D3.1 – Innovative Inspection Procedures

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ABREVIATIONS

BEP	Building Energy Performance
EPC	Energy Performance Certificates
SRI	Smart Readiness Indicator
WPs	Work Packages
HVAC	Heating, Ventilation, and Air Conditioning
BMS	Building Management System
DHW	Domestic Hot Water
TBS	Technical Building Systems
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
VR	Virtual Reality
LiDAR	Light Detection and Ranging
IR	Infrared
CO_2	Carbon Dioxide
BACS	Building Automation and Control Systems
FOV	Field Of View
EPBD	Energy Performance of Buildings Directive
PV	Photovoltaic
AI	Artificial Intelligence
BIM	Building Information Modelling
BE	Building Elements
CAD	Computer-Aided Design

PARTNERS SHORT NAMES

Partner No.	Short Name	Full Name
1	**ED**	European Dynamics
2	**QUE**	QUE TECHNOLOGIES
3	**EUP**	EUPHYIA-TECH
4	**SBC**	SBCGR (Sustainable Buildings Council Greece)
5	**EPBC**	EPB Center
6	**ENERSAVE**	EnerSave Capital
7	**EU.BAC**	European Building Automation and Controls Association
8	**EGC**	European Green Cities
9	**EFIEES**	European Federation of Intelligent Energy Efficiency Services

About openBEP4EU

*The **openBEP4EU** project is co-funded by the European Union under Grant Agreement No. 101167613 (LIFE Clean Energy Transitions Subprogramme). The project started of September 1st, 2024, and is anticipated to conclude in March 2027 (30 months duration).*

The building sector is recognised as one of the pillars for achieving the target of European climate neutrality by 2050. The EU is undergoing a twin transition, a digital and green transition as outlined in recent European directives. Buildings are a significant contributor of emissions, and they consume a sizeable portion of EU's energy consumption. Towards EU's direction of improving the performance of its building stock, Energy Performance Certificates (EPCs) have, among other initiatives and actions, been instrumental in achieving the set targets. EPCs have become a powerful tool for the end-users, such as service providers who can identify business opportunities, or policymakers who are empowered with better data on the building stock, enabling them to oversee the effects of policies and financial schemes.

A more harmonised European calculation methodology for the EPCs could, among others, increase comparability between regions, trust, and market uptake for features related to smart readiness, comfort, real energy consumption and district energy. To this end, OpenBEP4EU aims to deliver an open-source, universal software implementation of the CEN/ISO 52000 EPB standards family, namely the EU Kernel EPB Engine, to facilitate simultaneous and coordinated adoption of an innovative EPC calculation approach among all the Member States. This initiative aims to make building performance data easily accessible to various stakeholders like financial institutions, energy service providers, and building owners, fostering the development of financial products supporting sustainable renovation projects.

Core elements of openBEP4EU's activities also include the creation of an EPC Support Team to drive market adoption as well as a Sustainable Design Data Hub, aligned with the overarching goals of the European Bauhaus initiative, that not only serves as a data repository but also promotes collaboration and research for sustainable architecture and design. These activities will facilitate stakeholder engagement, contribute to improved EPC reliability, accuracy, accessibility, while paving the way for EPC market uptake across the EU Member States though well promotion strategies. All data sharing within this framework adheres to the principles of the Common European Energy Data Space, prioritizing sovereign data sharing and respecting data ownership among the involved stakeholders.

Executive Summary

This handbook outlines a harmonised and practical methodology for conducting innovative inspection procedures for EPCs. The handbook offers extensive technical and procedural assistance that combines cutting-edge digital technologies with conventional approaches in response to the European Union's growing desire for data-driven, transparent, and performance-based building assessments. Supporting the shift to next-generation EPC schemes that are more accurate, indicative of actual performance, and compatible among Member States is the main goal.

In this deliverable, "inspection" refers broadly to the process of gathering, analysing, and evaluating data on-site about technical systems and building elements in order to create energy performance certificates (EPCs) and evaluate smart readiness indicators (SRIs). This use is consistent with the goals of performance, based evaluations and energy audits as outlined in ISO 52120 and ISO 52000 standards.

It is crucial to differentiate this use from the definition of "inspection" found in Article 23 of the recast Energy Performance of Buildings Directive (EPBD), which particularly refers to the required, recurring examination of accessible components of large-scale HVAC systems with capacities greater than 70 kW. According to national schemes, the inspections covered in Article 23 are compliance procedures for guaranteeing the sizing and operational efficiency of HVAC systems. They are also subject to frequency, scope, and reporting criteria. In order to avoid confusion, this deliverable refers to "inspection" in the more comprehensive methodological sense that is pertinent to EPC and SRI assessments rather than as a replacement or equal to the regulatory inspections required by Article 23 of the EPBD [1].

The handbook consolidates the results of Task 3.1, which focused on designing, validating, and operationalising new audit procedures for building elements and technical building systems

(TBS). These guidelines were created in accordance with relevant international standards (such as ISO 52000 [2], EN 1434 [3] [4], and ISO 6781 [5]) and in line with more general policy frameworks, such as the European Green Deal and the Energy Performance of Buildings Directive. The audit methodology integrates dynamic TBS monitoring technologies, such as CO_2 sensors, flow meters, temperature sensors, and smart thermostats, with static tools, such as LiDAR scanners, 3D laser mapping devices, thermal imaging cameras, and thickness gauges. High-resolution characterization of the operational and physical aspects of building performance is supported by this integrated method.

Structured around a step-by-step inspection workflow, the handbook guides users through the full audit lifecycle: from pre-assessment planning and tool calibration to on-site data collection, sensor integration, data processing, and final reporting. Templates, best practices, and quality control measures are provided to support methodological consistency and traceability across diverse building typologies and use cases.

The scope of the handbook is intentionally broad currently covering the project member states, ensuring its applicability to a wide range of stakeholders. Energy assessors, building inspectors, facility managers, operators of EPC schemes, governmental bodies, technology developers, training providers, and researchers are among the intended users. Customized insights into data interpretation, tool selection, procedural assistance and openBEP4EU EPC calculation engine integration are advantageous to each group.

To demonstrate the practical viability and adaptability of the proposed audit procedures, the handbook presents a series of case studies from pilot applications conducted across seven European countries, which are Greece, Denmark, Spain, Cyprus, Switzerland, France, and Portugal. These pilots provide practical validation of the concept by representing a diverse range of building types with varying climate weathers (residential, institutional, commercial, and heritage) and technological contexts. Stakeholder engagement was used to assist the deployment of innovative techniques in operational contexts, and inspections were arranged around user schedules. In addition to highlighting the significance of environmental variables, user interaction and procedural standardization, the lessons gathered from these pilots helped to develop the methodology

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1. Introduction

1.1. Purpose of the Handbook

The handbook's main objective is to provide a thorough framework for the efficient application of innovative Energy Performance Certificate (EPC) inspection techniques throughout the European Union. The handbook addresses the increasing demand for standardized, performance-based approaches that improve the precision, effectiveness, and transparency of EPC evaluations as part of the OpenBEP4EU project and in line with WP3 goals. This handbook provides energy assessors, auditors, facility managers, and other stakeholders with a useful and standardized reference for the upcoming generation of EPC evaluations, considering the European Union's climate neutrality goals set for 2050 and the growing policy emphasis on measured energy performance and smart readiness indicator (SRI) [6].Task 3.1, which focuses on the creation, verification, and field testing of advanced data collection instruments and procedural frameworks, is compiled in the handbook. By using a hybrid approach that blends model-based and measurement-based inspection techniques, it aims to close the gap between theoretical energy modelling and actual building performance. This involves integrating both dynamic TBS monitoring tools (like CO_2 meters, flow meters, temperature sensors, and smart thermostats meters connected via building automation systems) and static building element tools (like LiDAR scanners, 3D laser scanners, thermal cameras, and thickness gauges). In this context, advanced Building Automation and Control Systems are a pivotal enabler which they provide continuous operational data and smart control functionalities that directly improve measured performance and Smart Readiness Indicator scores.

The handbook equips energy assessors with a set of validated procedures and techniques aligned with relevant European and international standards (e.g., ISO 52000 [2], EN 1434 [3][4], ISO 17123 [7], ISO 6781 [5]). Assessors can conduct audits that are efficient, repeatable, and consistent with regulations across a range of building types and climate zones because every step—from planning and on-site inspection to data analysis and documentation—is provided within a standardized framework.

In addition, the handbook supports capacity building by offering best practices, case study insights, and step-by-step guidance based on pilot applications carried out in several EU Member States. These case studies illustrate how innovative tools and workflows can be deployed in different building typologies—from heritage museums to smart campuses and residential settlements, ensuring broad applicability and transferability. They also showcase the flexibility of the methodology in adapting to constraints such as building access, operational schedules, and occupant sensitivities.

These case studies demonstrate the wide applicability and transferability of new technologies and workflows in a variety of building typologies, including residential settlements, smart campuses, and heritage museums. They also demonstrate the methodology's adaptability to limitations, including tenant sensitivities, operational timetables, and building access.

1.2. Scope and Intended Users

The handbook's scope covers both the technical and procedural aspects of EPC audits, combining cutting-edge data collection technologies, digital tools, and stakeholder-driven workflows with conventional assessment methods. The handbook supports the overall objective of moving toward more precise, transparent, and performance-based EPCs by being adaptable to a broad range of building types, climatic zones, and national regulatory frameworks within the European Union.
The scope of this handbook covers three essential areas:

1. Inspection of Building Elements: defining geometry, envelope integrity, and material composition using cutting-edge instruments like LiDAR scanners, 3D laser mapping, thermal cameras, and non-destructive thickness gauges.

2. Technical Building Systems (TBS) Inspection: Assessing the operational efficiency and indoor environmental quality using real-time data from temperature, CO_2, flow, heat, lux, and irradiance sensors, including data from Building Automation and Control Systems (BACS) where available.

3. Integration with EPC Workflows: To improve reliability and policy alignment, innovative audit data is aligned with digital twins, simulation models, and EPC reporting systems.

To ensure practicality and consistency, the handbook is structured around a step-by-step inspection methodology that covers:

- Pre-inspection planning and documentation review
- On-site assessment procedures
- Sensor calibration and data collection
- Data processing, analysis, and visualization
- Reporting and integration into EPC platforms using openBEP4EU EPC calculation engine

This handbook is intended to serve a broad spectrum of stakeholders involved in BEP assessment and certification:

- **Energy Assessors and Certified Auditors**: Primary users who require detailed, reliable, and replicable methodologies for performing EPC audit using modern technologies.
- **Facility Managers and Building Operators:** Experts in tracking and enhancing building performance who gain from comprehending audit data and participating in continuing evaluations.
- **Public Authorities and Policy Bodies**: Entities tasked with implementing and overseeing EPC schemes, who can use the handbook to support the rollout of harmonised and performance-based assessment practices at the national or regional level.
- **Technology Providers and Tool Developers**: Manufacturers and software providers who can align their products with the procedural and technical requirements outlined in the handbook.
- **Training Institutions and Vocational Educators:** These are organizations that offer professional development courses and EPC training programs. The manual can be used by these organizations to help practitioners become more proficient in smart audit techniques.
- **Researchers and Standardisation Bodies**: Professionals who work to improve EU-wide standards and advance energy performance methodologies.

2. Overview of Innovative Inspection Procedures

2.1. Inspection Methods for Building Elements (BE) and Technical Building Systems (TBS)

To analyse and innovate existing EPC data collection tools and techniques, questionnaires have been developed and provided to partners and stakeholders as templates. The primary objective of these questionnaires was to gather and assess data regarding the most recent and current EPC data collection tools and techniques. Additionally, they provide a methodical framework for evaluating how various tools, techniques and approaches complement and advance the goals of the openBEP4EU and Project KERNELS programs. The full questionnaire is provided in the Annex 1 (A1).

2.1.1 Building Elements

To enable more accurate, standardized, and performance-driven Energy Performance Certificate (EPC) assessments, a wide range of tools and structured procedures have been developed. These tools fall into two distinct categories: those designed to assess the physical characteristics of BE (e.g., walls, windows, roofs) and those intended for monitoring and analysing TBS such as HVAC, lighting, and DHW systems.

