

REPORT

D4.1 First requirements and implementation plan

WP4 Sustainable energy strategy with artificial intelligence: Dynamic energy efficiency control

Title of the work package: **AI-Driven buildings**

Responsible partner: **Slovak University of Technology in Bratislava**

Partners: IT4Innovations (VSB), Asseco CE, DFKI, TSK

November 2025

www.innovaite.sk



Financované
Európskou úniou
NextGenerationEU

PLÁN [OBNOVY]



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A ZNALOSTNÚ EKONOMIKU

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Revision history			
Version	Date	Comment	Author
v1	02.10.2025	First draft	SvF STU
v2	10.10.2025	Editing	SvF STU, IT4I
v3	23.10.2025	Editing	Asseco, IT4I, EMOS, SvF STU
v4	06.11.2025	Editing	Asseco, IT4I
v5	14.11.2025	Compilation review	SvF STU, IT4I
v6	21.11.2025	Formatting, review	SvF STU
v7	25.11.2025	Editing	DFKI, TSK, IT4I
v8	27.11.2025	Final review	SvF STU

1 Executive summary

This document forms part of Deliverable D4.1 within Work Package 4 (AI in Building Energy Management) of the InnovAite project. The purpose of this deliverable is to provide a comprehensive overview of the user requirements collected during the initial phase of the project and to translate them into clear research priorities and an implementation plan for WP4.

The analysis focuses on the needs of building owners, tenants, facility managers, energy providers, and municipalities in relation to energy efficiency, comfort, and digital transformation. Key requirements include improved prediction and control of energy consumption, integration of renewable energy sources, user-friendly building management systems, and advanced “what-if” scenario simulations supported by artificial intelligence.

Based on these findings, research priorities for WP4 are defined, covering the development of building digital twins, advanced optimization algorithms, predictive maintenance, and validation of AI-based methods in real environments. The deliverable also specifies relevant data sources, their optimal ranges, and methodologies for preprocessing and validation to ensure high-quality inputs for subsequent research and development tasks.

Finally, the document sets out the implementation plan for WP4, defining milestones, partner responsibilities, and interconnections with other work packages. The outcomes of D4.1 provide the foundation for the subsequent deliverables (D4.2, D4.3, D4.4), which will report on research progress, methodological validation, and real-world deployment.

2 Introduction

The research and analysis presented in this document was conducted as part of the InnovAite project, within Work Package 4 (AI-Driven buildings), coordinated by the Slovak University of Technology in Bratislava, Faculty of Civil Engineering, in collaboration with project partners IT4Innovations at VSB-TU Ostrava, Asseco Central Europe, and DFKI.

The aim of this initial phase is to gather the perspectives of building owners, facility managers, energy managers, energy efficiency experts regarding energy efficiency, comfort, and digital transformation in the built environment. The objective is to identify their needs and expectations, and to determine whether advanced digital tools and artificial intelligence can support measurable improvements in building performance.

The report provides the foundation for defining research priorities, specifying data sources, and outlining the implementation plan for WP4, which will serve as the basis for subsequent deliverables and validation activities.

3 Project Context and Objectives of WP4

The *InnovAlte Slovakia: Illuminating Pathways for AI-Driven Breakthroughs* project (TIC call 09I02-03-V2) is funded by the **Recovery and Resilience Plan – NextGenerationEU**. It lasts 30 months (M1 → M30) and brings together 11 partners from academia, the private and public sector, led by Gratex International, a.s. The main objective is to *"advance the state of knowledge in the field of artificial intelligence applications across multiple domains and deliver measurable innovations that will support economic growth, sustainability, and quality of life during the project implementation period."*

This document defines how the InnovAlte project advances the application of artificial intelligence in the field of building energy management. The strategy of WP4 is closely linked to the project's overall ambition of enabling sustainable, data-driven, and intelligent solutions for the built environment. WP4 builds upon requirements from stakeholders and translates them into research, development, and validation activities that support energy efficiency, comfort, and digital transformation of buildings. The objectives of WP4 can be summarized as follows:

O4.1: Enable AI dynamic (flexible) management of energy supply and consumption with regard to economics, energy efficiency, and carbon footprint minimization, by creating an AI-intelligent superstructure on top of existing EMS systems.

O4.2: Introduce modern AI/ML algorithms to improve current EMS solutions and optimize the building management in connection with O 4.1.

O4.3: Create a functional multidisciplinary connection of the addressed topic (AI and energy domains). Every step will be communicated with the potential users and EMS system developers to ensure the highest level of quality and relevance to the users.

By fulfilling these objectives, WP4 ensures that the InnovAlte project contributes to reducing energy consumption and emissions in the building sector while improving user comfort and supporting Europe's transition towards sustainable and intelligent building stock.

3.1. Key deliverables WP4

Code	Name	Due date (M)
D4.1	First requirements and implementation plan	M8
D4.2	Second year research and development report	M16
D4.3	Validation of researched methodology solutions	M24
D4.4	Final report	M24

3.2. Tasks related to WP4

Kód	Názov	Termín (M)
T4.1	User requirements collection	M1-M8
T4.2	Digital building image data collection tools	M3-M16
T4.3	Tools for advanced automatic smart building monitoring	M9-M24
T4.4	Module for building operation effectivity optimization	M11-M24
T4.5	Building management and solution deployment	M14-M24
T4.6	Research the solution on pilot use case	M2-M24

4 Updated scope definition

4.1. Current needs in the field of end-user energy management

The building sector remains the largest energy consumer and the second-largest emitter of CO₂, following the industrial sector [1]. Given that the current building stock vastly outnumbers the new constructions expected in the coming decades, energy-efficient renovation of existing buildings is crucial for reducing energy use and environmental impact [2]. This importance should be reflected in regional policies targeting energy efficiency and environmental sustainability. In the European Union (EU), for instance, approximately 75% of existing buildings are classified as energy inefficient, and around 85% of today's buildings are expected to still be in use by 2050. Consequently, the EU aims to at least double the annual energy renovation rate to meet its goal of reducing net emissions by 55% by 2030 [3].

Heating, ventilation, and air conditioning (HVAC) systems, along with domestic hot water (DHW) systems, are well recognized as the primary energy consumers in buildings. Recent reviews on building energy use indicate that HVAC systems account for approximately 38% of global end-use energy consumption. In comparison, DHW systems typically consume about one-third of the energy used by HVAC systems worldwide [1]. However, as building energy efficiency standards have become more stringent, leading to reduced energy demand for heating, cooling, ventilation, and lighting, the relative significance of DHW energy use has been steadily increasing [4].

The immense potential for energy, greenhouse gas, and monetary savings in the building sector, combined with recent economic and geopolitical developments that necessitate accelerating the transition to renewable energy sources, has driven the creation of several major EU strategies, legislative frameworks, and funding schemes. Among these are the European Green Deal and its component initiative, the Renovation Wave, which aims to renovate around 35 million buildings by 2030, effectively doubling the current annual renovation rate [5]. The Green Deal is supported by the Fit-for-55 legislative package, which updates the EU's core energy laws and introduces ETS2 carbon pricing for fuels used in buildings [3]. In addition, the REPowerEU plan, developed in response to the post-2022 energy crisis, accelerates the implementation of energy efficiency and renewable energy measures [6].

These high-level policy efforts are translated into binding requirements on building operations, facility management, and energy performance. For example, the Energy Performance of Buildings Directive (2024/1275) introduces stricter requirements for electrical vehicle-charging readiness and mandates the deployment of Building Automation and Control Systems (BACS). Similarly, the Energy Efficiency Directive (2023/1791) embeds the Energy Efficiency First principle into decision-making, extends the 3% annual renovation obligation to all public buildings over 250 m², and strengthens metering and billing transparency for end users [7].

Collectively, these directives and initiatives require organizations and building operators to improve energy efficiency, reduce emissions, and adopt data-driven management practices. In this context, the ISO 50001 standard offers a structured framework that aligns with the objectives of the EU's updated energy legislation. It provides methods for analyzing energy consumption, establishing baselines, monitoring performance indicators, and implementing documented efficiency measures. The standard also supports the modernization of technologies and processes, alongside continuous performance evaluation based on real-time data, audits, and transparent reporting. For organizations operating increasingly digitalized buildings with integrated energy monitoring and automation, ISO 50001 serves as an important instrument for managing energy performance in a systematic and verifiable manner.

Building on the policy developments outlined above, the growing pressure to reduce carbon footprints, lower energy use, and meet new regulatory expectations requires facility and energy managers to adapt their practices. In Slovakia, the transposition of EU plans and legislation results in several concrete requirements:

- Data/monitoring infrastructure: Build or upgrade systems for energy monitoring, sub-metering, and building automation.
- Digital readiness: Plan for BMS/BACS, digital building logbooks, predictive maintenance, and occupant feedback loops.
- BACS and auto-lighting upgrades: Identify buildings with significant HVAC loads and schedule system upgrades to meet required performance thresholds, linking to smart Readiness Indicator (SRI) where applicable.
- Sub-metering and transparent billing: Ensure granular metering, clear billing information, and data accessibility for occupants, integrating this data into facility/energy management dashboards.
- ISO 50001 integration: Implement the standard within facility and energy management systems.
- Modernization of existing buildings: Deploy modern management systems in existing buildings and use them for optimization and predictive control.
- Digital twins: Streamline the creation and integration of digital twins into building management systems, with particular emphasis on fast development of digital twins for existing buildings and their seamless transfer into the building management platform.
- Effective communication: Provide stakeholders (owners, tenants, facility and energy managers) with actionable intelligence on energy savings, profitability, alarms, and maintenance events.
- System improvement and integration: Interconnect systems and datasets to optimize building operation, applying artificial intelligence to enhance performance.

