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PLUG-AND-USE RENOVATION WITH ADAPTABLE LIGHTWEIGHT SYSTEMS

D3.1a

Requirements for PnU smart control

Version: 1.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958218

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Terms, definitions and abbreviated terms

AHU	Air Handling Unit
API	Application Programming Interface
BIM	Building Information Modelling
BIPVT	Building Integrated Photovoltaic/Thermal
BLE	Bluetooth
BMS	Building Management System
DA	Daylight Autonomy
DGI	Daylight Glare Index
eAHC	Air handling unit with Heating & Cooling
Erb	Rebound Energy
EVU	Extreme Ultraviolet
eWHC	External Wall Heating and Cooling
f	Flexibility Performance
FDD	Fault Detection and Diagnosis
FF	Flexibility Factor
GCA	Global Comfort Availability
HI	Heat Index
HMI	Human-Machine Interface
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
IoT	Internet of Things
IR	Infrared
KPI	Key Performance Indicator
LAN	Local Area Network
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCD	Liquid Crystal Display
MPC	Model Predictive Control

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MQTT	Message Queuing Telemetry Transport
nZEB	nearly Zero Energy Buildings
OSI	Open Systems Interconnection
PLC	Programmable Logic Controller
PMV	Predicted Mean Vote
PnU	Plug and Use
PPD	Predicted Percentage of Dissatisfied
RER	Renewable Energy Ratio
RES	Renewable Energy Sources
RTU	Remote Terminal Unit
SBS	Sick Building Syndrome
SEM	Smart Energy Management
SRI	Smart Readiness Indicator
TCP	Transmission Control Protocol
TTL	Time to Live
VCA	Visual Comfort Availability
VOC	Volatile Organic Compounds

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Executive summary

The main aim of D3.1 “*Requirements for PnU smart control*” is the definition of the requirements for the control of the Plug-and Use (PnU) kits, considering the different PLURAL solutions. At the same time, the presented outcomes aim to establish the required monitoring data, not only for control purposes, but also for assessment oof the impacts of the PLURAL solutions.

In order to account for the close relationship among control/monitoring requirements and the related on-going developments, D3.1 is unfolded in two submissions. This current deliverable, named D3.1a aims at introducing a draft of the control scheme, the first assessment of the different PLURAL technologies (according to their capabilities and control needs), and the assessment of the monitoring requirements. The second Part of this deliverable, named D3.1b will be submitted in M12 (30/09/2021) and will include the final potential solutions (sum of technologies) for the Demo cases and the technologies. It will also present the final schemes on control solutions regarding real (basic) and virtual (advanced) PLURAL cases, the equipment for control and monitoring and the integration requirements.

Thus, in D3.1a after a brief introduction (Chapter 1), a first overview on the control schemes is featured (Chapter 2). This overview includes the definition of the different elements that must compose the control systems, as well as their potential integration, coordination and communication relationships. Thus, the chapter introduces the architectures and requirements of two different levels of control: local-based control and cloud-based control; inherently the control hierarchies are also considered, assessing the possibilities of acting at the level of occupied area or dwelling, or at the level of the building in general. These architecture schemes and requirements, drafts the different available and required sources relationships, as well as the final outcomes expected.

In Chapter 3, the different PLURAL technologies are presented, from the point of view of their requirements and control capacities, and operational characteristics. Thus, for any one of those, a general description is offered, as well as their available control and interfacing characteristics. Even so at this stage is almost impossible to define in detail, considering the still pending technological developments and integrations into the final PLURAL solutions, also a first approach on the aims for integration in the Supervisory control strategy for each technology introduced.

Chapter 4 focuses, mainly, in the monitoring for assessment requirements. To define a coherent background, in the first instance, the different variables and required parameters are considered, introducing their related KPIs, which are defined in detail. Likewise, a list of the different equipment available by the PLURAL technologies (sensors and meters) is presented, with the aim to evaluate which of them could also be used for monitoring for assessment purposes. Finally, from the above, the monitoring for assessment framework is established, defining the parameters and variables to be analyzed, their technological requirements, their level of use (thermal zone, dwelling, building), and their implementation timing (pre and post intervention). Finally, Chapter 5 presents the conclusions of D3.1a.

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1. Introduction

The main aim of D3.1 "*Requirements for PnU smart control*" is the definition of the requirements for the PnU controls, considering the different PLURAL solutions. At the same time, the presented outcomes aim to establish the required monitoring data, not only for control purposes, but for assessment on PLURAL solution impacts.

PLURAL presents different technologies that, in combination, should result in adapted-to-case PnU solutions that allow to carry out renovations of buildings efficiently and effectively, resulting in lower investment costs, shorter implementation times, and evident reductions in energy consumption. In order to achieve these objectives, but also to demonstrate them, it is necessary to establish both intelligent control mechanisms and a monitoring system.

In this way, the different technologies that make up the PLURAL environment must consider coordination mechanisms and, finally, control systems that make it possible to ensure the established reduction of energy consumption and operating costs, as well as the optimal comfort conditions of the end users. This implies, as first step, understanding each of the technologies, their respective control and operation systems, and their coordination requirements between them, considering their potential integrations.

At the other side, the purposes of building monitoring are related to recording and reporting PLURAL impacts, and implementing operational control. Thus, the different monitoring equipment (dedicated and/or own-technologies sensors and meters), must be described and structured considering both aspects, the control requirements and the assessments needs. For this, it is necessary not only to establish the control mechanisms, but to design a monitoring strategy that, necessarily, requires the definition of parameters and variables to consider, within the framework of the KPIs that allow demonstrating the benefits of PLURAL solutions, mainly from energy and comfort points of view.

Considering the relationship among these topics and other on-going developments, D3.1 is unfolded in two submissions; a first delivery (D3.1a, CO, 30/04/21), which presents a draft of the control scheme, the first assessment of the different PLURAL technologies (according to their capabilities and control needs), and the assessment of the monitoring requirements. In a second delivery (D3.1b, PU, 30/09/2021), once the PLURAL solutions have been established in a more detailed way (as combinations of technologies and according to the requirements of the demonstrations), and the fundamentals of the Lysis platform have been introduced, the characterization of the system of control and specific monitoring requirements will be established case by case.

Of all the above, both D3.1 deliverable must be quite linked to other PLURAL on-going and/or next-future developments. For D3.1a, the developments of T1.5 (Key performance indicators) and T1.6 (Pilot use case definition) have been considered, as well as the first information coming from WP2 (Selection of technologies) and T7.1 (Buildings' survey and preliminary design). For D3.1b, the more mature outcomes of these currently on-going developments will be included, in such a way the final version would offer key information for T3.2 (Building and assets data management) and T3.5 (SEM implementation, systems test adaptation and validation under theoretical conditions), as well as for WP5 (IT renovation tools-BIM based LYSIS platform and Multi-objective Decision Support Tool) and T7.6 (Monitoring campaign).

2. Vision on the PLURAL control as a whole

Hereunder, the general vision of PLURAL supervisory control is depicted. The PnU technologies as retrofit solutions require good operational compatibility with the existing building environment and other energy systems & services. The innovative PLURAL PnU solutions must be controlled in a coordinated and optimal manner to reach the desired outcomes.

Two fundamental approaches were identified to support the PnU smart control development. In this section the two supervisory control architectures are depicted in Figure 1 local-based supervisory control and in Figure 2 cloud-based supervisory control. The key components, processes, actors and data pipelines are described at several levels: physical devises, datalinks and local control, network connection and cloud-based services. In addition, the PLURAL tooling across the WPs (such as Smart Energy Management (SEM), LYSIS-KAFKA, PnU Toolboxes and simulation framework) is indicated in frame of the supervisory control use-case.

2.1 Supervisory control components

2.1.1 PnU solutions and existing systems

A wide range of technologies with various technical solutions, capabilities and aims and various control requirements are combined within the PLURAL Project. The PLURAL PnU solutions comprise actively controlled Indoor Environment Quality (IEQ) control systems (e.g. mechanical ventilation, air-conditioning and heating and cooling systems including building envelope thermal activation, heat pumps, blinds and heat recovery windows, etc.), PV and vacuum solar panels, batteries, as well as structural elements and insulation materials. The various technologies are combined into three PnU Kits (SmartWall, External Wall Heating and Cooling (eWHC) and Air handling unit with Heating & Cooling (eAHC)), as described in detail in the Chapter 3, including their control and interfacing characteristics. The PnU Kits can be added to external or internal side of the building envelope. They require combination of short-term and long-term control strategies of PLURAL supervisory control, including functions for grid status monitoring and outdoor environment monitoring and prediction.

As PLURAL PnU technologies serve as retrofit solutions, the newly installed systems contained in the PLURAL PnU Kit must be integrated within existing buildings. The existing systems (such as Domestic Hot Water (DHW) preparation systems, existing heating and cooling systems, existing ventilation systems, etc.) are complemented or entirely substituted. This places special requirements on the PLURAL

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supervisory control, which may integrate control of the existing building systems and newly installed PnU Kits.

The PLURAL supervisory control must be universal and robust enough to be used for various technical solutions of the developed PnU Kits and various building retrofit scenarios, following different building types and building owner requirements. It must allow manual as well as automatic control modes, performance prediction and decision-making support based on system monitoring as well as external data (e.g. Building Information Modelling (BIM) documentation, weather forecast, etc.).

The concepts addressing supervisory control architecture are elaborated in next section. Hereunder, the required components/features are depicted:

2.1.2 Local monitoring and control toolboxes

Local controllers (PLC) of existing and PLURAL building components communicate with hardware dedicated for SEM installation/configuration. The following monitoring can be expected:

a. Advanced metering management (Power monitoring)
b. PLURAL PnU solution local monitoring (e.g. PnU temperatures, local Renewable Energy Sources (RES) production, occupant's desired settings)
c. PLURAL Indoor Environment quality monitoring (e.g. room air temperature, humidity, Carbon Dioxide CO_2)
d. Existing building system monitoring (e.g. storage tanks temperature, DHW power load, heating demand)
e. …

2.1.3 Communication middleware

Communication middleware enables to link various communication data paths using wide range of communication interfaces and protocols to be used in the PLURAL technologies as well as in existing Building Management System (BMS). Based on a DEMO survey presented in Chapter 3, the following interfaces and protocols are used. The communication middleware should be compatible with the following interfaces and protocols, or they need to be converted to suitable version to be handled by communication middleware.

Communication interfaces:

a. LAN (Local Areal Network);
b. RS485;
c. WiFi b/g/n 2.4 GHz;
d. LoRaWAN;
e. …

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The following communication protocols can be expected:

a. Modbus TCP/RTU (Transmission Control Protocol/ Remote Terminal Unit)
b. LonWorks
c. MQTT (Message Queuing Telemetry Transport)
d. HTTP (Hypertext Transfer Protocol)
e. …

2.1.4 External data acquisition

The 3rd party services and other building data may be loaded to the external data acquisition via Application Programming Interface (API) or other interfaces and used for purpose of supervisory control.

The use of following data can be expected:

a. BIM documentation
b. Outdoor environment monitoring and prediction (e.g. actual or forecasted weather conditions)
c. Grid status monitoring (e.g. actual or day-a-head energy tariff or CO_2 intensity)
d. …

2.1.5 Human Machine Interface

The Human-Machine Interface (HMI) (also refer to 'front-end') visualizes building data and enables energy data analysis to facility operators. The operators can select the SEM regime of optimization, remotely supervise the whole system and eventually change or overrule the system settings (e.g. setpoints settings, switch off some zones/devices etc.)

The following actions can be done via HMI:

a. Data monitoring and building statistics visualization
b. Energy assessment
c. Supervisory commands
d. …

2.1.6 Supervisory control

The supervisory control is a core 'back-end' algorithm that processes monitoring data and aim to optimizes and coordinates local controllers of both PLURAL and existing technologies. It provided functions such as:

a. Whole-building control optimization and coordination
b. Processing of supervisory commands

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c. Data analytics
d. Control optimization
e. Fault detection and diagnosis
f. …

2.2 Supervisory control architecture

In general, the architecture for the supervisory control can be characterized by spatial aspects or system interconnection aspects. The spatial aspect deals with hardware architecture in sense of physical location of the control hardware i.e. location of control hardware at room, dwelling, building and 'remote' levels. The design of underlying physical infrastructure, location of electronics, switchboards etc. is initially defined in section 3. The hardware architecture will be further elaborated in D3.1b, following the detail design documentation of PnU technologies and Toolboxes within WP2 and WP4. In this deliverable D3.1a, the architecture is understood rather from the perspective of system interconnection following standardized ISO Open Systems Interconnection (OSI) model, that introduces conceptual model for telecommunication or computing system describing interconnection at various layers/levels without regard to its underlying internal structure and technology. The ISO/OSI models depicts levels of system interconnection i.e., physical hardware, data link, network, transport, session, presentation and application layers.

Two general approaches for implementation of supervisory control algorithms were identified, each fitting different needs and requirements of PLURAL demo sites. These approaches are depicted in two architectural diagrams explaining the components relation at level of controlled systems, local controllers or cloud-based services. The architectural diagrams hereunder show the fundamental components, main dataflows, and key actors/services in the control process. In addition, the available PLURAL tooling, that will be developed across the WPs within the project, is highlighted in the diagram. As such, the role of PLURAL tools and platforms is shown here in frame of control use-case.

The supervisory control in the PLURAL project will be carried out by SEM (WP3 outcome). The developed control strategies can be implemented on local control level or as cloud-based service according to depicted architecture diagram. The local control of individual PnU devices is provided by their toolboxes (WP2 and WP4 outcome). The LYSIS (Kafka) platform (WP5 Outcome) is used here as communication middleware. The LYSIS platform (WP5 outcome) will provide the external data acquisition and HMI features. Although the LYSIS platform is mainly developed for planning and design support, the developed interface and processes can be used in the context of WP3 and applied in operations as well. A brief recapitulation of PLURAL tooling follows:

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PnU solutions

PnU solutions are represented by following technological PLURAL concepts: SmartWall, eWHC and eAHC. These technological concepts are partially described in section 3 and will be further defined in WP2 deliverables.

PnU Toolboxes

PnU Toolboxes represents set of the crucial components of the operational systems. They will be installed at various spatial level in such a manner as to provide access for future maintenance & repairs. The hardware architecture depends on given demo site and will be elaborated in D3.1b after its detailed definition in WP4.

Smart energy Management (SEM)

Smart energy management is a set of algorithms or basic rules to be installed or configured at dedicated control hardware, or communicate via an on-line platform (namely LYSIS). Thus, SEM uses this gathered real data, to characterize the energetic and economic behavior of the conditioned zones, the whole building and its centralized Heating Ventilation and Air Conditioning (HVAC) and DHW systems and RES production, and to optimize the behaviors from the energetic and/or economic point of view. For some specific technologies, SEM will be able to implement predictive management, considering weather forecast and energy pricing conditions.

LYSIS platform

A comprehensive Information Engineering (IT) big data handling platform incorporating technical specifications and performance data of all involved technologies and components and assessment module with defined Key Performance Indicators (KPIs) based on energy performance, cost-effectiveness, IEQ, comfort, renovation time and Life Cycle Cost (LCC) / Life Cycle Assessment (LCA) evaluation tools. The platform is capable to implement the developed smart management and self-detecting algorithms (SEM) to ensure the real intelligence of the LYSIS platform.

LYSIS (Apache kafka) platform

This platform can efficiently ingest and handle massive amounts of data into processing pipelines, for both real-time and batch processing.

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2.2.1 Local-based supervisory control architecture

Processes and data flows

In this case, the core 'back-end' algorithms of supervisory control are configured at local control level. The supervisory strategies are set at centralized PLC, that is physically installed within the building control systems and coordinate the local controllers of individual devices. The central PLC collects building system monitoring, local settings from occupant's interface (e.g. room thermostat) and incoming supervisory. These data are processed and at local control level and the devices are actuated based on configured supervisory control strategy. Processed data are provided to "cloud-based service" level via communication middleware. Apart from the system data, other cloud available services (e.g. grids status and weather forecast) are handled via communication middleware into external data acquisition, where other building information (e.g. BIM documentation, tenant database etc.) can be loaded and stored. These data are available to be visualized and analyzed by facility management via HMI. Facility management may remotely change settings of the building systems and insert supervisory commands, that are transferred via HMI and communication middleware to supervisory control algorithm to be processed.

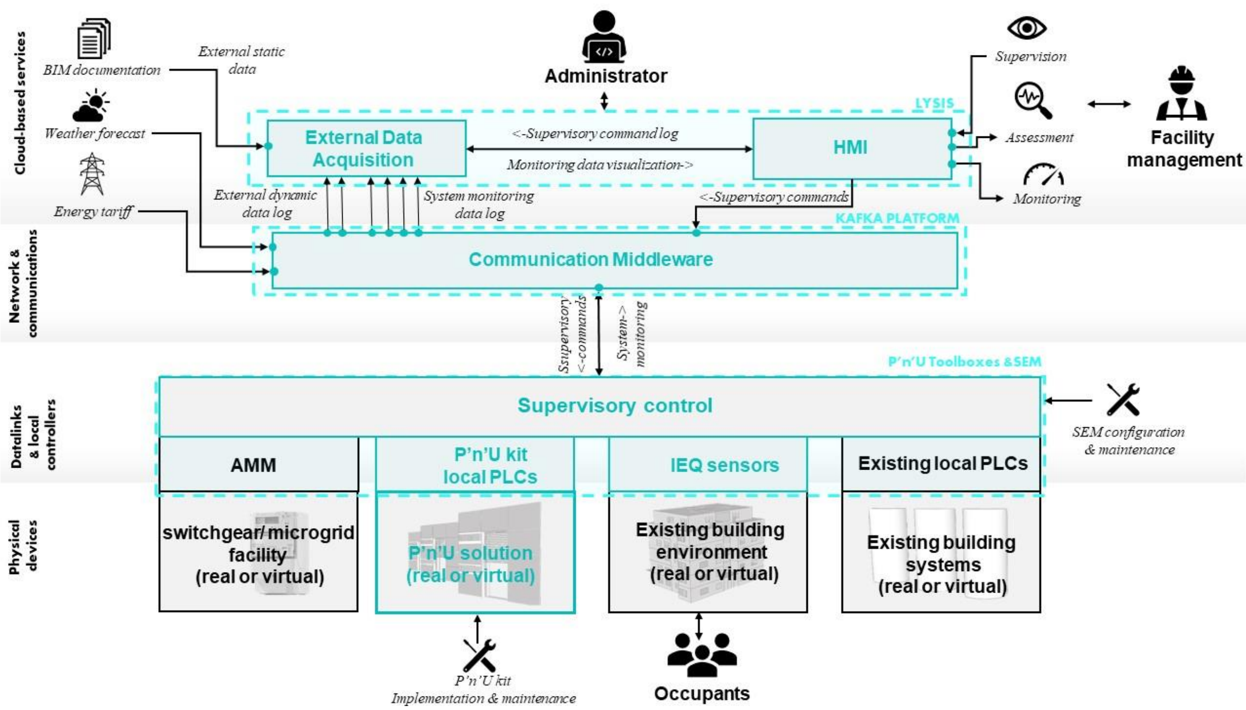

FIGURE 1 LOCAL-BASED SUPERVISORY CONTROL ARCHITECTURE

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Potential and limitations of PLURAL tooling

The local-based architecture provides highly robust control solution enabling supervisory actuation of individual devices and their components. The SEM strategies are integrated into the structure of PLURAL Toolboxes. The SEM strategies are configured at the central PLC, that is part of local electro installation. It supports integration of devices (both PLURAL and existing technologies) with no local controllers or controllers with limited level of autonomy. This solution also offers united interface to cloud-based services.