Table 1- Common building elements of the audited dwelling

Elements	
Walls	Laser Distance Meters – Thickness Gauges - 3D Laser Scanners- Thermal Cameras
Roofs	LiDAR Scanners – Thermal Cameras – Thickness Gauge
Floors	Laser Distance Meters – Thickness Gauges
Windows	Laser Distance Meters – Lux Meters – U-Value Measurements
Doors	Tape Measures – Thermal Cameras
Insulation	Thickness Gauges – Thermal Cameras – Inspection Cameras – Sample Collection tools

In order to break down and analyse the details of each building element and associated inspection technologies, a template has been designed. The template showcases general information, EPC use cases and relevant EU standards, as well as inspection procedures designed specifically for each tool and its specialities. Furthermore, each category includes tools aligned with calibrated procedures to ensure consistency, reliability, and integration into EPC methodologies.

Category	Details
Technique	**LiDAR Scanning**
Purpose	LiDAR (Light Detection and Ranging) scanners are used to generate 3D spatial models of buildings to: • Measure envelope geometry: floor area, wall area, roof geometry • Capture volumes and surface ratios for U-value and energy loss calculations • Create BIM models or CAD plans for EPC modelling tools • Mostly used for outdoor scanning of building envelope
EPC Use Cases	• Historic buildings with no plans - Accurate geometry capture • Complex building element geometries - Surface area and thermal bridge modelling • Retrofit validation - Compare pre- and post-geometry • For daylight and solar analysis - Window dimensions and orientation scenario analysis
Standards	**ISO 17123-9 – Field Procedures for Terrestrial Laser Scanners [7]** • Specifies accuracy testing, field validation, and calibration methods. • Ensures the geometric precision of LiDAR scanners in building surveys. **IEC 60825-1:2014- Safety of laser products - Part 1: Equipment classification and requirements [13]** • Safety of laser products emitting laser radiation in the wavelength range 180 nm to 1 mm. **EN ISO 52000-1/52003-1 – Energy performance of buildings & Indicators, Requirements, Ratings — General framework [2]** • The core of the EU's EPBD. Defines what data (including geometry) such as areas, volumes, ratios are needed for performance evaluation that can come from LiDAR data.
Inspection Procedures while Using LiDAR for EPC Measurements	**Planning & Setup** • Define areas to scan (interior, exterior, roof). • Choose appropriate scanner type (terrestrial for highest accuracy) compliant with **ISO** 17123-9 [7]. For unreachable scan areas, LiDAR mounted drones can be used. • Confirm laser class and use appropriate eye protection according to IEC 60825-1:2014 [13]. **Scanning Process [14]** • Position scanner on stable ground or tripod. • Capture multiple scans to ensure that the aimed area is covered completely. • Scan during low light to achieve maximum capture of the desired elements with minimum reflection errors. **Post-Processing** • Align scans using cloud or software tools. • Quality control of the scanned elements can be done by comparing real life measurement versus the scanned [7]. • Use formats compatible with EPC workflows and export to: ○ IFC or gbXML format for EPC software

	○ 2D floor plans for SAP/SBEM • Validate model geometry by comparing with known dimensions **Integration with EPC Software** • Import model to tools like: ○ DesignBuilder or IESVE for dynamic modelling • Adjust for thermal layers, wall build-up, and construction types
Accuracy & Reliability	• LiDAR systems typically offer ±1–3 mm accuracy at 10–50 m range [7]. • Multiple scans at different times/days show minimal geometric deviation, especially under controlled lighting and stable tripod setups.
Advantages	• High geometric accuracy • Rapid data collection • LiDAR captures full 3D models, including complex building features which are hard to document. • Scanned documents can be used in BIM or Digital twin applications. • Support SRI • Enables visual inspections without going to the inspection sites.
Limitations & Challenges	• Highly reflective, transparent, or dark surfaces (e.g. glass, mirrors, black metal) can be scanned incomplete or distorted data. • If there are any blocks to the vision of the laser, multiple scan positions are required. • Direct sunlight, rain, fog, and dust can reduce scan clarity or increase noise levels, particularly in outdoor scans. • LiDAR captures only geometry but not material properties or thermal attributes, so EPC-specific inputs (U-values, thermal bridges) must be manually assigned.

Template 1 – LiDAR Scanning for BEs

Category	Details
Technique	**IR Thermography**
Purpose	Thermal cameras are used in EPC-related building assessments to: • Detect insulation defects, thermal bridges, and air leaks • Assess the thermal performance of building envelopes • Verify the effectiveness of retrofits and insulation installations • To support U-value calculations and energy efficiency measures
EPC Use Cases	• Used during on-site building envelope evaluations for EPC rating improvements • Often integrated with workflows for validation of envelope U-values

Standards	**EN ISO 6781-1:2023 – Performance of buildings — Detection of heat, air and moisture irregularities by IR methods [5]**
	• Provides a standardized methodology for using thermography in building diagnostics and covers:
	  ○ Measurement conditions
	  ○ Camera requirements
	  ○ Image interpretation
	  ○ Reporting requirements
	
	ISO 18436-7:2014 – Condition monitoring and diagnostics of machines - Thermography training and certification [15]
	• Specifies the requirements for qualification and assessment of personnel who perform machinery condition monitoring and diagnostics using IR thermography.
	• Sets requirements for thermographer qualification levels (I, II, III) — applicable for professional surveys

Inspection Procedures while Using Thermal Cameras for EPC Measurements	**Preparation**
	• Ensure temperature difference of at least 10°C between indoor and outdoor for valid results (e.g. cold day + heating on inside) [16].
	• Close windows and doors for at least 2–3 hours before scanning [17].
	• Ensure calibration is up to date (usually annually certified).
	
	Camera Setup [18]
	• Choose correct emissivity setting
	• Set appropriate range and focus for the environment.
	• Disable automatic scaling to keep temperature ranges consistent across images.
	
	On-Site Survey
	1. Perform external and internal scans of:
	  ○ Walls
	  ○ Roofs
	  ○ Window junctions
	  ○ Pipes or ducting (if needed)
	2. Capture both visible and IR images for comparison.
	3. Annotate images with room/zone, surface, time, and ambient temperature.

	Post-Survey Processing
	• Analyse:
	  ○ Cold spots = thermal bridging, missing insulation
	  ○ Warm spots = air leakage, heating loss
	• Prepare a report including:
	  ○ Camera model and calibration
	  ○ Ambient conditions (temperature, humidity, wind)
	  ○ Interpretation of thermal images
	  ○ Location plan

Accuracy & Reliability	• Most building-grade thermal cameras offer ±2 °C or ±2% accuracy under standard conditions. High-end models used in EPC work may achieve ±1 °C, depending on calibration and emissivity settings [19]. • Annual calibration is recommended to maintain traceable measurement accuracy. Some models support field-adjusted reference checks [20].
Advantages	• Non-contact measurements avoid disturbance. • High sensitivity ensures detection of minor thermal anomalies. • Built-in timestamping and imagery support audit-trail documentation. • Quick in-field feedback allows immediate review and takedown of suspect areas.
Limitations & Challenges	• Accuracy depends on correct emissivity input, per ISO 18434 guidance [20] • Cameras are influenced by ambient conditions and limited to surface readings, requiring operator interpretation. • Annual calibration is critical: without it, accuracy degrades, undermining EPC credibility

Template 2 - IR Thermography for BEs

Category	Details
Technique	**3D Scanning**
Purpose	3D scanners are used in measuring EPCs to: • Accurately measure building geometry: areas, volumes, wall/roof/window dimensions • Capture as-built conditions for old, undocumented, or retrofitted buildings • Feed building geometry into BIM or EPC modelling tools • Improve the precision of U-value calculations and thermal envelope assessments of indoor envelope
EPC Use Cases	• Consistency and automation reduce risk of human measurement bias for reducing manual errors • Scanning comparison for volume and envelope geometry for verifying insulation/retrofit
Standards	**ISO 17123-9 – Field procedures for terrestrial laser scanners [7]** ISO 17123-9 is a document that specifies field procedures for determining and evaluating the precision (repeatability) of terrestrial laser scanners and their ancillary equipment when used in building, civil engineering and surveying measurements • Sets out testing methods for accuracy, repeatability, and calibration of **s**tatic 3D laser scanners. • Ensures dimensional accuracy of building models derived from scans. **IEC 60825-1:2014- Safety of laser products - Part 1: Equipment classification and requirements [13]** • Safety of laser products emitting laser radiation in the wavelength range 180 nm to 1 mm. **EN ISO 52000-1 – Energy performance of buildings & Indicators, Requirements, Ratings — General framework [2]** • The core of the EU's EPBD defines what data (including geometry) such as areas, volumes, ratios is needed for performance evaluation that can come from 3D Scanner data.
Inspection Procedures while Using 3D Scanners for EPC Measurements	**Pre-Scan Planning** • **Zone identification:** Define scan areas —roofs, walls, floors—according to EPC input needs, such as area and orientation for thermal calculations (ISO 520001) [2]. • **Control point setup:** Install at least three stable reference (target) points per zone, positioned at different heights and spaced apart, following best practices for survey control for a comprehensive and reliable scanning and gathering information. **On-site Scanning** 1. **Calibrate the scanner:** Perform self-test and calibration per manufacturer guidelines, ensuring compliance with standards like ISO 171239 (measurement precision) [7]. 2. **Tripod positioning & scanning:** Mount on a stable, levelled tripod; perform full 360° scans per zone

	Post Processing Workflow • **Scan registration:** Use point cloud software to align multiple scans to control points, ensuring registration accuracy. • **Quality control checks:** Compare registered distances and overlaps against field measurements. • **Format export:** Convert to EPC-ready BIM/CAD formats (IFC, gbXML, DWG/DXF), ensuring correct layer structures and orientation logical for processing
Accuracy & Reliability	• LiDAR systems typically offer ±1–3 mm accuracy at 10–50 m range (per ISO 17123-9). • Multiple scans at different times/days show minimal geometric deviation, especially under controlled lighting and stable tripod setups. • Aligns with ISO 17123-9 (field procedures for testing the accuracy of terrestrial laser scanners) and supports formats compatible with BIM/EPC tools [7].
Advantages	• High geometric accuracy • Rapid data collection • Scanned documents can be used in BIM or Digital twin applications. • Support SRI • Enables visual inspections without going to the inspection sites.
Limitations & Challenges	• Highly reflective, transparent, or dark surfaces (e.g. glass, mirrors, black metal) can be scanned incomplete or distorted data. • If there are any blocks to the vision of the laser, multiple scan positions are required. • Direct sunlight, rain, fog, and dust can reduce scan clarity • LiDAR captures only geometry but not material properties or thermal attributes, so EPC-specific inputs (U-values, thermal bridges) must be manually assigned. • Requires skilled software use for registration and mesh simplification

Template 3 - 3D Scanning for BEs

Category	Details
Technique	**Virtual Reality**
Purpose	VR enhances EPC processes by: • Visualizing building geometry and performance simulations in immersive environments • Engaging behaviour impact and analysis (e.g., heating, lighting usage) • Allowing interactive "what-if" scenarios for refurbishment and retrofit planning
EPC Use Cases	• Enhancing stakeholder engagement • Improving quality of refurbishment recommendations • Helping close energy performance gaps via simulation-informed occupant behaviour prompts
Standards	**ISO/IEC DIS 5927 - Computer graphics, image processing and environmental data representation — Augmented and VR safety [21]** Outlines the correct method to set up and operate augmented reality (AR) and virtual reality (VR) devices in an enterprise workplace so that health and safety (H&S) is maintained, the effects of H&S are understood, and no new hazards are introduced; • Guides safe and effective use of AR/VR in professional settings • Guide for setting up VR systems
Inspection Procedures while Using Virtual Reality for EPC Measurements	**Model Preparation & Execution** • Use BIM or scan-to-BIM from LiDAR and 3D scanning to create accurate point clouds and building models—foundation for VR and EPC geometry inputs [22]. • The input model should cover all of the required BE for EPC measurement. • Export clean geometric models to VR-friendly formats (e.g., IFC) • Apply energy metrics to VR scenes: assign U-values, connect thermal zones, and simulate airflow effects visually (e.g., via colour maps). • Create “what if” scenarios to analyse how the calculated outputs will vary and to observe how occupant behaviour differs for the EPCs. **Walkthrough, Observation & Feedback Collection** • Facilitate walkthroughs allowing users to see thermal behaviour: detect hotspots, airflow patterns, and envelope weaknesses. • Collect structured feedback on comfort, interaction, and preferred energy measures [23] **Refine EPC Inputs & Retrofit Strategies** • Adjust EPC model parameters using VR-derived insights: refine occupancy schedules, U-values, and ventilation assumptions. • Document retrofit options (e.g., insulation upgrades) with visual context for EPC calculation scenarios.
Accuracy & Reliability	• VR models depend on source data (e.g., LiDAR, 3D scans, BIM). When based on ISO 17123-9-compliant scanning, they can achieve ±1–3 mm spatial precision [7]. • VR accuracy for EPC depends on the quality of input parameters (e.g., U-values, zones, schedules), which are imported manually or via BIM. • VR is used for visualizing simulated energy behaviour, not generating it. Accuracy is as reliable as the linked energy simulation (e.g., EnergyPlus or DesignBuilder).
Advantages	• Immersive energy insight • Enhanced stakeholder engagement • Predictive behaviour modelling for occupants