The next generation of facility and energy management systems will increasingly incorporate AI to optimize building operation, maintenance, and energy flows. Recent reviews of AI applications

in buildings identify three main areas where AI and machine learning can significantly improve current practices:

- **Observing:** This includes applications such as identifying equipment and systems, recognizing activity, detecting anomalies and faults, and monitoring building performance.
- **Predicting:** This includes applications such as predicting human behaviour, state variables, heat gains and loads, and energy and power usage.
- **Adjusting:** This includes applications such as controller tuning, actuating heating, cooling, ventilation, and lighting systems, building energy management, and demand response and scheduling. Probably the biggest impact on autonomous management has been the development of reinforced learning techniques which allow cumulative learning without labeled data and complex controlling problems. This makes reinforcement learning problems very compatible with building management where we have enormous amounts of data and usually, we are searching for the best policy to minimize multiple goals. According to a recent report by the McKinsey Global Institute, ML could save the building sector up to \$1.5 trillion by 2030. The report suggests that by improving efficiency, sustainability, and comfort, ML can help to make buildings more affordable, healthier, and more livable. Currently there are several solutions using AI/ML algorithms to increase building management most notably BuildingIQ, Enel, and Google.
- **Impact:** Society wide energy strategy is a dynamic system where optimal energy consumption varies greatly throughout a day due to a multitude of reasons. Renewable energy sources have only partially predictable profile, suppliers and distributors scale prices using dynamic business offers, spot prices, etc. on a hours or minutes basis, total society-wide electric energy consumption needs better management with increase of sudden burst of high energy consumption due to movement towards more electricity centric solutions such as electromobility.

These challenges need advanced solutions which are able to account for them and give more information and control to the consumers and energy distributors at the same time. Dynamic control using EMS systems is already required by EU legislation for larger consumers. For the purpose of technical verification of the results, sample connection to a specific modular EMS system FlowBox will be performed within WP4.

4.2. Basic workflow of efficiency management process of end-user microgrid

This chapter summarizes the ideal **workflow and trajectory** for a microgrid end-user striving for systematic and measurable energy efficiency in their consumption.

4.2.1. Core Principle: Multi-Criteria Optimization Goal

The fundamental principle is achieving a state defined as the **minimum value** across three primary competing criteria, the weighting of which is set by the user:

1. **Cost Minimization** (Operational and purchasing costs).
2. **CO2 Footprint Minimization** (Carbon emissions).
3. **Energy Resilience Maximization** (Ability to react to unexpected situations and outages).

Regardless of the initial degree of energy maturity, every microgrid end-user follows the same methodical trajectory toward optimization.

4.2.2. Trajectory of Energy Optimization: Five Key Phases

1. Data Architecture and Granularity

The critical starting point. This involves ensuring optimal data granularity in space (breakdown of measurement for main and sub-metered consumption) and in time (optimally quarter-hourly recording (≤ 15 min) of consumption, generation, and contextual variables).

2. Analysis and Identification of Inefficiencies

Based on the collected data, analytical architecture is established (addressing consumption by process/technology) and metrics are defined. The goal is the identification and quantification of inefficiencies (including inherent and removable ones).

3. Strategy and Impact Simulation

This phase involves prioritizing available measures based on criteria such as return on investment (ROI), benefit, and strategic goals. Before realization, impact simulation (what-if scenarios) must be performed to optimize the precise settings.

4. Implementation of Measures

The actual execution of selected measures. Types of measures include one-off/process adjustments and investments in new technologies. A key component is the deployment of dynamic (continuous) control (e.g., based on MPC/AI) for maximum available and continuous optimization.

5. Measurable Benefit

The successful execution of the entire cycle (Steps 1-4) leads to the emergence of a verifiable measurable benefit, represented by financial and energy savings and improved system resilience.

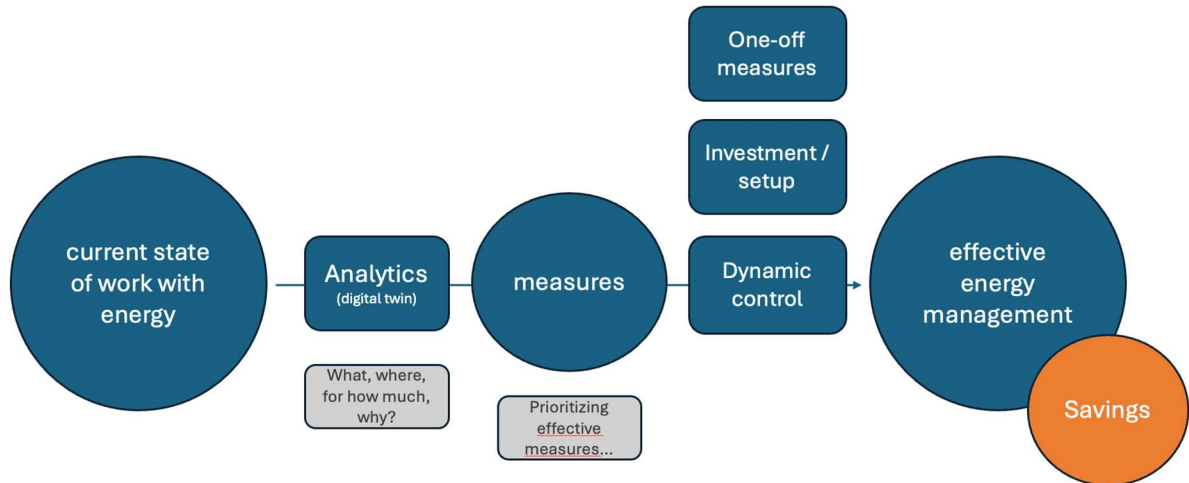


Fig. 1 Trajectory of energy optimization

4.3. Key energy optimization areas in microgrid site

Energy optimization in a microgrid is a technologically driven process aimed at achieving a multi-criteria optimum (Costs, CO₂, Resilience). It is divided into supply management, flexibility management, and inefficiency elimination.

4.3.1. Source and Procurement Optimization (Supply Side)

The goal is active asset management and procurement strategy in response to market volatility.

- BESS: Dynamic charging/discharging and SoC reserve management for price arbitrage and energy resilience.
- Local Generation (PV, CHP): Power modulation for maximizing self-consumption and minimizing costs.
- Procurement Scheme: Dynamic procurement planning (Day-Ahead/Intraday) to minimize costs and deviation penalties.
- Virtual Capacity: Power management within a community to meet requirements.

4.3.2. Consumption Flexibility Management (Demand Side)

Utilizing controllability for Load Shifting and Peak Shaving based on conditions.

- Thermal Inertia: Setpoint adjustment (cooling) acts as a virtual battery for load shifting.
- Controllable Loads: Short-term power reduction (HVAC) for peak shaving.
- Opportunistic Loads: Postponing processes to economically favorable times.

4.3.3. Elimination of Inefficiency

Analytical removal of waste before deploying dynamic control.

- Detection: Identification of static (stand-by) and dynamic (poor regulation) inefficiencies.
- EnPI and Modeling: Comparing actual consumption with a model reveals anomalies. Eliminating them lowers baseline consumption, allowing dynamic control (MPC) to optimize only what is necessary.

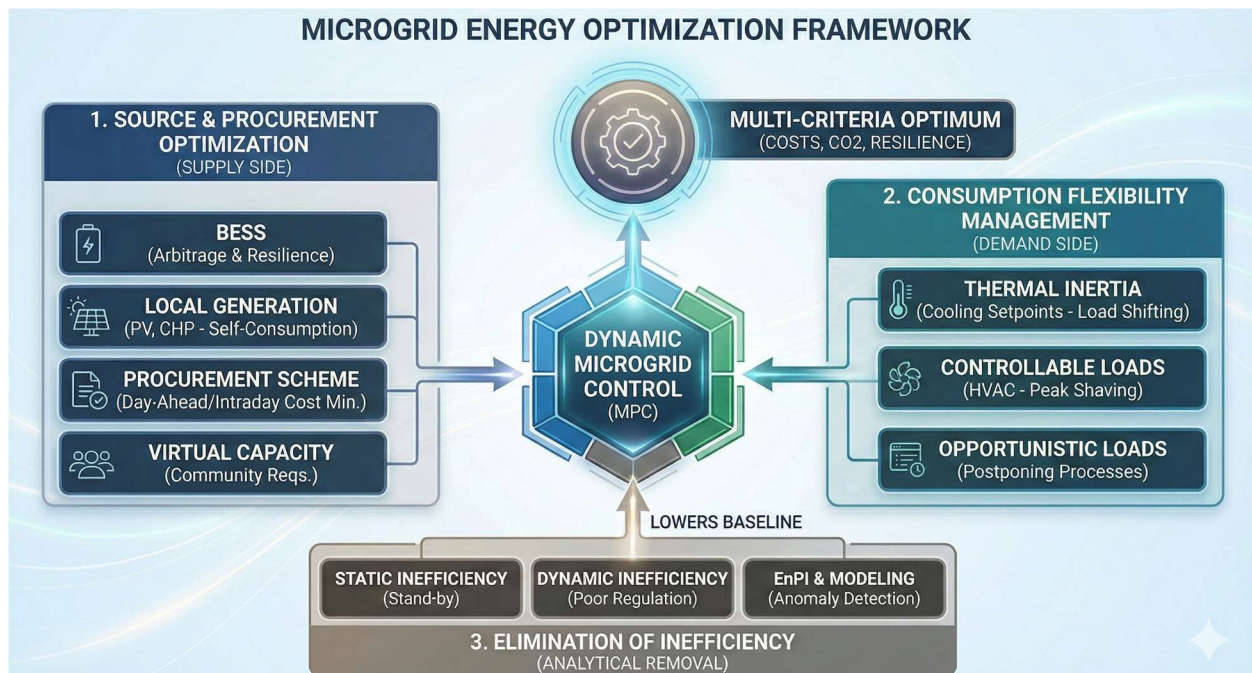


Fig. 2 Microgrid energy optimization framework, AI generated picture

4.4. Main principles of understanding user interface needs

The goal is efficient interaction: intelligent data ingestion and multi-layered output tailored for various roles.

