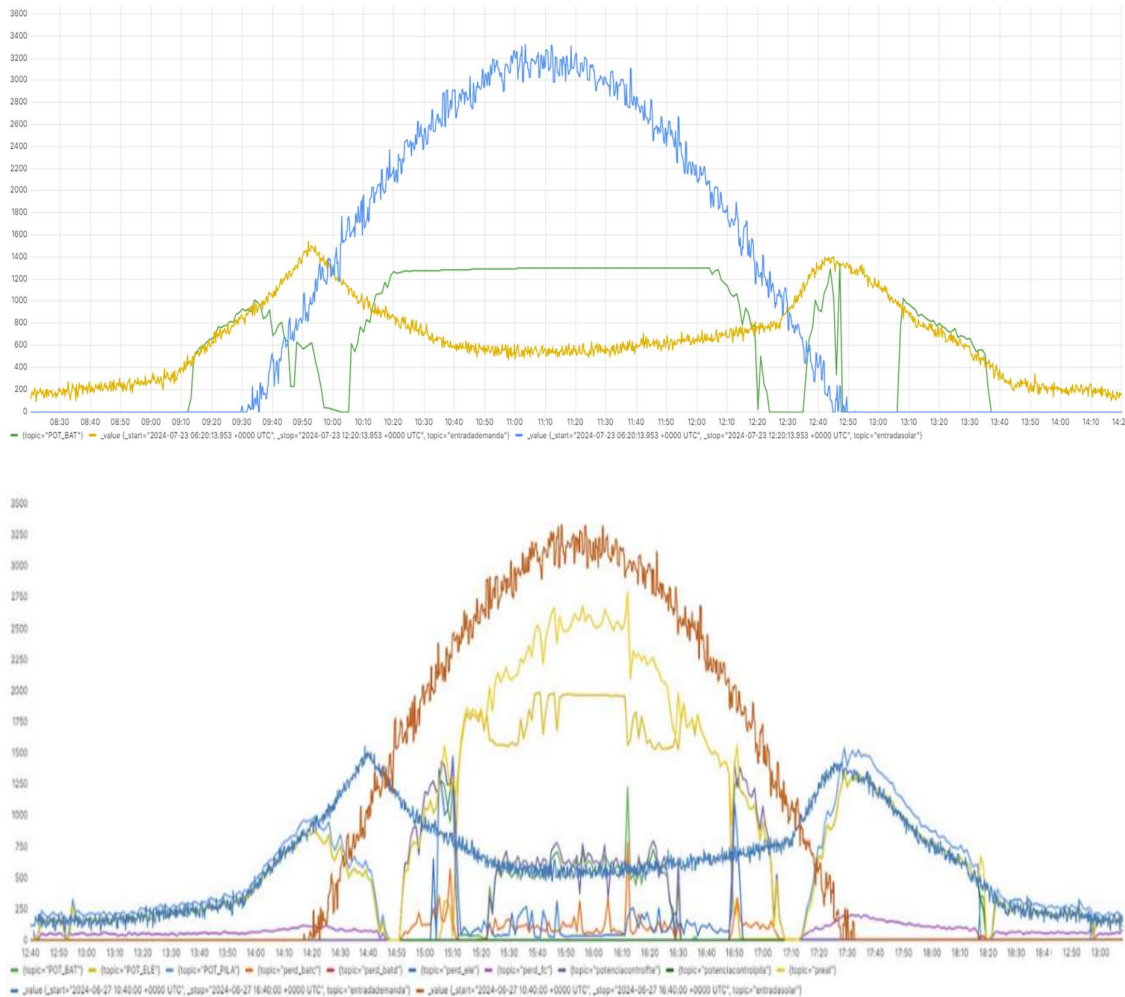


Figure 6-3. Baseline calculations for the CARTIF's TEF KPIs (without and with H2)

### 6.3.3 KPIs for Service P5.3 Hybrid energy integration and flexibility analysis

Table 6-3. KPIs for CARTIF's TEF service P5.3: Hybrid energy integration and flexibility analysis

| KPI name                                      | KPI description                                                                                              | KPI validation                                    | KPI baseline            | KPI target values |
|-----------------------------------------------|--------------------------------------------------------------------------------------------------------------|---------------------------------------------------|-------------------------|-------------------|
| <b>System flexibility index</b>               | Ability of the integrated system (electrical, thermal, and hydrogen) to adapt to variable generation/demand. | Evaluation of load-following performance.         | Flexibility ratio = 0.6 | ≥ 0.85            |
| <b>Thermal–electrical coupling efficiency</b> | Performance of heat recovery and utilization in cogeneration mode.                                           | Measurement of heat pump and FC thermal exchange. | 70%                     | ≥ 85%             |