	• Scenario testing for retrofits
Limitations & Challenges	• High technical complexity which requires combined skills in energy modelling, 3D modelling, and VR development • VR requires high-spec PCs and VR headsets, which can be high cost. • High learning curve • Lack of standardisation

Template 4 - Virtual Reality for BEs

Category	Details
Technique	**Aerial Scanning**
Purpose	To collect aerial spatial and thermal data for inaccessible or large-scale building components. This includes rooftops, facades, skylights, PV panels, and shading elements for EPC geometry and energy analysis.
EPC Use Cases	• Capture surface geometry (roofs, walls) for use in BIM/CAD • Assess solar potential and shading for PV systems • Detect insulation gaps, thermal bridges, or heat losses (with IR cameras) • Feed EPC models with accurate dimensions for volume and surface area
Standards	**ISO 21384-3:2023 - Unmanned aircraft systems [24]** • This document defines operational procedures and safety for unmanned aircraft systems (UAS) **ISO 17123-9 - Field procedures for Terrestrial lasers - Optics and optical instruments [7]** The precision (repeatability) of terrestrial laser scanners and their auxiliary equipment when used in building, civil engineering, and surveying measures is determined and evaluated using field methodologies outlined in this paper. • Field procedures for testing LiDAR scanner accuracy, applicable when using LiDAR-equipped drones **EASA UAS Regulations – Drone pilots must follow EU airspace and licensing rules (EU 2019/947 and 2019/945) [25] [26]** Under EASA (European Aviation Safety Agency) EU Regulation 2019/947 (Implementing Rules), drone flights fall into Open, Specific, or Certified categories, depending on risk level and operational limits (e.g., max altitude, keeping safe distances, VLOS). **IEC Standard for Thermal Drone Use** • For PV/energy systems, the **IEC 624463:2017** standard is applicable—even when inspections are carried out via drones—to ensure resolution, accuracy, documentation, and fault identification [27]. • A drone-based method aligned with this IEC standard is considered best practice for reliable and repeatable thermographic analysis [27].
Inspection Procedures while Using Drones for EPC Measurements	**Pre-flight planning:** • Obtain flight permissions if required (especially near airports) • Define flight paths over buildings **Equipment setup:** • Mount payload (LiDAR or camera (thermal)), balance gimbal, verify camera calibration **Flight Execution:** • Follow grid or orbit scan pattern at optimal altitude (30–70 m), ensuring line-of-sight • Scan the entire building 360 multiple times to achieve the most capture to compare the collected data versus real and to minimise any incomplete scan errors.

	Data Processing: • Register LiDAR point clouds or combine captured camera images • Export data as IFC, LAS, or DXF for EPC modelling software like DesignBuilder
Accuracy & Reliability	• Thermal cameras can visualize surface temperatures, with accuracy ±2 °C, useful for qualitative EPC inputs • Data consistency is improved with pre-programmed flight paths, GPS lock, and stable atmospheric conditions • When combined with ground validation, drone data is reliable for EPC envelope modelling and solar simulations
Advantages	• Safe inspection of rooftops and tall buildings without scaffolding or lifts safeguarding human life • Rapid data collection • Enables collection of thermal imagery, elevation models, and solar exposure maps • Useful for before and after retrofit comparisons in EPC re-certifications
Limitations & Challenges	• Flight restrictions in urban areas; drone operations must comply with EASA UAS rules [26] • Weather limitations: Rain, wind, and snow affects flight conditions and degrade LiDAR and thermal & image quality • Flight time is dependent on the drone battery duration • Line-of-sight and signal interference in dense environments can cause control loss and damage the drone, surrounding environment and others • Thermal camera accuracy is affected by emissivity and surface reflectivity which can affect the u-value • Post-processing complexity: Requires skilled software use

Template 5 - Aerial Scanning for BEs

Category	Details
Technique	**BE Thickness Measurement**
Purpose	In EPC-related energy assessments, thickness gauges are used to measure: • Insulation thickness (walls, roofs, pipes) • Coating or cladding thickness (thermal performance of external surfaces) • Dry film thickness (DFT) of reflective or insulating coatings (e.g., cool roofs, intumescent paints) **These values are critical for:** • U-value calculations (thermal transmittance) • Assessing compliance with building fabric energy efficiency • Retrofit validation for insulation upgrades
EPC Use Cases	• Verify wall insulation thickness • Check reflective coating thickness on roof/walls • Retrofit quality control
Standards	**ISO 2808 – Paints and Varnishes — Determination of Film Thickness [28]** • Details procedures for dry and wet film thickness of insulating or reflective coatings. • Applicable for performance coatings contributing to building energy ratings. **ISO 16809 – Non-destructive Testing — Ultrasonic Thickness Measurement [29]** • Provides detailed procedures for ultrasonic thickness gauging of metallic and non-metallic components. • Based on project specifications, standards, or client requirements.
Inspection Procedures while Using Thickness Gauges for EPC Measurements	**Preparation** • Select appropriate gauge based on material type: Magnetic gauges for ferrous metal substrates (e.g., steel cladding) Ultrasonic (UT) gauges for non-metallic substrates (e.g., concrete, foam, gypsum) **Surface preparation**: • Clean and dry the measurement surface. Remove dust, rust, or paint flakes, particularly when using contact or magnetic gauges, to eliminate the risk of getting a wrong reading (Surface should be free of grease or moisture for accurate probe coupling). **Calibration status**: • Ensure the gauge has a valid calibration certificate, preferably within 12 months. • Calibration of the tool can be done annually to maintain the standard. **Calibration** • **Zero adjustment**: Place the probe on a zero block or reference foil of known thickness. Adjust readings accordingly. • **Material-specific settings**: For ultrasonic gauges, set the correct velocity of sound based on the substrate or refer to the manufacturer datasheet or material specs: ▪ e.g., 6320 m/s for aluminium [30]

	▪ 3500–6000 m/s for iron types [30] **Measurement Procedure** 1. Place probe perpendicular to the surface using light, even pressure. Ensure full contact (especially for curved or rough surfaces). 2. Take multiple readings at representative points across each element: o Minimum of 3–5 points per area o Record highest, lowest, and average value 3. For sandwich panels, take readings along edges if centre access is limited. **Data Recording** • **Data export**: Label and categorise the readings and if supported, export readings via USB, SD card, or Bluetooth to data loggers or EPC software (e.g., in CSV format).
Accuracy & Reliability	• Standard ultrasonic thickness gauges provide ±1–3% accuracy for calibrated homogeneous materials, or ±0.1 mm in absolute terms [29]. • Results are reliable and repeatable when surfaces are clean, probe is perpendicular, and velocity is correctly set for the material. • Regular zero-point calibration using reference blocks and annual factory calibration
Advantages	• Non-destructive measurement • Wide material compatibility • Minimum set-up and measurement time • Digital logging
Limitations & Challenges	• Material specific setup required with correct velocity of sound settings • Requires trained operator to position probe correctly, interpret results, and detect anomalies • Dirty, damp, or curved surfaces can prevent good probe coupling and reduce accuracy.

Template 6 - BE Thickness Measurement for BEs

2.1.2 Technical Building Systems *(TBS)*

The BTS form the operational core of any structure's energy use and comfort regulation. To evaluate their energy performance accurately within the EPC framework, each system type must be inspected using suitable measurement and monitoring tools. This table outlines key BTS categories, their typical subcomponents, and the recommended tools or sensors for assessing their performance as part of the innovative inspection procedures developed in the OpenBEP4EU project.

Table 2- TBS tools for measuring energy consumption of systems

Technical Building Systems (TBS)	
Heating systems	
Boilers	Heat Meters (Thermal Energy Meters) Gas/Electricity Meters/ Thermostats (smart) – Temperature Sensors – Data Loggers (if available)
Furnaces	
Heat Pumps	
Radiators	

Underfloor Heating	
Building Lightning	
Lights	Electricity Meters – Occupancy Sensors
Domestic Hot Water (DHW)	
Heating & Cooling	Temperature Sensors – Flow Meters – Heat Meters
Cooling systems	
Air conditioners	Electricity Meters – Smart Thermostats
Sustainable and Renewable Systems	
Solar PV Systems	Heat meters & Solar Irradiance Sensors
Building Automation and Control Systems (BACS) - If Available	
Heating systems	Smart Heat Meters – Temperature Sensors
Building Lightning	Occupancy Sensors
Domestic Hot Water (DHW)	Smart Temperature Sensors & Flow Meters & Heat Meters
Cooling systems	Electricity Meters – Smart Thermostats
Data Loggers	

Category	Details
Technique	**Temperature Measurement**
Purpose	Temperature sensors are critical components for: • Monitoring and controlling space heating/cooling (HVAC) • Measuring hot water generation and delivery temperatures • Evaluating performance of solar thermal • Supporting energy modelling and verifying operational parameters for EPCs and SRI
EPC Use Cases	• Adjusting room and zone temperatures for space heating efficiency • Tracking DHW temperatures at storage and outlet points and managing heat/cooling energy need. • Collecting solar thermal collector to estimate solar fraction
Standards	**EN 1434-2 – Requirements for temperature sensors used in heat meters [3]** The general specifications for thermal energy meters are covered in this paper. This paper only discusses meters for closed systems, where there is a limited differential pressure over the thermal load. **EN ISO 7726 - *Instruments for measuring physical quantities of the thermal environment* [31]** This document standardizes definitions, measurement methods, interpretation criteria, and recommended limits for assessing thermal environments, including comfort conditions and extreme heat or cold, as well as evaluating protective measures.
Inspection Procedures for Temperature Sensors for EPC Measurements	• Verify sensor placement: Ensure correct height for temperature control systems in indoor areas, immersion depth for DHW, or pipe contact for clamp-on types. Place sensors where they avoid radiation, airflows, or thermal bridges • Choose sensor with appropriate range, accuracy, and standard compliance [3] • Validate calibration of the sensors annually for ensuring consistency • Data logging and recording for ambient temp/humidity
Accuracy & Reliability	• Standard EPC-grade sensors offer ±0.2 °C to ±0.5 °C accuracy for space and pipe temperatures • Reliability depends on stable placement, material contact (for pipe sensors), and correct configuration in the control system • For SRI applications, consistent readings are crucial for performance verification and fault detection
Advantages	• easy to install across zones and systems • Enables adaptive heating, DHW timing, and zoning • Real-time monitoring
Limitations & Challenges	• Wrong placement of sensors can lead to over/under-reporting • Wireless sensors may suffer from signal loss or interference

Template 7 - Temperature Measurement For TBS

Category	Details
Technique	**Carbon Dioxide Measurement**
Purpose	CO_2 sensors are used to control IAQ by measuring CO_2 concentration levels (typically in ppm) and enable demand-controlled ventilation (DCV) systems by adjusting airflow based on occupancy
EPC Use Cases	• Used for CO_2 concentration as a proxy for occupancy to optimize ventilation demand • CO_2-based DCV contributes to automated environmental control criteria in SRI assessments
Standards	**EN 50543 - Specifies performance characteristics of electrical CO_2 sensors for HVAC applications [32]** This European Standard outlines the construction, testing, and performance criteria for portable and transportable electronic devices used to detect and measure CO_2 and/or carbon monoxide (CO) in indoor air. • It applies to air within buildings—such as homes, offices, industrial facilities, and public spaces—including air supplied to mechanical ventilation systems. **EN ISO 16000-26 - Measurement of CO_2 in indoor air [33]** • ISO 16000-26:2012 provides guidelines for planning the measurement of CO_2 in indoor air. • It emphasizes the importance of carefully designing the sampling and overall measurement strategy, as the results can significantly impact decisions—such as determining whether corrective measures are needed or evaluating the effectiveness of actions already taken. **ISO 16484-5 - Building automation and control systems [34]** This document explains how the TBS systems are managed in the buildings. It also refers to the integration of CO_2 sensors in BACnet networks
Inspection Procedures for Carbon Dioxide Sensors for EPC Measurements	**Sensor Placement** Install at body height (1.5–2 m), avoid direct airflow, windows, or heat sources [35] **Calibration** • Sensors require auto or manual calibration; factory-calibrated or field-calibrated via zero reference • Check the calibration of the sensor annually **Logging** Confirm sensors have logging or integration with BMS/BACnet for data traceability
Accuracy & Reliability	• CO_2 sensors typically offer accuracy of ± (50 ppm + 3% of reading) under standard conditions [36] [37] • Sensor readings are highly repeatable and correlate closely with occupancy-related ventilation needs when installed and maintained correctly
Advantages	• Enables energy-saving ventilation via demand control • Typically, easy to install, integrate, and maintain in existing BMS • Aids in actual occupancy schedules for EPC simulations
Limitations & Challenges	• Placement near vents or windows can distort readings • PC software tools may not always directly accept CO_2 data—requires integration via BMS or simulation-based approaches