4.4.1. Intelligent Inputs (Data Ingestion)

- SLM & Independence: Utilizing Small Language Models to understand unstructured inputs (text, PDF, various CSVs) without rigid templates.
- Interactive Validation: The system automatically checks data and actively queries the user during entry in case of ambiguities.
- Automatic Transformation: The ability to convert batch data (e.g., production per shift) into interpolated time series for modeling purposes.

4.4.2. Analytical Outputs and Visualization

- Managerial View: Immediate Actionable Insights in financial language (TCO, P&L, ROI) for rapid decision-making.
- Expert View: Full transparency ("White-box") – the ability to drill down into results down to the formula level and configure metric parameters.
- Drill-down: Seamless transition from a strategic overview (overall balance) down to granular detail (specific machine consumption over time).

4.4.3. Design and Ergonomics

- Clean Design: A modern, clear interface that does not overwhelm the user with complexity.
- Multimodal Perspective: The option to switch roles (Economist vs. Technician), where the system displays the same underlying data in a context relevant to the specific user.

4.5. Definition of research priorities

The requirements analysis highlights the following priorities for WP4:

1. **Building digital twins** integrating BIM and sensor data for real-time monitoring and analysis.
2. **Predictive and optimization algorithms** for HVAC, lighting, and other building systems, responding dynamically to occupancy and external conditions.
3. **What-if scenario simulations** enabling stakeholders to explore operational alternatives and their effects.
4. **Validation frameworks** ensuring that AI-based methods are tested both in simulations and in real-world pilot buildings.

These priorities directly respond to market needs for cost reduction, comfort improvement, and alignment with the **European Green Deal** and the **Energy Performance of Buildings Directive (EPBD)**.

These priorities will be further developed in Deliverable D4.2 and validated in D4.3.

5 Implementation Plan of WP4

5.1. High-level process of project realization

The implementation of WP4 follows a structured approach divided into phases that align with project milestones and deliverables:

Phase 1 – Requirements and Planning (M1–M8):

- Collection and analysis of user and stakeholder requirements.
- Definition of research priorities and alignment with European sustainability goals.
- Identification of relevant data sources and their optimal ranges.
- Preparation of methodologies for data preprocessing and validation.

➔ **Output: Deliverable D4.1 (M8).**

Responsible partner: SvF STU

Phase 2 – Research and Development:

- Development of AI-based models for predictive control and optimization of building energy management.
- Initial design of digital twins integrating sensor, historical, and environmental data.
- Establishment of workflows for testing and simulation.

➔ **Output: Deliverable D4.2 (M16).**

Responsible partner: IT4I@VSB

Phase 3 – Validation and Testing:

- Validation of developed methodologies in real-world pilot sites and simulated environments.
- Assessment of performance in terms of energy savings, user comfort, and environmental impact.
- Refinement of models based on pilot results.

➔ **Output: Deliverable D4.3 (M24).**

Responsible partner: SvF STU

Phase 4 – Finalization and Reporting:

- Consolidation of findings and lessons learned.
- Preparation of final recommendations for adoption and scalability.

➡ **Output: Deliverable D4.4 (M24).**

Responsible partner: SvF STU

5.2. WP4 Partner responsibility overview

SvF STU: requirements analysis, BIM workflows, spatial data capturing, BIM model creation, energy modeling, and coordination.

IT4I (VSB): algorithm development, digital twin and computational support, general user interface.

ASSECO: data preparation, integration into software environments and user data interfaces.

DFKI: methodological support and AI validation.

TSK: functional requirements and user experience validation

5.3. Topic matrix of implementation plan and partners

division of the project into topics and topic researchers

		T. Funtik	P. Petrovic	T. Karasek	T. Jungman	T. Bumbalek	I. Zinnikus
MASTER PLAN		STU	ASSECO	IT4I	EMOS	TSK	DFKI
S.1. COMMUNICATION AND VISUALIZATION INTERFACE	communication strategy						
	3D data energy BIM model						
	BIM frontend						
S.2. DATA PREPARATION	- format adjustment						
	- validation						
	- automatic labeling /						
	- filtering (selection e.g. for a model) of data output from the DB						
P.3. MODEL	- sensitivity analysis						
	HVAC model						
S.4. OPTIMIZATION	Model for energy consumption according to performance reference						
	arrangement						
S.5. DYNAMIC CONTROL	algorithm						
	prediction						
	optimization						
S.6. EMOS LAYER	control output						
	architecture and infrastructure						
	supporting backend services						
	computing backend services						
	frontend and BI dashboard						
S.7. Reference verification	AI agents						
	prototyping						
	reference requirements						
	current status - assessment						
	design and implementation of measures						
	efficiency evaluation						

legend:

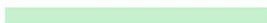
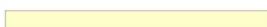
	key / coordination role
	participatory role

Fig. 3 Partner's expected engagement per topic

6 Topic 1 – Communication and visualization interface

6.1. Introduction

This deliverable defines the initial requirements and implementation plan for Work Package 4 (AI-Driven buildings) within the InnovAite project. The objective is to consolidate user and stakeholder needs, define research priorities, specify data sources, and establish a methodology for data processing and validation. As the first deliverable of WP4, D4.1 serves as a strategic, cross-cutting planning document that sets the framework for subsequent R&D activities and guides the preparation of Deliverables D4.2, D4.3, and D4.4.

6.2. Analysis of user and stakeholder requirements

A combined methodology consisting of a literature review, state-of-the-art analysis, and stakeholder engagement was applied to identify requirements relevant to AI in building energy management. Insights from this preparatory work informed the design of a questionnaire survey, ensuring that the questions captured both technical and practical perspectives. To further enrich the findings, semi-structured interviews with facility managers were conducted. Together, these inputs provide an evidence-based foundation for defining the priorities of WP4 and ensuring that all proposed solutions are practically grounded and demand-driven.

An anonymous online questionnaire was distributed to more than three hundred building owners, facility and energy managers, as well as several energy-efficiency experts involved in energy management. The questionnaire survey aimed to explore how stakeholders perceive the current state of building management and energy management, what technologies they use, and what challenges they face in their daily work. The intention was to obtain a realistic picture of how buildings in Slovakia are managed, how their energy consumption is monitored, and what the current level of digitalization and indoor climate comfort is. A total of seventy-five respondents participated in the survey, representing residential, administrative, and public buildings. The largest group consisted of residential building managers, while a smaller part represented public, industrial, and specific facilities such as schools, hospitals, hotels, and cultural institutions. Most participants work in the management of residential buildings, which are typically operated in larger numbers, often dozens or even hundreds of buildings. Smaller managers are responsible for individual or specialized properties. This diversity of responses provided insight not only into the technical level and equipment of the buildings but also into the approaches taken by managers toward efficient and sustainable energy management.

The questionnaire consisted of twenty questions, with many participants answering all of them, which increases the reliability of the results. The findings were subsequently divided and analyzed across six key aspects.

In addition to the survey, individual interviews were conducted with representatives of selected organizations from various regions of Slovakia. These interviews involved professionals responsible for the energy management of municipal, regional, or larger building complexes, as well as individual public or residential buildings.

The following section presents an overview and evaluation of the six key aspects identified through the questionnaire survey and the supplementary interviews.

1. **Comfort and satisfaction levels** – perceptions of temperature, air quality, lighting, acoustics, and issues such as overheating, humidity, or insufficient ventilation.

The results of the survey show that most building managers do not monitor the quality of the indoor environment and do not have any monitoring systems installed for its measurements. Only a smaller portion of respondents indicated that they track such data, most commonly indoor temperature, and in some cases, also humidity levels and carbon dioxide concentration. When it comes to satisfaction with indoor environmental quality, the opinions of managers differ. Many are only partially satisfied with the conditions, a smaller group is generally satisfied, while some express dissatisfaction. The responses suggest that the main concerns relate to the basic parameters of indoor air temperature, humidity, and CO₂ concentration, which managers perceive as the key factors affecting comfort. In contrast, aspects such as lighting and acoustics were mentioned only rarely, indicating that respondents do not consider them a major source of discomfort. Interviews further revealed that organizations tend to view comfort primarily through the lens of efficient heat and energy management. Their main objective is to maintain acceptable indoor conditions while minimizing operational costs.

2. **Awareness of energy efficiency measures** – smart thermostats, efficient HVAC, demand response, and their perceived value in terms of cost savings, comfort, and environmental benefits.

The survey responses indicate that building managers generally recognize the benefits of modern technologies for improving energy efficiency and optimizing building operations. Some of them already use smart meters or Building Management Systems (BMS) to measure and record energy consumption. However, these systems are not always used to their full potential, that is, data are most often employed for consumption control or billing rather than for active operational management. Approximately half of the managers are considering modernizing their energy management systems, showing the greatest interest in automated control with optimization features, indoor environment monitoring, and remote consumption data collection. From an economic perspective, most respondents view an investment payback period of up to six years as acceptable. The measures are primarily perceived as a way to reduce costs and enhance user comfort, while their environmental benefits are seen as a secondary effect of technological improvements. The interviews revealed that approaches to energy efficiency differ depending on how advanced individual systems are. Some organizations already have dedicated energy departments and integrated digital tools, while others are still in the early stages of developing

their systems or focus mainly on operational savings and regulation. A common finding across all organizations is that energy efficiency is viewed primarily as a matter of technical measures and consumption control, rather than as a change in user behavior within buildings.