Drawback of this solution is the limited computational capability of standard PLC. The supervisory control in standard PLC is usually configured in form of rule-based strategies and as standard feedback control. The limited computational capability usually disables some advanced/state-of-the-art control features (e.g. supervisory Model Predictive Control (MPC) strategies). The energy performance quite often relies on level of expertise of the facility management and their manual settings of supervisory commands. The automated setting optimization is limited.

The maintenance and configuration requiring control engineering and low voltage electrician expertise is required at both local and supervisory level.

2.2.2 Cloud-based supervisory control architecture

Processes and data flows

In this case, the core 'back-end' algorithms of supervisory control are installed as cloud-based service at the remote server. The building system monitoring data and local settings from the occupant's interfaces (e.g., room thermostats) are directly transferred via the communication middleware and delivered to external data acquisition same as external cloud-data services. The supervisory control is provided with the required monitoring data and requests from the facility manager regarding the desired performance. These requests are inserted to the algorithm via HMI. HMI allows the same features as in the previous case, such as data visualization and analysis. Supervisory control processes the data at the cloud-based level and provides supervisory policies/control signals (usually in the form of system setpoints), that are delivered via communication middleware to the local controllers serving the individual devices in the building. Facility management may remotely overrule/change the settings of the building systems as in the previous case or may set the desired performance limits and let the supervisory control algorithm to automatically optimize the operations.

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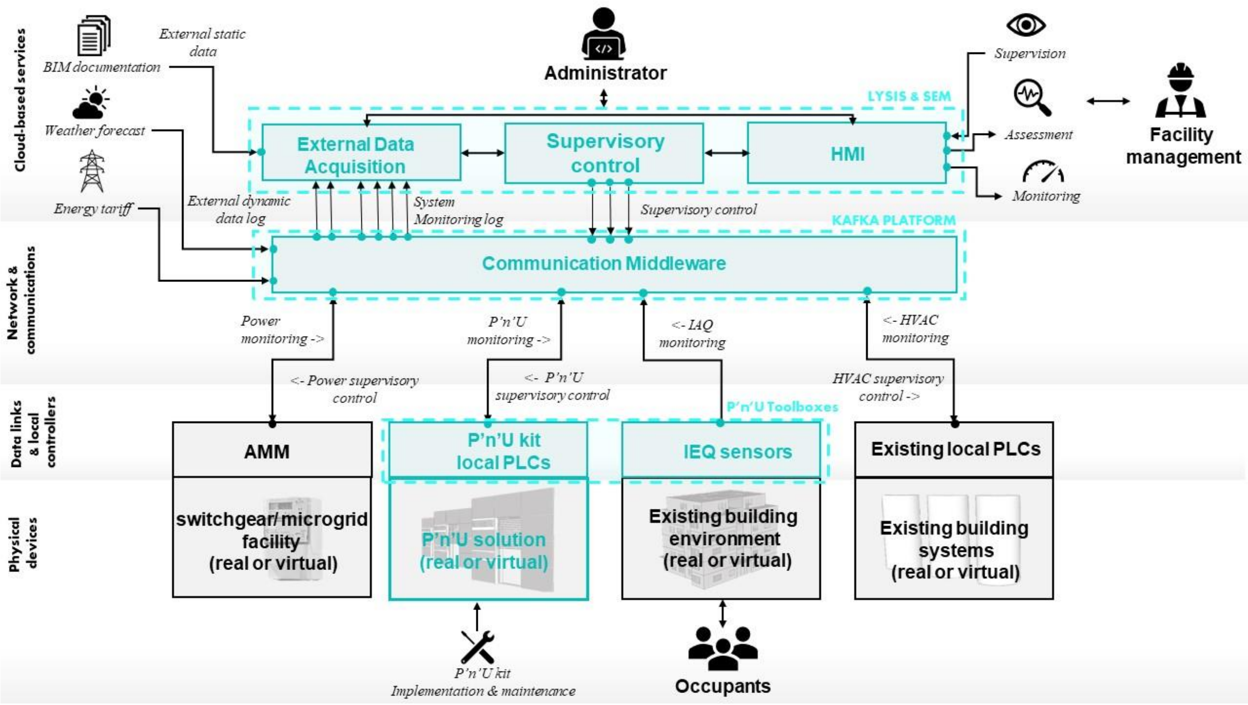

FIGURE 2 CLOUD-BASED SUPERVISORY CONTROL ARCHITECT

Potential and limitations

The cloud-based architecture provides sufficient computational resources for advanced optimization techniques and fully utilizes external data services (e.g., weather forecast or energy day-ahead market info) for predictive control approaches (refer to MPC). The cloud-based supervisory solution may offer a large variety of state-of-the-art control features such as model-based control optimization and smart coordination as well as model-based Feature Driven Development (FDD). This architecture may further support advanced Internet of Things (IoT) solutions or building-to-grid interaction strategies.

In this case, SEM strategies are integrated within the LYSIS platform. The installation is done by the platform administrator. The facility management usually selects high level objectives (e.g., maximize savings or maximize RES, etc.) and IEQ limits (e.g., minimum or maximum indoor air temperature, minimum air exchange rate, etc.) and the optimization of performance is done automatically within the selected margins.

As a drawback, the cloud-based supervisory control cannot provide robust control at the local level. This solution requires a relatively high level of autonomy from the underlying local controllers (Toolboxes) since the actuation of individual device components (e.g., Heat Pump (HP) valves, Air Handing Unit (AHU) dumpers, etc.) **must not** rely on the internet connection. The toolboxes must ensure the autonomous

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control without any risk of failure during the internet outage. In this case, the local PLC might be switched to default settings to ensure the regular operation of the building until the cloud-based services are back online.

2.3 Supervisory control requirements

2.3.1 Requirements on PLURAL tooling

The requirements on individual PLURAL tooling are stressed here related with selection of conceptual architecture.

Local-based architecture

In this case, SEM (WP3) will be configured/installed locally within the building datalink layer as advanced BMS system. Using this architecture, the role of toolboxes (WP4) is extended to carry out the SEM algorithm. The selected control hardware at the local level will need to offer sufficient computational capability to run advanced control algorithms for supervisory controllers e.g. MPC algorithm. This hardware solution is also referred to as Master Toolbox. The tight collaboration between SEM developers (WP3) and toolbox developers (WP4) is required in this case. The LYSIS platform (WP5) will provide mainly external data repository and HMI features for remote access to the settings from the facility management as in planning and design decision support use-case. LYSIS-Apache Kafka (WP5) will communicate with the Master Toolbox using a single protocol.

Cloud-based architecture

In this case, SEM (WP3) installed remotely within the presentation and application layer as cloud-service. SEM algorithm will be installed within the LYSIS platform. The sufficient computational capability of remote server can be expected. The tight collaboration between SEM developers (WP3) and LYSIS developers (WP5) is required in this case. In this case, each PLURAL or existing solution must be equipped with local control Toolbox. The higher level of autonomy is required for Toolboxes (WP4). They must ensure the uninterrupted operation of underlying technologies even in emergency when the cloud-service is unavailable. This architecture will have also higher requirements for LYSIS-Apache Kafka platform (WP5) to handle various range of protocols.

2.3.2 Development and commissioning support for supervisory control

The development and commissioning support for supervisory control is required. The simulation framework (WP3) will be built based on the established building energy simulation tool TRNSYS, will support the SEM (WP3) design and commissioning. As an example of this support, the data-driven models can be pre-trained based on physical based model of each demo site (so-called virtual twin). The virtual twin can also support commissioning by the 'offline control settings optimization'. The simulation framework will be used in the optimization process to identify the best possible master Toolbox settings enabling coordinated operation both PLURAL and existing technologies.

3. Control technologies description

Chapter 3 introduces each of the PLURAL technologies, by defining their capabilities, requirements and aims regarding the control topic. Thus, for each of the technologies, a general description is presented, its current characterization of the control elements, and its integration objectives in a supervisory (centralized) control strategy.

A nomenclature is proposed in which technology refers to each of the technological components presented by different PLURAL partners, while solution is the set of technologies that will be applied in each of the demonstration cases. The current version of this document is technology oriented, not solutions oriented.

Considering these aims, Chapter 3 will not describe neither the so-called Prefabricated Timber Façade and Roof (CS2), nor the Prefabricated Ventilated Façade (CS3), as these are technologies without inherent elements to be controlled.

3.1 SmartWall

3.1.1 General description

The multifunctional wall panel of the SmartWall core system was developed in 2019 and combines several technologies including fully prefabricated walls with eco-friendly insulation, slim-type fan coil for heating and cooling, mechanical ventilation, IEQ control system with automatic and manual capability consisting of filters, BMS-Toolbox connection interface, energy recovery system and batteries, high performance commercial PV panels, vacuum solar panels and heat recovery windows. It can be fitted either to the building's exterior as a façade wall, or to the interior as a covering wall and can be applied in every European climate and it is ideal for warm climates. Figure 3 and Figure 4 below show the technology layout.

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FIGURE 3. INTERNAL AND EXTERNAL SIDE

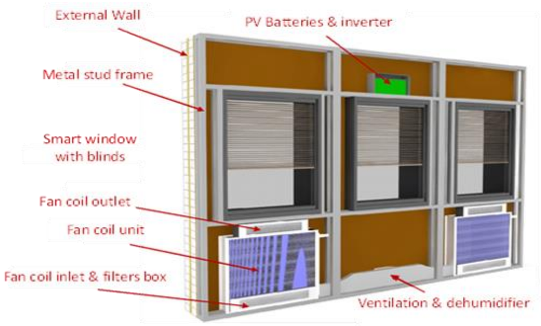

FIGURE 4. SMART WALL LAYOUT.

As a plug and use panel, SmartWall contains flexible pipe and electrical wiring connections that can accommodate either the existing or a new heating/cooling system, as well as connections to various electrical services (switches, plugs etc.). The ventilation system of the already installed wall is based on a standard integrated function of modern fan coils, to recycle the air from the interior of the room. However, ventilation is planned to utilize an integrated compact system with heat recovery in order to supply fresh air to the interior through electronically controlled dumpers. The air flow and indoor quality can be controlled either manually or automatically via CO_2, temperature and humidity sensors.

A series of 20 electronically controlled dumpers will regulate the quantity of the air, which will be transferred via the air ducts to the fan coil inlet. Then, the blown fresh air will be cooled or heated (depending on the operational mode of the fan coil) prior to entering the room. The system could operate in a manual or automatic mode, and it can embed other sensors (e.g. for CO_2, temperature and humidity) for the SmartWall operations control.

3.1.2 Available control and interfacing characteristics

The Toolbox developed will be responsible for the control of the SmartWall. In the Toolbox, the AMS Control Panel, that will be acting as the coordinator of the Toolbox by controlling bidirectional relationships is found. The current prototype is fitted with an integrated control system, equipped with: temperature sensors connected to its smart control regulating indoor temperature; CO_2 and humidity sensors regulating indoor air quality, controlling the main ventilation system of the building; AMS's multifunctional coating (self-cleaning) with PCM's; and AMS's Infrared (IR) reflective - photochromic coating on the windows. The current version does not include heat recovery systems such as windows with embedded heat recovery system, PV or solar panels, etc. The system could operate in a manual or automatic mode, and it can embed other sensors (e.g. for CO_2, temperature and humidity) for the "Smart Wall" operations control. Detailed information regarding the control and interfacing characteristics can be found in 3.6.2.

3.1.3 Aims for integration in the Supervisory control strategy

The control technology will be based on a controller that will receive data by the various sensors connected to it. The controller needs to be connected to the BMS as it will be the supervisory control system via a BMS-Toolbox connection interface. The communication protocols between the local control panel, and the sensors, as well as the data gathered by the central system (BIM) must be further determined and technically adjusted by ISOFT and other core technology partners. The data monitoring and how this information will be sent to the controlling system supported by ISOFT needs to be resolved.

3.2 External Wall Heating and Cooling (eWHC)

3.2.1 General description

Prefabricated module that integrates i) a low temperature exterior hydronic wall heating system between the existing wall layer and the new added external envelope, ii) a decentralized ventilation system with heat recovery and iii) optionally PV-modules. The eWHC module is a solution referring to the wall that is merely applicable externally (either on the external wall or on the roof), as it integrates a low temperature exterior hydronic wall heating system between the existing wall layer and the new added external envelope. All the main components of this solution are enclosed in a prefabricated timber-based module (envelope-kit) (see Figure 5 and Figure 6), operating towards nearly Zero Energy Buildings (nZEB) state with minimum ecological footprint and high degree of comfort conditions for the inhabitants.

This multifunctional unit consists of:

- Timber frame construction with insulation of about 20-30 cm (depending on climate).
- Integrated triple-glazed windows.
- Window integrated ventilation system with heat recovery.
- Low temperature external wall water-based heating distribution system.
- External blinds for window shading.
- Building Integrated Photovoltaic (BIPV) modules for renewable electricity production (roof and facade).

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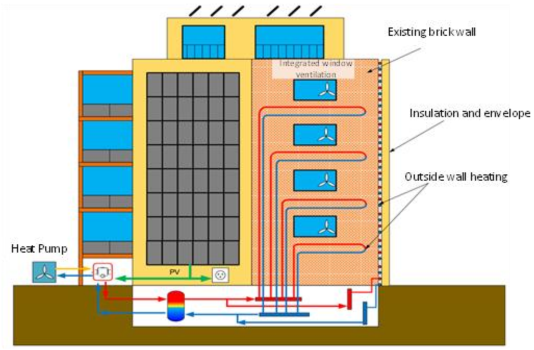

FIGURE 5 LAYOUT OF EWHC SOLUTION

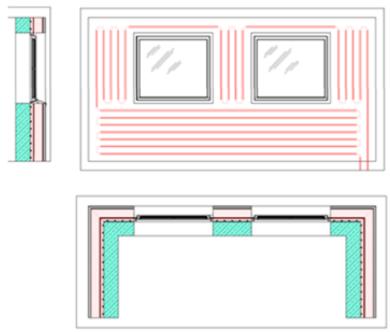

FIGURE 6 REDESIGNED EWHC ENVELOPE KIT

This technology introduces the low temperature hydronic heating or cooling distribution from the outside, with minor or low disturbance on the inside of the building. This is accomplished by combining the heat distribution system with the additional high-performance insulation at the external side. Such solution addresses mostly buildings with high heating demand in colder climates, since it activates the thermal mass of the existing wall and shifts the heating period to day time, increasing “self-consumption” and mitigating as a result the energy demand for heating. However, eWHC applications may also cover low cooling demands in heating dominated countries such as Switzerland, Germany and Czech Republic. This issue will be investigated in the upcoming tasks of the PLURAL concept. The eWHC PnU kit can be enriched with the integration of solar energy converters for the production of heat and electricity (PV or Building Integrated Photovoltaic/Thermal (BIPVT) collectors). Such a combination can be used for thermal energy harvesting or even passive cooling during night hours.

3.2.2 Available control and interfacing characteristics

This description of the control of the heating system for the Kasava Demo is preliminary and will be adapted accordingly to the further analyses in PLURAL project. It is planned to use sensor types for the heating systems like commonly used in HVAC systems

An integrated control system by means of an advanced monitoring system will measure weather data, the supply temperature of the heating system, room temperature and CO_2 concentration, and will control the thermal comfort as well as the Indoor Air Quality (IAQ).

The heat pump control system (if possible) or an additional building control system will handle the following functions:

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- On/off heat pump for Space Heating (SH), power control if possible (variable speed control HP)
- On/off heat pump for domestic hot water (DHW) preparation (depending on weather forecast and PV surplus power production)
- On/Off heating circuit pump (depending on heating season and weather forecast)
- Heating curve depending on:
  - weather forecast (max 48h) → Outside temperature
  - weather forecast (max 48h) → Global radiation (If possible)
- PV- surplus power production
- Variable set temperature hot water → to "overload" the storage. The influence on life expectancy of the HP has to be clarified. (In addition, a variable set temperature for the space heating could be considered. Influence on self-consumption and internal comfort will be analysed by means of simulations)

In the following pages the main points related to the control of the system are presented. Detailed description regarding the control of each element is presented in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**.

Heating Season (HS)

The Heating Season is active when the building currently needs heat or will need in the near future (24h/48h forecast). The standard heating season refers to the usual Heating Limit temperature (HL). If the building does not require heat at the moment, but in the next 24h a demand is expected, the heating should start.

Heat Pump

The heat pump has not yet been defined. Depending on the type of heat pump chosen, this chapter may vary (single-stage, two-stage or variable capacity HP).

The regulation capacities of the various components must be defined by the heat pump manufacturer. Heat pumps basically have three operating modes: heating mode, cooling mode and domestic hot water mode. These are subdivided even more finely in the superordinate control, since the heating and DHW mode can also be forced based on the weather forecast or the PV surplus current production.

Heating circuit pump of the wall heating

Pump switches on as soon as heating season is active. For the rest of the months it is switched off.

Temperature control inside the building

It is yet not decided how to proceed with adjusting the internal temperature of the rooms.

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Heating circuit pump of the radiators

If wall heating is not sufficient (room temperatures too low) and heating season is active, the pump is activated and is constant pressure controlled (radiators must be equipped with thermostatic valves).