Template 8 - Carbon Dioxide Measurement For TBS

Category	Details
Technique	**Flow Measurement**
Purpose	Flow meters are devices used to measure the volume or mass of fluid (typically air and water) in an envelope or moving through a pipe system. In buildings, they are essential for: • Monitoring heating/cooling system performance (including solar systems) • Measuring DHW consumption • Supporting thermal energy metering • Enabling accurate EPC inputs and energy balance calculations
EPC Use Cases	• Verifying DHW usage and temperature delivery for EPC inputs • Quantifying heat energy delivered in central heating systems (via heat meters) • Monitoring solar thermal flow for calculating usable solar gains
Standards	**EN 1434-6 - Thermal energy meters,** installation**, commissioning, operational monitoring and maintenance [4]** This document specifies commissioning, operational monitoring and maintenance and applies to thermal energy meters. • Defines requirements for thermal energy meters, including flow and temperature sensors **ISO 4064 / EN ISO 4064 - Metrological and technical requirements [37]** This document covers water meters that use mechanical principles to measure the volume of hot and cold water as well as those that use electrical or electronic principles and mechanical principles combined with electronic devices. • Water meters for cold/hot potable water; accuracy classes and performance **ISO 52120-1:2021 - Energy performance of buildings — Contribution of building automation, controls and building management [9]** An organized list of technical building management, building automation, and control functions that affect a building's energy efficiency; functions have been organized and classified based on building automation and control (BAC) and building disciplines

Inspection Procedures for Flow Meters for EPC Measurements	**Pre-Installation Validation**
	• **Verify flow meter type**: Confirm whether the meter is:
	  ○ Volumetric (e.g., mechanical turbine, paddle wheel)
	  ○ Ultrasonic (transit-time or Doppler)
	• **Confirm application suitability**: Select thermal energy or water meter class based on intended use [3][4]
	Site and Orientation Checks
	• **Mounting orientation**:
	  ○ Check if the meter is approved for horizontal or vertical pipe installations
	  ○ Align flow direction with the arrow on the meter body
	• **Environmental exposure**: Inspect for humidity, heating, and freezing risks
	
	Installation Quality Review
	• **Pipe integration**: Check that gaskets, fittings, and threaded unions are correctly tightened and leak-free
	
	Functional Testing
	  ○ Run water through the system and verify that:

	▪ Flow is registered correctly ▪ Direction and magnitude match expected values • Compare with reference meter: o If possible, validate meter output against a calibrated reference flow meter or known volume test (bucket test for water meters) **Calibration & Documentation** • **Check calibration certificate**: Ensure the meter is calibrated according to EN 1434 or ISO 4064, traceable to a national metrology lab [37] **Integration & Data Logging** • **Verify communication protocol**: Confirm meter can be connected with the BMS, data logger, or EPC platform • **Enable real-time or periodic logging**: o Ensure the device is logging flow (and energy if applicable) at intervals appropriate for EPC evaluation (e.g., 15 min to 1 hr)
Accuracy & Reliability	• Meters typically achieve Class 2 accuracy (±2% at nominal flow) [3] [4] • Ultrasonic and magnetic flow meters offer long-term stability with no moving parts
Advantages	• Essential for real-time thermal energy measurement in heating and DHW circuits • Compatible with BMS and energy monitoring platforms • Supports measured EPCs (vs. calculated) using logged energy delivery
Limitations & Challenges	• Accuracy affected by low or highly variable flow rates (e.g., oversized pipes, intermittent DHW use) • Requires straight pipe runs upstream/downstream to prevent turbulence • Sensor fouling (e.g., in hard water systems) can degrade readings • Installation requires knowledge of pipe material, diameter, and fluid type

Template 9 - Flow Measurement For TBS

Category	Details
Tool	**Illuminance Measurement**
Purpose	Lux sensors measure the intensity of light (illuminance) in lux (lumens/m²). In EPC contexts, they are used to: • Assess artificial lighting levels in interior spaces • Enable daylight-responsive lighting control systems (for BACS/SRI) • Support verification of lighting energy consumption and user comfort
EPC Use Cases	• Evaluating lighting sufficiency and efficiency • Support lighting control strategies
Standards	**EN 12464-1 - Lighting requirements for indoor workplaces (lux targets) [38]** • EN 12464-1 specifies lighting requirements for indoor workplaces, including recommended illuminance levels (lux) for various tasks and areas. • The standard aims to ensure visual comfort and performance by specifying illuminance, uniformity, and other lighting parameters for different work environments. **ISO 8995-1:2025 - General lighting requirements, including sensor references [39]** • This document defines the lighting standards for indoor work environments to support visual comfort, safety, and efficiency. • It applies to both natural and artificial lighting sources and promotes integrative lighting approaches, while maintaining flexibility for designers and not imposing specific aesthetic or atmospheric guidelines.

Inspection Procedures for Lux Sensors for EPC Measurements	**Setting the Sensor**
	• **Frequency**: Ensure the lux sensor is calibrated at least annually or according to the manufacturer's recommendation.
	• **In-field validation**: If possible, perform a zero-point check and quick reference comparison with a known light level (e.g., daylight under clear sky or manufacturer calibration lamp).
	
	Sensor Positioning and Orientation
	• **Measurement surface**: Place the sensor horizontally on the task plane:
	  ○ 1.0 m for desks, tables, or general horizontal work areas
	  ○ 1.5 m vertically (against a wall or on a stand) for evaluating vertical tasks or signage
	• **Sensor alignment**: The photodiode should face straight upward (for horizontal plane) to avoid angular deviation
	• **Avoid obstructions**: Ensure no obstacle, furniture, or people block direct or indirect light during measurement and always use the same location and height for repeat assessments to ensure reliable consistency
	
	Lighting & Environmental Conditions
	• **Lighting state**: For EPC and regulatory compliance, measurements should reflect “typical operational conditions”:
	• **Shadow & reflection control**:
	  ○ Avoid standing near the sensor during reading
	  ○ Watch out for strong beam angles from spotlights or direct sunlight

<table>
<tr><td></td><td>Measurement Settings
Daylight contribution: If daylight is present, record time of day, sky condition (sunny, overcast), and whether solar gain was evident in the room
Dual-condition readings: For dynamic simulation or daylight factor calculations, perform measurements in multiple daylight scenarios
Compare measured values to EN 12464-1 illuminance requirements by space type [38]:<table><tr><th>Space Type</th><th>Target Illuminance (lux)</th></tr><tr><td>Office (general tasks)</td><td>300–500 lux</td></tr><tr><td>Classroom</td><td>300–500 lux</td></tr><tr><td>Corridors / circulation</td><td>100–200 lux</td></tr><tr><td>Technical rooms / workshops</td><td>500–750 lux</td></tr><tr><td>Stairs</td><td>100–150 lux</td></tr></table>
Allow a ±10–20% margin, especially in naturally lit areas, provided overall visual comfort is achieved and lighting control compensates dynamically [38].</td></tr>
<tr><td>Accuracy & Reliability</td><td>Class A lux meters offer ±2–3% full-scale accuracy, suitable for EPC/BACS assessments [40]
Consistent, repeatable readings when positioned correctly and used under stable lighting
Reliability depends on angle of incidence, age of sensor, and calibration</td></tr>
<tr><td>Advantages</td><td>Simple and low-cost tool for controlling lighting levels and daylight performance
Supports energy-saving lighting control strategies (e.g., presence detection, daylight dimming)
Can be easily integrated into BMS or SRI-compliant lighting systems</td></tr>
<tr><td>Limitations & Challenges</td><td>Measurements are highly dependent on placement and location of the sensor and environmental conditions.</td></tr>
</table>

Template 10 - Illuminance Measurement For TBS

Category	Details
Tool	**Heat Flux Measurement**
Purpose	A heat meter is a device that measures the amount of thermal energy transferred in a heating or cooling system. In DHW systems, heat meters are used to monitor: • Hot water energy usage • Individual tenant consumption (submetering) • System efficiency • Energy inputs for EPC and billing
EPC Use Cases	• Measure space heating or DHW energy delivered to apartments/dwellings • Track renewable heat contribution from solar cells • Provide actual energy use values for measured EPCs, rather than modelled data • Verify system performance for retrofit validation or SRI purposes
Standards	**EN 1434-6 - Thermal energy meters,** installation**, commissioning, operational monitoring and maintenance [4]** This document specifies commissioning, operational monitoring and maintenance and applies to thermal energy meters. • Defines requirements for thermal energy meters, including flow and temperature sensors

Inspection Procedures for Heat Meters for EPC Measurements	**Installation [41]**
	• Ensure the flow sensor matches the nominal pipe diameter (DN).
	• Confirm the installation direction matches the flow arrow on the meter body.
	• Confirm if flow is horizontal or vertical, and ensure the meter is certified for the chosen orientation.
	• Ensure required straight lengths of pipe are present. Incorrect pipe sizing or orientation can introduce turbulence, flow errors, and invalid readings.
	Calibration Check
	• Review manufacturer documentation for:
	  ○ Initial calibration certificates
	  ○ Sensor pairing status (each pair calibrated with specific meter)
	• Ensure there is no tampering or mixing of sensors between different installations.
	• Confirm that temperature sensors match the flow sensor serial number in the configuration data.
	
	Start-Up and Functional Verification
	• Open system valves and initiate fluid flow.
	• Observe:
	  ○ Live flow rate (e.g., in L/h or m³/h)
	  ○ Supply and return temperatures (°C)
	  ○ Calculated energy (kWh or MJ)
	• Check that:
	  ○ All sensor readings are stable

Accuracy & Reliability	• Class 2 meters (per EN 1434) typically provide ±2–3% accuracy for thermal energy over operational flow and temperature range [3]

	• Long-term accuracy depends on correct pairing of sensors, installation geometry, and regular maintenance • Reliable in both low- and high-temperature systems (e.g., solar DHW vs. radiator heating) when properly specified
Advantages	• Supports measured EPCs and retrofit impact verification • Integrates with BMS and energy platforms via standard communication protocols
Limitations & Challenges	• Requires precise sensor placement and hydraulic setup for accurate readings • Inaccurate flow sizing or air in pipes can affect readings

Template 11 – Heat Flux Measurement For TBS

Category	Details
Tool	**Solar Irradiance Measurement**
Purpose	Solar irradiance sensors measure the solar power per unit area (W/m²) received on a surface. They are used to: • Validate solar thermal system input and efficiency • Monitor photovoltaic (PV) system performance relative to expected production • Gather and support climate data validation for dynamic EPC models
EPC Use Cases	• Provides measured solar input for calculating solar fraction in solar thermal systems • Validate PV generation potential or real output for on-site renewable contributions • Compare actual irradiance to simulation data (from EPC software like PHPP or SBEM) • SRI functions that adjust HVAC or shading based on solar gain • Improve accuracy in measured EPC methodologies using building-specific data
Standards	**ISO 9060:2018 - Classification of pyranometers into Secondary Standard, First Class, and Spectral Class [42]** This document defines the categories and specifications for instruments used to measure hemispherical and direct solar radiation across the full spectral range. **IEC 61724-1:2017 - PV System Performance Monitoring; specifies sensor use for plane-of-array irradiance [43]** It provides guidelines for monitoring and analysing the performance of photovoltaic (PV) systems. It covers the equipment, terminology, and methods used, including sensor installation and accuracy requirements, data collection of measured parameters, data quality checks, and the calculation of performance indicators. **ISO 9847 - 2023 Solar energy — Calibration of pyranometers by comparison to a reference pyranometer [44]** This document defines standardized indoor and outdoor calibration methods for pyranometers, ensuring traceability to SI units via the World Radiometric Reference (WRR), and provides guidance on calibration procedures, applicability across pyranometer classes, and uncertainty evaluation.