3. **Openness to AI-based technologies** – willingness to adopt sensors, automation systems, and decision-support tools, with concerns related to cost, complexity, privacy, and trust.

In terms of modernization, the survey revealed that roughly half of the building managers are considering expanding or upgrading their existing systems. The greatest interest is in automated control with optimization-feature technologies capable of autonomously responding to changes in energy consumption or indoor conditions. This represents a step toward intelligent solutions that apply the principles of artificial intelligence. On the other hand, some managers remain cautious about adopting such technologies. Their concerns mainly relate to high initial costs, operational complexity, the need for specialized personnel, and potential issues surrounding data privacy and security. Others noted that these systems might be unnecessarily complex or disproportionate to the type of buildings they manage. Overall, building managers demonstrate a good level of awareness regarding the potential of modern technologies and generally perceive them positively. Artificial intelligence and automation are not seen as a threat but rather as tools that can help save energy and simplify building management. Their willingness to adopt such systems depends primarily on financial feasibility, ease of use, and clearly demonstrated benefits. The interviews confirmed that the approach to AI implementation varies depending on each organization's technical readiness. Some have already begun testing predictive algorithms for energy consumption, while others still view AI mainly as a complementary or future tool. Nevertheless, all organizations approach the topic with caution, recognizing its practical value, but remain concerned about financial costs, technical complexity, and the lack of skilled personnel.

4. **Data availability and building systems** – current BMS use, sensors, meters, and collected parameters (temperature, occupancy, CO₂, energy consumption).

The survey results show that most building managers have access to energy consumption data, most obtained through smart meters or integrated measurement systems. A smaller group of managers still performs manual readings or combines automated and manual data collection methods. In most cases, consumption data is available on a monthly or annual basis, while only a small portion of managers can access them daily or in real time. Despite this, the majority claim to have a clear overview of energy consumption trends and related costs over the past period. Regarding indoor environmental quality, only a few managers have monitoring systems installed, typically limited to temperature tracking, and less frequently to humidity or CO₂ concentration. Most managers therefore possess only basic data on energy consumption, while comprehensive information about indoor conditions in their buildings is still largely missing. Interviews revealed that the level of digitalization and system integration varies significantly across organizations. Some already operate comprehensive solutions that combine billing data, smart metering, and online monitoring, while others remain in a transitional phase between manual data collection

and full digitalization. In general, all organizations aim to move toward centralized and automated energy management systems.

5. **Expectations for “what-if” simulations** – ability to test operational strategies (e.g., reducing setpoints, adjusting heating/cooling schedules) and key decision criteria (cost, comfort, emissions).

The survey results indicate that building managers do not yet use simulations or model-based scenarios as tools for operational decision making. In most cases, they rely on current energy consumption data and respond reactively, only after identifying a problem or based on actual measured values. As a result, few managers employ predictive analyses that would allow them to test different operational alternatives, such as adjusting temperature settings, modifying heating schedules, or optimizing cooling strategies. Interviews suggest that although simulations are not explicitly mentioned, their relevance is implied through objectives such as operational optimization, consumption prediction, and testing of energy-saving measures. Some organizations already use elements that could form the basis for such approaches, including data visualization or the analysis of operational changes and their impacts. Overall, these tools are not yet a standard part of building management, even though they have the potential to significantly improve planning and reduce energy consumption.

6. **Barriers and priorities** – challenges to adoption and desired outcomes such as energy savings, emissions reduction, and increased comfort.

The survey and interviews show that building managers recognize the need to modernize and improve building management systems, but they face several practical challenges. The most frequently mentioned issues are a lack of financial resources, administrative complexity, and a shortage of qualified personnel. Additional barriers include low data transparency, the absence of automated alerts, and limited technical support. Some respondents also point to inadequate legislation that slows down digitalization. Despite these obstacles, there is a high interest in increasing automation and transparency. Managers would welcome intelligent, integrated solutions that combine energy monitoring, maintenance, and technical management into a single system. Their main motivations are to reduce energy costs, improve operational efficiency, and enhance user comfort, while environmental benefits are seen mainly as a natural secondary effect. Most organizations face similar challenges — particularly investment constraints, staff shortages, and fragmented building management systems. Key priorities include digitalization, data integration, and achieving long-term energy savings, emission reductions, and operational efficiency. Managers are open to digital transformation, but its pace depends largely on available resources, institutional support, and the usability of modern technologies.

6.3. Case Scenarios for BIM-Integrated Energy Management

In practice, two primary scenarios arise when preparing BIM models for integration with energy-management workflows: BIM model available (6.3.1), or no BIM model is available (6.3.2). Both scenarios were examined because facility managers expressed strong interest in 3D models for visualization, analysis, and energy-optimization tasks.

6.3.1. Case 1: BIM model available

Assessment and Verification of Existing BIM Models

The first and seemingly simplest option is to use an existing BIM model, if one is available. Practical experience in the Slovak Republic confirms that many buildings already have BIM models, as BIM adoption increases each year. However, the quality and structure of these models are highly inconsistent and cannot be assumed suitable for energy-management workflows. It is common to encounter models created primarily as a 3D coordination reference, which therefore lack essential non-graphical data, contain misclassified elements, or follow modelling conventions that differ across design companies.

For this reason, it is crucial to establish a clear data-requirement specification defining what information an existing model must contain to ensure its usability in subsequent processes. This necessitates the creation of a reusable template or verification schema, allowing heterogeneous models from various sources to be checked and normalized for downstream applications.

As part of this task, multiple tools and standards for automated data validation - such as the Information Delivery Specification (IDS) - were investigated. These tools can support semi-automated verification of graphical and non-graphical requirements. At the same time, the development of a custom automated model-quality verification tool is being considered. Initial exploration of the functional needs revealed several challenges, all of which remain technically solvable.

In addition to verification, a methodology for correcting identified discrepancies also had to be designed. Since Industry Foundation Classes (IFC) serves as the primary exchange format and access to models in their native software is frequently unavailable, existing IFC editing tools were assessed. A critical finding was that many off-the-shelf tools alter unique identifiers (e.g., GUIDs) when modifying elements. This is unacceptable, as GUIDs are essential for linking sensor data to individual building elements or spaces. Any modification of these identifiers would break the linkage required for WP4 functionality.

This finding further underscores the need for a custom IFC modification tool capable of adjusting or supplementing IFC data while preserving unique identifiers. A proof-of-concept implementation validating this capability has already been completed successfully within the project.

The next phase will therefore focus on developing a formal verification schema based on the defined data requirements and establishing a methodology for correcting erroneous data in IFC models.

Ensuring Consistency with As-Built Conditions (Scan-vs-BIM)

While data correctness is essential, model accuracy relative to the as-built state must also be ensured. A BIM model may be structurally correct yet deviate from the physical building due to construction changes not captured in documentation or later refurbishments that were never reflected in the model. This is a common challenge in the Slovak construction environment.

To address this, laser scanning is proposed as a verification method. The resulting point cloud allows high-fidelity geometric and spatial comparison between the BIM model and the actual building. Part of the activities is the development of software for automating this process. This task includes assessing the extent to which the verification process (Scan-vs-BIM) can be automated and identifying areas where manual interpretation remains necessary.

Once discrepancies are identified, they must be incorporated back into the model. While the previously described custom IFC-editing tool can address non-graphical properties or reclassification tasks, extending such a tool to modify or create geometric elements (e.g., walls, HVAC components) presents a significantly more complex development challenge. Investigating whether such geometric modifications can be executed without resorting to native BIM authoring environments represents an important next step.

Integration of BIM Models with Dynamic Sensor Data

After verifying that the model is both structurally correct and aligned with the as-built condition, the next critical task is to link the model with dynamic sensor data.

Two sensor scenarios are anticipated:

- Existing sensors already installed in the building, or
- Newly installed sensors, where legacy devices must be replaced or augmented.

A notable challenge arises with legacy sensors, which may not be integrated into a modern Building Management System (BMS) or may require manual data reading - still common in some facilities. In such cases, solutions include either replacing sensors with devices capable of signal transmission or using commercially available automated data-retrieval systems, which the project has already validated as feasible.

Sensor outputs vary widely in terms of communication protocols, database structures, and formats. Nevertheless, at the integration level, all measurement streams ultimately converge into a time-stamped database providing near real-time information.

One of the key challenges investigated was how to link dynamic data to the BIM model while maintaining historical values for retrospective analysis. An early option considered was repeatedly overwriting an IFC parameter (e.g., a parameter stored on an IfcSpace or sensor element). This approach was discarded due to its significant inefficiency, the large size of IFC files, and the inability to store historical measurements, which are essential for diagnostic and optimization tasks.

The investigation therefore focused on a live-link approach, enabling the BIM model to reference external data sources without modifying the IFC file itself.

To validate this methodology, the team employed PowerBI, well-established analytics and dashboarding tool. PowerBI enabled the integration of:

- the BIM model (IFC),
- real-time data from a sensor database, and
- interactive navigation (rotation, zooming, 3D inspection).

The primary objective was to ensure that the measured value is not shown merely as an abstract number but is directly visualized in its corresponding building space.

To achieve this, a mapping table was created, linking each sensor's data stream to a corresponding BIM element or space via its unique identifier (GUID). Maintaining GUID integrity in the IFC model is therefore essential.