3.2.3 Aims for integration in the Supervisory control strategy

On a local system level, energy flow monitoring will be performed by energy meter and electricity meter.

In order to control the window ventilation and the external shading (blind) a control panel should be adopted in which the end-user could easily interact with. The heating system control will be centralised and the different heat distribution loops might be controlled individually based on the temperatures of the rooms they are supplying.

3.3 Air handling unit with Heating & Cooling (eAHC)

3.3.1 General description

The eAHC PnU system is an air handling unit with an advanced heat/cool recovery system, see Figure 7. It combines a patented combination of standard passive heat exchanger in series with active thermoelectric heat exchanger providing the capability of temperature control of supplied air. The active air heat exchanger uses thermoelectric elements to heat up the air in the winter season or cool down the air during the summer. The switching between cooling and heating is simply provided by reversing the current in the thermoelectric modules. Depending on the climate conditions, drainage of condensed water vapour is required. The solid-state cooling-heating technology simplifies the AHU and provides a novel solution to be easily integrated in the facade panels. Since there is no compressor circuit, the produced sound from the operation is significantly reduced.

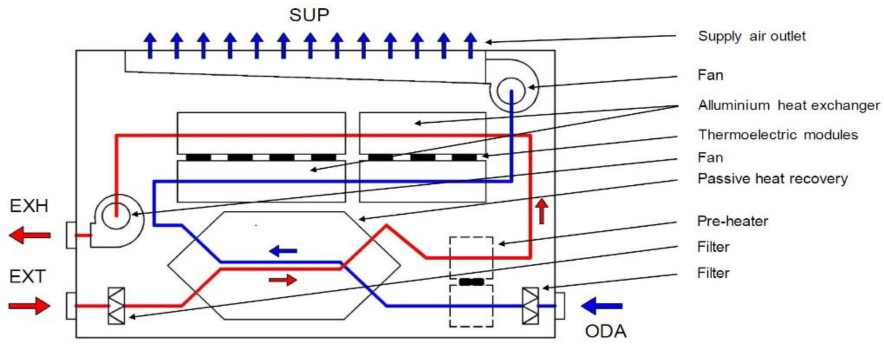

FIGURE 7. EAHC SOLUTION LAYOUT

The integration of PV systems to eAHC unit provides adequate energy that can be used for cooling - mainly in summer season and especially during daytime. Photovoltaic energy sources can be used for direct heat generation in winter or cold generation in the summer. An important advantage is that the system can operate without using expensive battery energy storage and can adjust the power to the energy generated. The eAHC wall element is applicable only for the external building surface.

3.3.2 Available control and interfacing characteristics

The system will be controlled by fully automated local monitoring and controllers. The control system of the "eAHC" kit along with a sensor platform are able to configure the supply air temperature for heating and cooling, to control the IAQ of the room and the thermal comfort as well as, to protect the indoor environment against outside noise.

A PLC controller will be provided as an inbuilt controller responsible for controlling the functionality of the device. The communication interface of the controller will be LAN, supported by Modbus TCP and will be communicating with a cloud server.

The control system of the "eAHC" kit along with a sensor platform are able to configure the supply air temperature for heating and cooling, to control the IAQ of the room and the thermal comfort as well as, to protect the indoor environment against outside noise.

3.3.3 Aims for integration in the Supervisory control strategy

The CVUT provides a sensor platform for monitoring the IAQ. This is equipped with wireless communication interfaces as well as standard interfaces such as RS485. This platform can be easily integrated into the building energy management system and serve in phase 1 as a monitoring tool and in phase 2 as control HMI for technologies deployed in the building. There is potential to provide user-control of the AHU and fresh air temperature. The system is able to operate as a separate unit or to work as a part of the centralized BMS. The system is able to monitor: a) Air temperature, b) Relative air humidity c) CO_2 and Volatile Organic Compounds (VOC) concentration, d) PM0.5, 2.5, 4, 10 (optionally) and e) barometric pressure. The data communication is provided by the following possible interfaces: a) WiFi 802.11, b) LoRaWAN and c) RS485 Modbus.

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3.4 Sensor platform for monitoring and control of IEQ

3.4.1 General description

The CVUT provides a sensor platform for monitoring the indoor air quality. This is equipped with wireless communication interfaces as well as standard interfaces such as RS485. This platform can be easily integrated into the building energy management system and serve in phase 1 as a monitoring tool and in phase 2 as control HMI for technologies deployed in the building. There is potential to provide user-control of the Air Handling unit and fresh air temperature.

The system is based on a combined sensor of indoor temperature, humidity, CO_2 concentration, and volatile organic compounds, Figure 8. A technologically updated version of the system, taking in consideration the user's preferences and decisions might be used in PLURAL Project. A touch LCD version could be available as an end-user adjustable set point controller. **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** shows the CVUT IEQ sensor platform to monitor indoor air quality and building technologies.

As more than 200 units have been manufactured and deployed in various buildings measuring on real conditions, no problems in terms of its design and production are expected.

FIGURE 8 CVUT IEQ SENSOR PLATFORM TO MONITOR INDOOR AIR QUALITY AND BUILDING TECHNOLOGIES

3.4.2 Available control and interfacing characteristics

On a local level it will be controlled by a microcontroller – ESP32. The communication will be based on: WiFi 802.11 b/g/n 2.4GHz, RS485, LoRaWAN and will be supported by modbus TCP/RTU, MQTT, HTTP.

3.4.3 Aims for integration in the Supervisory control strategy

The ambition in PLURAL is to use this platform in two phases: Phase 1: Monitoring of current pre-renovation state of the indoor environment and Phase 2: Post-renovation of the building, control of the building technologies and provide a device for user input. Also, to use wireless IoT interfaces for fast deployment and installation without necessity to prepare the wire infrastructure. The same device can be used to monitor user feedback in terms of indoor environment quality by simple questions and answers through the Liquid Crystal Display (LCD) touch display.

The system is able to operate as a separate unit or to work as a part of the centralized BMS. The system is able to monitor: a) Air temperature, b) Relative air humidity c) CO_2 and VOC concentration, d) PM0.5, 2.5, 4, 10 (optionally) and e) barometric pressure. The data communication is provided by the following possible interfaces: a) WiFi 802.11, b) LoRaWAN and c) RS485 Modbus.

3.5 High performance window with integrated heat harvesting and ventilation functions

3.5.1 General description

The BGTEC system is composed of several elements: heat exchanger, fan, water pump, throttle valve and water tank. The core of the system is the air-water heat exchanger that enables the exchange of heat between hot air flowing through the window and water that flows through water tank. The BGTC heat harvesting smart window is a module with additional energy harvesting and ventilation functions and adaptive control. The energy harvesting function directly contributes to indoor heating, cooling and/or domestic tap-water demand.

Figure 9 shows a high-level approach of the working principle of the high performance window.

FIGURE 9. BGTEC SYSTEM

It's foreseen that the high-performance windows could be integrated within the three core concepts (SmartWall, eWHC and eAHC), with integrated heat harvesting and ventilation functions, heat pumps, additional IEQ regulating components, nano-enabled and nature based materials and adaptive control, driving the BMS ensuring renewable energy generation storage and harvesting.

3.5.2 Available control and interfacing characteristics

During the project, BGTEC will develop a cooling system after heating the water and automate the system to make it compatible with home control system.

3.5.3 Aims for integration in the Supervisory control strategy

The ambition in PLURAL is to introduce, when necessary, a heat recovery system into the integrated mechanical ventilation units and/or motorized shading elements. As a first approach, the mechanical ventilation system with the heat recovery aims to be controlled by the Toolbox. For the motorized shading elements, it would be considered, as an open option, the possibility to be controlled too by the Toolbox system. So, in both cases, the aims regarding the supervisory control will be linked to the Toolboxes approach.

3.6 Centralized and decentralized Toolbox for HVAC, DHW and RES system with energy storage

3.6.1 General description

A core component of the PLURAL solutions will be the "Toolbox". The Toolbox is a set of systems and sensors responsible for controlling the various subsystems of a PnU kit and optionally other systems of the indoor space where the Toolbox is installed (e.g. lighting, shading, window ventilation system). The Toolbox receives input from various sensors installed within the PnU kit and/or the space where it is installed. The Toolbox processes the received signals and may control various subsystems via actuators (e.g. external mechanical ventilation, thermo-electric elements etc) or by communicating with their control panels (e.g. fan coil). The Toolbox can be physically described as a box that includes the control unit (microprocessor etc.), the power unit and/or battery and all the necessary transmitters/receivers to communicate with the various sensors or other systems to be controlled wirelessly.

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Every Toolbox will communicate with a heat pump unit. In the selection of the heat pump two different approaches will be utilized; one through centralized systems and decentralized one. Regarding the 1st one: as today's system requires improved energy efficiency, tighter temperature control, wider range of operating conditions and incorporate features like remote monitoring and diagnostics, the application of electronic expansion valves becomes mandatory. Finally, the unit offers the possibility to connect with a BMS through different solutions like Modbus RTU, LonWorks and BACNet BTP. Regarding the decentralized: the unit will be a Daikin Altherma low temperature unit. To control on a daily basis the home temperature, settings can be controlled at any time and place via the Daikin Online Controller app. This online controller allows adjustment of home comfort levels to suit individual preferences while achieving further energy efficiencies.

The Toolbox consists of 5 sections. Section 1: The NTUA Multisensor responsible for acquiring and sending data. Section 2: The AMS Control Panel (AMScope) responsible for connecting the Toolbox's different parts. Section 3: Automation - Automated Actions performed, based on Data Acquired, using Algorithms and Controllers. Section 4: Internal and external Smart Wall Sensors, for Smart Wall Safety. Section 5: The Daikin Unit, including the Daikin Control Panel, the Fan Coil and the Fan Coil controller. NTUA Multisensor and AMS Control Panel communicate via Wireless protocols. AMS Control Panel and Daikin Control panel communicate via Wi-Fi. AMS Control Panel and Fan Coil Controller communicate using TTL protocols. Daikin Unit internal communication is based upon PLC programming Smart Wall Sensors send independent data for appropriate actions as to keep the Smart Wall safe.

3.6.2 Available control and interfacing characteristics

In the following pages the main points related to the control of the system are presented. Detailed description regarding the control of each element is presented in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**.

The NTUA MultiSensor

The "Multi-Sensor" is dedicated for the measurement of the thermal comfort indicators, according to ISO 7730. The "Multi-Sensor" is based on the IoT concept with independent connection of each sensor to the internet. It integrates a set of seven sensors (ambient and radiant temperature, humidity, wind, CO_2-TVOC, distance); it is micro-controller (ESP-32S) programmed for continuous monitoring of 12 signals and communicates wirelessly both with local and remote servers. Each sensor can be operated alone or in a cluster mode while it can be reprogrammed (if needed) over the air from any place on earth without the need for local interaction. The communication is achieved via an integrated Wi-Fi module and the local communication with vicinity sensors via low power Bluetooth (BLE). Table 1 shows the sensors' characteristics.

TABLE 1. HARDWARE CHARACTERISTICS OF THE TOOLBOX

Sensor	Unit	Value Range	Accuracy	Nominal Values
Adafruit SHT31-D	Humidity Temperature	0-100 (%RH)	2% RH -0.3C’	45% 22C’
Wind Sensor Rev C	Air Velocity	0 – 27 m/sec	N/A	~5m/sec (space dependent)
MCP9808	Temperature	-40 - 125°C	0.25C’	22C’
MAX31856	Amplifier Thermocouple	N/A	N/A	22C’
Adafruit CCS811	Air Quality Sensor	eCO2/TVOC	400-8192 011887 ppb	10 mg/m3 CO 0.3-0.5 mg/m3 TVOC

Automation

By describing the Automations carried out, we more likely describe the whole Toolbox functionality as follows: The NTUA MultiSensor that is built inside the wall is taking measurements such as temperature, luminance, air quality and air pressure using the above mentioned sensors. These measurements are then being processed by the ESP32S (NTUA) and sent to the AMS Control Panel’s ESP32S Figure 10.

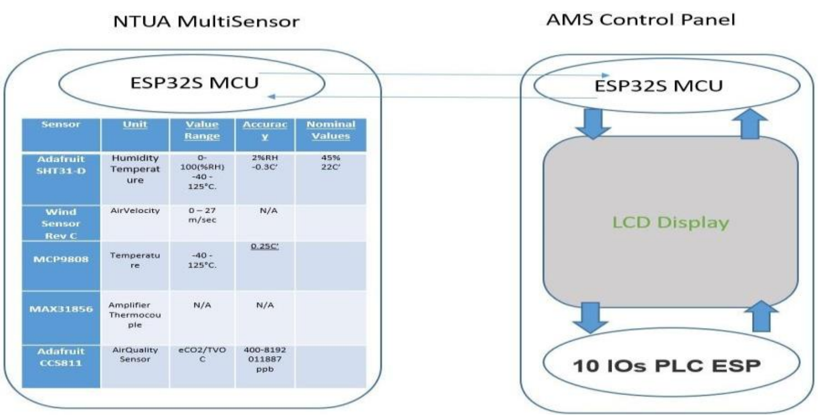

FIGURE 10. HIGH LEVEL COMMUNICATION OVERVIEW

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3.6.3 Aims for integration in the supervisory control strategy

The ambition in PLURAL is to implement the required elements and algorithms to use this technology to monitor and control the main parameters and in zone technologies at room level. From there, the aim of the multi-sensor regarding the supervisory control strategy is to stablish an online communication for general assessment and to optimize the PV sharing considering the dwellings consumption and the PV production.

Specifically, for this purpose, AMS, as will be shown in the Tree of Command is already establishing and testing the appropriate actions, both in hardware and software, as to read, analyze data and take actions accordingly. A first blueprint of the Toolbox – AM Scope functionality in local and supervisory level is under design and testing, by using the PLC-Based Hardware in conjunction with the Fan Coil Unit and the intermediate parts of PLURAL System. Mainly the analysis and design of the display architecture is almost complete using Human Machine Interfaces, HMIs, in local/room level and the main Unit, Supervisory Control and Data Acquisition, SCADA, for controlling every part, from just a sensor up to the control of power consumption and PV readings acquired. This implementation satisfies efficiently the elements of Data Acquisition and Controlling in local level especially and supervisory as well as wireless communications.

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4. Monitoring requirements for assessment

Chapter 4 introduces the main monitoring requirements for assessment considering the PLURAL targets, the related KPIs and the control strategies. At last, the monitoring requirements must be coherent to the related Key Performance Indicators established in T1.5 "*Key Performance Indicators*", regarding to the economic, environmental and internal comfort evaluations.

As the introduced monitoring requirements will be used as the basis for the T7.6 "Monitoring campaign", for this T3.1a deliverable the main concepts are introduced, and these will be fine-tuned case by case in T3.1b, once the PLURAL solutions have been introduced for the different demo cases.

4.1 Main parameters for assessment

Chapter 4.1 introduces the main parameters that must be monitored for assessment purposes, considering energetic, environmental, internal comfort and economic evaluations. This would be considered as a first approach, consistent with T1.5 introduced KPIs, and to be agreed with the detailed demo cases defined in WP2 and WP7, in order to harmonize the process. For each introduced parameter, the related KPI is explained considering the basic formulation, as it would be needed to define the variables to be monitored in each case; even so, the ones already introduced in T1.5 are not here defined in details, as they'll be in D1.4.

4.1.1 Energy and Environmental Performance parameters and related KPIs

This section presents and describes the set of indicators selected to characterize the energy and environmental performance of each building/technology and their interaction through their system boundaries.

The proposed set of indicators, as presented in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**Table 1 follows the assessment methodology of the Energy Performance of new and existing Buildings (EPB) described in the ISO-52000 standards [1]. In general terms, the overall energy consumption of a building, by measurement or calculation, should be based on hourly or sub-hourly values of the different energy flows in the buildings and by the exchanged energy carriers (delivered and exported energy) with the energy networks (electricity, thermal energy with district heating and cooling networks, natural gas, etc.).

In order to calculate the overall energy balance or performance of a building, the use of weighted metrics as primary energy has been established. For that, it is necessary to define the weighting factors, also known as conversion factors, used to convert the different final energies into a common magnitude, such as non-renewable primary energy or CO_2 emissions.

The imported and exported final energy should be multiplied by the appropriate site to-source conversion multipliers, based on the utility's source energy type. The source energy is the most equitable unit of evaluation. Source energy represents the total amount of raw fuel that is required to operate the building. It incorporates all transmission, delivery, and production losses. Special attention should be given in defining primary energy factors for energy carriers produced from on site, nearby or distant.

The quantification of proper conversion factors is a complex task, especially for electricity and thermal networks, as it depends on several considerations; i.e. the mix of energy sources within certain geographical boundaries (international, national, regional or local), the average or marginal production, actual or expected future values etc. In general, there are no correct conversion factors in absolute terms. Rather, different conversion factors are possible, depending on the scope and the assumptions of the analysis and the treatment of exported energy. Furthermore, "strategic factors" may be used in order to include considerations indirectly connected with the conversion of primary sources into energy carriers. Strategic factors can be used to promote or discourage the adoption of certain technologies and energy carriers, as it has been proven in [2] for the case of Net Zero energy Buildings (NZEB). Weighting factors can be generally time dependent, as the share of renewables depends on the season and the time of the day. However, usually mean annual national and regional factors are available for different regional or national approaches. In case of absence of national/regional factors, European or global factors could be used as reference. The ISO-52000 proposes default values for primary energy weighting factors that can be used as reference. Usually, energy and environmental performance are normalized to the building sizes. Reference size for the building is the useful floor area (m^2) calculated according to national definitions and standards.

4.1.1.1 Overall Energy Performance

The overall energy performance of a system is based on the balance at the assessment boundary of the weighted delivered energy and weighted exported energy. The delivered energy is the one required to cover the energy demand of each building, including the on-site produced energy which potentially can be exported.

To describe the overall performance of a building, two main indicators are selected. The non-renewable primary energy balance, which weights the delivered and exported energy; If this balance is lower than zero, it means that it is a positive energy system. And the Renewable Energy Ratio, which represents the share of renewable energy in the system. These have been completed, as shown in Table 2**,** with other primary energy and environmental performance parameters for control and monitoring.