Inspection Procedures for Solar Irradiance sensors for EPC Measurements	**Verify Sensor Class (ISO 9060) [42]**
	EPC outputs such as solar contribution and heating demand rely on precise, traceable irradiance values. Sensor class determines confidence in those values.
	• Choose a sensor class based on the required measurement accuracy:
	  ○ **Class A (Secondary Standard)**: For research or high-accuracy reference use (±1–2% error)
	  ○ **Class B (First Class)**: Suitable for building-level EPC use (±3–5% error), commonly used in commercial systems
	  ○ **Class C (Second Class or Photodiode)**: Lower cost, ±10% or more error, used mostly for indicative purposes
	• Ensure the device is **ISO 9060:2018 compliant**
	• Cross-reference accuracy claims with **IEC 61724-1:2021**, which sets accuracy requirements for irradiance monitoring in PV systems [43].

	Sensor Placement
	Horizontal mounting: For measuring global horizontal irradiance (GHI), used in climate zone or weather file validation
	Tilted mounting: Matches PV module or collector surface (e.g., 30° south-facing) for specific solar gain assessments
	• Use a stable mount with minimal thermal expansion or movement, fixed to a roof, frame, or tripod
	
	Irradiance Analysis
	Shading causes underestimation of actual irradiance, which can misrepresent potential solar contribution in EPC reports
	• Perform a shading analysis (using tools like a solar pathfinder or 3D scanning) to detect:
	  ○ Nearby trees
	  ○ Roof protrusions (e.g., chimneys, HVAC ducts)
	  ○ Antennas or scaffolding
	• If shading is present during part of the day, either [45]:
	  ○ Document it and exclude those hours in analysis
	  ○ Or relocate the sensor to a shade-free zone
	
	Levelling the Sensor
	Misalignment alters the angle of incidence, reducing sensor response and introducing errors—especially with high solar zenith angles.
	• For tilted sensors, use angle gauge to match the exact collector/PV angle
	• Re-check after weather exposure or maintenance, especially on roof-mounted systems
	
	Sensor Maintenance
	• Use clean cloths and distilled water to remove dust, pollen, bird droppings, or condensation
	• Avoid abrasive cleaners that could scratch the surface of the sensor
	• Schedule cleaning periodically from time to time, or install automatic wipers if used long-term

Accuracy & Reliability	• Can provide very accurate measurements (Class A&B) [42] • Reliable when properly mounted, levelled, and cleaned • Accuracy affected by sensor class, maintenance, cosine response, and spectral sensitivity • Long-term reliability depends on annual calibration and regular cleaning of sensor surface
Advantages	• Supports real-time performance monitoring of solar thermal and PV systems • Enables accurate solar fraction or renewable contribution calculations for EPC and SRI • Simple to install and compatible with data logging and BMS platforms • Validates simulated vs. actual solar energy input at specific site location

Limitations & Challenges	• Must be cleaned regularly because soiling affects accuracy • Requires clear-sky exposure and careful alignment to avoid shading • Accuracy sensitive to mounting angle and reflected radiation from nearby surfaces

Template 12 - Solar Irradiance Measurement For TBS

2.2. Summary of Developed Procedures and Techniques

2.2.1 Technique for Measuring Building Elements

The primary goal of building element techniques is to gather material, thermal, and geographical data concerning the building envelope's static components. The form, insulation performance, heat losses, and surface conditions of a structure are all determined by these instruments, and these factors have a direct impact on airtightness evaluations, daylight/sun exposure simulations, and U-value computations.

1. LiDAR Scanning

High-resolution 3D point cloud data of building exteriors is captured using LiDAR (Light Detection and Ranging) systems. These scanners assess walls, roofs, and other structural components quickly and accurately. Their outputs can be exported in formats like IFC, which are crucial for energy modelling, and are compatible with BIM. IEC 60825-1 and ISO 17123-9 standards apply to LiDAR tools [7] [13].

2. 3D Laser Scanning

3D laser scanners have been developed to capture interior geometry. Their capacity to produce complex volumetric models of rooms facilitates surface area computations, internal volume estimation, and spatial zoning. These are particularly useful for constructing digital models of the building that may be utilized in digital twin applications, various situations, and simulation tools to observe how the building reacts. They are also useful in retrofit circumstances where original drawings may be out-of-date or unavailable.

3. IR Thermography

Areas of heat loss, air infiltration, missing insulation, and thermal bridges are all detected with IR thermal imaging technology. For these cameras to produce reliable images, there must be a temperature differential between inside and outdoor settings (usually greater than 10°C) which sets the visual difference between surfaces much clearer [16]. By confirming assumptions regarding thermal envelope performance, thermal images assist EPC software inputs.

4. Virtual Reality

Assessors can interactively examine 3D building models—usually created using LiDAR or point cloud scans and converted to BIM, using VR technologies, which are visualization platforms. VR technologies are crucial for immersive evaluation of spatial layouts, temperature zones, and energy simulations, even though they don't carry out direct measurements. They facilitate the evaluation of retrofit options, occupant comfort, and energy performance interpretations during the EPC process by enabling users to interact with complicated building data intuitively.

5. Aerial Scanning

Drones make it possible to check building roofs and inaccessible places safely and effectively. They can create point cloud models or aerial thermal maps when fitted with LiDAR or IR payloads. Drones, which are subject to regulations like ISO 21384-3, are especially helpful for inspecting broad or complicated areas [24]. To generate scanned models of the building envelope, they can be outfitted with LiDAR or 3D scanners.

6. BE Thickness Measurements

Thickness gauges which come in magnetic and ultrasonic varieties, are used to measure the thickness of material layers and insulation without causing any damage. Precise measurements of thickness aid in verifying U-values and input material characteristics in simulation programs like DesignBuilder.

Table 3- Comparison of Techniques for BEs

Technique	Key Output	Best Use Case	Notable Limitation
LiDAR Scanning	3D geometry	External envelope	Affected by reflection/sunlight
3D Scanning	Interior envelope	Interior layouts, refurbishment	Complex post-processing
IR Thermography	Heat loss imaging	Detecting leaks/bridges	Emissivity and environmental impact
Virtual Reality	Immersive model walkthroughs	Retrofit planning, EPC simulation visualisation	Hardware/software compatibility
Aerial Scanning	Aerial envelope scan	Rooftop inspection and PV modelling	Weather limits, legal compliance
BE Thickness Measurement	Insulation thickness	U-value accuracy	Material-specific setup

The functions of the discussed instruments are different but complementary. The ability to capture spatial data with millimetre accuracy using LiDAR and 3D scanners is crucial for defining building geometry for EPC modelling. Thermal cameras can visually detect areas of inefficiency and offer crucial information about the thermal performance of building materials. This capability has been enhanced by drones, which provide quick and secure access to high or inaccessible locations. Despite being more straightforward, thickness gauges provide vital material information that is required to enable precise U-value calculations. Even though most tools are digital and non-invasive, their effectiveness greatly depends on the auditor utilizing them, the setting, and the correct calibration. Drones and thermal cameras are two examples of equipment that also need operator experience and weather concerns. Some tools, such as thermal cameras and drones, also require operator expertise and weather considerations.

2.2.2 Techniques for Measuring Technical Building Systems (TBS)

Tools in this category provide a performance-based perspective of how systems function in actual environments by monitoring temperature, flow, light, air quality, and solar input. SRI, system efficiency calculations, and the development of measurable EPCs all depend on these measures.

1. Temperature Measurement

Temperature sensors track supply/return temperatures, zone comfort levels, and system management logic in HVAC, DHW, and renewable energy systems. Standards like EN ISO 7726 and EN 1434-2 are applicable, and accuracy generally ranges between ±0.2 and 0.5 °C [31] [3].

2. Carbon Dioxide Measurement

CO_2 sensors are essential parts of demand-controlled ventilation systems and aid in determining occupancy levels. Their results improve SRI evaluations for indoor environmental quality and EPC ventilation rate assumptions.

3. Flow Measurement

Flow meters are used to measure the amount of water or heat transfer fluid in heating loops and DHW systems. For thermal energy calculations, they are utilized in conjunction with temperature sensors; the applicable standards are EN 1434 and ISO 4064 [3] [4] [37].

4. Heat Flux Measurement

Heat meters estimate energy use in kWh or MJ by combining temperature and flow sensors. They are crucial in situations involving shared systems or district heating where real energy use must be assigned and verified for EPC reasons.

5. Illuminance Measurement

By measuring interior light intensity in lux, these sensors help BACS management methods, daylight autonomy, and lighting adequacy. They aid in assessing SRI measurements and lighting energy demand when used in compliance with EN 12464-1 [38].

6. Solar Irradiance Measurement

Incoming sun radiation (W/m2) is measured using silicon photodiodes or pyranometers. They facilitate the investigation of solar thermal contribution and the confirmation of PV system output. Guidelines for classification and performance are provided by ISO 9060 and IEC 61724-1 [42] [43].

Table 4- Comparison of Techniques for TBS

Technique	Key Parameter Measured	EPC Role	Notable Limitation
Temperature Measurement	Pipe/zone temperatures	Space heating, DHW inputs	Misplacement affects reliability
CO_2 Measurement	Air quality / occupancy	Demand-controlled ventilation	Sensitive to airflow, vents
Flow Measurement	Water/heat flow rate	DHW/space heating validation	Needs clean, stable hydraulics
Heat Measurement	Thermal energy	Core to EPC thermal monitoring	Needs matched sensors, stable ΔT
Illuminance Measurement	Illuminance (lux)	Lighting audit and controls	Daylight/sensor angle interference
Solar Irradiance Measurement	Solar energy input	PV/Solar gain accuracy	Soiling, tilt, and orientation

These techniques are essential for dynamically tracking the performance of buildings. For HVAC and hot water systems to accurately measure energy transfer, temperature sensors, flow meters, and heat meters are crucial. CO_2 sensors improve IAQ measurements and ventilation control methods which will contribute to the idealness of IEQ. Lighting and solar energy contributions, which can be overlooked in conventional EPC evaluations, are supported by lux and irradiance sensors. These instruments need to be calibrated more frequently than tools for BE, and they might need to be integrated with the building's operating systems (such data loggers or BMS). Performance tracking is made possible by their real-time capabilities, which also guarantee that the EPC accurately depicts the state of the building.

Tools for BE provide the physical and thermal foundation of the building's performance, while tools for TBS reflect its real-time operational behaviour. Their combined use supports the transition to measured, performance-based EPCs, aligning with EU policy goals for smarter and more transparent energy labelling.

By integrating data from both categories, assessors and energy modelers can produce more accurate, context-sensitive, and verifiable EPCs that better reflect the energy behaviour of buildings in actual use.

2.2.3 Leveraging Building Automation and Control Systems (BACS) for EPC Audits

Building Automation and Control Systems (BACS) are recognized by the Energy Performance of Buildings Directive (EPBD) 2024/1275 as both legally compliant and performance-critical components that can replace or drastically reduce the frequency of required HVAC inspections [1]. BACS must therefore be specifically incorporated into the planning and implementation stages of creative EPC inspection processes.

Buildings that have "effective BACS with continuous monitoring capabilities and fault detection diagnostics" may be exempt from some physical inspections under Article 19 of the EPBD 2024/1275. Therefore, EPC assessors must determine whether the building's BACS satisfies these requirements and whether its trend data, exception alerts, and operating logs can be used as compliant alternatives to manual checks [1]. For example, on-site combustion or setpoint verifications can be replaced by routine boiler efficiency trend logs or control override events recorded by the BMS.

Regular inspections of accessible heating, cooling, and ventilation systems with an effective rated output more than 70 kW are required under Article 23 of the EPBD. However, when effective BACS are in place, systems that provide automated fault detection, operational control, and continuous monitoring—Article 23(5) expressly permits exemption from these inspections [1]. As a result, having a compliant BACS is not optional; rather, it may serve as legal justification for replacing or lowering the frequency of manual inspections, given that the system provides comparable results for fault identification, performance verification, and energy efficiency monitoring.

- Modern BACS, often integrated with Building Management Systems (BMS), log large volumes of operational data including:Temperature variations in rooms and zones and departures from setpoints
- Demand-controlled ventilation and CO2 levels
- Overrides, controller reprogramming events, or fault alerts

During EPC audits, inspectors should obtain and examine this data in order to:

- Perform a pre-visit or remote "digital inspection."
- Determine any anomalies or inefficiencies in the system (such as an extended runtime outside of occupancy hours).
- Verify the sensor values used for SRI scoring, for example, in EPC simulations.