Several visual encoding methods were tested. One particularly effective solution was color-coding spaces based on threshold exceedance - for example, highlighting a room in red if temperature or CO₂ levels surpass defined limits - providing an immediate visual cue for facility managers.

Finally, the process of configuring the PowerBI dashboard proved invaluable, as it allowed the entire workflow to be captured and documented clearly. This serves as a well-defined, replicable methodology that can be handed over to a development team for implementation in a dedicated software application.

6.3.2. Case 2: No BIM model available

The survey clearly indicated that visualizing information about the built asset through a BIM model is highly desirable, and respondents expect that such visualization would have positive impacts on building energy management and optimization processes. Despite the growing adoption of BIM tools for design, documentation, and renovation projects, many buildings still require energy-optimization measures without having any BIM model available. In these situations, it becomes necessary to create a new BIM model.

The creation of a BIM model for an existing building depends directly on the availability and reliability of existing information sources. These sources often include original design documentation or renovation drawings, but such materials are frequently incomplete, outdated, or insufficient in terms of geometric accuracy or level of information required for current energy-management workflows. In cases where available documentation does not provide a sufficient basis, it is necessary to collect or generate additional data to support the development of the BIM model.

At this stage of the project, several use cases and scenarios for BIM deployment are being examined. These scenarios differ based on both the type of building (industrial, residential, office) and the intended use of the visual representation. So far, two primary categories of BIM usage have been identified:

1. **Integration with IoT sensors and linking the collected data to the BIM model**, enabling the detection of spaces with non-compliant measured values and supporting the analysis of root causes and improvement options.
2. **Monitoring and evaluating the thermal-technical properties of building structures** and assessing their impact on overall energy consumption and operational performance.

Defining the intended use of the BIM model sets the necessary requirements for both graphical and non-graphical information. Clear information requirements are essential for determining whether the existing documentation is sufficient or additional data capture is needed.

In many cases, the conclusion is that existing documentation must be supplemented by newly captured data to enable reliable digitalization. One of the most accurate methods for obtaining geometric information is terrestrial laser scanning (TLS) performed on site. TLS captures the actual shape of the building and its surroundings with high spatial accuracy. The resulting point cloud, containing 3D coordinates and radiometric information (RGB and reflection intensity) provides a robust basis for creating an information model suitable for multiple purposes.

Reconstruction of BIM models

In situations where existing documentation is sufficient for creating a BIM model suited to the intended purpose, several approaches to efficient model development can be applied. The most fundamental method is the traditional workflow within BIM authoring tools (e.g., Autodesk Revit, Graphisoft ArchiCAD, Nemetschek Allplan), where individual building elements are modeled manually. This approach provides a high degree of accuracy and control, but it is labour-intensive and time-consuming, especially for large or complex buildings.

When no native BIM model is available, legacy 2D drawings or point-cloud data may serve as a starting point for generating a lightweight BIM model appropriate for visualisation, spatial navigation, and facility management. Modern automated, AI-supported services (e.g., AmpliFy, Plans2BIM, Make a BIM) enable the rapid creation of simplified 3D models directly from PDF or

raster plan inputs. These solutions offer fast deployment and are particularly useful when only a moderate level of detail is required.

If reliable 2D drawings are unavailable—or if they must be complemented—efficient data-capture workflows can be applied to obtain the geometric information necessary for BIM creation. Depending on the building and its conditions, this may include:

- **Terrestrial laser scanning (TLS)** to produce highly accurate point clouds,
- **Close-range or UAV photogrammetry** for capturing façades, roofs, and larger external areas,
- **Conventional surveying** methods for establishing control geometries,
- **Archived drawings**, where available, to supplement measured data.

These methods produce detailed spatial information that forms the foundation for reconstructing the BIM model.

Once the geometric model is created, it can be enriched with contextual information derived from multimedia sources such as 360° images, video sequences, or photographs. These materials assist in identifying building elements, materials, HVAC components, technical systems, and functional zones, providing valuable non-graphical information that complements the geometric and parametric data in the BIM model.

For situations requiring higher geometric fidelity or parametric precision, BIM-native assisted tools such as WiseBIM for Revit can convert vector drawings (DWG/DXF) into parametric elements including walls, doors, windows, and slabs. Additionally, point-cloud intelligence tools (e.g., Samp.ai) can support immediate 3D navigation, asset contextualisation, or semi-automated reconstruction workflows in Revit or ArchiCAD.

Multi-storey BIM models are typically developed by modelling individual floors and then assembling them into a coherent, multi-level building structure using consistent coordinate systems and naming conventions. After assembling the geometry, each element can be enriched with non-graphical information relevant for energy management, such as space functions, material characteristics, and object classifications. This ensures reliable IFC data exchange and seamless integration with facility-management systems and energy-analysis tools.

The resulting standards-compliant BIM model (IFC or native file formats), whether generated from 2D drawings or point-cloud inputs, can be efficiently used for facility management, energy-performance simulations, and digital-twin development within WP4.

Creation of simplified BIM models containing floors, rooms, and zones, sufficient for energy optimization tasks.

The creation of simplified BIM models consisting only of essential elements - such as floors, walls, roofs, and spatial units (rooms and zones) - provides a practical and efficient approach for supporting energy-optimization tasks. By maintaining a deliberately low level of geometric detail, it is possible to generate a BIM model quickly while still achieving a substantial improvement in understanding the building's spatial structure, thermal zoning, and energy-relevant characteristics. Such models deliver sufficient accuracy for simulation workflows and form a solid foundation for further optimization processes.

As part of this approach, an alternative “box model” concept was also evaluated. In this configuration, the IFC-based BIM model is limited to a high-level spatial hierarchy represented through the classes *IfcSite*, *IfcBuilding*, *IfcBuildingStorey*, and *IfcSpace*. All detailed energy-relevant information is stored exclusively in dedicated property sets and associated with the corresponding *IfcSpace* entities. Various *IfcSpace* types may then be used to represent different categories of rooms - such as circulation areas, sanitary spaces, technical rooms, office spaces, or other functional zones.

Regardless of the chosen level of simplification, a clear definition of information requirements (Level of Information Need - LOIN) and the selection of a robust and consistent modelling workflow are essential for ensuring that the resulting BIM model can be reliably linked with external datasets, sensor measurements, and analytical tools, as discussed in the preceding chapter.

6.4. Data alignment with standards

Mapping and overlap analysis between data from energy optimization software and the BIM association Slovakia's non-graphical information standard.

The objective is to utilize the BIM model for visualizing building information with a focus on energy optimization. For this purpose, it was necessary to determine which non-graphical information should be represented in the model, thereby defining its data structure. As part of the task, a mapping and overlap analysis was conducted between data from the EnergyPlus building energy simulation software and the non-graphical information standard of the BIM association Slovakia. Both the BIM association Slovakia and the EnergyPlus framework categorize elements into classes (e.g., Chiller, Boiler, etc.). The comparison of parameters from both approaches revealed a minimal overlap of properties used for individual element types.

Proposal to adapt the non-graphical standard for energy optimization purposes.

We propose to define a standardized data structure for storing information required for the energy optimization of analyzed buildings. BuildingSMART International applies the classification of information assigned to individual BIM model elements based on the principle of object-

oriented modeling. This principle also classifies elements according to their IFC class and further groups them into types. A type within a given class represents a set of specific elements that share common information. This approach enables the use of so-called “property inheritance,” which allows the data structure to reference preceding entries or types. In doing so, it significantly reduces the volume of data while preserving all contained information, thereby increasing efficiency in data management and avoiding repetitive recording of identical information. After identifying the necessary information, the BIM model in the open IFC format will serve for data visualization and interaction.

6.5. Research Priorities Derived from Findings

Based on survey and BIM case scenarios, additional specific priorities are:

- Development of digital twins integrating BIM and dynamic sensor data. Once the BIM model is established, it can be linked with real-time or periodic sensor data to create a digital twin of the building. This integration allows monitoring of energy use, environmental conditions, and system performance, providing a live, interactive representation of the building for simulation, analysis, and decision-making.
- Exploration of “what-if” scenario simulations for building energy optimization. Digital twins and BIM models enable simulation of different operational scenarios, such as alternative HVAC strategies, lighting schedules, or occupancy patterns. These “what-if” analyses help optimize energy consumption, identify potential savings, and support decisions for building management.
- Refinement of data standards to enable interoperability between BIM and energy management systems. Ensuring that BIM data communicates with energy management systems requires standardization of formats, attributes, and protocols. This step focuses on harmonizing data structures, enabling integration with simulation software.
- Validation strategies ensuring that user requirements are transformed into practical solutions. Finally, systematic validation ensures that the digital models, simulations, and analyses meet the intended user requirements. This includes checking the models (up-dateness), verifying sensor integration, and confirming that energy optimization scenarios align with current building performance, ensuring that the solutions are reliable and useful.

7 Topic 2 - Data Preparation

7.1. Definition of the main challenges

The Data Preparation area within WP4 is composed of five consecutive modules: the Transformation module, Data Validation, Automatic labeling, the Filtering module, and Sensitivity (correlation) analysis. Together, these modules form a complete data chain—from uploading input files to the analytical processing of energy time series. Their orchestration is ensured by LangGraph, which acts as a central control layer among the individual MCP modules. It enables automated triggering and interconnection of processes, manages their order and dependencies, processes logs and results, and ensures that the output of one module smoothly becomes the input to the next. LangGraph thus guarantees the continuous and coordinated operation of the entire WP4 data pipeline.

The primary challenge is to create a robust, unified, and fully automated data pipeline capable of processing energy and operational data from various sources (CSV, XLSX, JSON, XML, API, SCADA, PDF) and converting them into a single, machine-readable format. This pipeline must ensure:

1. a unified data format according to the WP4 schema (VAINNOVAI-394),
2. data quality control and completion of missing values,
3. assignment of context (e.g., day type, weather, technological structure),
4. selection of data suitable for models,
5. and computation of relationships and sensitivities between consumption and external factors.