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TABLE 2 PRIMARY ENERGY AND ENVIRONMENTAL PERFORMANCE PARAMETERS FOR CONTROL AND MONITORING

Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors[1]
Pdel,I. The delivered power on site or nearby for energy carrier	Non-renewable primary energy balance (EP_nren)	Balance on all types of energy consumed and produced by the system, and the exchange with the energy networks	RES systems energy meter	Households level - representative sample	Post intervention	To be defined with regard to PLURAL solutions
EPren - Renewable primary energy consumption	Renewable energy ratio (RER)	The share of renewable energy by the building	RES systems energy meter	Households level - representative sample	Post intervention	To be defined with regard to PLURAL solutions
EPtot - Total primary energy consumption			Households meter		Pre & Post intervention	
Pec – Primary Energy Consumption	Primary energy demand (Ped)	Definition at T1.5 Chapter 4.1-1	Energy meter	Statistic representation of affected apartments (depending on HVAC + RES systems)	Pre & Post intervention	To be defined with regard to PLURAL solutions

[1] These are the minimum requirements to date. However, these details will be finalized for the final version of the deliverable D3.1.b for each demo case.

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors[1]
Q - Thermal Energy	Thermal Energy demand (Ted)	Definition at T1.5 Chapter 4.1-2	Energy meter	Statistic representation of affected apartments (depending on HVAC + RES systems)	Pre & Post intervention	To be defined with regard to PLURAL solutions
E^{norm}_{fan} - Ventilation Energy Consumption	Electric consumption of mechanical ventilation (E_{fan})	Definition at T1.5 Chapter 4.1-3	Energy meter	Statistic representation of affected apartments (depending on HVAC + RES systems)	Pre & Post intervention	To be defined with regard to PLURAL solutions
E_{DHW} - Energy consumption for Domestic Hot Water	Energy consumption for Domestic Hot Water (E_{DHW})	Definition at T1.5 Chapter 4.1-6	Energy meter	Statistic representation of affected apartments (depending on HVAC + RES systems)	Pre & Post intervention	To be defined with regard to PLURAL solutions

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors[1]
U_{E_light} - Electric energy consumption for lights	Electric consumption normalized for lighting during occupied or working period ($E^{norm}_{light,t}$)	Definition at T1.5 Chapter 4.1-7	Energy meter	Statistic representation of affected apartments (depending on HVAC + RES systems)	Pre & Post intervention	To be defined with regard to PLURAL solutions
Heating/Cooling peak power	Heating/Cooling peak power	Definition at T1.5 Chapter 4.1-8	Energy meter	Statistic representation of affected apartments (depending on HVAC + RES systems)	Pre & Post intervention	To be defined with regard to PLURAL solutions

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Thus, the different introduced KPIs are explained here below, except for the following KPIs, which can be found in deliverable T1.5:

- Primary energy demand: Definition and details chapter 4.1-1 of T1.5
- Thermal Energy demand (Ted): Definition and details chapter 4.1-2 of T1.5
- Electric consumption of mechanical ventilation (E_{fan}): Definition and details chapter 4.1-3 of T1.5
- Energy consumption for Domestic Hot Water (E_{DHW}): Definition and details chapter 4.1-6 of T1.5
- Electric consumption normalized for lighting during occupied or working period ($E^{norm}_{light,t}$): Definition and details chapter 4.1-7 of T1.5
- Heating/Cooling peak power: Definition and details chapter 4.1-8 of T1.5

4.1.1.2 Non-renewable primary energy balance

This indicator takes into consideration all types of energy consumed and produced by the system, and the exchange with the energy networks. It is calculated using Equation 1 which sums up all delivered and exported energy for all energy carries into a single indicator with the corresponding non-renewable primary energy weighting factors. Therefore, this indicator considers as well differences in the energetic effort within the supply chain of different energy carriers, e.g. domestic gas versus electricity.

EQUATION 1

$$E_{P,nren} = \sum_i E_{p,nren,del,i} - \sum_i E_{p,nren,exp,i} = \sum_i \int P_{del,i}(t) \cdot w_{del,nren,i}(t) \cdot dt - \sum_i \int P_{exp,i}(t) \cdot w_{exp,nren,i}(t) \cdot dt$$

where

$E_{p,nren}$ - the non-renewable primary energy, [kWh/ m² y];

$E_{p,nren,del,i}$ - delivered non-renewable primary energy per energy carrier i, [kWh/ m² y];

$E_{p,nren,exp,i}$ - exported non-renewable primary energy per energy carrier i, [kWh/ m² y];

P_{del,i_i} - the delivered power on site or nearby for energy carrier i, [kW/ m²];

$w_{del,nren,i}$ - the non-renewable primary energy factor (-) for the delivered energy carrier i;

$P_{exp,i}$ - the exported power on site or nearby for energy carrier i, [kW/m²];

$w_{exp,nren,i}$ - the non-renewable primary energy factor (-) of the exported energy for energy carrier i;

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Primary Energy use is one of the main indicators for the assessment of the energy balance in the EPBD and adopted in most of European countries. However, ISO 52000-1, which defines the overarching framework and procedures for the EPB assessment, distinguishes between non-EPB uses (appliances and lighting in some cases for residential) and two different forms of the energy balance. The different forms vary in the consideration of the resources avoided by the external grid due to the export of the energy carrier, and each EU country can choose what considerations to apply in the energy balance.

In the framework of PLURAL, weighting factors for exported energy should be selected based on the resources avoided from the external grid, which is equivalent to "Step B" stated in ISO-52000. This means that for example the values of the delivered and exported weighting factors for electricity are considered to be equal. In the PLURAL framework, assessed energy uses include HVAC, DHW and lighting needs.

For the calculation of the amount of exported energy, it is necessary, for each energy carrier, to perform a balance between the energy needs and the produced energy inside the assessment boundary. Either using calculations or measured values, it is recommended that the interval period used to calculate the balance per energy carrier was one-hour resolution, as maximum. In some countries, as for example Spain [3], the targets established for nearly zero energy buildings are based on a monthly assessment, which means that, within a month, exported energy compensates for the delivered energy. Using an hourly or sub-hourly calculation gives a closer picture of the amount of exported energy available for sharing with other buildings in the reality.

4.1.1.3 Renewable Energy Ratio

The share of renewable energy is defined by the Renewable Energy Ratio (RER), which is calculated relative to all energy use in the building, in terms of total primary energy and accounting for all the renewable energy sources. These include solar thermal, solar electricity, wind and hydroelectricity, renewable energy captured from ambient heat sources by heat pumps and free cooling, and renewable fuels [4].

RER is the percentage of energy from renewable sources in the total energy consumption, Equation 2. The objective of efficient buildings is not using renewable sources as much as possible, but using as little energy as possible from non-renewable sources. A better renewable energy ratio should not lead to worse energy performance. The amount of primary energy from renewable source for RER calculation, E_{Pren} (in kWh). is calculated taking into account only delivered energy to the assessment boundary, in line with the renewable energy ratio (RER) in EPBD Article 2(2)". The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

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RER is defined in the ISO 52000-1 and is dependent on the chosen perimeter. Usually two types of RER can be distinguished. The on-site RER considers only the energy that is used in the building. The renewable primary energy produced on-site have the total primary energy factor of 1.0 and the non-renewable primary energy factor of 0.

EQUATION 2

$$RER = \frac{E_{Pren}}{E_{Ptot}}$$

where:

E_{Pren} - *renewable primary energy consumption kWh/(m² y)*

E_{Ptot} - *total primary energy consumption kWh/(m² y)*

On the other side, a set of so-called secondary parameters are introduced, considering these as potentially interesting parameters depending on the finally implemented PLURAL solutions case by case. Table 3 shows the secondary energy and environmental performance parameters for control and monitoring.

TABLE 3 SECONDARY ENERGY AND ENVIRONMENTAL PERFORMANCE PARAMETERS FOR CONTROL AND MONITORING

Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
FF - Building electrical power consumption during the demand response scenario (or the reference case)	Flexibility Factor (FF)	Ratio that compares the amount of energy used in high price or low price hours (related to a price signal)	Households meter/power	Building Level	-	To be defined with regard to PLURAL solutions
$P_{DR/REF}$ - Building electrical power consumption during the demand response scenario (or the reference case)	Adapted ADR (DR,P)	Efficiency of the storage-like operation of the building thermal mass.	Building power	Building Level	Pre & Post intervention	To be defined with regard to PLURAL solutions
	Flexibility Performance (f)	Performance of a DR strategy from the perspective of the utility, considering the rebound energy				
$P_{el,gen}$ - General electricity (corridor lighting, external lighting, washroom etc.)	Rate of self-sufficiency	$(P_{el,Tot} – P_{el,Grid}) / P_{el,PV}$ $P_{el,Tot}$ – Total electricity consumption - $P_{el,Tot} = P_{el,Gen} + P_{el,HH}$	-	-	-	To be defined with regard to PLURAL solutions
$P_{el,HH}$ - Household electricity (Sum of all apartment counters)						

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
$P_{el,Grid}$ - Grid power supply (electric energy purchase of the house from the power grid)	Self-consumption rate	$(P_{el,Tot} - P_{el,Grid}) / P_{el,PV}$ One of the most important values. By optimizing the control of the heating system the Self consumption rate should be as high as possible.	-	-	-	To be defined with regard to PLURAL solutions
	Rate of self-sufficiency	$(P_{el,Tot} - P_{el,Grid}) / P_{el,Tot}$				
	Grid Purchase ratio	$P_{el,Grid} / E_{UEC}$				
$P_{el,PV}$ – PV Production	Rate of self-sufficiency	$(P_{el,Tot} - P_{el,Grid}) / P_{el,Tot}$	-	-	-	To be defined with regard to PLURAL solutions
	Self-consumption rate	$(P_{el,Tot} - P_{el,Grid}) / P_{el,PV}$ One of the most important values. By optimizing the control of the heating system the Self consumption rate should be as high as possible.				

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
E_{UEC} – Total useful energy consumption $E_{UEC} = P_{el,Tot} + Q_{th,DHW} + Q_{th,HS}$	Grid Purchase ratio	$P_{el,Grid} / E_{UEC}$	-	-	-	To be defined with regard to PLURAL solutions
$P_{e,Tot}$ - Total electricity consumption $P_{el,Tot} = P_{el,Gen} + P_{el,HH}$	Self-consumption rate	$(P_{el,Tot} – P_{el,Grid}) / P_{el,PV}$ One of the most important values. By optimizing the control of the heating system the Self consumption rate should be as high as possible.	-	-	-	To be defined with regard to PLURAL solutions
$Q_{th,DHW\&SH}$ - Heat demand (heat delivered to the building) of SH and DHW $P_{el,DHW\&SH}$ - Electricity consumption of the HP-system during space heating mode and DHW production	Seasonal performance factor (SPF)	Seasonal performance factor of the heat pump system for domestic hot water (DHW) and space heating (SH) supply	-	-	-	To be defined with regard to PLURAL solutions
$P_{el,cool}$ - Electricity consumption of the HP Cooling supply			-	-	-	

Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
$Q_{th,cool}$ - Cooling supply into the building	SEER, seasonal energy efficiency ratio	Seasonal energy efficiency ratio during the cooling-season - $Q_{th,cool}$ / $P_{el,cool}$				To be defined with regard to PLURAL solutions

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At this stage, it is not clear yet if all the afore-mentioned secondary KPIs and the "Monitored and controlled variables" will be used for each demo site, since due to the nature of each demo case and the building regulations imposed on a national level different approaches might be considered. These will be clearly fixed in T3.1b, once the different PLURAL solutions will be defined in detail case by case.

Again, here below the secondary energy and environmental KPIs are described.

4.1.1.4 Flexibility Factor

The Flexibility Factor (FF) has been developed at DTU during the past years, and several publications which explain it in detail are available, [5], [6]. These publications explain how the index is built and describe specific applications of it. On the contrary, the Smart Readiness Indicator (SRI) has been adopted by the EU as the main measure to evaluate how smart-ready buildings are. The FF is related to the SRI that is defined in T1.5.

The flexibility index is defined as the savings due to utilizing energy flexibility for a given price-signal [6]. For example, given a price-signal, a building obtaining a FF of 0.1 means that the building is able to save 10% of its energy costs, by applying energy flexibility, for that particular price signal. An example of this is shown in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, where the top plot shows the temperature of an office building if it is heated in a smart way in green, and in a regular way in read. The middle plot shows the cost of energy consumption of time in black, while the heating schedules are shown in green and red. The bottom plot shows the accumulated cost for each of the heating schedules, and the final values (to the right) are the total costs for this period that can be used to compute the flexibility index, which in this case is around 0.1.

4.1.1.5 Flexibility Performance

This set of energy flexibility indicators consists of two additional indices as described below and taken from [7]. They are named Flexibility Performance (f) indicators because they aim to measure the performance of a DR strategy from the perspective of the utility. The Rebound Energy (E_{rb}) captures the change in energy consumption following or before a DR event compared to the reference case and it is defined as follows in Equation 3:

EQUATION 3

$$E_{rb} = \int_{-\infty}^{I_{DR,start}} (P_{DR} - P_{Ref})dt + \int_{I_{DR,end}}^{+\infty} (P_{DR} - P_{Ref})dt$$

The first part of Equation 3 indicates the energy consumed during the preconditioning period (prebound); the second part indicates the possible rebound after the DR event. The possible prebound is also included for cases of predictive control where anticipation of a demand response event can occur. The $-\infty$ as well as the $+\infty$ denotes the prebound or rebound horizon. When calculating E_{rb}, the horizon can be several hours or longer depending on the system response of the control strategy. This information is important for the grid operator to ensure the stability and balance of the grid outside the DR period is not adversely affected by DR measures.

The flexible energy efficiency (η_f) is a measure of how much energy was shifted relative to the rebound effect, Equation 4. This indicator considers the flexibility from the utility perspective: the rebound energy after the DR event is always considered as "disadvantageous" for the grid operator, unlike the first two sets of indicators which are building-centric and where extra energy consumption by the building is considered less than ideal. This indicator is defined as:

EQUATION 4

$$\eta_f = \left|\frac{E_f}{E_{rb}}\right| \times 100\%$$

4.1.1.6 Adapted ADR

In this section, the indicators proposed by Pean et al. [8] are described. The storage efficiency is defined as follows:

EQUATION 5

$$\eta_{\mathrm{DR,P}} = 1 - \frac{\int_0^{+\infty} (P_{DR} - P_{Ref})dt}{\left|\int_{I_{DR,start}}^{I_{DR,end}} (P_{DR} - P_{Ref})dt\right|} = 1 - \frac{\int_0^{+\infty} (P_{DR} - P_{Ref})dt}{\left|E_{DR,P}\right|}$$

This quantity represents the efficiency of the storage-like operation of the building thermal mass. The denominator refers to the capacity of energy flexibility available. The indicator of Reynders was originally developed only for upward flexibility cases, therefore it did not contemplate cases with negative C_{ADR} [9]. For this reason, an absolute value is added to the denominator, so that $\eta_{DR,P}$ remains positive in normal flexibility scenarios. Whilst this definition is very similar to η_{AEEF} above for downward flexibility, the ratio is defined differently such that rebound effect corresponding to the DR capacity results in a value of 1.

4.1.1.7 Rate of self-sufficiency

The rate of self-sufficiency is the ratio between the PV production and the total electricity consumed at the same time, Equation 6. E.g. if the rate has the value of one, it means that the building is fully self-sufficient and does not consume electricity from the grid [10].

EQUATION 6

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$$Rss = \frac{P_{el,Tot} - P_{el,Grid}}{P_{el,Tot}}$$

4.1.1.8 Grid purchase ratio

The grid purchase ratio represents the ratio of energy (electrical energy) purchased from the grid to the total energy (electrical energy) used by the system, over a time period [11].

Input Parameters & Calculation	Grid Purchase Ratio: **Equation 7** $R_{grid} = \frac{El_{grid}}{El_{used}} = \frac{El_{grid}}{El_{sys} + El_h}$ Where: El_{grid} = *Electricity purchased from the grid (kWh/y)* El_{used} = *Total used electricity (kWh/y)* El_{sys} = *Electricity used for the system operation (kWh/y)* El_h = *Electricity consumed in the households (kWh/y)*
Unit	%

4.1.1.9 Self-consumption rate

The self-consumption rate is the ratio between the PV production and the portion of the PV production consumed at the same time by the loads [10].

Equation 8

$$Rsc = \frac{P_{el,Tot} - P_{el,Grid}}{P_{el,PV}}$$

4.1.1.10 Seasonal performance factor

The seasonal performance factor represents the ratio of total energy demand (taking into account heating, cooling and domestic hot water demand), to the total energy (electrical energy) used to heat or cool the system, over a time period (day, month, year, etc.). It is assumed that all auxiliary or back-up energy is provided by electricity, i.e. there is no fuel-based supply [12].

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Seasonal Performance Factor, heating:

EQUATION 9

$$SPF_{heating} = \frac{Q_{SH} + Q_{DHW}}{El_{heat,sys}}$$

Seasonal Performance Factor, cooling:

EQUATION 10

$$SPF_{cooling} = \frac{Q_{SC}}{El_{cool,sys}}$$

Seasonal Performance Factor, global:

EQUATION 11

$$SPF_{global} = \frac{Q_{SH} + Q_{DHW} + Q_{SC}}{El_{used}} = \frac{Q_{SH} + Q_{DHW} + Q_{SC}}{El_{sys}}$$

Where:

Q_{SH} = Space heating demands (kWh/y)

Q_{SC} = Space cooling demands (kWh/y)

Q_{SC} = Domestic hot water demands (kWh/y)

$El_{heat,sys}$ = Total electricity for providing heating (kWh/y)

$El_{cool,sys}$ = Total electricity for providing heating (kWh/y)

El_{sys} = Total used electricity ($El_{heat,sys}$ + $El_{cool,sys}$) (kWh/y)

4.1.1.11 Seasonal energy efficiency ratio

The seasonal energy efficiency ratio represents the overall energy efficiency ratio of the unit, representative for the whole designated cooling season. It is calculated as the reference annual cooling demand divided by the annual energy consumption for cooling [13].

Input Parameters & Calculation	Seasonal energy efficiency ratio:

EQUATION 12

$$SEER = \frac{Annual\ cooling\ demand\ (kWh/y)}{Annual\ energy\ consumption\ for\ cooling\ (kWh/y)}$$

4.1.2 Indoor Environment Quality Parameters and related KPIs

People spend approximately 90% of their time in indoor environments [14]. Over the last decades, an abundant number of studies has shown that the indoor environmental quality (IEQ) has a significant impact on human health [15]. IEQ refers to the quality of a building's environment with respect to wellbeing and health of the building occupants and is determined by many factors such as indoor thermal environment, air quality and lighting [16]. Energy efficiency and plus energy buildings can bring multiple benefits such as improvements in air quality and health and it is crucial to ensure that the IEQ positively contributes to health, comfort, well-being and productivity of the building occupants. Multiple benefits of energy efficiency and plus energy buildings, will be thoroughly explored and quantified at a later stage of this project (WP7). The main determinants of the IEQ are IAQ, thermal comfort, lighting and visual comfort and acoustics [17].