3. Step-by-Step Guidance for Implementation

3.1. Preparation for Inspection

Preparation for inspection ensures that all necessary arrangements are in place, the scope and objectives are defined, appropriate tools are selected, and potential risks and limitations are identified. This step should strictly follow the quality and procedural frameworks established by EN 16247-1 and EN 16247-2, ensuring consistency, reliability, and traceability throughout the energy assessment [46] [47].

3.1.1 Define Scope and Boundaries

A clear understanding of what will be inspected is essential. Determine whether the audit targets the building envelope (walls, roofs, floors, windows) or technical systems (heating, cooling, lighting, ventilation). Define the physical boundaries (e.g., entire building or specific zones), audit purpose (e.g., initial EPC, post-retrofit validation), to be assessed. Boundaries should reflect both spatial and functional divisions.

3.1.2 Stakeholder Coordination and Start-Up Meeting

Schedule a kick-off meeting involving the building owner, facility manager, EPC assessor, and any relevant third-party service providers (e.g., drone operators, tool specialists). The goal is to:

- Confirm audit goals and expected outcomes.
- Clarify access requirements and safety constraints.
- Designate roles, responsibilities, and communication channels.
- Agree on data sharing on formats, timing, and confidentiality protocols.
- Coordinate the audit schedule with building occupancy and operational conditions to minimize disruption.

3.1.3 Tools and Equipment

Select tools based on inspection type. Ensure every device is fit for purpose, functional, and compliant with current calibration standards. Organize tools by category:

Building Envelope Tools

- LiDAR Scanner: High-speed external 3D mapping.
- 3D Laser Scanner: Detailed interior scanning.
- Thermal Camera: Detect heat loss, insulation gaps.
- Thickness Gauge: Determine insulation/cladding thickness.
- Drone (LiDAR/IR Payload): Access to roofs and high areas.
- VR Interface: Visual simulation and interaction.

Technical Building Systems Tools

- CO_2 Sensor: Assess IAQ and ventilation.
- Temperature Sensor: Check supply/return temperatures.
- Flow Meter: Verify fluid flow in heating/DHW loops.
- Heat Meter: Calculate heating/cooling energy output.
- Lux Sensor: Evaluate lighting conditions.
- Solar Irradiance Sensor: Determine solar energy input.

Verify:

- Calibration certificate (traceable to EU/National standards, not older than 12 months).
- Battery level and spare units.
- Cables, software, mounts, and weatherproofing accessories.
- Data logging capacity and secure transfer options.

3.1.4 Data Collection Preparation

Prior to field inspection:

- Request energy bills (gas, electricity, district heating) for at least the past 12 months.
- Gather building documentation: as-built drawings, HVAC layouts, lighting plans, BMS screenshots.
- Collect operational details: occupancy schedules, thermostat setpoints, heating season dates.
- Request BACS logs (trend data, alarms, efficiency reports) covering at least one heating/cooling season.

3.1.5 Develop an Inspection and Measurement Plan

Create a structured document detailing:

- Objectives: e.g., identify thermal bridges, verify PV potential, validate DHW consumption.
- Measurement methodology: location, instrument, frequency, and responsible person.
- Inspection sequence: exterior envelope > interior elements > TBS zones > renewables.
- Safety procedures: working at heights, power system isolation, protective gear.
- File naming and data storage conventions.

3.1.6 Risk and Limitation Assessment

- Identify weather-related risks (e.g., fog for drones, low temperature delta for thermal cameras).
- List known obstructions (e.g., inaccessible rooftops, secured zones).
- Assess reliability of available data (e.g., age of drawings, missing consumption logs).
- Plan for uncertainties by noting fallback values or conservative estimates.

3.1.7 Final Inspection Checklist

Use a readiness checklist to ensure:

- Access permissions and escort personnel arranged.
- Measurement tools tested and charged.
- All calibration certificates are valid and logged.
- Inspection route and timing confirmed.
- Health and safety gear available (PPE, signage, ladders).
- Data recording templates printed or digitally prepared.

Thorough preparation enhances measurement precision, avoids delays, and improves confidence in EPC outputs. It also ensures compliance with European standards and supports robust documentation for verification, audits, or future certifications.

3.2. Conducting the Inspection

Once preparation is complete, the inspection phase involves systematic on-site data collection using appropriate measurement tools, technical observation, and real-time verification of building characteristics. This phase is crucial for translating theoretical inputs into actual, observable energy performance data. The procedures must be carried out in accordance with the principles of EN 16247-1 and EN 16247-2, emphasizing accuracy, traceability, safety, and quality control throughout the audit process [46] [47].

3.2.1 Arrival and Site Briefing

Upon arrival, the inspection team should check in with the designated site contact. This includes:

- Verifying access permissions and confirming restricted areas.
- Reviewing safety protocols relevant to the site, such as working at height, electrical isolation, or confined spaces.
- Clarifying the audit schedule, order of zones, and tool deployment areas.
- Ensuring all staff on-site understand the purpose of the inspection and what it entails, particularly if the inspection occurs during operational hours.

3.2.2 On-Site Setup and Tool Validation

Before beginning measurement:

- Position equipment in secure, stable locations to avoid measurement interference or hazards.
- Check ambient conditions (e.g., sunlight, wind, internal heat gain) to ensure they meet required standards for tools like thermal cameras or irradiance sensors.
- Perform pre-use validation of equipment including calibration check, sensor zeroing, and software connectivity.
- Synchronize all tools and devices to the same timestamp (critical for time-based logging such as flow rates or heat consumption).

3.2.3 Inspection of Building Elements

Exterior Envelope Inspection:

- Use LiDAR or drone-based scanning to create a point cloud or 3D model of the building envelope.
- Conduct drone-based thermal imaging under suitable temperature gradients (minimum 10°C) to detect insulation defects, heat loss, or thermal bridging [16].
- Annotate and photograph findings to document visual evidence for EPC justification.

Interior Envelope Inspection:

- Deploy 3D laser scanners to capture floor plans, volumes, and structural details (window dimensions, wall placements, thermal envelope boundaries).
- Use ultrasonic or magnetic thickness gauges to measure insulation and material layers in walls, roofs, or floors.
- Capture visual and textual data for any areas where measurement was not possible, applying conservative estimates with justification.

VR Model Validation (if used):

- Merge scanned data with BIM to visualize in VR.
- Walk through the building using VR tools to confirm spatial logic and highlight thermal zoning or comfort problems.

- Record any occupant behaviour patterns or retrofit considerations suggested during simulation.

3.2.4 Inspection of Building Technical Systems

HVAC and DHW Systems:

- Install temperature sensors at strategic locations on supply and return pipes to measure ΔT.
- Measure flow rates using ultrasonic or mechanical flow meters to compute energy flows.
- Cross-reference values with installed heat meters or BMS where possible.

Ventilation Systems and Indoor Air Quality:

- Deploy CO_2 sensors during occupied periods to assess ventilation effectiveness.
- Observe and record mechanical ventilation activity, including fan status, control schedules, and noise levels.
- Check air terminal cleanliness and potential obstruction.

Lighting Systems:

- Measure lux levels across work zones or general areas under typical lighting conditions (daylight and artificial).
- Verify existence and responsiveness of automatic or manual lighting controls.
- Photograph fixture placements and document any changes in lighting layout.

BACS:

- Verify that BACS is functional, logging data, and connected to key systems (e.g., HVAC, lighting)
- Confirm access to the BMS interface and data export functionality
- Interview building operators to understand custom configurations

EN ISO 52120-1:2021 provides a harmonized methodology to classify building automation capabilities based on their contribution to energy efficiency. The classification ranges from:

- **Class A** – High efficiency (advanced control systems: occupancy, demand response, setpoint optimization)
- **Class B** – Advanced functionality
- **Class C** – Standard control (baseline)
- **Class D** – Inefficient or minimal automation

Inspectors should:

- Determine and record the **BACS class** of the building based on system capabilities and coverage
- Use a **checklist derived from ISO 52120** to assess control functionalities including:
    - Time scheduling and occupancy control
    - Temperature setpoint and setback strategies
    - Lighting control integration (e.g., daylight or presence sensors)
    - Ventilation and IAQ control mechanisms
    - Fault detection and diagnostics (FDD) presence

Solar Energy Systems:

- Deploy solar irradiance sensors on-site or validate permanent sensors.
- Record GHI (Global Horizontal Irradiance) or POA (Plane of Array) levels.
- Cross-check alignment, tilt angle, and shading against PV system assumptions.

3.2.5 Data Logging and Observation

Each measurement should be accompanied by:

- Time and date stamp.
- Location and zone description.
- Tool ID, operator initials, and calibration status.
- Qualitative notes where anomalies are observed.
- Photos or thermal images, labelled with location and orientation.
- Verify BACS functionality (sensor operation, logging capability, network structure)

Use digital log sheets or audit apps where available. Confirm that data are saved, backed up, and formatted per the EPC tool's import requirements.

3.2.6 Communication and Clarifications

During inspection:

- Engage with building occupants and staff to validate operational behaviours (e.g., when heating is on, whether rooms are consistently used).
- Note informal insights that can explain energy use variations or equipment irregularities.
- Document any concerns, contradictions, or undocumented modifications (e.g., unregistered air conditioners, space heaters, window films).

3.2.7 Decommissioning and Quality Control

After inspection:

- Carefully remove all installed sensors, respecting surface materials and building finishes.
- Conduct a visual sweep to ensure no damage or misplaced items.
- Backup all data to a secure drive.
- Perform a completeness review: were all zones inspected? Any missed tools or gaps?
- Update the site contact on findings and next steps, including report timeline.

Audits are not only technical evaluations but are also user- and context-sensitive. Each observation must be converted into a validated and reproducible dataset that can inform EPC modelling with high confidence. The depth and discipline of the inspection phase directly affect the credibility of the final certification, especially as measured performance becomes central to EU energy policies.

3.3. Reporting and Documentation

The reporting and documentation phase is the final and essential step that ensures all information collected during the inspection is interpreted, archived, and communicated effectively. This phase turns raw data into actionable insights, supports the calculation and validation of energy performance ratings, and provides a transparent trail that can be reviewed by auditors, building owners, or public authorities. It also enables alignment with national EPC formats and the EU's SRI framework. Following EN 16247-1 and EN 16247-2, this process must be methodical, comprehensive, and reproducible [465] [47].

3.3.1 Data Verification and Validation

Upon completion of the inspection:

- Cross-check each measurement against acceptable performance thresholds or expected system behaviour. For example, heat meter energy values should align with heating runtime and expected demand.
- Confirm that equipment calibration status, timestamp synchronization, and location markers are correct for each dataset.
- Flag and annotate any anomalies—such as inconsistent flow rate data, missing zones, or unmeasurable components—with justifications or fallback assumptions.
- Use paired data to confirm internal consistency. For example:
  - Lux readings vs. lighting control schedule.
  - CO_2 trends vs. ventilation equipment operation.
  - Thermal images vs. U-value calculations.
- Apply correction factors if environmental conditions varied from ideal (e.g., surface emissivity correction in IR images or solar angle for irradiance sensors).
- Incorporate BACS data into the EPC calculation engine, especially for real energy use validation or predictive maintenance insights.
- Where available, **export trend logs or summaries from the building's automation system** (e.g. historical consumption, temperature setpoints, HVAC run-times) and include them in the documentation. These provide validated evidence of actual building operation to complement the measured values taken during the site visit. They can also serve as a baseline for future performance comparisons or for verifying improvements after interventions

3.3.2 Structure of the Inspection Report

A complete and user-friendly report helps various stakeholders—from facility managers to policymakers—understand the building's performance. Recommended structure:

1. **Executive Summary**
- Context: Building use, location, size.
- Scope: Which tools were used and what was inspected.
- Summary of major issues and quick-win interventions.

2. **Methodology**
- Inspection timeline and phases.
- Measurement plan overview.
- List of tools and sensors used (with IDs and calibration details).
- Sampling or walkthrough strategy.

3. **Findings – Building Elements**
- Geometric model summary (LiDAR/3D scans).
- Thermal envelope description.
- Notable insulation issues, air leakage zones, or structural defects.

4. **Findings – Technical Systems**
- HVAC, lighting, DHW system efficiency.
- Measured consumption, flow, or control logic.
- Functional description of automation levels and sensor feedback.