Key problems include:

1. high heterogeneity of data and formats,
2. different time-series granularities,
3. real-time processing requirements (streaming, parallelization),
4. ensuring consistent mapping of units, measurement types, and metadata,
5. and transparency of the entire process with the possibility to audit individual steps.

7.2. Description of the current state of solvability

A functional prototype of the first processing step in the data chain has been implemented. This prototype allows uploading an energy-data file in multiple formats, verifies whether the file contains measurement time series (AI/LLM validation), and then processes the data asynchronously via Redis and a worker that launches the AiParse service (or a local SLM). AiParse is an AI-assisted parsing and transformation service that extracts time-series measurements and relevant metadata from heterogeneous input files. It normalizes these inputs into the unified SeriesSchema (VAINNOVAI-394) so that downstream WP4 modules can operate on consistent, machine-readable data. The results are stored in MongoDB in a unified data format, SeriesSchema, which was designed within WP4 and is already fully used for storing transformed data. This format serves as a common basis for all subsequent data-processing steps, as well as for downstream analytical, predictive, optimization, and BIM components of the project.

The prototype also supports a local SLM model that can substitute for a cloud-based LLM solution. The model is currently in the fine-tuning stage because it does not yet generate fully correct JSON outputs according to the validation rules defined in the WP4 schema.

From an architectural perspective, the data flow has been functionally verified:

- Redis – temporary storage for parallel and asynchronous processing,
- Worker – executes processing and launches AiParse or the local SLM,
- MongoDB – target database where data are stored in SeriesSchema format using idempotent writes.

Additional WP4 data-processing modules build on this transformation layer:

- Data Validation – automatically checks consistency, format correctness, ranges, and units; uses an autoencoder for deviation detection and interpolation of missing values. The output is a cleaned series with quality flags stored directly in MongoDB.
- Automatic labeling – assigns qualitative and contextual labels to each point (e.g., interpolated, masked_event, holiday_public) and enriches metadata with structural information (technological, process, switchboard relationships).
- Filtering step – enables data selection by temporal, environmental, or qualitative context. Thanks to labeled data, it can easily prepare a modeling dataset, for example only daytime data with temperatures above 20 °C.
- Sensitivity and correlation analysis – analyzes relationships between consumption and external or internal factors (weather, seasonality, attendance, operating regime). Outputs include metrics such as the K-factor, input-vector weights, model predictability, and decomposition of consumption by influencing factors.

Overall, the proposed solution currently provides a coherent data-pipeline architecture in which the transformation part is fully functional and ready to be extended with validation, analytical, and modeling components.

7.3. Proposed implementation procedure and priorities

The next phase will focus on extending, interconnecting, and optimizing individual modules under LangGraph orchestration. The main priorities are:

1. Completion and stabilization of the Transformation module
 - improving JSON output correctness checks, adding parsers, and optimizing the Redis queue for parallel processing.
2. Fine-tuning of the local SLM
 - adapting the model to domain data (energy, HVAC, SCADA) to achieve deterministic and schema-valid outputs.
3. Implementation of the MCP Validator and Labeler
 - deploying modules as standalone MCP services for parallel validation and labeling, with shared communication via LangGraph.
4. Integration of the Filtering module
 - connecting filtering to the analytical layer and correlation analysis; enabling data selection by context and quality.
5. Extension of analytical functions (Sensitivity analysis)
 - computing weather influence, K-factor, weights of input parameters, consumption baselines, and decomposition of total consumption.
6. Performance and scalability testing of the pipeline
 - measuring throughput, worker response times, and stability on large datasets.

With this approach, a complete WP4 data pipeline will be ensured, operating autonomously, consistently, and in line with the MCP/LangGraph architecture—from raw data ingestion through to analytical modeling.

8 Topic 3 - Model

Within WP4, two demonstrators are used to showcase the use of AI in dynamic energy efficiency control. The first demonstrator deals with predicting energy consumption in manufacturing plants and identifying production inefficiencies. The second one showcases the use of AI in Digital Twins of buildings. In this deliverable, major challenges in both are outlined, and solutions to those challenges are proposed.

8.1. Challenges in predicting manufacturing plants' consumption and production inefficiencies

8.1.1. Data & Measurement Challenges

Challenge	Solution
Insufficient measurement granularity.	Deploy sub-metering across critical lines.
Unsynchronized time-series from different systems.	Align and resample multi-source data.
Missing or noisy sensor data.	Use advanced imputation and smoothing techniques.
Difficulty separating baseline and production-dependent consumption.	Model baseline and variable loads via regression or ML.

8.1.2. Modeling & Prediction Challenges

Challenge	Solution
Nonlinear relationships between output and energy.	Use nonlinear ML models (RF, GBDT, LSTM).
Multiple operating regimes and product mixes.	Apply change point detection for regime shifts.
Limited historical data for new equipment.	Use transfer learning between similar processes.
External factors (weather, raw materials, operator behavior).	Combine physical and ML models.

8.1.3. Detecting Production Inefficiencies

Challenge	Solution
Hard to distinguish normal variability from true inefficiency.	Use frontier models (quantile regression, DEA).
Many potential root causes across process, equipment, and operations.	Residual analysis to quantify inefficiency. Apply anomaly detection (Isolation Forest, AutoEncoder).
No standard benchmark for “optimal” consumption.	Link energy data with operational events (scrap, downtime).

8.1.4. Operational & Organizational Challenges

Challenge	Solution
Fragmented IT/OT systems.	Build automated ETL/ELT pipelines.
Lack of metadata standards.	Apply data governance standards.
Model drift due to production changes.	Schedule automatic model re-training.
Low adoption among operators.	Provide dashboards with actionable metrics.

8.2. Challenges in development of Digital Twins of buildings

8.2.1. Data & Measurement Challenges

Challenge	Solution
Inadequate measurement: often only one main meter for the entire building.	Introduction of secondary metering (by floor, circuit, rental unit).
Discrepancy between consumption data and external factors (e.g., weather, occupancy, ventilation control).	Integration of meteorological data (outdoor temperature, solar

radiation, wind) with consumption time series.

Lack of sensors for temperature, humidity, CO₂: real load and comfort cannot be determined.

Data cleaning: removal of anomalies (e.g., thermometer failures, service days).

Different operating modes during the week (weekdays vs. weekends).

Inclusion of calendar effects: day of the week, holidays, season, operating hours.

8.2.2. Modeling and prediction of heat consumption

Challenge	Solution
Strong dependence on weather and dynamic thermal behavior of the building.	Models with temperature and dynamic inputs: <ul style="list-style-type: none"> • Statistical: linear regression, ARIMA, polynomial regression. • Physical: RC models (Resistance–Capacitance), grey-box approach. • Combined (hybrid): physical basis + correction using ML.
Different thermal behavior depending on the type of building: <ul style="list-style-type: none"> • Offices: high gains from people and technology. • Residences: high variability in resident behavior. • Shopping centers: strong influence of ventilation and operating hours. 	Machine learning for nonlinear relationships: Random Forest, Gradient Boosting, XGBoost, or neural networks (e.g., LSTM for time series).
Delayed system response (heat accumulation in the structure).	Weather Normalization: conversion of consumption to unit temperature deviation (Heating Degree Days, HDD).
Sudden changes in operation (e.g., change in heating curve control, transition from heating to cooling).	Change Point Analysis: detection of changes in heating control or user behavior.

8.2.3. Identification of inefficiency (energy anomalies)

Challenge	Solution
<p>Difficult to determine whether increased consumption is caused by weather, malfunction, or behaviour.</p>	<ul style="list-style-type: none"> • ENPI (Energy Performance Indicator) regression models: e.g., heat [kWh] / (HDD * area), or heat / occupancy. • Residual analysis: difference between predicted and actual consumption = degree of inefficiency.
<p>Hidden losses: poor control settings, circulation, and distribution losses.</p>	<p>Frontier models: quantile regression (e.g., 0.1–0.2 quantile as theoretical minimum consumption).</p> <p>Automatic anomaly detection:</p> <ul style="list-style-type: none"> • Statistical methods: z-score, IQR. • ML methods: Isolation Forest, AutoEncoder, Prophet decomposition.
<p>Different reference efficiencies for different types of buildings (no uniform benchmark).</p>	<p>Comparison with reference objects: benchmarking by building type and climate zone.</p>

9 Topic 4 - Optimisation

The optimisation process aims to determine the best continuous orchestration of energy-related operations within a microgrid, covering electricity purchasing, on-site generation, energy storage, and consumption. The objective is to minimise three key performance indicators simultaneously:

- total energy-related costs,
- carbon footprint,
- overall energy resilience, the system's robustness against unexpected events that could lead to excessive costs or emissions.

To achieve this, the optimisation framework is divided into three complementary layers, each with a distinct purpose and temporal focus: static/investment optimisation, continuous day-ahead operational optimisation, and what-if simulation-based optimisation.

9.1. Static / Investment Optimisation

This stage represents the broadest and most comprehensive level of optimisation. It is executed typically as a one-off analysis using historical data, often spanning an entire previous year. The goal is to determine an optimal configuration of the microgrid from a long-term perspective. This includes identifying the best purchasing strategy, the appropriate sizing of photovoltaic generation and battery storage systems, the required capacity reservation, and the feasible level of operational flexibility. The analysis also considers the potential replacement of existing technologies and the benefits of participating in energy communities through buying and selling mechanisms.