According to the Annex 68[2], for buildings to achieve a net zero energy use, they will need to be more efficient and optimized. This in turn leads to more insulated buildings and the attentions goes to reducing the space heating and energy consumption by reducing the demand for ventilation. The reduction of ventilation rates can save energy even though it can have negative impacts on the IAQ. It is consequently critical to ensure a balance between energy efficiency and maintaining appropriate levels of all the components of the IEQ.

This section aims at developing an approach to assess the IEQ of plus energy buildings by focusing on the main factors that determine the indoor environment. This will result in highlighting potential areas for improvement and will further provide useful feedback to designers, construction managers but also and operators, facilities managers, and property agents.

There are several building rating and assessment systems around the world that link IEQ with health, comfort and wellbeing of building occupants. The development of the evaluation framework of the IEQ has been inspired from already developed methodologies, frameworks, indexes and certification schemes

[2] IEA-EBC Annex 68 Indoor Air Quality Design and Control in Low Energy Residential Buildings

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such as Level(s) [3], CBE Survey[4], TAIL[5], DEQI[6], WELL[7] , IEQ-Compass[8] and CBE Survey while it complies with the EN Standard 16798-1 and CEN/TR 16798-2 (2019) [18] [19] [20] [21] [22] [23].

The evaluation framework can be used at several stages of the life cycle of a building. The predicted IEQ characteristics of the plus energy buildings will be explored at the design phase through calculations and simulations while the actual IEQ will be investigated during the operational phase through on-site measurements, checklists, and questionnaire surveys. This will allow to investigate whether the plus energy buildings meet their design objectives but also make a link between design and occupied performance.

The definition of IEQ key performance indicators will allow a more systematic assessment of the indoor environment. As also mentioned in the introduction of this chapter, the main determinants of the IEQ which will be referred to as evaluation areas, are indoor air quality, thermal comfort, lighting and visual comfort, and acoustics (Figure 11 **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, Table 4). Each of these evaluation areas is comprised by characterizing elements which will be the KPIs of this chapter. For example, CO_2 concentration is of the most important contaminants of the indoor air and will be the KPI of the IAQ.

This section will include brief descriptions of the evaluation areas of the IEQ and their KPIs required to determine them. Their main calculation methodologies are also explored, while country specific IEQ requirements are presented.

The European Standard EN15251:2007, recently revised to the EN16798-1-2019, defines four categories of the indoor environmental quality, related to the level of expectations of the building occupants (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**) [24] [25]. Category 'Medium' represents a normal level; a high lever can be selected by people with special needs such as people with disabilities, children, and elderly. A lower level may decrease comfort but will not cause health risks [25].

Table 4 presents the primary indoor environment quality parameters for monitoring and control.

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[3] Level(s)-A common EU framework of core sustainability indicators for office and residential buildings, JRC Technical reports

[4] Center for the Built Environment (CBE), Occupant Indoor Environmental Quality Survey, https://cbe.berkeley.edu/research/occupant-survey-and-building-benchmarking/

[5] TAIL index, D2.4 ALDREN Methodology note on addressing health and wellbeing

[6] A methodology for the determination of the indoor environmental quality in residential buildings through the monitoring of fundamental environmental parameters: A proposed Dwelling Environmental Quality Index, Indoor and Built Environment, Laskari et al. 2017

[7] The WELL Building standard

[8] IEQ-Compass-A tool for holistic evaluation of potential indoor environmental quality, Larsen et al., 2020, Building and Environment

TABLE 4 PRIMARY INDOOR ENVIRONMENTAL QUALITY PERFORMANCE PARAMETERS FOR CONTROL AND MONITORING [9]

Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
Tr, Radiant mean temperature Tind, Indoor Temperature	PMV	Predicted Mean Vote Index to predict the mean response of a larger group of people according the ASHRAE thermal sense scale	Indoor sensors	Statistic representation of affected apartments	Post intervention	Detection range 0 to 50°C Accuracy ±0.4°C Resolution 0.1°C
Rind, Indoor Relative Humidity						Detection range 0-100% RH Accuracy ±4% RH Resolution 0.1%
From previous	PPD	Predicted Percentage Dissatisfied An estimation of how many people will find PMV comfort conditions thermally satisfactory.	From previous	Statistic representation of affected apartments	Post intervention	N/A
Cint, CO_2 indoors concentration in ppm	C(t)	Carbon Dioxide (CO2) concentration	Indoor sensors	Statistic representation	Post intervention	Detection range 0-5000ppm

[9] For these Indoor Environment Quality KPIs we are not distinguishing between primary and secondary and they are all considered primary

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
Cout, CO_2 outdoors concentration in ppm	C(t)	Based on assumptions related to building occupancy (number of occupants, age, activity level etc.) and operation (e.g. window opening, HVAC operation), CO2 concentrations may be predicted using a mass balance equation, giving an indication on the overall indoor air quality	Outdoor sensors	of affected apartments		Accuracy ±50ppm Resolution 3%
VOC, VOC indoor concentration in ppb or mg/m3	VOC	Volatile Organic Compounds Concentration of VOC compounds that have a high vapor pressure and low water solubility	Indoor sensors	Statistic representation of affected apartments	post intervention	100 ppb - 20 ppm

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
Illumination level	Local Time available metrics Daylight Autonomy (DA), Visual Comfort Availability (VCA), Global Comfort Availability (GCA)	Quantifies the local availability of a sufficient daylight level in a considered period	Lux meter	Statistic representation of affected apartments	post intervention	DA – Threshold 200 lx for residential buildings/ 500lx for offices VCA – Threshold DGI lower than 22
Tout, Time step external ambient Temperature	External Environmental Factors	N/A	Weather station	Building level	Pre & Post intervention	Detection range 0 to 50°C Accuracy ±0.4°C Resolution 0.1°C
Rout, Time step external Relative Humidity						Detection range 0-100% RH Accuracy ±4% RH Resolution 0.1%
Eo, Simultaneous available lux outdoors under a CIE overcast sky						N/A

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Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors
I_H, Solar irradiation (total or on facades)						N/A

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Thus, the different introduced KPIs are explained here below, except for the following ones, which can be found in deliverable D1.4:

- Volatile Organic Compounds (VOC): Definition and details chapter 4.2-4 of T1.5.
- Daylight Autonomy (DA): Definition and details chapter 4.2-2 of T1.5
- Visual Comfort Availability (VCA): Definition and details chapter 4.2-2 of T1.5
- Global Comfort Availability (GCA): Definition and details chapter 4.1-2 of T1.5

4.1.2.1 Thermal Comfort

According to the EN ISO 7730, 'thermal comfort is that condition of mind which expresses satisfaction with the thermal environment'. Extreme temperatures (either too high, or too low), are linked to SBS symptoms, reduce the perceived air quality by building occupants and are also associated to reduced productivity and bad sleeping quality [26] [27].

The thermal environment is defined by environmental parameters, such as temperature (air, radiant), relative humidity and air velocity, and by personal parameters such as clothing, level of activity, gender and age, which affect a person's metabolic rate (Figure 11) [28]. Operative temperature is a combination of air temperature and mean radiant temperature in a single value, and it used to express their joint effect [29]. Operative temperature is often used to determine the impact of the thermal environment to building occupants, however it is difficult to measure. Recent studies of CBE show that in low-energy buildings where radiant heating is used, air temperature is a good approximation of the operative temperature [30].

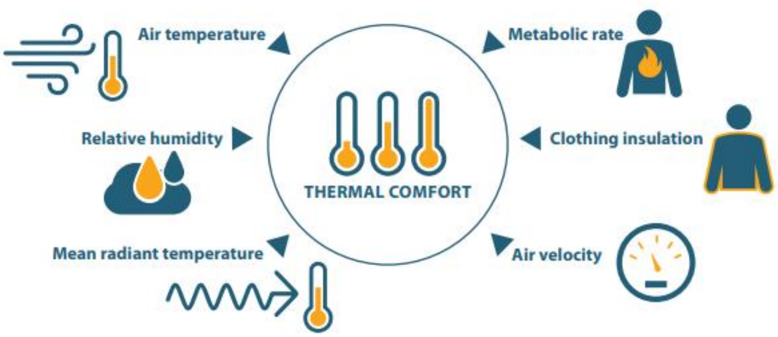

FIGURE 11 FACTORS PRIMARILY AFFECTING THERMAL COMFORT BASED ON EN ISO 7730

4.1.2.2 PMV and PPD indexes

The level of occupant thermal comfort is often expressed in percentage of the number of people who are satisfied or dissatisfied with the thermal conditions. The most commonly used indexes are the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD), these will be KPIs of the thermal

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environment. The calculation formulas for the PMV and PPD indexes according to ISO 7730 and ASHRAE Standard 55 are developed below.

The first model of thermal comfort was developed by Fanger in 1967 (Fanger's comfort model) and based on the heat-balance equation, it can calculate the PMV and PPD indexes using a 7-point thermal sensation scale: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), -2 (cool) and -3 (cold) [31].

For mechanically heated and cooled buildings, different categories of the indoor environment are established for different criteria of PMV and PPD indexes. According to the EN 16798-2019, the recommended PPD ranges are summarized in Table 5.

TABLE 5 DEFAULT CATEGORIES FOR THE DESIGN OF MECHANICAL HEATED AND COOLED BUILDINGS (SOURCE EN ISO 16798-1-2019).

Category	Predicted Percentage of Dissatisfied (PPD) (%)	Predicted Mean Vote (PMV)
IEQ_{I}	<6	-0.2 < PMV < +0.2
IEQ_{II}	<10	-0.5 < PMV < +0.5
IEQ_{III}	<15	-0.7 < PMV < +0.7
IEQ_{IV}	<25	-1.0 < PMV < +1.0

According to ISO 7730 and ASHRAE Standard 55 the PMV and PPD indexes can be estimated using the following formulas, Equation 13:

EQUATION 13

$$PMV = [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot$$
$$\{(M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15]$$
$$-1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a)$$
$$-3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl}+273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}$$

$$t_{cl} = 35.7 - 0.028 \cdot (M-W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl}+273)^4 - (\bar{t}_r+273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & for \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & for \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 l_{cl} \; for \; l_{cl} \leq 0.078 m^2 \cdot K/W \\ 1.00 + 0.645 l_{cl} \; for \; l_{cl} > 0.078 m^2 \cdot K/W \end{cases}$$

Where:

M is the metabolic rate (W/m^2)W is the active mechanical power (W/m^2);

I_{cl} is the clothing insulation ($m^2 \cdot K/W$);

f_{cl} is the clothing surface factor; t_a is the air temperature (ºC);

t_r is the radiant mean temperature (ºC);

v_{ar} is the relative air velocity (m/s);

p_a is the vapor pressure of air (Pa);

h_c is the convective heat transfer coefficient ($W/m^2 \cdot K$); and

t_{cl} is the clothing surface temperature (ºC).

The PMV index is used for values that range between -2 and +2, when the six main parameters are within the intervals of:

M 46 W/m^2 to 232 W/m^2 (0.8 met to 4 met)

I_{cl} 0 $m^2 \cdot K/W$ to 0.310 $m^2 \cdot K/W$ (0 clo to 2 clo)

t_a 10 °C to 30 °C

$\bar{t}_r$ 10 °C to 40 °C

v_{ar} 0 m/s to 1m/s

p_a 0 Pa to 2 700 Pa

Once the PMV value is estimated the PPD can be estimated using the following Equation 14.

EQUATION 14

$$PPD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)$$

4.1.2.3 Air temperature

Due to complexity, the nature of the monitoring campaign but also aspects related to the economic feasibility, it will not be possible to monitor specific parameters such as mean radiant temperature and air velocity. For these parameters which are required for the calculation of the PMV index, specific assumptions are made following the methodology used for the GrowSmarter project[10]. Unless detailed data is available, mean radiant temperature is approximated to air temperature (t_r approximated to be equal to t_a), while the air velocity is assumed to be constantly equal to 0.1m/s. PMV and PPD indexes can be theoretically estimated during the design stage.

[10] GrowSmarter Project, https://grow-smarter.eu/home/

To determine the metabolic rate and clothing insulation specific information is required related to the activity that occupants perform and level or clothing that they wear. During the design stage this information can be assumed depending on the season, while at the operational phase this information can be acquired from the post occupancy evaluation survey.

Acceptable indoor temperatures for buildings without mechanical cooling systems: Adaptive comfort

Whilst the heat balance model described above applies to air-conditioned buildings, for naturally ventilated spaces, the adaptive model is applicable. The adaptive model allows the building occupants to adapt to the thermal environment through behavioral, psychological and physiological means. The adaptive comfort applies for buildings used for human occupancy with sedentary activities (e.g. residences, offices) where people have access to openable windows and can freely adapt their clothing depending on the thermal conditions. In this case the adaptive criteria can be applied for summer and mid-seasons (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, upper and lower limits for cat. I, II and III) [25].

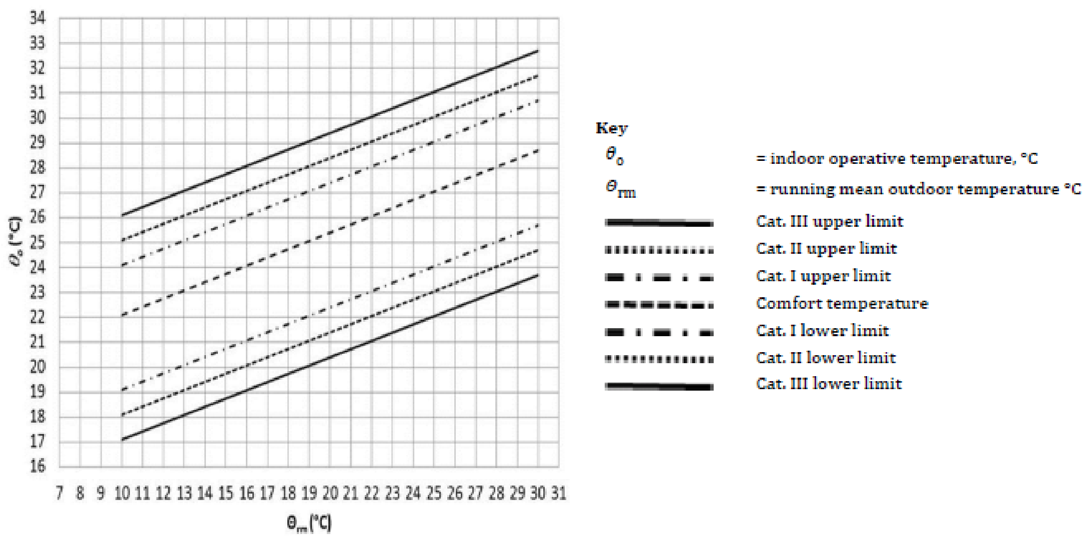

FIGURE 12 DESIGN VALUES FOR OPERATIVE TEMPERATURE IN BUILDINGS WITHOUT MECHANICAL COOLING SYSTEMS (SOURCE: EN 16798-1-2019).

Air temperature (°C) and relative humidity (%) will be further KPI of the thermal environment for buildings without mechanical cooling. To evaluate the thermal environment, the percentage of time that temperatures are out of the ranges specified in the categories of EN 167989-1-2019, should be estimated for buildings with and without cooling systems for the heating and cooling seasons (Table 6). Considering the aforementioned findings of the CBE study, it should be highlighted that in this study, operative temperature is assumed equal to the air temperature. The temperatures can exceed the recommended

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range by 1 °C by not more than 5% and by 2°C by not more than 1% of the annual occupied time, so as to be classified in the different categories, based on an approach similar to Level(s) and the TAIL index of Aldren project. It should be noted that this evaluation concerns the living rooms where the monitoring equipment will be installed and during times that the dwellings are occupied. Information about typical occupancy patterns can be acquired from the questionnaire surveys filled in by the building occupants. This methodology is also proposed in Level(s) and in the TAIL index of the Aldren project.

Table 6 shows the operative temperature ranges for summer and winter in buildings with and without mechanical cooling systems classified in the 4 categories.

TABLE 6 OPERATIVE TEMPERATURE RANGES FOR SUMMER AND WINTER IN BUILDINGS WITH AND WITHOUT MECHANICAL COOLING SYSTEMS CLASSIFIED IN THE 4 CATEGORIES (SOURCE: EN 16798-1-2019).

Category	Operative temperature (°C)			
	Buildings with mechanical cooling systems		Buildings without mechanical cooling systems	
	Minimum for heating season, (Winter) ~ 1,0 clo	Maximum for cooling season (Summer) ~ 0.5 clo	Minimum for heating season (Winter) ~ 1,0 clo	Maximum for cooling season (Summer) ~ 0.5 clo
IEQ_{I}	21	25.5	21	upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 2$ lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 3$
IEQ_{II}	20	26	20	upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 3$ lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 4$
IEQ_{III}	18	27	18	upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 4$ lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 – 5$
IEQ_{IV}	16	28	16	

Where:

$\Theta rm =$ *Outdoor Running mean temperature for the considered day (°C) which can be calculated by:*

$\Theta rm = (1-\alpha)\{\Theta_{ed-1} + \alpha\, \Theta_{ed-2} + \alpha^2\, \Theta_{ed-3}\}$

$\Theta ed - 1 =$ *daily mean outdoor air temperature for previous day*

$\alpha =$ *constant between 0 and 1 (recommended value is 0,8)*

$\Theta ed - i$ = *daily mean outdoor air temperature for the i-th previous day*

In case that daily running mean outdoor temperatures are not available, the following formula can be used:

$$Qm = (Q_{ed-1} + 0.8\, Q_{ed-2} + 0.6\, Q_{ed-3} + 0.5\, Q_{ed-4} + 0.4\, Q_{ed-5} + 0.3\, Q_{ed-6} + 0.2\, Q_{ed-7})/3.8$$

The dotted line in the middle of ***Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.*** *is the optimal operative temperature represented by:*

$$\Theta c = 0{,}33\Theta_{rm} + 18{,}8$$

where:

Θo = *indoor operative temperature, °C*

Θrm = *running mean outdoor temperature, °C*

Θc = *Optimal operative temperature, °C*

Where the limits apply when $10 < \theta_{rm} < 30^{o}C$

Naturally ventilated homes should assess overheating by using the adaptive method. For living rooms, bedrooms and kitchens, the number of hours during which the temperature difference ΔT between the indoor and outdoor environment is greater to or equal to 1°C during May to September (inclusive) should not be more than 3% of the occupied hours. To ensure comfort during sleeping hours, in bedrooms only, the operative temperature between 10pm and 7am should not exceed 26°C for more than 1% of the annual hours (1% of the annual hours is 32 hours, therefore if 33 hours or more are above 26°C, then are recorded as a fail) [32] [33]. The thermal performance of buildings during summertime is usually measured against a benchmark temperature that should not be exceeded for a certain number of hours during an annual occupied period. When the benchmark temperature is exceeded then the building is 'overheated' and when this occurs for more than a specified amount of time it is then said that the building suffers from 'overheating [34].