5. **Quantitative Data**
- Calculated U-values, lighting levels, solar gain, CO_2 concentrations.
- Visual presentation of data: charts, histograms, thermal image overlays.

- Summary of benchmarks against regulatory thresholds.

6. **Occupant and Operational Feedback**
- Notes from staff or residents about perceived comfort or system behaviour.
- Any operational issues observed that affect performance (e.g., windows open during heating).

7. **Limitations and Assumptions**
- Uninspected areas or assumed data points.
- Deviations from plan (e.g., unavailable rooms, malfunctioning sensors).
- Data adjustments and methodological disclaimers.

8. **Recommendations and Roadmap**
- Energy conservation measures prioritised by impact and feasibility.
- System upgrades, sensor modernization, or BACS suggestions.
- Short-term vs. long-term implementation guidance.

9. **Appendices**
- Tool calibration certificates.
- Photo logs, BIM exports, VR model references.
- Audit checklists, raw data summaries, and site sketches.

3.3.3 Data Format and Traceability

All inspection data must be:

- Exported in compatible formats for EPC software: XML for national registries, IFC/gbXML for BIM, CSV for time series data.
- Properly named and tagged with metadata: zone name, date/time, operator ID, and purpose.
- Stored securely and backed up in a cloud-based or institutional repository.
- Traceable back to specific field actions, audit procedures, and tool configurations.
- Retained according to legal requirements (typically 5–10 years for certified audits).

3.3.4 Communication and Handover

- Deliver report materials in digital and/or printed formats depending on client and regulatory expectations.
- Provide a summary presentation to discuss key results, insights, and next steps.
- Clarify uncertainties or decision points, such as assumptions used in energy modelling.
- Guide stakeholders through integration into EPC submission platforms and, where applicable, SRI documentation.

3.3.5 Alignment with EPC and SRI Methodologies

Ensure that:

- The structure of reporting supports the EPC tool's input needs (e.g., room dimensions, system types, performance values).
- Results such as lighting control automation, sensor integration, or zone control are clearly reported for SRI calculations.
- The output is compliant with national transpositions of the EPBD and reflects requirements such as measured energy input, building typology, and automation levels.

The capabilities of Building Automation and Control Systems (BACS) have a fundamental connection to many Smart Readiness Indicator (SRI) aspects, including automated control, self-regulation, and demand-

responsive systems. Documenting the presence and functionality of BACS features during the EPC audit can immediately aid in the SRI evaluation. One example of an SRI function pertaining to automated ventilation control is a CO_2 sensor that is attached to a demand-controlled ventilation (DCV) system. Similarly, SRI scoring is supported in the smart lighting and user interaction categories for lighting systems that have daylight or occupancy sensors and are controlled by a BMS. In order to increase the building's smart ready profile and enable alignment between EPC evaluations and SRI criteria, assessors should make sure these components are accurately noted in audit results

High-quality documentation reinforces the credibility of EPC results and supports transparent building energy governance. By standardizing the reporting process, energy assessors can contribute to consistent benchmarking, policy evaluation, and effective building renovation strategies across Europe.

4. Case Studies

4.1. Pilot Applications

The pilot applications within the OpenBEP4EU project can be practical testing grounds for the innovative inspection procedures developed in Task 3.1. According to the standardized methodology described in Section 3, a customized set of techniques and tools for building element assessment and TBS monitoring can be used to address each pilot case that is implemented. By doing this, these pilots can show how cutting-edge measurement tools, digital modelling software, and detailed procedural instructions can be used to enhance the quality and economics of EPCs across a range of building types and climates. The key technological components, advancements, and procedural frameworks used in each nation are highlighted in the summaries that follow.

Table 5 - Key Criteria Used for Methodologies & Pilots

Criterion	Description
Building Typology	Tools were selected based on whether the site was residential, commercial, institutional, or heritage. For example, non-invasive tools were prioritized for heritage buildings.
Audit Objective	Tool selection was tailored to the primary aim of the audit—e.g., thermal performance, IAQ, retrofit readiness, or user behaviour analysis.
Envelope vs. System Focus	Projects with a focus on the building envelope used LiDAR, 3D scanners, and thermal cameras, while those focused on systems monitoring used flow meters, CO_2 sensors, and heat meters.
Access Limitations	Drones and remote-sensing tools were selected where physical access to roofs or façades was restricted.
BACS/BMS Availability	Where advanced building automation systems existed, BMS integration was emphasized over new sensor deployment to avoid redundancy.
Climatic Conditions	Cold climate pilots prioritized tools for heating performance, whereas Mediterranean pilots emphasized solar analysis and cooling load characterization.
Digital Readiness & Data Infrastructure	Pilots with BIM capabilities or smart metering infrastructure were equipped with tools that could export data in interoperable formats (e.g., IFC, gbXML).

Table 6 - Decision Matrix – Pilot Application

Pilot Site	Primary Objective	Building Type	Selected Tools	Justification
Aspra Spitia, Greece	Thermal loss mapping, retrofit prep	Residential Settlement	LiDAR, Thermal Cameras, Smart Meters	Low documentation - need for geometric capture and thermal imaging
Philhellenism Museum, Greece	Non-invasive envelope assessment	Heritage	3D Scanners, VR, Irradiance Sensors	Tool selection limited to non-intrusive techniques, plus digital stakeholder engagement

Herning, Denmark	Cold-climate system monitoring	Residential Dwellings	Drone LiDAR, Flow Meters, CO_2 Sensors	BMS availability - focus on system-level monitoring and predictive maintenance
Murcia Region, Spain	Comfort modelling, digital twin dev.	Mixed (Res/Com)	Simulation Software, IR Cameras, Environmental Sensors	Focus on modelling occupant comfort and HVAC-environment interaction
Frederick University, Cyprus	Zone-level energy optimization	Educational Campus	Heat Meters, VRF Monitoring, CO_2 Sensors	Multi-zone layout - need for integrated IEQ, temperature, and usage monitoring
La Sosta, Switzerland	Continuous performance monitoring	Elderly Care Facilities	Thermal Imaging, Predictive Maintenance Tools	High occupant sensitivity - real-time, minimally disruptive data collection
OKTAVE, France & Portugal	Retrofit validation, behaviour input	Single-Family Homes	Smart Meters, Occupant Interviews, Drones	Old stock with poor documentation - emphasis on envelope capture and lived experience

Table 7- Overview of OpenBEP4EU Pilot Applications: Building Types, Techniques & Tools Used, and Key Outcomes

Country	Pilot Site	Building Type	Key Tools Used	Highlights
Greece	Aspra Spitia Smart Community	Residential Settlement	LiDAR, Thermal Cameras, Smart Meters, Environmental Sensors	Envelope mapping, real-time monitoring, retrofit planning
Greece	Philhellenism Museum (Athens)	Heritage/Public Building	3D Scanners, Thickness Gauges, VR, Irradiance Sensors	Non-invasive diagnostics, stakeholder & visitor visualization
Denmark	Herning Municipality	Residential Dwellings	Drone LiDAR, Flow Meters, CO2,, Sensors, BMS Integration	Cold-climate energy profiling, predictive maintenance, automation integration
Spain	Murcia Region (Joven Futura, Parque CientÃfico, MAGALIA)	Residential & Commercial	LiDAR, Simulation Software, VR, IR Cameras, Environmental Sensors	Simulation-aligned data, occupant comfort modelling, digital twins
Cyprus	Frederick University Campus	Educational Campus	3D Scanners, Flow & Heat Meters, CO2, Sensors, VRF System Monitoring	Complex zone monitoring, academic scheduling coordination, IAQ tracking
Switzerland	La Sosta & Casa Caprasica	Elderly Care Facilities	LiDAR, Thermal Imaging, CO2, & Irradiance Sensors, Predictive Maintenance	User-sensitive performance assessment, continuous monitoring, solar analysis

France & Portugal	OKTAVE Residential Pilots	Single-Family Dwellings	3D Scanners, Drones, Smart Meters, Thermal Cameras, Occupant Interviews	Measured EPCs, legacy building adaptation, user behaviour integration

- **Greece**

1) Aspra Spitia Smart Community

This pilot focused on residential dwellings within a large-scale social housing complex. LiDAR scanners and thermal imaging cameras can be examples of innovative inspection techniques that are used for envelope geometry mapping and thermal loss detection. As well as the roofs of the buildings, the village's thermography can also be scanned using drones equipped with thermal cameras. IAQ measurements and real-time consumption data can be recorded using smart meters, CO_2, temperature, and illumination sensors. The entire procedure adheres to the detailed audit workflow outlined in the handbook, which includes pre-audit planning, equipment calibration, focused data collection, and digital reporting.

2) Philhellenism Museum (Athens)

As a heritage building, the museum presented constraints on intrusive audit. Tools such as 3D scanners, thickness gauges, and thermal cameras can be deployed to assess the building envelope with minimal disruption Thermostatic control systems and smart windows with photovoltaic capabilities can be utilized for TBS as indoor temperature monitors and irradiance sensors. A VR-based visualization, built from BIM data and LiDAR models, allows stakeholders to examine potential renovation options digitally. The utilization of BIM and VR can also benefit museum visitors by offering a digital representation of the museum on internet platforms, allowing for online museum visits through a webpage.

- **Denmark**

Herning Municipality Pilot

This pilot in Denmark addresses cold-climate residential buildings, where high-resolution energy audit required both envelope analysis and system performance tracking. While flow meters, CO_2 sensors, and temperature probes can track the efficiency of heating and ventilation, drone-mounted LiDAR and thermal camera systems can be particularly useful for mapping rooftops and other building structural elements. Real-time energy flow monitoring, predictive maintenance scheduling, and instant data logging for EPC computations are made possible by integration with the BMS. In accordance with the procedure outlined in Section 3.1.6, inspectors used sample techniques to represent the larger dwelling stock.

- **Spain**

Murcia Region Sites (Joven Futura, Parque Científico, MAGALIA)

On-site data from flow sensors, CO_2 meters, and temperature loggers can be used to calibrate energy audits for the three building types (residential, commercial, and office) that are displayed. IR cameras revealed envelope flaws, whereas LiDAR-based scans allowed for accurate geometric modelling for simulation inputs. VR environments can support the comfort analysis and energy modelling process by offering insight into occupant behaviour. Through immersive stakeholder involvement, these pilots demonstrated how digital twin approaches can be incorporated into typical EPC workflows to support decision-making.

- **Cyprus**

Frederick University Campus

Frederick University's Main building, located in Limassol, Cyprus, is a modern facility designed to enhance the educational environment through advanced building management technologies. The technical infrastructure of the building supports a comprehensive suite of services aimed at creating a conducive learning and working environment. These services include systems for heating, cooling, ventilation, lighting, and the operation of electrical appliances. The building is also equipped with advanced energy monitoring systems that cover the entire structure, divided into four distinct zones for detailed management and analysis. The building leverages smart metering technology to facilitate real-time tracking of electricity consumption and internal environmental conditions such as temperature, humidity, and CO_2 levels. This real-time data acquisition is crucial for optimizing the building's energy efficiency and ensuring the comfort of its occupants. The network of sensors and meters installed throughout the building, which provides long-range, low-power wireless connectivity that is ideal for collecting data from various sensors distributed across a large area. This setup includes sophisticated devices for measuring indoor environmental conditions, namely temperature, relative humidity, and CO2 levels, ensuring continuous monitoring and compliance with health and safety standards. Additionally, the building is equipped with power meters and data loggers, which are integral to the building's energy management system. These devices collect and log a vast array of electrical inputs, providing detailed insights into the building's energy use patterns. This data is crucial for identifying opportunities for energy conservation and efficiency improvements. A dedicated platform for data monitoring, downloading, and analysis supports the administrative and maintenance staff in managing the building's operations efficiently. This platform not only facilitates the immediate visualization of data but also enables the detailed analysis necessary for making informed decisions about building management and modifications.