## 7 REA/SCCB's Digital Twin-Assisted and AI-driven Building Energy Efficiency Decision Support Testing and Experiment Facility

### 7.1 TEF services

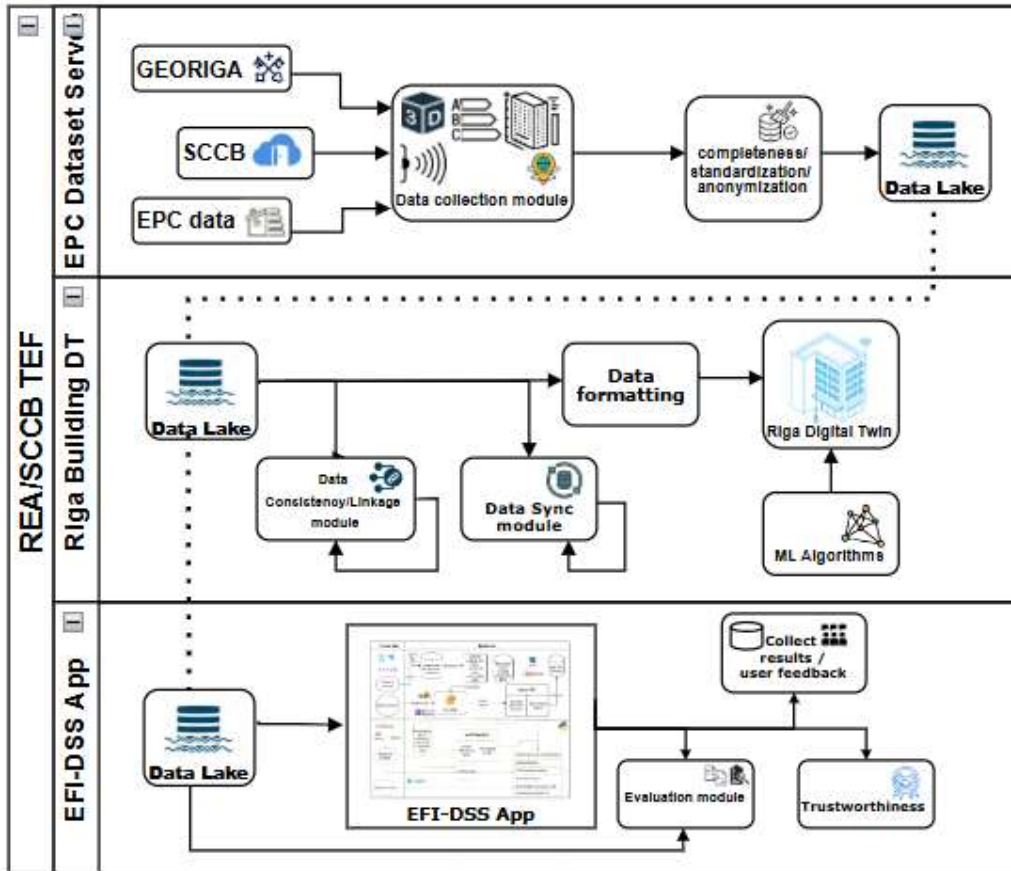


Figure 7-1. REA/SCCB TEF Services Diagram

The Riga pilot will provide three TEF services, shown in Figure 7-1, which will be accessible through the EnergyGuard TEF:

#### 1. EPC Dataset Service

- Provides harmonised EPC data stored in the EnergyGuard Data Lake, including geometry, construction year, energy class, heating type, and calculated consumption.
- Available to EnergyGuard clients (AI developers, SMEs, and researchers) for training and validating AI models on building energy efficiency.

#### 2. Digital Twin of Riga Buildings

- A geospatial representation of Riga's multi-apartment buildings enriched with building consumptions and energy-related attributes from EPCs.
- Enables developers to visualise, query, and integrate building-level energy data into their applications.