In locations of high humidity, the Heat Index (HI) can be used as a basis of overheating conditions. Heat index is an index that combines air temperature and relative humidity in a single value that shows how hot the weather will feel. The higher the index, the hotter the weather will feel [35]. The result is also known as the "felt air temperature", "apparent temperature", "real feel" or "feels like". For example, when the temperature is 32 °C with 70% relative humidity, the HI is 41 °C. Caution is needed when the HI is between 26 ºC and 32 ºC as fatigue is possible with prolonged exposure and activity. Heat cramps and heat exhaustion are likely to appear when the index is above 32 °C.

Good indoor air quality is the air without harmful concentrations of contaminants with which the great majority of tenants are satisfied [36]. The most well-known contaminants are carbon dioxide, carbon monoxide, particulate matter and VOCs [37]. Sources of contaminants in residences are emissions from

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indoor combustion sources, activities such as cooking or smoking, emissions from furnishings, cleaning products, construction material, or even occupants themselves (e.g. through human respiration CO_2 concentrations released) [24]. Apart from the indoor sources, indoor air quality is also affected by the outdoor air pollution from combustion sources, construction and agricultural activity or traffic entering the building through the windows, infiltration or mechanical ventilation systems.

A great number of studies have linked bad indoor air quality with adverse health effects such as asthma, eczema and allergic diseases. Eye, nose, skin and throat irritations, upper respiratory symptoms, fatigue and headaches are of the most frequently appeared building related health symptoms [34]. These symptoms are usually not linked to specific illnesses, disappear when the person leaves the building and are described as 'Sick Building Syndrome' (SBS) symptoms [29]. These symptoms usually disappear when the affected person leaves the 'mal-functioning' building.

4.1.2.4 Carbon Dioxide (CO_2)

A critical method of removing indoor air contaminants is via proper ventilation. Ventilation is also essential to ensure thermal comfort and provide pre-cooling of the building's structure during the night in summer months, but also to extract moisture, odors and air pollutants [38]. However, introducing adequate ventilation rates without removing internal sources of air pollutants this can result in partial and limited improvement of the indoor air quality. Overall, the indoor air quality is affected by the outdoor air quality, the levels of ventilation, the installed building materials, the household activities and the occupant's level to control these.

Through ventilation, fresh air is supplied in buildings that plays a critical role in removing harmful pollutants from a space. Higher ventilation rates are generally associated to improved health. Ventilation is also used to passively cool a space [29]. Ventilation is further needed for extracting contaminants at source (e.g. extract systems for kitchens and bathrooms), distributing of conditioned air (heating and cooling) or precooling building' structure (e.g. night ventilation). The amount of required ventilation depends on the occupant density, the occupant activities and the amount of pollutants emitted in a space. Natural ventilation is intended to provide adequate outside air to maintain appropriate standards of air quality and provide cooling when needed. It is one of the most fundamental ways of reducing energy use of buildings and is a process of introducing air to the indoor space (supply) or remove contaminated air (extract), driven by temperature (stack effect) and wind (wind effect). Natural ventilation can support a mixed-mode strategy where mechanical ventilation or cooling is coupled with the natural systems. There are also cases where mechanical ventilation is exclusively used to cover ventilation requirements [29].

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According to the EN 13779 and based on the categorization of IEQ presented in Table 4 the recommended minimum outdoor air rates per person[11] and indoor air quality classifications are given on the table below Table 4. Based, on EN 13779, the design outdoor air rate may take into account emissions f other sources like building and furnishing material.

Considering that the CO_2 is emitted through metabolic processes, the increase of indoor CO_2 concentrations above the outdoor values are often used to estimate the sufficiency of ventilation. Carbon dioxide is a good proxy of the indoor air quality as it can provide an indication of the ventilation rate in a space (Table 11). Typically, for a sedentary occupied zone, a concentration of 800-1000 ppm represents a ventilation rate of 10 l/s/p [34].

CO_2 (in units of ppm) will be the KPI of the IAQ, it will be measured in all of the dwellings, and its concentration ranges will be used to evaluate the indoor air quality according to the four quality categories specified in Table 5. The percentage of time that the CO_2 concentrations fall within these ranges should be calculated. In line with the methodology followed by the TAIL index of the Aldren project, to be able to classify the measurements in the four quality categories, the measurements should not exceed the defined range by more than 5% of the occupied time (assuming continuous measurements). The technical specifications of the monitoring instrument to measure CO_2 concentrations along with the monitoring protocol, is presented in the following chapter.

Based on assumptions related to building occupancy (number of occupants, age, activity level etc.) and operation (e.g. window opening, HVAC operation), CO_2 concentrations may be predicted using the mass balance equation, Equation 15 seen below, giving an indication on the overall indoor air quality.

EQUATION 15

$$C(t) = C_v + (C_o - C_v)exp\left(-\frac{Q_v t}{V}\right) + \left(\frac{G}{Q_v}\right)\left[1 - exp\left(-\frac{Q_v t}{V}\right)\right]x10^6$$

Where:

$C(t)$ is the CO_2 concentration in ppm at time t,

Cv is the outdoor CO_2 concentration in ppm (~400ppm without much fluctuation during the day)

Qv is the outdoor air flow rate in m^3/h (depends on air tightness of the building envelope, wind and stack effect and HVAC system design),

V is the volume of the conditioned space in m^3,

G is the CO_2 generation rate in m^3/h (~0.3 l/min/person for activity level of 1.2 met),

[11] National legislation requirements are applied where available

Co is the initial concentration which can be approximated to Cv at the beginning of the day.

4.1.2.5 Lighting and visual comfort

According to the EN12665 visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment". Lighting in buildings should create a pleasant appearance of the space and allow building occupants move safely and conduct their working tasks productively. Excessive brightness or glare from either solar or electric sources can be disruptive therefore appropriate lighting levels can be ensured by natural or/and artificial lighting.

For visual comfort, metrics can be determined depending on the reference time and position. The impact of daylighting can be taken into account quantitatively through the DA while Daylight Glare Index (DGI) can be the appropriate factor for analyzing the glare issues [39]. DA, quantifies the adequate daylighting level in a considered reference time period. The selected threshold can be considered at 200lx for residential buildings and 500lx for non-residential buildings for tasks such as writing, typing, reading and data processing [40]. Daylight Glare Index is the factor for quantifying the presence of glare as a result of daylight in a certain area. Threshold for visual comfort refers to DGI values lower to 22 [41].

Recent studies have shown a negative impact on human health from inadequate illumination. Specifically, the lack of appropriate lighting levels is connected to potential harmful effects such as circadian disruptions leading to lack of sleep, depressive symptoms and reduced alertness and cognitive performance [42]. A good visual environment (e.g. adequate levels of natural and artificial lighting, reduced glare etc.) can add to the well-being and productivity of the building occupants [43]. Daylight exposure through windows has a significant positive effect on sleep quality as well. However, increased use of glazing can increase the heat losses of a building, therefore a correct balance between thermal losses and daylight levels is needed.

4.1.2.6 Illuminance and daylight factor

Lighting design criteria are given in terms of maintained illuminance for different building types. Illuminance it the total amount of light delivered on a surface by either natural daylight or electrical fitting. In this project, the **illuminance and the daylight factor** will be measured and simulated to evaluate the visual environment and will be the **KPIs of the lighting and visual comfort**. The recommended lighting design criteria for dwellings are summarized below in Table 9.

Daylight factor is a metric expressing as a percentage the amount of daylight that is available in a room in comparison to the amount of daylight available outside under overcast sky conditions [44] . The daylight factor depends on the size, the transmission properties of the of the façade, the size and shape of the space and well as the extent to which external structures obscure the view of the sky. The calculations for the daylight factor are shown below, Equation 16 and Equation 17.

EQUATION 16

$$DF = \frac{E_I}{E_O} \times 100\%$$

Where:

DF is the daylight factor measured at a specific point (%)

Ei is the available lux indoors at a specific point on a working plane (lux)

Eo is the simultaneous available lux outdoors under a CIE overcast sky (lux)

To assess the adequacy of daylight, the average daylight factor can be used:

EQUATION 17

$$Average\ DF = \frac{W}{A}\frac{T\Theta}{(1-R^2)}$$

Where:

W	*area of the windows (m^2)*
A	*total area of the internal surfaces (m^2)*
T	*glass transmittance corrected for dirt*
Θ	*visible sky angle in degrees from the centre of the window (deg)*
R	*the average reflectance of area A*

For the purpose of this particular project, daylight factors can be estimated through calculations on a horizontal surface at 0.85m above the floor, following the methodology of the TAIL index of the Aldren project.

Rooms that have daylight factor of 2% or more are considered as daylit, however electric lighting may still be needed for specific visual tasks. Rooms with daylight factor of 5% or more, it's likely that electric lighting will not be used during the day. BS 8206[12] recommends average daylight factors of at least 1.5% in living rooms, 1% in bedrooms and 2% in kitchens even when predominantly daylit appearance is not necessary.

4.1.2.7 Tout - Time step external ambient Temperature

The ambient temperature is the average air temperature surrounding something (such as a person) whether inside or outside. In relation to weather, the ambient temperature is the same as the current air temperature at any one location. Strong wind, and other factors such as surface temperatures may make

[12] BS 8206-2: 1992: Lighting for buildings. Code of practice for daylight

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it feel warmer or colder, but the ambient temperature only relates to the air temperature. Ambient temperature can also be used to describe the state of objects. For instance, in electronics, the ambient temperature is the air temperature surrounding an object such as an LED. This is a very important parameter that allows equipment such as computers and other electronic devices to operate at peak efficiency.

Ambient temperature is usually expressed in degrees Centigrade (°C) or degrees Fahrenheit (°F). [45]

4.1.2.8 RHout - Time step external Relative Humidity

Relative Humidity (RH) is the ratio of the actual partial vapor pressure of water to the saturation vapor pressure at that temperature [46].

The saturation vapor pressure of water increases rapidly with temperature, from 610 Pascal at zero degrees to 2800 Pa at 23°C. At 100°C the vapor pressure reaches 101,000 Pa, which is about atmospheric pressure. The partial pressure of water vapor is proportional to its concentration, so the increase in concentration is from 5 g/m^3 at zero degrees to 20 g/m^3 at 23 °C

4.1.2.9 Eo - Simultaneous available lux outdoors under a CIE overcast sky

The luminance of the standard CIE overcast sky changes with altitude. It is three times as bright in the zenith as it is near the horizon. The overcast sky is used when measuring daylight factors. It can be modelled under an artificial sky [47].

Ambient lighting, or what is commonly called as general lighting, serves as the primary source of light for a certain room. It is the foundation of all the lighting of a room. Aside from the basic lighting functionality, the ambient lighting improves the sense of warmth and depth of a room or space.

It works to provide a comfortable level of illumination without too much glare. This allows you to navigate an entire room safely too. A central source of it for every room is essential to achieve an excellent lighting plan. A perfect source needs a strategy in choosing which lights to use and in what area or part of the room to place it.

Ambient lighting can be accomplished by using basic lighting fixtures such as chandeliers, track lights, recessed lights, and wall or ceiling-mounted lighting fixtures. There are various ways to achieve balance in ambient lighting and this often depends on what type of room you are using it for [48].

4.1.2.10 I_H - Solar irradiation (total or on facades)

Solar irradiation is the amount of electromagnetic radiation received from the sun per unit area (usually square meters) [49]. In other words, it's the amount of the sun's power detected by a measuring instrument. When these data are integrated over time, the information is called solar irradiation, insolation, or solar exposure. The amount of solar irradiance varies depending on how far the object is from the sun, the angle of the sun, and the solar cycle—the change in the sun's appearance and activity every 11 years. Irradiance can be measured for the moon, stars, or any other glowing object.

Breaking solar irradiance data up into its individual wavelengths (colors) of light, also called spectral irradiance, gives scientists additional information. The irradiance of the sun is studied at several wavelengths including visible light, IR, ultraviolet (UV), extreme ultraviolet (EVU), and X-rays.

Studying spectral irradiance is important because each wavelength is absorbed in various parts of the atmosphere. For example, the radiation from visible and IR light warms surfaces like the skin and the roofs of buildings. Also, changes in solar EVU output effects space weather which is an important concern for spacecraft and space travel.

The irradiance at the top of the Earth's atmosphere is about 1361 W/m2. After passing through the atmosphere and losing energy, irradiation at the surface of the planet is 1000 W/m2 on a clear day at sea level. The average daily irradiance of the Earth is about 6 kWh/m2. Even small changes in the sun's irradiance can have dramatic effects on the climate, atmosphere, and ionosphere.

4.1.3 Economic parameters and related KPIs

To become mainstream developments, SPENs must be demonstrated to be competitive also on economic performance. According to the EPBD, all new buildings are required to be nZEB by the end of 2020, which makes the nZEB guidelines a good comparison for alternative developments. Here, we will foreground the economic performance for the building owners and investors, such that the economic priorities in the macro level and from the end user perspective will be in the background for now.

4.1.3.1 Economic Performance (energy related/requirement-related costs)

Requirement-related costs include power costs, auxiliary power costs, fuel costs, and costs for operating resources and in some cases external costs, energy tariffs. In any case, for monitoring for assessment purposes only specific economic parameters will be considered; Table 7 shows the primary economic/cost parameters for control and monitoring.

TABLE 7 PRIMARY ECONOMIC/COST PARAMETERS FOR CONTROL AND MONITORING

Monitored and controlled variable (Acronym and definition)	Related KPI	Related KPI Definition and formulation	Monitoring requirement	Monitoring scope	Monitoring gantt	Minimum required technical specifications of sensors[13]
Power costs	Requirement-related costs	Power costs, auxiliary power costs, fuel costs, and costs for operating resources and in some cases external costs	Grid connection OR contract invoices	Building level	Post intervention	To be defined with regard to PLURAL solutions

Even if this parameter is widely described in bibliography, detailed explanations will be introduced in T3.1b, once the regulatory and grid prizing schemes for each demo case have been described in detail.

[13] These are the minimum requirements to date. However, these details will be finalized for the final version of the deliverable D3.1.b for each demo case.

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4.2 Available sensors from PLURAL technologies

Chapter 4.2 summarizes, from the already known characterization, the available sensors for all the different PLURAL technologies, and their capabilities to be used for assessment. The monitoring devices they are going to use for the needs of the PLURAL project can be separated in three different categories; namely, the Multisensor, the Heat meter and the Room ventilation, supply of fresh air and exhaust of waste air and Sensor Platform and they are all installed on a room level.

The Multisensor comprises of the following sensors:

- Air quality sensor (CO_2 concentration).
- Air quality sensor (VOC concentration).
- Wind sensor (air velocity).
- Amplifier thermocouple (thermocouple temperature readings).
- Digital temperature sensor (temperature).
- Temperature and humidity sensor breakout (temperature & humidity).

The Room ventilation, supply of fresh air and exhaust of waste air and Sensor Platform is able to capture:

- Temperature
- Relative humidity
- CO_2 concentration
- VOC concentration
- Ambient light
- Particulate Matter concentration: PM10, PM4, PM2.5 and PM1

The Heat meter measures only temperature.

In Table 8 **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** the main characteristics of each device are presented.

For all three above mentioned PLURAL technologies it is important to mention that for the demo cases that the Toolbox will be installed the captured data can be made available for supervisory control and/or monitoring purposes.

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TABLE 8 OVERVIEW OF THE MAIN SENSORS CHARACTERISTICS

Device	Manufacturer	Physical input	Accuracy	Measurement Range	Nominal values	Measurement interval	Communication
Heat Meter	GWF	Temperature	N/A	0 - 180 °C	N/A	N/A	M-BUS
Room ventilation, supply of fresh air and exhaust of waste air and Sensor Platform	University Centre for Energy Efficient Buildings, CTU in Prague	Temperature	±0.5 °C	-40–85 °C	N/A	60 sec (Measured quantities can be averaged depending on the communication interface through which they are sent.)	WiFi 802.11 b/g/n 2.4 GHz LoRaWAN – Class A, 14 dBm, SF 7-12, 868 MHz support for both ABP and OTAA device activation Modbus RTU (RS485) At the same time it can send measured values using WiFi (MQTT, HTTP API, Modbus TCP), LoRaWAN, RS485 (Modbus RTU) interfaces.
		Relative humidity	±2 % (in range 20-80 %)	0–90 %RH (non-condensing)	N/A		
		CO_2 concentration	±30 ppm ±3% of the value	300–5000 ppm	N/A		
		VOC concentration	indicative value	300–5000 (dimensionless index)	N/A		
		Ambient light	indicative value	0–7500 lx	N/A		

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Device	Manufacturer	Physical input	Accuracy	Measurement Range	Nominal values	Measurement interval	Communication
		Particulate Matter concentration	±10 μg/m3 (in range 0–100 μg/m3) ±10% (in range 100-1000 μg/m3)	0.0-999.9 μg/m3 (optional)	N/A		
NTUA multisensor	AMS	CO_2 concentration	N/A	400 - 8192 [ppm]	10 mg/m3 CO	1 sec, 10 sec, 60 sec, 250 msec	IoT based – independent connection of each sensor Wi-Fi –Bluetooth - 2.4GHz Frequency Data Rate up to 150MBs Adjustable Transmit Power Supports Antenna Diversity, GPIO Controls, RF Switch
		TVOC	N/A	0 - 1187 [ppb]	0.3-0.5 mg/m3		
	Modern devices	Air Velocity	N/A	0 – 27 m/sec	~ 5m/sec (space dependent)	N/A	
	Maxim Integrated	Thermocouple Temperature Readings	±0.15%	-20 - +85 [degC]	22 [degC]	100ms	

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Device	Manufacturer	Physical input	Accuracy	Measurement Range	Nominal values	Measurement interval	Communication
	Microchip Technology	Temperature	±0.25 (typical) from -40°C to +125°C ±0.5°C (maximum) from -20°C to 100°C ±1°C (maximum) from -40°C to +125°C	-20°C - +100°[degC]	22 [degC]	N/A	
	AMS	Humidity	±2.0%	0-100%	45%	0.5, 1, 2, 4 & 10 sec	
		Temperature	±0.3 degC	-40 - 125°C	22 [degC]		

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4.3 Specific monitoring requirements

In Chapter 4.3, the monitoring requirements for any PLURAL solution implemented in the demonstrative buildings are introduced. In D3.1a, as it is a technology-based approach, the monitoring requirements will be drafted under a general vision, and will be introduced in detail in D3.1b.