All investment, operational, and technical parameters are integrated into the simulations, and results are often visualised as multidimensional heatmaps showing the best-performing combinations. This stage answers questions such as the ideal size of a PV installation, whether battery storage should be added and at what capacity, how long the return on investment will be, and how system performance changes if part of the battery is reserved for backup purposes.

9.2. Continuous Day-Ahead Operational Optimisation

The second layer of optimisation focuses on daily system operation and is performed continuously, at least once per day, often with the possibility of intra-day recalculations. This optimisation is forward-looking and relies on external forecasts, such as weather predictions and spot market prices, as well as internal parameters, including planned production schedules. A crucial part of this process is the creation and use of a consumption model, which provides predicted power demand based on controlled variables such as production planning.

Because operational decisions can only be adjusted within a short time frame, this optimisation restricts itself to parameters that can be influenced within the day. These include the algorithm

governing battery charging and discharging for the purposes of spot price surfing, peak shaving, and carbon-aware load shifting; the active control of process-based storage systems (e.g., hysteresis control for cooling blocks); the active management of 15-minute load maxima; and preparing storage or consumption capacity for expected advantageous operating conditions. The output of the day-ahead optimisation is a detailed plan, essentially a structured set of commands or parameters, distributed to the technological components for execution by third-party control systems. The objective is to ensure that daily operations yield maximum benefit from variable prices, on-site generation, and flexible consumption.

9.3. What-If Simulation–Based Optimisation

The final component is designed for scenario analysis and exploration of hypothetical changes. Using historical datasets (typically one year), the user can specify selected degrees of freedom, and the system calculates the impact of potential modifications. This tool enables the comparison between the current (“AS-IS”) situation and hypothetical (“WHAT-IF”) scenarios. Typical use cases include evaluating the consequences of technology replacement, adjusting production schedules (such as transitioning from a two-shift to a three-shift regime), or modifying specific parameters of the consumption model.

By modifying model components, such as reducing the energy intensity of a production line to emulate the purchase of a more efficient machine, the tool produces a quantitative assessment of the benefits or drawbacks of the proposed change.

10 Topic 5 - Dynamic Control of Consumer Energy Microgrid

This chapter defines the key functional requirements and principal challenges for the Dynamic Microgrid Control (the so-called Action Layer) within Work Package 4 (WP4). The core of the solution is the implementation of a Dynamic Algorithm that ensures continuous and adaptive control of assets based on predictions and the user's operational plan.

10.1. Principal Challenges and Problems to Solve

Dynamic control must overcome the rigidity of existing systems and address the complex interplay between internal and external factors:

10.1.1. Main Challenges

- Consumption Inherence Problem (Planned Consumption):
 - Challenge Description: In the case of industrial complexes and large office buildings, a large part of consumption is determined by the operational plan (production plan, utilization plan, HPC task plan, etc.).
 - System Requirement: The system must be able to work with the plan but also react dynamically when the actual consumption differs from the original prediction.
- Volatility of inputs:
 - Challenge Description: It is necessary to incorporate dynamic profiles of external parameters (e.g., day-ahead quarter-hourly profile of market spot prices) while integrating the only partially predictable unstable generation from local renewable sources.
- Multi-Criteria Control:
 - Challenge Description: The challenge lies in implementing logic capable of balancing competing goals: cost minimization, reduction of the CO2 footprint, and maintenance of energy resilience (e.g., UPS reserve)—in other words, finding the best compromise.

10.1.2. Current State of Solvability – Must Be Overcome

Existing Approach	Functional Limitation	Requirement for New Solution (WP4)
Proprietary Microgrids	Closed architecture, preventing the deployment of advanced AI algorithms.	Creation of an open control interface (API) for communication with assets.
Rigid Algorithms	Fixed rules (e.g., a timer for battery charging) that do not adapt to current conditions.	Implementation of a Dynamic Algorithm (MPC) that is continuously adaptive .

10.2. Functional Requirements for Asset Control

The Dynamic Algorithm must be able to generate and send commands to control the following categories of assets (control is performed in **minute intervals**).

10.2.1. Consumption Control

Consumption Category	Functional Requirement (Required Action)	Primary Goal of Functionality
Opportunistic Loads	The system must be able to issue a signal to Permit/Postpone the start of non-critical (opportunistic) loads (e.g., maintenance, testing).	Load Shifting to periods of low prices or high local generation.
Controllable Quarter-Hourly Loads	Ability to modulate the performance of elements (e.g., HVAC, main pumps) in short intervals for immediate reaction.	Peak Shaving (cost reduction during peaks) and load stabilization.
Accumulation (e.g., Chilling Systems/Boxes)	Issuing commands to change the setpoint (pre-cooling or temperature increase) within the user's tolerance band.	Utilizing thermal inertia for temporary energy accumulation.

10.2.2. Source and Accumulation Control

Source Category	Functional Requirement (Required Action)	Primary Goal of Functionality
Battery Energy Storage System (BESS)	Continuous Charging/Discharging control based on the optimal dispatch curve.	Maximizing profit from price arbitrage and increasing own consumption of renewables.

UPS Functionality / Resilience	The system must maintain a minimum SoC (State of Charge) reserve in the BESS defined by the user.	Risk mitigation and ensuring the reliability of critical system power supply.
Own Generation	Ability to issue commands for Switching On/Off and performance modulation (e.g., CHP, PV) based on operational and market conditions.	Optimizing source operation to minimize cost/emissions.

10.3. Input Variables and Implementation Priorities

The Dynamic Control module (Action Layer) receives data and control sequences from other modules and the user.

10.3.1. Input Variables for Control

Input Source	Input Variable	Purpose for Control (Action Layer)
User Input (Planning)	Reference Variables (production plan, attendance plan, HPC task plan).	Key input for the MODEL Module (consumption inference).
Criteria	Criteria Weights (Costs, CO ₂ , Robustness).	User-set priorities for the OPTIMIZATION Module calculation.
Non-standards	Non-Standard Plan (shutdown, service, shift change, etc.).	Accounting for short-term operational anomalies in prediction and optimization.
External Sources (Web Services)	Day-ahead spot prices and CO₂ emission factors . Predicted RES generation (irradiance prediction).	External data for the optimization criterion.
MODEL Service Link (Inference)	Predicted Area Consumption (including inference from the user's plan).	Input prediction curve for the OPTIMIZATION Module.

10.3.2. Output

Output	Output variable / control action	Purpose for Control (Action Layer)
OPTIMIZATION Module (MPC Core)	Optimal Dispatch Sequence (a plan of control actions for BESS and	Main control command for the Action Layer.

	consumption over a 48-hour horizon).	
regular recalculation and optimization of the dynamic control plan	intelligent, automatically performed update in connection with the improvement of prediction accuracy / real development of input parameters	Continuously optimize to achieve optimal results

10.3.3. Implementation Proposal and Priorities (WP4)

The implementation of dynamic control should focus on the rapid deployment of the core and user control features.

1. Priority 1: Dynamic Algorithm Deployment:

- a. Integration of the **OPTIMIZATION Module (MPC)** as the central control intelligence.
- b. **Design and implementation of an interface** for receiving optimal sequences from the MPC and converting them into real control commands (setpoints and ON/OFF) for the end assets.

2. Priority 2: Plan Input and Control:

- a. Creation of a **robust user interface** for entering the **Production/Task Plan** (Reference Variable).
- b. Implementation of the function to **set the weights of the optimization criteria** (cost, CO₂, robustness) and **technical constraints** (e.g., minimum SoC, maximum thermal inertia of cooling).

3. Priority 3: Visualization and Override:

- a. Implementation of a **BIM/Visualization interface** to show how the calculated optimal plan affects consumption, BESS, and costs.
- b. Ensuring the functionality of **manual intervention (Override)** for unexpected events.

11 Topic 6 - EMOS Layer

11.1. EMOS Overview and Main Challenges

The EMOS layer is the core technological and data backbone of this work package. It is a cloud-based multi-tenant SaaS platform where data preparation, modelling, optimisation, dynamic control and user interfaces run together as one integrated system. EMOS centralises access to data and services, enforces security and governance, exposes standardised REST APIs for partner microservices, provides BI dashboards and charting, including 3D BIM-based views, and ensures long-term operability, monitoring and extensibility across multiple organisations and sites. In practice it is the environment where research prototypes become usable tools connected to real EMS/BMS systems and pilot buildings.

11.1.1. Challenges of the EMOS Layer

A key challenge is coordinating multiple independent microservices developed by partnering teams. This requires clearly defined and versioned API contracts, an API-first mindset, and consistent separation of responsibilities so that services can evolve independently without breaking integrations.

EMOS must provide robust security for both human users and machine-to-machine communication. This involves modern authentication and authorisation mechanisms, safe token handling, SSL termination and certificate management, and complete audit logging of critical operations, forming a transparent and governable environment.

Multi-tenancy adds an additional layer of complexity. Data, configuration and access rights must be strictly separated between tenants while still allowing shared infrastructure and services. Tenant-aware identity, routing and data partitioning are needed to ensure that each organization sees only its own assets, buildings and metrics, and that scaling or onboarding new tenants can be done without impacting existing ones.

The data layer is to offer a unified yet extensible model for time series, BIM information, configuration data and analytical or optimization outputs. It has to support efficient queries and aggregations for monitoring, analysis and reporting, while allowing new sites or indicators to be added without disruptive migrations. On top of this, the platform must deliver responsive visualizations of energy use, costs, efficiency, emissions, data quality and optimization impacts, including 3D building representations where BIM is available.

All these elements depend on solid DevOps practices. EMOS must provide CI/CD pipelines, monitoring, alerting and centralized logging, along with clearly separated development, testing and production environments, so that the platform can be deployed, updated and maintained in a controlled way over time and can safely host multiple tenants on shared infrastructure.