#### 3. EFI-DSS Application Service

- An AI-driven decision-support tool that predicts the impact of renovation actions and supports funding or policy planning.
- Accessible to REA's public clients (municipalities, energy agencies, funding organisations, household owners) via EnergyGuard's web interface.

The three services demonstrated in the Riga pilot together form a coherent workflow inside the EnergyGuard TEF. Data from EPC records feed the Data Lake, are visualised and structured through the Digital Twin, and finally drive the EFI-DSS decision-support tool used by REA and its stakeholders. Their combined operation validates the full data-to-decision chain of the TEF, showing how EnergyGuard can provide both developers, public authorities, and household owners with an integrated environment for testing, training, and applying AI-based building-efficiency solutions.

## 7.2 Pilot 6 operation and experiments to validate the TEF services

The REA/SCCB pilot demonstrates the use and validation of these services under real urban conditions.

### 1. Testing the service P6.1: EPC Dataset Service

- Ingest EPC data into the EnergyGuard Data Lake following the harmonised schema.
- Evaluate data completeness, metadata standardisation, and interoperability through API queries.
- Test dataset accessibility by external developers through EnergyGuard's sandbox.

### 2. Testing the service P6.2: Digital Twin

- Integrate EPC data with GeoRiga building geometries to create the baseline twin.
- Validate data consistency and linkage between EPC entries and spatial objects.
- Verify that newcoming or corrected consumptions and/or EPC records are automatically updated in the twin.

### 3. Testing the service P6.3: EFI-DSS Application Service

- Run the AI-based decision-support tool using EPC data from the Data Lake.
- Compare predicted renovation recommendations with existing audit data for validation.
- Gather user feedback from REA staff, municipal energy experts, and household owners on usability and decision-support effectiveness.
- Use the EnergyGuard AI development and Trustworthiness Acceptance Environments to assess the effectiveness and trustworthiness of EFI-DSS.

## 7.3 KPIs to validate the TEF services

### 7.3.1 KPIs for P6.1: EPC Dataset Service

Table 7-1. KPIs for P6.1: EPC Dataset Service

| KPI name                        | KPI description                                               | KPI validation       | KPI baseline         | KPI target values  |
|---------------------------------|---------------------------------------------------------------|----------------------|----------------------|--------------------|
| <b>Metadata standardization</b> | % of fields compliant with EnergyGuard schema                 | Data audit           | Inconsistent formats | 100 % standardised |
| <b>Metadata completeness</b>    | % of EPC entries containing all essential building attributes | Automated data check | Fragmented data      | ≥ 90 %             |

(geometry, energy class,  
heating type, etc.)

|                                     |                                                |            |   |                         |
|-------------------------------------|------------------------------------------------|------------|---|-------------------------|
| <b>Accessibility for developers</b> | No. of external TEF users who accessed dataset | Usage logs | 0 | ≥ 10 developers/testers |
|-------------------------------------|------------------------------------------------|------------|---|-------------------------|

### 7.3.2 KPIs for P6.2: Digital Twin Service

Table 7-2. KPIs for P6.2: Digital Twin GeoRIGA Service

| KPI name                        | KPI description                                                                                                                                | KPI validation                     | KPI baseline                                    | KPI target values         |
|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|-------------------------------------------------|---------------------------|
| <b>Digital twins created</b>    | Number of buildings represented in the Digital Twin environment                                                                                | Count within GeoRiga platform      | 0                                               | 20 buildings              |
| <b>System update latency</b>    | Time between EPC update and visual refresh in GeoRiga                                                                                          | Log timestamps                     | Manual update process                           | < 1 day                   |
| <b>Awareness and engagement</b> | Number of residents, building managers, and municipal users informed or involved in GeoRiga visualisation and renovation awareness activities. | Attendance lists, feedback surveys | Initial awareness limited to REA internal users | ≥ 100 individuals engaged |