4.3.1 Sensors and meters requirements

In the following tables, Table 9 and Table 10, an overview of both primary and secondary specific monitoring requirements for the PLURAL project needs are introduced.

TABLE 9 REQUIREMENTS FOR EACH PRIMARY PARAMETER MONITORED WITHIN PLURAL

Monitoring device	Monitored parameter	Monitoring scope	Monitoring gantt	Potential device redundancy [14]
RES systems energy meter	$P_{del,I}$ - The delivered power on site or nearby for energy carrier	Households level – representative sample	Post intervention	-
	E_{Pren} - Renewable primary energy consumption			
Households meter	E_{Ptot} - Total primary energy consumption	Households level - representative sample	Pre & Post intervention	Need to be defined, depending on the demo cases description, in which cases the existing PLURAL technologies monitoring devices could be used Pre and Post intervention.
Energy meter	P_{ec} - Primary energy consumption	Statistic representation of affected apartments (depending on	Pre & Post intervention	Need to be defined, depending on the demo cases description, in which cases the existing PLURAL technologies monitoring
	$Q_{h,c}$ - Energy consumption for heating and cooling needs			

[14] For the cases that we are going to use monitoring devices both **Pre** and **Post** PLURAL intervention, in relation to what is going to be installed in each demo site, it will be evaluated if it is worth to use the same measurement device or instead install new ones.

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Monitoring device	Monitored parameter	Monitoring scope	Monitoring gantt	Potential device redundancy [14]
	E^{norm}_{fan} - Energy consumption for mechanical ventilation needs (fan)	HVAC + RES systems)		devices could be used Pre and Post intervention.
	$E^{norm}_{light,t}$ - Electric consumption normalized for lighting during occupied or working period			
	Heating and Cooling peak power			
Indoor sensors	T_r - Radiant mean temperature	Statistic representation of affected apartments	Post intervention	-
	T_{ind} - Indoor Temperature		Pre & Post intervention	Need to be defined, depending on the demo cases description, in which cases the existing PLURAL technologies monitoring devices could be used Pre and Post intervention.
	RH_{ind} - Indoor Relative Humidity			
	C_{int} - CO2 indoors concentration in ppm		Post intervention	-
	VOC - indoor concentration in ppb or mg/m3			
Outdoor sensors	C_{out} - CO2 outdoors concentration in ppm	Statistic representation of affected apartments	Post intervention	-
Indoor sensors	Ei - Available lux indoors	Statistic representation of affected apartments	Post intervention	-

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Monitoring device	Monitored parameter	Monitoring scope	Monitoring gantt	Potential device redundancy [14]
Weather station	T_{out} - Time step external ambient Temperature	Building level	Pre & Post intervention	-
	RH_{out} - Time step external Relative Humidity			
	E_o - Simultaneous available lux outdoors under a CIE overcast sky			
	I_H - Solar irradiation (total or on facades)			

TABLE 10 REQUIREMENTS FOR EACH SECONDARY PARAMETER MONITORED WITHIN PLURAL

Monitoring device	Monitored parameter	Monitoring scope	Monitoring gannt	Potential device redundancy [15]
Households meter/power	Flexibility Factor	Building Level	-	-
Building power	$P_{DR/REF}$ - Building electrical power consumption during the demand response scenario (or the reference case)	Building Level	Pre & Post intervention	Need to be defined, depending on the demand cases description, in which cases the existing PLURAL technologies monitoring devices could be used Pre and Post intervention.

[15] For the cases that we are going to use monitoring devices both **Pre** and **Post** PLURAL intervention, in relation to what is going to be installed in each demo site, it will be evaluated if it is worth to use the same measurement device or instead install new ones.

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4.3.2 Assessment methods

In order to ensure the best possible collection of information that will facilitate the evaluation of the IEQ holistically, both at the design and operational phase, the framework will be based on a four-pillar approach including modeling and simulations, on-site measurements, checklists, and questionnaire surveys. The following table, Table 11, summarizes the activities related to the different project stages.

TABLE 11 ACTIVITIES RELATED TO THE DIFFERENT STAGES OF THE PROJECT (SOURCE: LEVEL(S)).

Project stage	Related activities
Design phase (based on calculations/simulations)	Design of the building structure and HVAC systems to meet ventilation rate (CO_2 concentrations) and thermal comfort targets Ventilation design aiming to control sources of humidity and other pollutants In case of renovation projects: Identify problems related to dump, mould and cold bridging Calculation of CO_2 concentrations Prediction of daylight factor Prediction of sound pressure levels
Operational phase (based on measurements, surveys and checklists)	On-site measurement of T, RH, CO_2, illuminance, sound pressure level Post-Occupancy evaluation surveys Checklists to evaluate parameters that cannot be measured

4.3.2.1 Design stage modelling and calculation

Building simulations constitute an effective way to analyze the expected performance of buildings [25]. Thermal simulations will be performed to calculate the profile of the thermal environment at the design stage in compliance with the EN 16798-2019, EN 13790 and EN 15603. All assumptions must be clearly defined, while all inputs should be specified ensuring high levels of accuracy, preciseness, and representativeness. Annual thermal simulation using weather files of the respective pilot city will run by taking into account construction details and materials, and theoretical usage and occupancy of the dwellings.

- Overheating can be predicted before occupation through thermal dynamic simulations. It is essential that: simulations predict operative temperature of occupied buildings, sources of heat gains (such as electrical appliances) and solar radiation through windows are realistically taken into account and
- For free-running buildings simulations include realistically the use of window opening [32].

The design criteria for the thermal environment of heated and/or mechanically cooled buildings should be based on the indices of PMV and PPD described in the previous sub-section. For these indices, typical levels of activity and thermal insulation for clothing should be assumed. The operative temperature will be established based on the selected criteria. The upper values of comfort range during the summer (cooling season) shall be used for dimensioning the cooling systems and the lower values of the comfort range shall be used for dimensioning the heating system. In case that cooling systems are not installed, calculations should demonstrate that the mechanical and/or natural ventilation strategies prevent overheating according the IEQ established limits.

CO_2 concentrations for the evaluation of the IAQ and daylight factor for the evaluation of the lighting comfort, can be simulated by using building dynamic software such as TRNSYS, Energy Plus or IDA-ICE following criteria specified in the previous chapter of KPIs.

4.3.2.2 Operational phase on-site measurements

Monitoring objectives

The main objective of the on-site measurements of PLURAL is to characterize the IEQ of the NZEBs. Aiming to examine how the buildings perform in real life, spot illuminance levels but also accurate monitoring of three of the most important parameters of the IEQ, those of air temperature, RH and CO_2 will take place in selected apartments of each of the pilot projects. Air temperature is the main indicator of thermal comfort and key determinant for the use of heating and cooling. Relative humidity is of great importance as it is associated to health effects to building occupants due to condensation and mould at long-term exposures. CO_2 concentrations in residential buildings, where the occupants are the main source of pollution, are considered as a major indicator of the ventilation and air quality [21]. Monitoring will last for a year aiming to investigate seasonal patterns.

Selection of case studies

The criteria on selecting the locations of the samplers are based on aspects related to the representativeness of the indoor environment, technical (and accessibility), economic but also human-related aspects, aiming to avoid interference with building occupants.

To be able to get a representative whilst realistic sample per demo case, a significate number of apartments per pilot will be monitored. In order to have a good representation of orientations, at least one apartment per orientation and floor should be chosen to investigate the degree to which solar penetration and height from the ground affects the overall IEQ. For comparability purposes the apartments selected should be of the same area (and volume), occupied by the same number and similar age group of people and have similar occupancy patterns, if possible.

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Stakeholder engagement

All stakeholders involved in the on-site measurements such as tenants, owners and building managers should be well informed about the installation of the equipment and execution of the monitoring campaign to ensure their support. Building occupants are the main stakeholders and in order for them to engage and agree with the monitoring campaign it is recommended to organize raise awareness communication campaigns (e.g. workshops including information sheets and consent forms) to ensure their consent. Amongst other, data privacy should be also ensured and communicated to the building occupants. Risk assessment and health and safety considerations (e.g. during the installation of the equipment) should be taken into account.

Sampling site description

All four sampling sites should be briefly described. This description should include information ranging from a larger to a smaller scale covering description of the climate, the microclimate of the neighborhood, the construction characteristics of the building, orientation and size of the apartment as well as theoretical occupancy patterns which can be confirmed through the surveys.

Monitoring period, data collection

In order to examine the seasonal variation of the parameters of the indoor environment, measurement will last for at least a year in each of the pilots. Temperature (T), RH, CO_2 should be measured at a sampling interval of at last every 5min, short enough to ensure important fluctuations will not be missed.

Measurements should take place in representative zones and orientations of the building. The representative space of the houses has been agreed to be the living room, although measurements could be extended in other rooms such as the bedrooms for some monitoring campaigns. Following the EN 16789-1-2019, samplers should be ideally installed in the center of the room, at a breathing level height (e.g. living room people are assumed to be seated therefore, ideal height at 1.10m), not closer than 1m from the wall nor next to an air supply/extract point or direct exposure to the sun.

Type of samplers

The minimum requirements of detection range, accuracy and resolution for the temperature, relative humidity, CO_2, and illuminance samplers are presented in Table 12**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**. It is further recommended that all monitoring devices of the same pilot should be calibrated and tested before their installation for accuracy and comparability purposes.

TABLE 12 MINIMUM REQUIRED TECHNICAL SPECIFICATIONS OF SENSORS.

Psysical quantity	Detection range	Accuracy	Resolution
Temperature (°C)	0 to 50°C	±0.4°C	0.1°C
Relative Humidity (%)	0-100% RH	±4% RH	0.1%
Carbon Dioxide (ppm)	0-5000ppm	±50ppm	3%
Illuminance		±3lux	1Lux
Sound Pressure Level		± 1dB(A)	

4.3.2.3 Operational phase surveys

A great number of scientific studies examine how building users perceive the indoor environment and which are the conditions that they find as comfortable. Several physical and chemical parameters of the indoor environment can influence the comfort of building occupants. The acceptable ranges of these parameters are addressed in standards however even when these are met, building occupants are not necessarily satisfied due to personal preferences and characteristics or building-related factors [50]. Therefore, building occupants are an important source of information about the IEQ and its effect on comfort and well-being. Surveys can be used to evaluate the performance of individual buildings but also to systematically compare the performance of groups of buildings. Surveys can also inform the design community on the effectiveness of specific strategies and technologies but also provide useful information to facilities managers that are involved in operating and improving their building portfolio [51].

4.3.2.4 Operational phase checklists and visual inspection

Considering that great amount of information is not captured during the on-site measurements and post occupancy evaluation surveys, it is important to include a checklist for assessing additional risks of the indoor environment. This will ensure a reliable, of good quality and holistic evaluation framework of the IEQ [21].

The assessment methods will be deployed in detail in WP7 (T7.5 or T7.6).

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5. Conclusions

As mentioned above, D3.1a is the first part of the deliverable on "Requirements for PnU smart control", whose main objective is to establish the foundations (architecture and requirements) of the control systems, as well as the monitoring structures and equipment for assessment. As at present, there are still too many unknowns in relation to the expected developments of the technologies, and the integration of these in PLURAL solutions to be implemented in each demo case, D3.1a focuses mainly on establishing the frameworks under the considered technologies and their impact testing requirements of PLURAL.

Thus, from the control point of view, a first joint vision is proposed, based on the definition of schemes that conceptualize the architecture and the requirements of the control systems. For this, and considering the realities and needs of PLURAL, two different levels are proposed: the local-based level and the cloud-based level, of the so-called supervisory control. For each of the two, the different elements and their interrelationships are presented, as well as the sources and the expected objectives. Although the details and their adaptation on a case-by-case basis will be introduced in D3.1b, these schemes are essential to start the development of the exchange LYSIS platform (T3.2), as well as to adapt the functionalities of the different technologies.

On the other side, a framework of the monitoring for assessment requirements and the potential implementation need is introduced. Again, and even so it must be adapted case-to-case (D3.1b), the featured information allows for start drafting the monitoring for assessment requirements, that is the sensors and meters requirements, both from its technical characteristics, to their implementation degree and their time frameworks for assessment.

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7. Annex I. Additional key information for each technology

7.1 Smart Wall

Construction materials are selected with respect to the environmental-friendly and high-performance behavior of the wall. The majority of elements (98% of the materials, apart from the air filters) forming the “smart wall” module is eco-friendly, recyclable and non-combustible. The structural frame can be composed of several materials such as timber, aluminum, high-performance polymers or even industrial plastics that can be supported from 3D printing technology.

Furthermore, various combinations of commercial filtration types can be installed in the ventilated unit or the fan coil, depending on the occupants’ requirements and the local climatic conditions.

In order to further enhance the self-sustainability of the “Smart Wall”, the integration of a power energy system with (BI)PV panels and batteries embedded into the wall panel can be applied. The specific core system presents significant advantages for climates with high demand for cooling.

7.2 External Wall Heating and Cooling (eWHC)

7.2.1 Detailed information on control and interfacing characteristics

7.2.1.1 Heating Season (HS)

General	The heating season is active when the building currently needs heat or will need in the near future (24h/48h* forecast). Heating season, HS = 1 when: $HS,_{Standard}$ = 1 or $HS,_{Forecast}$ = 1
Standard ($HS,_{St}$)	The standard heating season refers to the usual heating limit temperature(HL). If the outdoor temperature is lower than this, the building is expected to require heat. The heating limit temperature is assumed to be 15°C* in a first step (still needs to be adjusted during monitoring, depending on user needs). If HL (15°C*) > $Tamb_{12/12}$* -> $HS,_{ST}$ = 1 $Tamb_{12/12}$ is the mean value of the outside temperature from the last 12h and the future 12h.

Forecast (HS_{Fo})	If the building does not require heat at the moment, but in the next 24h a demand is expected, the heating should start (if PV surplus is available). If HL (15°C) > $T_{amb\ 24+}$* & PV_{el+} > 5 kW* -> $HS_{,Fo}$ = 1 $T_{amb\ 24+}$ = average outside temperature of the next 24h PV_{el+} = Power currently going into the grid (excess power)

7.2.1.2 Heat Pump

Heating mode	If the internal heat pump control detects no malfunction or other limitation, the HP is controlled in heating mode with the following boundary conditions(compressor, expansion valve and circulating pumps are monitored and controlled by the HP internal control): The heat pump goes into heating mode when all of the following conditions are met: • Heating season ON (HS=1) • DHW mode is not active • The storage tank temperature falls below the set point (heatingcurve - 1.5K hysteresis) (upper sensor) The heating mode is deactivated when one of the following conditions is met: • Heating season OFF (HS=0) • Hot water demand is present • Storage tank temperature exceeds the supply temperature + 1.5 K (lower sensor) *Note: the heating limit temperature may still change during monitoring,depending on user behavior and comfort requirements of the users.*
Power control	(to be discussed with Daikin) The heat pump power control has not yet been defined. Depending on which power control will be used this part will be modified and better specified (variable compressor speed, two stage heat pump will be unlikely in the case of Kasava)
DHW mode	The DHW mode has first priority (SH with second priority). A DHW loading strategy with a focus on daytime-loading of the boiler will be analyzed with simulations beforehand and implemented in the control if beneficial regarding the system efficiency. The volume of the boilers have not yet been defined. Once defined this part will have to be modified. The control releases the DHW charge when: • Excess power is high enough to run the HP (PVel+ = 5 kW* = HP) and the DHW storage is not full → charging as long as PV surpluspower is available, the minimum HP runtime or maximum storage temperature has been reached. • Storage has 0% charge level and it is daytime (09:00 – 16:00*) → However, loads only as much as necessary (State of charge 50%* and minimum HP runtime is reached. • Possibly also heating at night if really needed, e.g. if the top sensor shows low temperature of e.g. 45°C

Tank charge state	The accuracy of defining the state of charge of the boiler depends on how many temperature sensors are installed on the storage. Ideally, it should have 3 temperature sensors so that the capacity of the storage can be defined in fractions of a quarter. (25%, 50%, 75%)

7.2.1.3 Heating Circuit Pump of the Wall heating

Normal mode	Pump switches on as soon as heating season is active. Flow rate of XXX* l/h at power stage of X* (possibly 0-10V?)
Flushing mode (air)	In the months of June/July/August (heating system off), the heating circuit pump and control valves go to flush mode: • Flow rate/output increased compared to normal operation • Valves XXX go to flush mode • Close manifold valves (closing program flush mode) It is also possible, that the flushing mode will be used in other periods (winter), that has to be checked during the project.
Special requirement	To switch between normal mode and flushing mode the pump should have the possibility to be controlled directly by 0-10V depending on the needed mass flow and pressure difference. Or in normal mode with constant pressure control and in flushing mode with maximal power (switch between pump control strategy).

7.2.1.4 Temperature control inside the building

	It is yet not decided how to proceed with adjusting the internal temperature of the rooms. One possibility is to adjust the flow rate of each module individually depending on the internal temperature of the rooms. The reaction time of temperature change can be very slow due to the mass of the building. This still needs to be examined further with simulations.

7.2.1.5 Flushing (air) operation manifold bar

Normal mode	All valves open
Flushing mode	Are heating circuit pump in flushing mode? Yes→ Switch off individual strings (can also be several) to increase the flow in the other strings to 150 l/h taking into consideration an internal tube diameter of 12mm* (150 l/h must be reached per string!) Open "one" other string every two hours and close all others
Remarks	Experience tells us that air can be evacuated effectively when filling pipes using a jet pump. In any case it is better to have the possibility to evacuate the air in another way.