11.2. Common Industry Practices in SaaS Development

EMOS should follow standard cloud-native SaaS practices to reduce risk and simplify maintenance. Functionality is decomposed into containerized microservices orchestrated by a cluster manager such as Kubernetes or Docker Swarm, with external traffic routed through an ingress proxy layer. This enables independent deployment, scaling and updating of individual components, while still supporting shared, multi-tenant infrastructure.

REST APIs described in open specifications (OpenAPI 3) serve as binding contracts between teams and services. These descriptions support client generation, automated testing and documentation. APIs are exposed via a gateway that manages routing, throttling and access control, and presents a single entry point for external systems, including tenant-aware routing and policy enforcement.

Security and identity management rely on token-based access, a dedicated identity provider, encrypted communication and controlled handling of secrets. Tenant information is part of the identity and authorization model so that user management, roles and permissions are always evaluated within the correct tenant context and machine access remains strictly scoped.

Analytics use embedded BI tools for dashboards and reporting, while custom charts and BIM integrations are implemented directly in the front-end with modern libraries. This approach combines flexibility for project-specific views with the option to utilize robustness of proven BI engines, and allows dashboards to be filtered and branded per tenant and per site.

Data structures are governed by code-defined schemas owned by the service that manages a given dataset and are typically not used directly by other services. Integration happens via defined APIs, only in specific, justified cases (e.g. shared time-series storage) is a database schema shared across multiple services. This keeps the platform coherent as it evolves, provided teams follow common conventions for APIs, schemas and documentation and validate their schemas during development and deployment.

11.3. Proposed Approach and Prioritization

The implementation of the EMOS layer is structured into four phases that build on each other. First, the initial phase establishes the core architecture, infrastructure, security and CI/CD foundations on which all other work depends. Once these foundations are in place, the intermediate phases focused on the data and integration layer and on the user portal with BI dashboards should progress in an agile, iterative way and largely in parallel, so that early back-end services can immediately feed into front-end development, reduce integration risk and keep EMOS aligned with real user needs. Finally, the concluding phase concentrates on stabilisation, testing and documentation and can only be completed once the main functionality from the earlier phases is available.

11.3.1. Phase 1 – Architecture and Infrastructure

The first phase introduces the core platform. The target architecture is specified, including internal components and interfaces enabling external data ingestion. CI/CD pipelines are set up, an API gateway and identity provider are deployed, and EMOS begins to provide secure access, request routing, logging and basic health checks.

11.3.2. Phase 2 – Data Model and Integration Layer

The second phase establishes the data and integration services. Unified data architecture for time series, configuration data, BIM mappings and analytical or optimization outputs is designed and supported by suitable storage technologies, with explicit support for tenant-level separation and scoping. Formal data contracts for key entities are defined, and backend services are implemented to ingest heterogeneous sources and expose cleaned, structured, tenant-aware data through stable APIs to other components.

11.3.3. Phase 3 – User portal and BI layer

The third phase adds the user-facing part of EMOS. A modern web portal is developed and integrated with the identity provider to offer role-based access for different user groups within each tenant. Dashboards and analytical screens are created to present consumption, costs, comfort indicators where available, optimization results and data-pipeline status, combining tables and charts with 3D building views in cases where BIM models exist, always restricted to the tenant's own assets.

11.3.4. Phase 4 – Stabilization, QA and Documentation

The fourth phase focuses on making the platform production-ready. Realistic end-to-end scenarios, including multi-tenant usage patterns, are used to verify functionality, performance and robustness under load, and to tune critical components. In parallel, comprehensive technical documentation, generated API references, deployment guides and integration patterns are prepared. The result is a stable, multi-tenant EMOS platform capable of reliably supporting pilot deployments and subsequent evaluation and reporting within this work package.

12 International energy topic connection

The connection of energy topics processed within WP4 with international experiences and projects in the target area is mediated within the team through the exchange of experiences with the DFKI team.

DFKI is active in a number of projects related to topics concerning energy and energy efficiency. Most notable in this context is the German project SmartLivingNEXT [8], funded by the federal ministry of Research, Technology and Space (BMFTR). SmartLivingNEXT is establishing an AI-based ecosystem that leverages data spaces as the core infrastructure supporting services and applications for residential buildings and the housing sector. The dataspace concept used in the project retains data on-site and provides the community with AI-assisted basic services for data analysis, forecasting, and pattern recognition.

The project is developed in accordance with the European Gaia-X framework. Gaia-X aims to create a federated, interoperable, and secure data and cloud ecosystem in which users retain full data sovereignty. Establishes common standards, identities, and trust mechanisms so companies can share and use data across borders and sectors without vendor lock-in. Technically, it provides a federated, standards-based technical framework in which services, data, and identities are described through interoperable, machine-readable Self-Descriptions. Using decentralized identity, open APIs, and a unified trust-and-compliance layer, it enables secure, portable, and verifiable integration of cloud and data-space components across different providers.

12.1. Energy dataspace

Data spaces are relevant especially for the energy sector, where participants with different roles (energy provider, grid operators, metering service provider, housing companies, etc.) are often hampered by fragmented data. Instead of relying on isolated solutions, energy data spaces enable grid operators, producers, aggregators, and consumers to share data in real time and in a controlled manner. This makes load management, grid stability, and shortage management more efficient. The integration and growing share of renewable energy sources, especially wind and solar—introduces significant variability and spatially uneven generation patterns. Here, redispatch is a central operational tool used by system operators to maintain grid stability under these conditions. Data exchange from various sources is crucial in this context.

12.2. Importance of data quality

Data and data quality is relevant and important for applications based on artificial intelligence. Using data provided by energy data spaces, value-added services can be developed, using recent approaches and advances in AI, in particular neural networks, as well as foundation models and large language models. Examples of AI-based services and applications consist of non-intrusive load monitoring (NILM) of smart meter data, prediction of energy consumption, including using

physics-informed neural networks (PINN), and prediction of solar power generation. Since training neural networks requires data with sufficient volume and variation, a simulation approach was developed which extends data available in energy data spaces. These services provide the opportunity to support various use cases with dedicated applications such as e.g. adaptive power control based on prediction of energy supply and consumption. Other use cases include predictive maintenance, anomaly detection, grid stability monitoring, and load forecasting.

12.3. LLM usage in energy optimization process

The recent advances in large language models allow further applications in data spaces. Agentic AI (with one or multiple agents acting on top of LLMs) facilitates the automation of various energy-related tasks. They can e.g. predict not just generation, but flexibility opportunities, e.g., shifting EV charging, or scheduling battery discharge to absorb excess renewables. Interacting directly with households or businesses, they may autonomously suggest and execute energy-saving measures based on behavior and real-time conditions.

12.4. BIM models

BIM models are a crucial source of information and can serve as digital twins when paired with agentic AI, enabling autonomous testing of interventions in a virtual environment before implementing them in real buildings - for example, adjusting HVAC schedules, retrofitting, or integrating EV chargers. This potential must be further researched and fully leveraged.

13 Reference verification

13.1. Practical verification

Together with our partner WPE TSK - Trenčín Self-Governing Region, we are validating the functional specification, validating the availability of input parameters. During the project, we plan to deploy individual functional blocks to specific buildings within TSK, evaluate the benefits, and validate quality and functionality.

During the specification of the assignment, we studied the needs and goals of energy management from the perspective of stakeholders in the field of property management and energy management of TSK.

13.2. Main challenges detected

As the main challenges, we detected the need to supplement meters and obtain reference contextual data.

13.3. Functional requirements verification

The functional requirements are in accordance with the detected conclusions from the conducted needs research.

14 Risks and mitigation measures

- **Insufficient data quality** → mitigation: robust preprocessing, redundancy in data sources.
- **Absence of BIM models** → mitigation: simplified models from PDF, point clouds, or photogrammetry.
- **Integration with BMS systems** → mitigation: modular architecture and adherence to open standards.
- **User adoption barriers** (cost, complexity, trust) → mitigation: user-friendly tools, stakeholder involvement, training.
- **Procurement and installation constraints for sensing equipment** → mitigation: early engagement with building owners, flexible sensor selection, and contingency planning for installation limitations.

Resources

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Annex

About the project

The InnovAlte Slovakia project was launched in response to the call “Transformation and Innovation Consortia” announced by the Government Office of the Slovak Republic under the Recovery and Resilience Plan of the Slovak Republic (Component 9 – Investment 2: Supporting cooperation between companies, academia, and research and development organizations). The call aims to drive systemic transformation and increase the added value of key sectors of the Slovak economy through intensive collaboration among research institutions, innovative enterprises, the public sector, and internationally renowned partners.

InnovAlte Slovakia seeks to build a dynamic and sustainable innovation ecosystem in the field of artificial intelligence (AI), effectively linking cutting-edge research with practical applications. The project emphasizes the development of AI solutions that are not only technologically advanced but also ethical, environmentally sustainable, and socially beneficial. The consortium brings together leading research centers, universities, and businesses from Slovakia, Germany, and the Czech Republic.

Key focus areas include the development of AI algorithms for improving building energy efficiency, enhancing traffic safety through video analytics, automating software development, driving digital transformation in the insurance sector, and validating functional prototypes. Special attention is also given to AI education, talent development, and the incubation of startups.

The project’s outcomes will significantly strengthen Slovakia’s position in research and innovation, reduce environmental burdens, increase the competitiveness of the national industry, and modernize public services. By bridging the public and private sectors with international research excellence, InnovAlte Slovakia stands as a key instrument in addressing the social and economic challenges of today.



“Funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I02-03-V01-00029”

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