### 7.3.3 KPIs for P6.3: EFI-DSS

Table 7-3. KPIs for P6.3: EFI-DSS

| KPI name                                                 | KPI description                                                                                                                                                                                                                              | KPI validation                                                                    | KPI baseline                                                         | KPI target values    |
|----------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------|
| <b>Prediction accuracy</b>                               | Match between predicted and real EPC class ( $\Delta\text{EPC} \leq 1$ class)                                                                                                                                                                | Automated data check                                                              | –                                                                    | ≥ 90 %               |
| <b>Explainability</b>                                    | % of test users who report understanding why the tool made a given recommendation                                                                                                                                                            | Short survey                                                                      | Currently no XAI available                                           | ≥ 4/5 clarity rating |
| <b>Time reduction</b>                                    | Reduction in time needed to assess current building performance compared to manual audits                                                                                                                                                    | Comparison with current REA audit process                                         | ~2 weeks                                                             | ≥ 95 %               |
| <b>Training and knowledge uptake</b>                     | Number of experts or public authority staff trained to use and interpret EFI-DSS results.                                                                                                                                                    | Attendance lists, feedback surveys                                                | 0 (training not started)                                             | ≥ 50 trained users   |
| <b>Renovation solutions for multi-apartment building</b> | Number of multi-apartment buildings in Riga for which renovation solution scenarios, energy-saving forecasts, investment estimates, and payback calculations are made available through the EFI-DSS application and the GeoRiga Digital Twin | The KPI will be validated through EFI-DSS usage logs and GeoRiga integration data | 0 – no digital renovation scenarios available EFI-DSS implementation | ≥ 100 buildings      |



## 8 ENGREEN's Enhancing performance of Renewable Energy Community Facilities through AI experiments Testing and Experiment Facility

---

### 8.1 TEF services

The ENGREEN Testing and Experimentation Facility (TEF) focuses on validating and demonstrating AI-driven tools and services designed to enhance the performance and management of Renewable Energy Communities (RECs). It provides an integrated environment that combines real-world operational data, simulation models, and Digital Twins to evaluate how artificial intelligence can improve energy efficiency, cost-effectiveness, and system reliability within distributed renewable ecosystems.

Building upon the EnergyGuard Data Lake and monitoring infrastructure, the ENGREEN TEF enables developers, researchers, and SMEs to test AI-based approaches and tools across multiple functional domains relevant to REC operation. Rather than focusing on a single application, the ENGREEN TEF provides a flexible, modular testing environment that accommodates diverse experimental configurations and data-driven services. It supports the development and benchmarking of algorithms for short-term forecasting, flexibility activation, energy balancing, and maintenance optimisation under realistic operating conditions, using real REC datasets as ground truth.

To build trust in AI-enabled solutions and demonstrate their benefits in real REC environments, the AI tools are evaluated through experiments based on actual operational data across eight REC key domains:

- a. Demand Management – predicting demand peaks and optimising energy consumption;
- b. Intelligent Battery Use – determining optimal charging and discharging cycles;
- c. Grid Integration – forecasting energy flows and flexibility requirements;
- d. Dynamic Pricing – linking real-time prices to variations in supply and demand;
- e. Integration of Energy Sources – coordinating multiple renewable inputs;
- f. Production Optimisation – improving efficiency through data-driven forecasting;
- g. Predictive Maintenance – anticipating faults to enhance system reliability;
- h. REC Planning – defining strategies to improve and expand community performance.

The findings generated form the basis for the four ENGREEN TEF services. Each service draws directly on validated results from one or more of the eight domains (a-h), ensuring that the knowledge developed through testing is translated into practical operational support. Table 8-1 summarises the four ENGREEN TEF services, describes the potential features of the AI tools that could support each service, and outlines the expected benefits for the REC.

The first service, the “Smart Energy Optimiser”, is intended to help the REC balance energy demand and battery storage more effectively. Using AI tools, it aims to identify favourable moments to shift, store or use energy, which could result in smoother load profiles, higher self-consumption and a more efficient use of community resources. The service may also indicate when surplus energy could be exported to the grid or when imports might be required, offering insights into potential future flexibility services. Overall, these capabilities are expected to support more informed operational decisions and contribute to a more stable and efficient community energy system.

The “Fair Dynamic Pricing” is the second service. It is designed to assist the REC in identifying the most advantageous moments for electricity use by analysing retail tariff signals, expected price variations in members’ supply contracts, and local renewable generation patterns. By examining how these factors evolve throughout the day, the service is expected to help the community maximise the value of self-consumption and benefit from more transparent and predictable cost structures. The AI tools behind this service are expected to model dynamic consumption strategies, identify optimal time windows for electricity use and battery operation, and assess the cost–benefit implications of different behavioural choices. These insights are intended to support better-informed decisions by REC users, ultimately contributing to lower expenditure and a more efficient use of locally produced renewable energy.