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The diagram below, Figure 13, is one variation of what the final solution may look like. Other variants are being developed. The c8 valve is part of the air flushing system and will probably be the same in all variants.

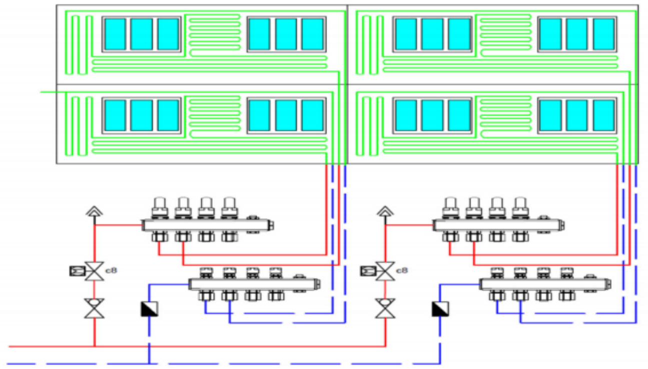

FIGURE 13. OUTLINE OF THE POTENTIAL FINAL SOLUTION

7.2.1.6 Heating circuit pump of the radiators

	If wall heating is not sufficient (room temperatures too low) the pump is activated when the heating season is active and is constant pressure controlled (radiators must be equipped with thermostatic valves).
Remarks	Through simulations and detailed analysis of the plans, the coldest rooms can be identified. In these rooms it will be necessary to decide whether to install new radiators or leave the existing.

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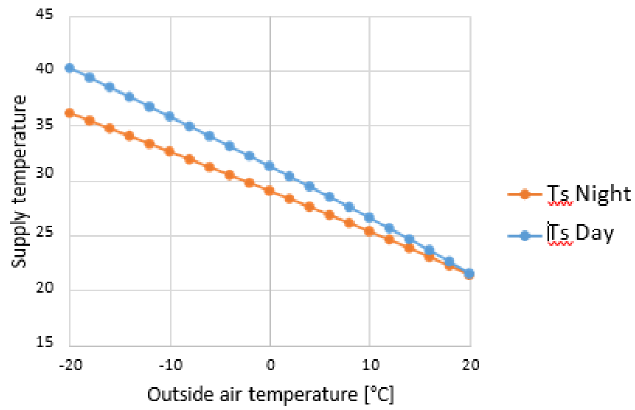
7.2.1.7 Heating curve

General	Due to the large thermal heat capacity of the external wall heating, the heating curve is higher during the day than at night. Hence, the heat should be brought into the building mainly during the day. This aspect leads the heat pump to work with a higher COP (because of higher external temperature) and could increase the potential of PV self-consumption. nore, it is taken into account whether a lot of sun is expected the next day, this ally reduces the heat demand and thus less heat must be stored (solar gains).  The graph is an example. The supply temperatures will have to be defined later exactly, when the requirements of the site are known and simulations are executed.
Day	Controller should provide sunrise and sunset for each day depending on the location.
Night	Controller should provide sunrise and sunset for each day depending on the location.
Outside air temperature	The ambient air temperature is one of the most important control values. The controller should allow different definitions of the value, for example T_{amb} of the last 24h or T_{amb} of the future 24h, etc.

7.2.1.8 Supply electrical Heater for the Heating System

On/Off	Is controlled by the main controller, not by the heat pump! Only in case of emergency, when HP are defective or blocked and heating demand is urgent. Check if alarm signal of heat pump can be used!

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7.2.1.9 Supply electrical Heater for DHW

On/Off	Is controlled by the main controller, not by the heat pump! Only in case of emergency, when HP are defective or blocked and DHW demand is urgent. Check if alarm signal of heat pump can be used!

7.2.1.10 Windows/Ventilation

	Ventilation will be integrated into the module. It is not yet clear if it will be part of the windows or if it will be installed separately. In case it will be part of the window it will be necessary to clarify with the provider at what level it can be controlled and what can be controlled. Are sensors for measuring CO_2 concentration or humidity installed in the window? Can these signals be used to control the ventilation? If the ventilation is installed separately from the window, it will be necessary to check if it is convenient to control the flow rate of ventilation through sensors installed inside the building (CO_2 and / or Humidity). It will be important to have at least a temperature control of the incoming air to avoid over-cooling of the building during the colder months. Ventilation control will be specified at a later point in the project.

* *these values could change during the project based on simulation results.*

7.3 High performance window with integrated heat harvesting and ventilation functions

The triple glazing unit allows the circulation of the air between the glass layers mainly in order to support heating system. The cold air enters from the bottom part of the glazing unit and it is then circulated between two glass layers by means of a mechanical system of fans. Thanks to the absorbing material of the glass, the air is warmed up using the solar gains. In winter mode (or during the night) air is directly distributed inside the building thus supporting heating system. In summer mode, the heat is transformed via a heat-exchanger allowing direct or later usage of energy (for heating domestic water or cooling). Sun energy heats up the air between glazing panes. Flowing through a heat exchanger, hot air gives the energy away to water. Heated water flows out from heat exchanger and heats up water that is stored in a water tank. Air movement through heat exchanger is forced by a fan that is located in the air duct. The fan actuates when air reaches proper temperature and is turned off when air temperature on heat exchanger inlet reaches temperature of water stored in the tank. When the vents are turned off, no heat exchange occurs and the whole system is static. The whole process starts again when air reaches usable temperature to efficiently heat up water stored in the tank. In all demo cases windows with integrated ventilation and heat recovery will be used Figure 9 and will be integrated in the prefabricated façade modules.

7.4 Centralized and decentralized Toolbox for HVAC, DHW and RES system with energy storage

Centralized HVAC-R systems especially in residential applications are not common. At the moment the market trend is towards decentralized ones unified as an "Energy hub" through specific servers. In some renovation cases, where the heating is provided with a central boiler, as for the demo site in KASAVA (CZE) a centralized renewable heating system can provide the cooling and heating energy. To reach NZEB the final energy consumption has to be radically reduced. The combination of the hydronic external wall heating and cooling (eWHC) with a heat pump can lead to reaching this goal. The control of (de)centralized heat pump systems has to be developed to fulfil the needs of the new PLURAL concepts. The combination of the eWHC, PV and heat pumps allows heating or cooling the building corresponding to the PV yield, because the thermal mass of the existing old wall can be used to shift the heating demand to daytime. That leads to significant reduction of electricity use from the grid. Batteries or thermal storage will be tested in the planning and simulation phase, if they can significantly contribute in NZEB.

The BMS will be interconnected with the control Toolbox of the building to maximize solar energy utilization for heating and electricity and coordinate the operation of the components based on occupancy profiles and user behavior.

7.4.1 Detailed information on control and interfacing characteristics

7.4.1.1 NTUA Multisensor

The ESP32S MCU Figure 14 is one of the cornerstones of the Toolbox as it must send data to the AMS Control Panel, data used for delivering part of the Automation of the Toolbox. Apart from that, as we will discuss further, the PLC Controller of the Daikin System shall communicate with a PLC Based ESP32S unit the 10IOSPLC ESP. So every hardware is ESP based (compatible with both Arduino and Raspberry Pi).

We focus especially in the Hybrid Wi-Fi and Bluetooth Chips as these are the extra features that makes it probably the best choice as the wireless protocols are one of the main features of the whole project.

FIGURE 14. THE MULTISENSOR IS BASED ON THE ESP32S MCU

- *IoT based – independent connection of each sensor*
- *Wi-Fi –Bluetooth - 2.4GHz Frequency*
- *Data Rate up to 150MBs*
- Adjustable Transmit Power
- Supports Antenna Diversity, GPIO Controls, RF Switch

7.4.1.2 AMS control panel

On the left we have the NTUA Multisensor and on the right the Automations and the Daikin Unit as shown in Figure 15 below.

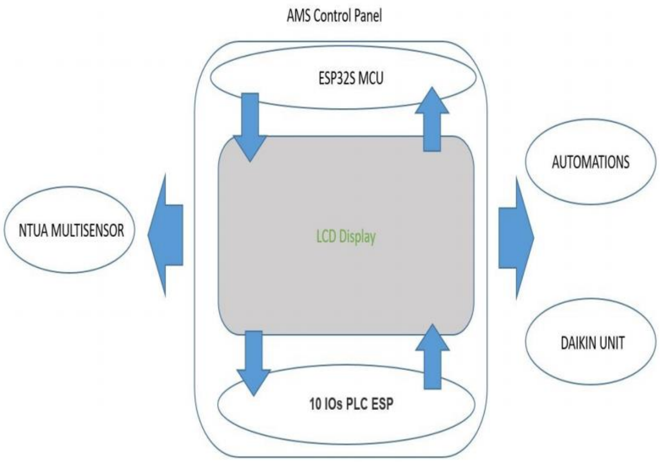

FIGURE 15. AMS CONTROL PANEL

The AMS Control Panel will achieve its purpose by satisfying 3 conditions in the best way possible that are crucial for the whole Toolbox as well.

i. COMMS -Establish Communications between systems
ii. DATA -Process Data (obtained by COMMS)
iii. AUTOMATE-Execute Algorithms (based on DATA obtained by COMMS)

For these reasons in the heart of AMScope we find 2 Processing Units:

a. ESP32S (pinout template) Figure 16 (left)
b. ESP based PLC Controller, 10IOs PLC ESP (link) Figure 16 (right)

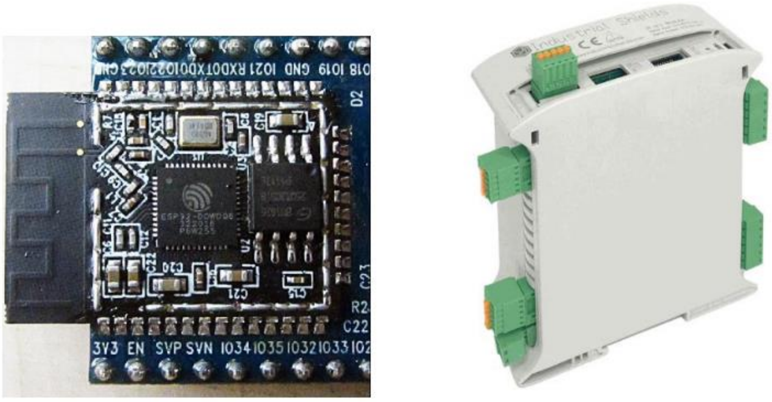

FIGURE 16. PROCESSING UNITS

Specifically, in Low-Level Engineering AMS Control Panel will use its PLC based processor,10IOs, to communicate (Comm1) with the controller of the Daikin Unit using TTL protocol. In High Level Engineering, AMScope will use the ESP32S compatible microcontroller to communicate (Comm2) with both the NTUA MultiSensor and the Smart Wall Sensors using Wi-Fi Protocols in order for the data obtained by the 6/15 2 comms, to be translated in actions, the 2 Units are working together as a DualCore CPU, to avoid bottleneck in the system and having to use extra software (debuggers, SDKs…) for the communication of all the different hardware. Much importance must be given in the protocols supported by the 2 CPUs and the Programming Language as well.

10IOSPLC ESP32S FEATURES:

- Mod Bus Communications configurable by jumper
- Inputs 5-24 Vdc
- Outputs: Relay (220Vac - 5A)
- Power supply voltage 12-24V
- MCU: ESP32 devkit
- Wi-Fi 2.4-2.5 Ghz Bluetooth/BLE
- Ethernet Port
- RS485

- TCP IP
- Modbus TCP
- Modbus RTU

ESP32S FEATURES:

- Interrupt Matrix
- Reset and Clock
- IO_MUX & GPIO Matrix
- DPort Register
- DMA Controller
- SPI
- SDIO Slave
- SD/MMC Host Controller
- Ethernet MAC
- I2C/I2S Controllers
- UART Controllers
- LED_PWM
- Remote Control Peripheral
- MCPWM 7/15
- PULSE_CNT
- 64_bit Timers
- Watchdog Timers
- eFuse Controllers
- On-Chip Sensors & Analog Signal Processing

Lastly the Panel has a built-in, capacitive touch display for Core Functionalities and general purposes. The display uses Serial Comm for accessing each core individually, which will serve primary and secondary software and hardware needs among others primitive tasks. The display has approximately an analysis of 1366x768 making it possible for every modern format to output properly. It also has built in Micro-USB for devices to plug-in and HDMI for external output, see Figure 17. So the AMS Control Panel is a complete Processing Unit consisting of 2 CPUs able to receive data taken by the Multisensor and transmit to the Daikin Unit and reverse. The architecture of the System is based primarily in the sophisticated communication of the ESP32S (Figure 18) and the 10IOS PLC EPS32S (Figure 19). ESP32S is based on Wi-Fi and Bluetooth making its programming more or less standard.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958218

FIGURE 17. AMS LCD DISPLAY

FIGURE 18. ESP-32S WI-FI & BLUETOOTH COMBO MODULE

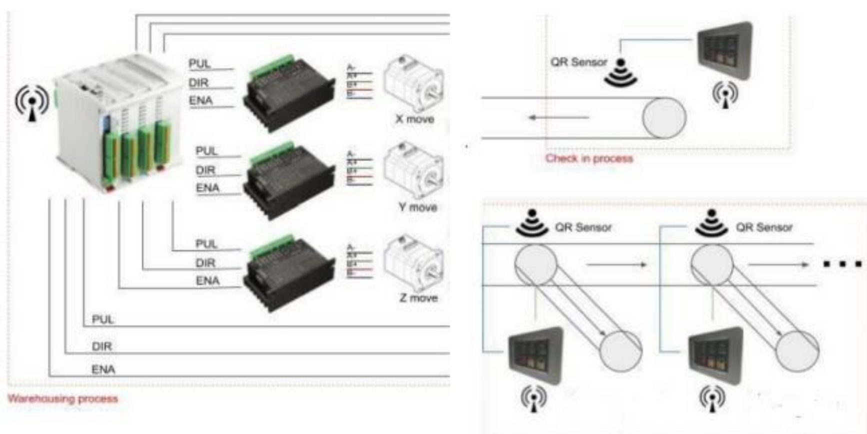

FIGURE 19. 10IOS PLC EPS32S

In Figure 19 we can observe how our ESP based PLC can wirelessly perform actions in a variety of needs, such as motors, xyz movement, wireless display, tasks that are needed for the Toolbox as well. The outcome of what we described so although it may seem a lot but, in fact all the required actions are performed easily since we have managed to integrate in the system, compatible, fast and very reliable microcontrollers that are very powerful and easy to program and communicate. The Toolbox's only

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difficulty is to break down the operations wanted, in a sensible manner, assigning each task to the appropriate CPU, meaning Low level to PLC, high level to ESP and choosing the right Comms, as already underlined. So, to add up we have these main communications protocols:

a. Bluetooth between the sensors
b. Wireless Communication between the Multisensor ESP32S and the AMS Control Panel ESP32S
c. TTL between the 10IOS and ESP32S of the AMS Control Panel
d. PCL Programming languages for the Daikin Unit

The system will be using a local controller of type: “mc unit microchip” and will WLAN-IoT as communication protocol. It is equipped with an integrated control system, equipped with temperature, humidity and CO_2 sensors, controls the main ventilation system of the building, as well as the luminance sensors adjusts the lighting equipment.

7.4.1.3 Automation

The ESP32S then Communicates with the 10 IOs PLC ESP and triggers (using Relays) Automated Function to the DAIKIN Unit and especially the Daikin Controller and Fan Coil as shown in Figure 20.

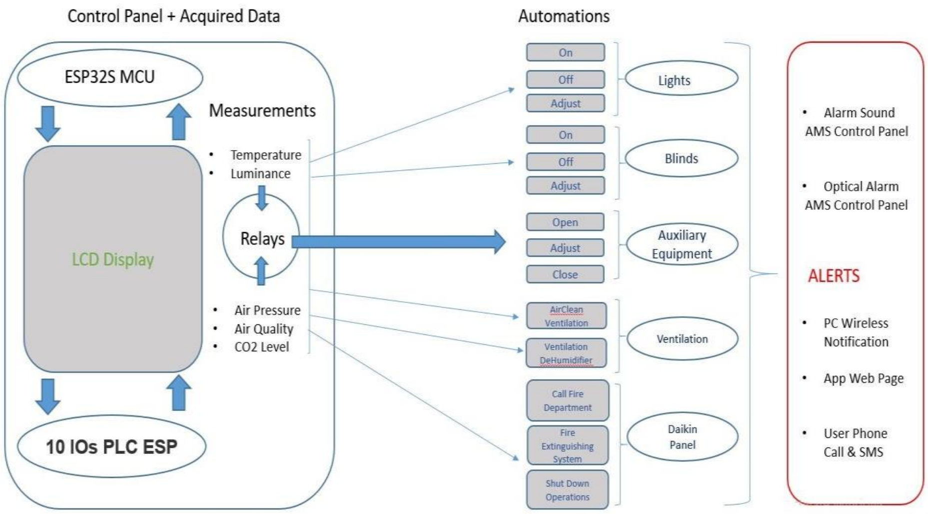

FIGURE 20. CONTROLS AND AUTOMATIONS OVERVIEW

7.4.1.4 INTERNAL AND EXTERNAL SMART WALL SENSORS (SMART WALL SAFETY)

This section describes the Smart Wall Sensors for its own protection. For this purpose, we find two sensors. One internal measuring heat of the wall (systems) and one external measuring Smoke (Levels of CO_2) Figure 21.

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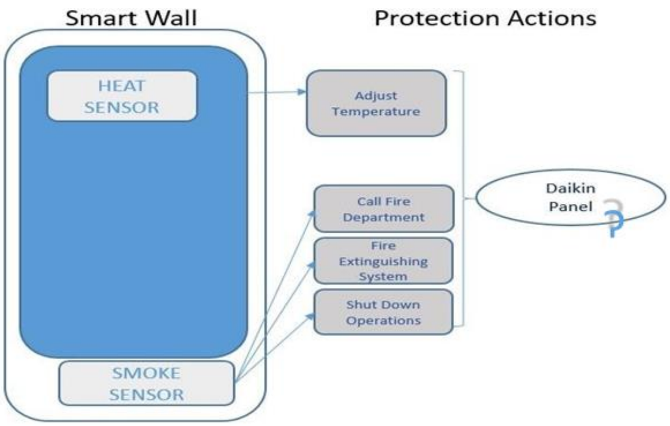

FIGURE 21. SENSORS FOR SMART WALL PROTECTION