The third service, the “Multi-Source Planning Suite”, is conceived to support the medium- and long-term development of the REC by assessing how different combinations of energy sources, assets and community configurations might perform over time. Using AI tools that evaluate technical performance, the service aims to identify future configurations that balance efficiency, sustainability and investment feasibility. These tools are expected to simulate the integrated operation of multiple energy sources, model expansion scenarios using historical and real-time data, and estimate long-term impacts on energy balance. In doing so, the service may provide a data-driven basis for decisions regarding new renewable assets, additional members or expanded storage capacity.

The fourth service, “Predictive Maintenance Monitoring”, is designed to strengthen the reliability and continuity of REC operations by identifying efficiency deviations, detecting anomalies, and anticipating potential equipment failures. By analysing real-time and historical data from key assets (e.g., PV inverters, battery storage systems, smart meters), the service aims to reduce unexpected system interruptions and lower maintenance costs. The enabling AI tools are expected to recognise unusual operational patterns, forecast emerging malfunctions, and generate transparent and actionable maintenance alerts. These predictive insights are intended to support timely and well-informed interventions, ultimately contributing to a safer, more efficient, and more resilient community energy infrastructure.

Table 8-1. ENGREEN TEF services

| TEF service                           | Potential AI Tools features                                                                                                                                                                             | Expected Outcomes for the REC                                                                                                                                                     |
|---------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>1. Smart Energy Optimiser</b>      | Analyses consumption and production patterns; simulates demand management; optimises battery charging and discharging; forecasts short-term demand; indicates surplus export and grid import needs.     | Lower peak demand; higher self-consumption; better battery use; reduced grid purchases; fewer unused surpluses; improved system stability.                                        |
| <b>2. Fair Dynamic Pricing</b>        | Analyses retail tariffs and local generation patterns; models dynamic consumption strategies; identifies cost-effective usage windows; provides clear pricing and incentive-allocation recommendations. | Lower expenditure; improved value from self-consumption; more transparent and predictable cost structures; enhanced alignment between consumption and local renewable production. |
| <b>3. Multi-Source Planning Suite</b> | Simulates the operation of multiple energy sources; models expansion scenarios using historical, real-time, and                                                                                         | More reliable medium-/long-term planning; reduced uncertainty in investment choices; improved system resilience; data-driven                                                      |

#### 4. Predictive Maintenance Monitoring

Digital Twin data; estimates long-term impacts on the energy balance; assesses technical feasibility and projected performance; compares planning options.

Analyses real-time and historical performance data from REC assets; identifies efficiency deviations and operational anomalies; predicts potential equipment malfunctions; generates transparent, explainable, and actionable maintenance alerts to support timely interventions.

support for future asset deployment, additional members or expanded storage capacity.

Reduced likelihood of unexpected system interruptions; lower maintenance and operational costs; improved asset reliability, safety, and efficiency; more timely and informed maintenance actions.

## 8.2 Pilot 7 operation and experiments to validate the TEF services

The experiments associated with Pilot 5 – Enhancing Performance of Renewable Energy Community Facilities through AI Experiments will be set up and conducted within the ENGREEN TEF, in collaboration with HAL and other partners. The pilot will demonstrate how the use of high-quality, real operational data (“ground truth observations”) from the EnergyGuard TEF enables comprehensive testing of AI solutions for RECs, supporting innovation, scalability, and reproducibility. Ultimately, the experiments will validate the four TEF services within the REC domain.

The implementation plan foresees three main stages to determine whether the AI tools powering the services can deliver improvements over the current situation:

**Integration and Setup:** Configuration of the EnergyGuard TEF environment for REC data acquisition and storage, including connection to monitoring systems, battery controllers, and other distributed assets. Digital twin models of community-level energy exchanges and grid interfaces will be integrated to enable safe, repeatable experimentation.

**Execution of AI Experiments:** The execution phase will consist of a set of experiments designed to assess how each TEF service performs when applied to real REC data and operational conditions.

- For the Smart Energy Optimiser, experiments will run optimisation routines using real consumption, production and battery data. These tests will explore whether the AI tools can identify favourable moments to shift, store or use energy, and whether the resulting operational strategies could reduce peak loads, increase self-consumption or make more effective use of the REC’s battery system. The experiments will also examine whether the optimiser provides early indications of periods when surplus energy may be available for export or when grid imports might be required, offering preliminary insights into possible flexibility services.
- For the Fair Dynamic Pricing, the experiments will apply AI-based pricing and cost-optimisation strategies to real tariff data and local energy production and consumption patterns. The testing activities will assess whether the AI can identify the most cost-effective windows for electricity use and battery operation, and whether these recommendations can enhance the economic value of self-consumption and reduce overall energy expenditure within the REC.
- For the Multi-Source Planning Suite, experiments will involve running scenario-analysis routines based on historical, real-time, and Digital Twin data. The objective is to determine whether AI

tools can reliably simulate alternative future configurations of the REC, such as new renewable assets, expanded storage capacity, or additional members, and estimate their long-term impacts on the energy balance and technical performance. The tests will evaluate whether these planning outputs are coherent, realistic and potentially helpful in guiding medium- and long-term decision-making.

- For the Predictive Maintenance Monitoring, the experiments will use real performance measurements from key REC assets to evaluate the AI tools' ability to detect efficiency losses, identify anomalies, and anticipate potential malfunctions. The tests will assess whether system-efficiency deviations are detected in a timely and accurate manner, whether alerts are actionable, and whether these predictive insights can support more effective maintenance decisions and reduce the likelihood of unexpected system interruptions.

**Evaluation and Validation:** The validation phase will assess whether the AI tools used in the four TEF services deliver measurable improvements compared to the REC's baseline performance. This assessment will combine results from digital simulations with evidence derived from real operational data, ensuring that the conclusions reflect both controlled test conditions and actual REC behaviour. Validation activities will focus on verifying whether the optimisation strategies, pricing recommendations, planning outputs and predictive maintenance alerts generated by the AI tools translate into concrete benefits for the REC. The analysis will use the KPIs defined in the following section to evaluate changes.

Through these stages, ENGREEN's TEF will play a central role in demonstrating the benefits of AI experimentation in real-world REC environments, showcasing EnergyGuard's capability to bridge the gap between algorithm development and deployment-ready solutions.

### 8.3 KPIs to validate the TEF services

The validation of the ENGREEN TEF services will rely on a set of Key Performance Indicators (KPIs) designed to assess the overall effectiveness, robustness, and added value of the AI-based solutions tested within the facility.

These KPIs apply to all experimental activities implemented within the ENGREEN TEF, regardless of their specific focus, such as demand management, intelligent battery use, integration with the power grid, dynamic pricing, integration of energy sources, production optimisation, or predictive maintenance for REC planning.

This approach ensures a harmonised evaluation framework across different experimental scenarios, facilitating comparability and scalability of results within the EnergyGuard ecosystem.

Table 8-2. ENGREEN TEF KPIs

| KPI name                        | TEF service                          | KPI description                                                                                         | KPI validation                                                                  | KPI baseline values | KPI target value |
|---------------------------------|--------------------------------------|---------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------|------------------|
| AI Experiment Success Rate      | All                                  | Percentage of planned AI experiments successfully completed within the ENGREEN TEF                      | Experiment tracking and log analysis                                            | 0%                  | 90%              |
| Data Integrity and Availability | All                                  | Percentage of REC operational data successfully stored and accessible through the EnergyGuard Data Lake | Automated data validation                                                       | -                   | 90%              |
| Increase in Self-Consumption    | 1. Smart Energy Optimiser            | Measures the increase in the share of locally generated renewable energy consumed within the REC        | Comparison between baseline and AI-enhanced scenarios                           | -                   | 8%               |
| Energy Cost Reduction           | 2. Fair Dynamic Pricing              | Average percentage reduction in community energy cost achieved through AI-based operation               | Comparison between baseline and AI-enhanced scenarios                           | -                   | 10%              |
| Renewable Utilisation Rate      | 3. Multi-Source Planning Suite       | Share of renewable energy consumed or stored locally within the community                               | Energy balance analysis                                                         | -                   | 50%              |
| System Efficiency               | 4. Predictive Maintenance Monitoring | Measures a set of energy efficiency indicators for each key system component of REC assets.             | Comparison between baseline performance data and AI-predicted efficiency values | -                   | 10%              |



## 9 Platform-level assessment KPIs for EnergyGuard TEF

The evaluation framework of the platform-level KPIs rely on the following KPIs:

Table 9-1. Platform-level KPIs for EnergyGuard TEF

| KPI name                                                         | KPI description                                                                                                        | KPI validation                                                                                                                          | KPI baseline values                                                                                                                                             | KPI target value             |
|------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|
| <b>Time to market</b>                                            | Decrease in time to bring a validated, trustworthy AI product to the energy market                                     | Measured through the feedback of targeted facility owners                                                                               | 1 year                                                                                                                                                          | 15%                          |
| <b>Cost reduction</b>                                            | Cost reduction of testing AI solutions for the energy sector                                                           | Measured through feedback from EnergyGuard pilot users                                                                                  | Average cost for each pilot to test the solution before the use of EnergyGuard TEF (e.g.avg. 5k-60k €: <a href="#">source 1</a> , <a href="#">source 2</a> )    | Decrease 20%                 |
| <b>Technical, legal and ethical breaches</b>                     | No of cybersecurity vulnerabilities and critical ethical and legal breaches detected in accepted EnergyGuard solutions | Measure through the life cycle analysis of the AI solution in the EnergyGuard TEF                                                       | N/A                                                                                                                                                             | 0                            |
| <b>Scientific discovery</b>                                      | Potential for new breakthrough scientific discovery based on EnergyGuard facilities (grids, hydrogen and storage)      | Measured by new techno-scientific publications referring the use of the EnergyGuard TEF                                                 | High                                                                                                                                                            | High (1 for each pilot site) |
| <b>Environmental impact of training and testing AI solutions</b> | Reduced environmental impact of training and testing AI solutions through EnergyGuard                                  | Measure the environmental impact (resources usage – co2 emissions calculator) based on resources usage outside and with EnergyGuard TEF | Resource usage and emissions for each pilot experiment outside EnergyGuard (use of <a href="#">CodeCarbon</a> ) – (avg 652 kg of CO2e: <a href="#">source</a> ) | Decrease 30%                 |

### 9.1 General timeline for pilot evaluation

Figure 9-1 depicts the general timeline for the evaluation of the pilots and TEF services. The current document presents the work for the first twelve months, namely, the definition of the evaluation framework, including general and specific KPIs, as well as development of digital twins and related services specific for each pilot site.

The next phase will end at month twenty-two with the publication of the second deliverable of the EnergyGuard – WP6. It includes further technical development and the first phase of testing and the next deliverable of the EnergyGuard – WP6 will include the evaluation, impact assessment and lessons learnt from the first phase of TEF usage.

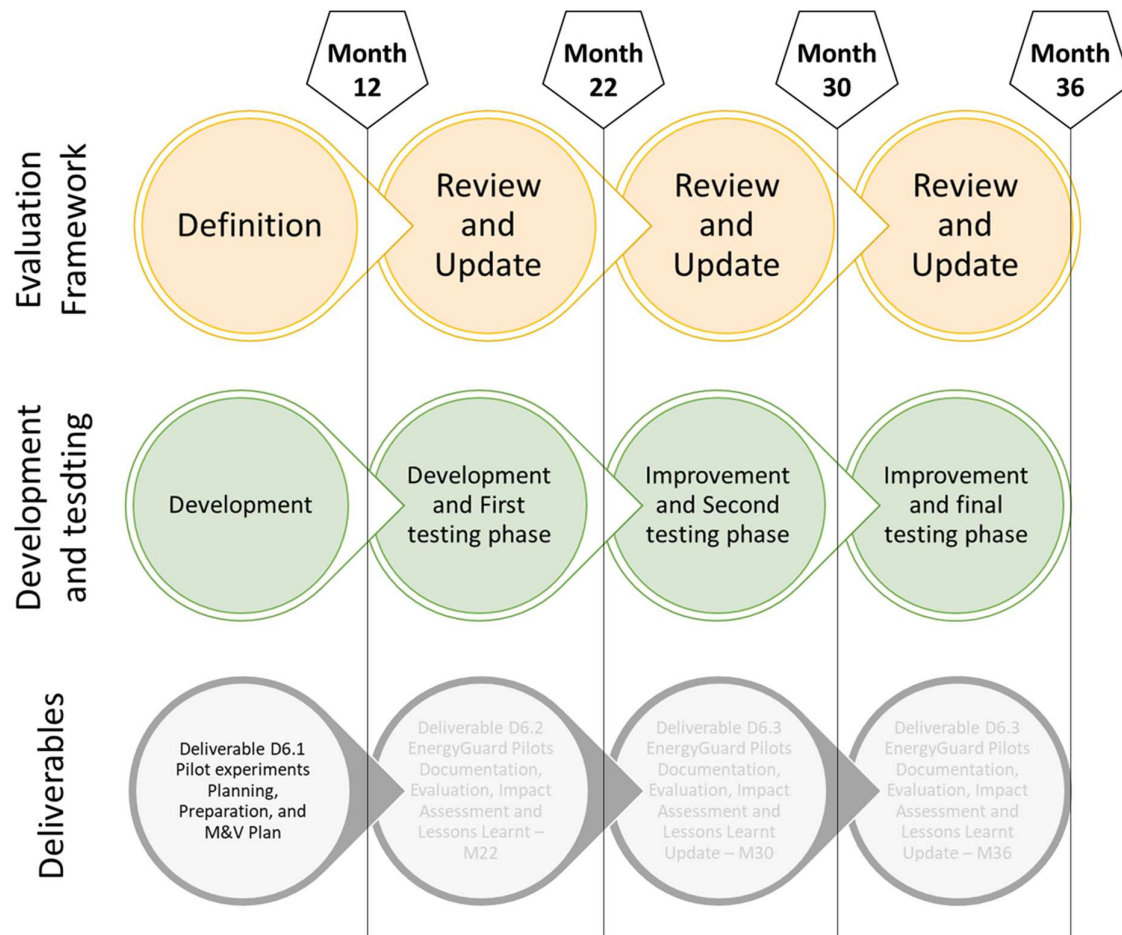


Figure 9-1. Timeline for the evaluation of pilots and TEF services.

---

## 10 Summary and Conclusion

---

Deliverable D6.1 outlines the planning, preparation, and measurement and verification (M&V) framework that will guide the implementation of pilot experiments across all EnergyGuard Testing and Experimentation Facilities (TEFs). It establishes the methodological foundation for Work Package 6 (WP6), ensuring consistency and alignment among the various pilot activities carried out within the EnergyGuard ecosystem.

The TEFs described in this deliverable are key components of the EnergyGuard infrastructure, enabling AI tools' testing and upscale across multiple energy vectors and across the full energy value chain. The electricity grid is represented by the R&D Nester's TEF provides a large-scale Digital Twin environment for transmission grid analysis and validation of grid-related services, and by the CIEMAT's facility enables hands-on experimentation with hybrid renewable microgrids. Hydrogen is represented by the BER, CEA, and CARTIF TEFs, contributing advanced hydrogen testing infrastructures that integrate production, storage, and utilisation within AI-supported operational frameworks. Heat is represented by the CARTIF and the REA/SCCB TEFs. Furthermore, the REA/SCCB and ENGREEN TEFs extend the EnergyGuard concept to the building and community scales, showcasing how data-driven and AI-assisted decision-making can improve energy efficiency and renewable energy integration in both urban and distributed settings. Together, these pilots form a comprehensive and interoperable ecosystem designed to validate digital and AI-based solutions across multiple layers of the energy value chain. Moreover, the deliverable defines the steps and procedures for the deployment and operation of each TEF, describing the associated data management processes, experiment configurations, and performance evaluation methodologies.

The next steps will focus on the practical implementation of the experimental setups described in this deliverable and the systematic collection of Key Performance Indicator (KPI) data to assess the technical and operational performance of the EnergyGuard TEF services. The outcomes of these activities will be consolidated and analysed in future deliverables, providing evidence of EnergyGuard's role in bridging the gap between AI innovation and real-world energy system operation, and supporting the transition toward a secure, resilient, and sustainable digital energy ecosystem.



## Annex I: References

---

- [1] [R&D Nester - Homepage](#)
- [2] [Home - ceder - RDGroups](#)
- [3] [CEA-Liten - CEA-Liten website Homepage](#)
- [4] [Home - CARTIF](#)
- [5] [Home - Bluenergy Revolution](#)
- [6] [GEO RĪGA](#)
- [7] <https://engreen.world/en/about-us/>
- [8] HAL, ICCS, RDN, CIEMAT, CEA, CARTIF, REA, BER, MS, LXP, FORA, ENGREEN, SCCB, EnergyGuard Project Deliverable D2.1 “Landscape review analysis, EnergyGuard User requirement and specifications”, 2025.