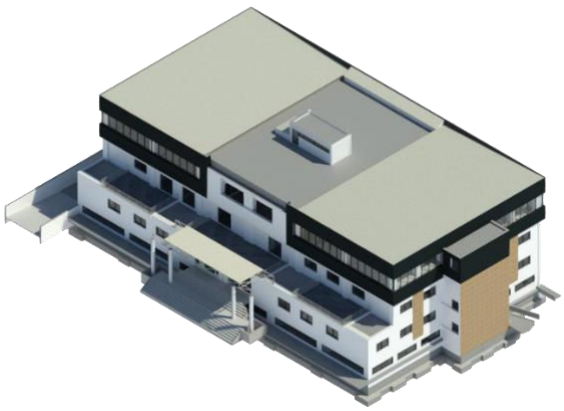

Figure 1 - Revit Model of Frederick University Limassol Campus Building

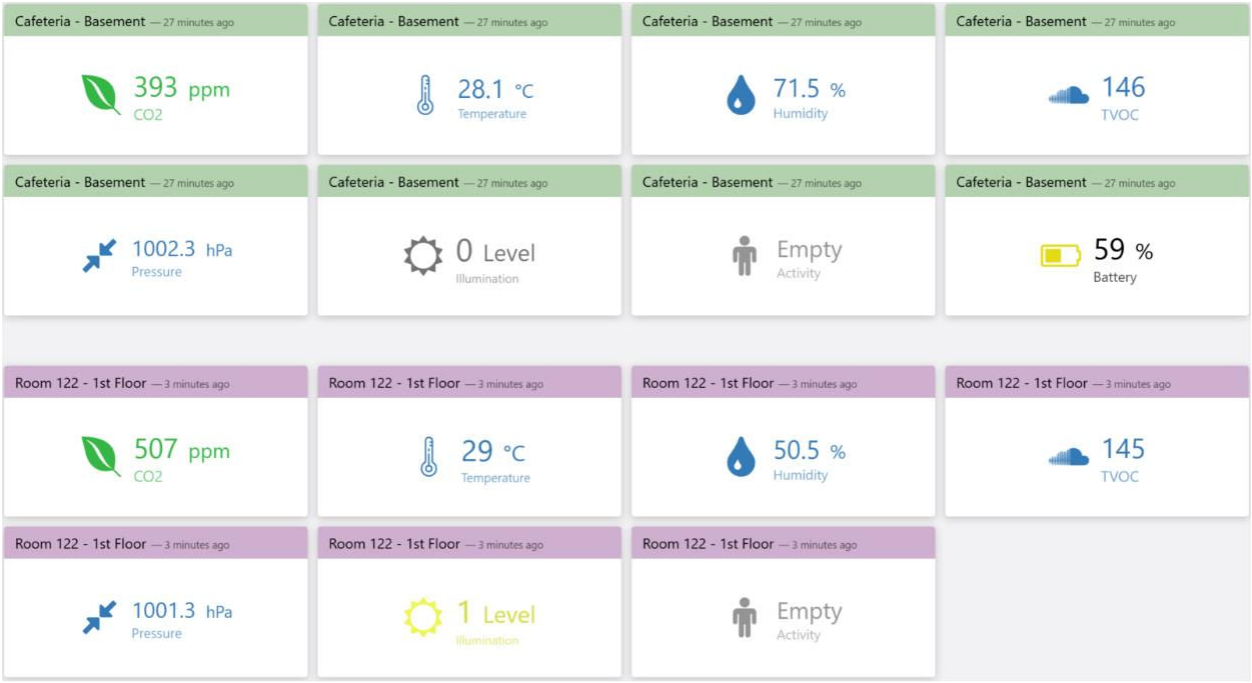

Figure 2 - Momentarily received Smart Meter measurements linked with IAQ tracking, taking action at Frederick University Limassol Campus, Cyprus

- **Switzerland**

La Sosta & Casa Caprasica (Retirement Homes)

This pilot focuses on user-sensitive settings where health and comfort metrics are important. If accessible, solar irradiance sensors assessment for sunlight can be crucial and the performance of renewable systems, while LiDAR and thermal imaging techniques can be modified to identify energy inefficiencies. Smart systems can be used to evaluate and continuously track building performance through the use of predictive maintenance tools that are backed by real-time inputs from temperature sensors, CO_2 meters, and heat meters. Stakeholder comprehension can also be improved, and traceability can be ensured by logging all audit steps using standardized documentation and metadata protocols.

- **France & Portugal**

OKTAVE Residential Pilots

Focused on detached and semi-detached single-family dwellings, these pilots address aging, poorly documented buildings in both urban and rural settings. 3D scanners, thermal cameras, and drones were used to reconstruct envelope geometry and detect performance flaws. Smart meter logging, paired with occupant interviews, enabled the transition from modelled assumptions to measure energy data. The scenario-based simulation of user behaviour—performed through VR tools and comfort modelling—offered a deeper understanding of actual building usage. The procedures demonstrated adaptability to diverse dwelling types and proved the feasibility of integrating human-centric data into EPC calculations.

Across all pilot locations, the application of innovative inspection tools is systematically anchored to the procedural framework introduced in this handbook. Key elements such as audit planning, sampling strategies, real-time data acquisition, simulation integration, and stakeholder communication are crucial

and consistently applied. These real-world case studies offer a comprehensive reference for energy assessors seeking to implement advanced, performance-driven EPC audits that are scalable, repeatable, and regulation-compliant.

4.2. Lessons Learned

- **Integrated Use of Static and Dynamic Tools**

A multidimensional characterization of building performance can be made possible by the deployment of both dynamic monitoring technologies (such as CO_2 sensors, heat meters, flow sensors, and thermostats) and static building analysis tools (such as LiDAR scanners, 3D laser mapping, and thermal cameras). This integration is essential for capturing both the operational behaviour and physical characteristics needed to produce high-resolution, performance-based EPCs.

- **Environmental Dependencies and Operational Constraints**

Environmental factors can have an impact on the accuracy and functionality of some equipment, such as IR cameras and drones equipped with thermal and LiDAR cameras. Suitable weather conditions (such as adequate indoor-outdoor temperature differentials for thermography, low wind, and clear skies for drone operations) are necessary for effective deployment. To guarantee reliable and repeatable results, these relationships highlighted the necessity of flexible scheduling, site-specific inspection planning, and high operator competency.

- **Stakeholder Engagement**

Active participation of building occupants, facility managers, and on-site personnel plays a critical role in complementing technical data with contextual information. In several pilots, information from building occupants proved crucial in learning operational intricacies and energy use behaviours, especially in cases where documentation is lacking or building systems are not fully automated. Additionally, this involvement supports the long-term success of suggested energy-saving measures and improves the recommendations for retrofits' practical application.

- **Advancement Toward Measured EPCs**

The project facilitated a tangible shift from modelled to measured EPCs by incorporating real-time data acquisition through smart meters, BMS integrations, and zone-specific environmental monitoring. This approach improved the representativeness and credibility of EPCs by aligning reported performance metrics with actual building operation. The ability to capture measured data directly supports EU policy objectives favouring more transparent, user-relevant, and dynamically updated certification practices.

- **Standardization**

By combining real-time data collection via smart meters, BMS connections, and zone-specific environmental monitoring, the project enabled a noticeable transition from modelled to measured EPCs. By bringing stated performance measures into line with real building operation, this method increased the representativeness and trustworthiness of EPCs. Measured data collection directly advances EU policy goals for more open, user-relevant, and continuously updated certification procedure

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5. Annexes

A1. Feedback from Questionnaires

The collection of data shall be appropriate to the scope and level of thoroughness of the energy audit and calculation of EPCs. Many on-site factors should be measured to assess the actual performance of the technical systems and the building envelope. This will allow for the evaluation of the building's overall energy performance and the calculation of the EPC according to the achieved results. This is done to measure the energy consumption of the technical building systems and the energy loss from BE.

The current energy audit methodologies/tools/technologies need to be assessed to analyse and innovate inspection methods and create a handbook regarding this topic. While getting an energy audit, multiple aspects such as heating, cooling, ventilation, DHW, lighting, appliances, etc., are considered under energy uses. Technical building systems (technical equipment for heating, cooling, ventilation, humidification, dehumidification, DHW, lighting, information systems including building automation and control, and on-site energy production) play a major role and contribute greatly to the energy usage of the building as well as the energy loss of the building envelope and BE.

The data required to calculate EPCs can be measured using methods and tools. Every component or system makes a vital contribution to the overall evaluation of a building's energy efficiency. To enable accurate EPC evaluation, specialized technical data can be gathered through on-site inspections, the use of inspection tools, building automation systems (BMS), and manual audits.

The inputs from Que Technologies, Belimo (RetrFit+ Productmanagement tool), and Siemens France, alongside technical evaluations of tools like Revit, Archicad, DesignBuilder, IESVE, and IDA ICE are gathered. They highlight both technological capabilities (e.g., interoperability, accuracy, data handling) and operational barriers (e.g., outdated systems, lack of qualified personnel, absence of digital documentation). The findings serve to guide the development of next-generation EPC audit procedures and tools that are technically robust, regulation-aligned, and practically implementable across a variety of building contexts and regions in the EU. The feedback collected helps identify the strengths and limitations of commonly used methods and offers valuable insights into on-the-ground realities in EU countries, where regulatory frameworks differ significantly and standardized inspection methods may still be lacking.

Que Technologies Input:

Que Technologies, as a partner, provided two tools that they are using for collecting data and calculating EPCs. It focuses on aspects such as:

- Tool description and primary functions
- Technology and data collection methods used
- Key features, accuracy, reliability
- Cost and resource requirements
- Advantages and limitations
- Potential for integration with Project KERNELS, especially regarding interoperability and support for improving EPC assessments

Table 8- First questionnaire feedback received from Que Technologies

Category	Details
Tool/Technique Name	***Enter the name of the tool or technique being assessed*** **BIM Authoring Tools (Revit & Archicad)**
Developer/Owner *(If Available)*	***Specify the entity that developed or owns the tool/technique*** ***Autodesk (Revit), Graphisoft (Archicad)***
Description	***Provide a brief description of the tool or technique, including its purpose and primary functions*** Building Information Modelling (BIM) software platforms enabling the creation, management, and documentation of digital models representing the physical and functional characteristics of buildings. Revit excels in US/UK compliance, while ArchiCAD specializes in EU standards.
Technology Used	***Specify any technologies used (e.g., AI, IoT, mobile applications, drones, thermal imaging, etc.)*** • 3D modelling, • parametric design, • cloud collaboration, • interoperability via open standards like IFC, DWG, gbXML
Data Collection Method	***Describe how data is collected (e.g., manual inspection, automated sensors, remote monitoring, etc.)*** • Manual input of U-values, HVAC specs • Operational data from smart meters (Revit Tandem, ArchiCAD BIMcloud)
Key Features	***List the main features of the tool/technique (e.g., real-time data capture, cloud storage, automated reporting, etc.)*** • parametric object modelling • multidisciplinary coordination • automated documentation • visualization • native and open BIM support including IFC export/import
Accuracy & Reliability *(If Available)*	***Indicate how accurate and reliable the tool/technique is compared to conventional methods*** • High technical and geographic representation accuracy • reliant on accurate user input and continuous model management. • Real-time collaboration (BIM 360/BIMcloud),
Cost & Resource Requirements *(If Available)*	***Provide cost estimates (if available) and the resources required (hardware, software, skilled personnel, etc.)*** • Revit: €2,500/year (with BIM 360) • ArchiCAD: €2,200/year (with BIMcloud)
Advantages	***List the key benefits, such as efficiency gains, cost reduction, improved accuracy, etc.*** • Improves design coordination • data consistency across disciplines • lifecycle management • enables energy and performance analysis via IFC export
Limitations & Challenges	***Identify any drawbacks, such as high costs, complexity, regulatory barriers, etc.*** • High initial setup and learning curve • potential data loss during IFC exchanges if models are poorly structured
Potential for Integration with Project KERNELS	***Assess how the tool/technique could complement or integrate with Project KERNELS, focusing on interoperability, data flow, and contribution to EPC assessment improvements*** Very high- IFC export enables interoperability with other simulation and analysis tools, facilitating seamless integration into a multi-tool energy performance ecosystem as planned by KERNELS

The first tool used provides an in-depth analysis of BIM Authoring Tools, specifically focusing on Revit by Autodesk and Archicad by Graphisoft which are integral to the Building Information Modelling (BIM) process, enabling the creation, documentation, and management of digital building models. These platforms make use of a variety of technologies, such as cloud-based collaboration, parametric design, and 3D modelling. These technologies require manual data collection, including the entry of crucial building factors like HVAC specs and U-values.

In terms of expenses and resources, Archicad costs about €2,200 a year with BIMcloud, whereas Revit costs about €2,500 a year with access to BIM 360. Both demand for strong computer infrastructure and qualified staff, including architects and BIM coordinators. Improved design coordination, better data integrity, efficient lifecycle management, and the capacity to do energy and performance analysis through IFC exports are some benefits of these tools. Furthermore, the potential for integration with Project KERNELS is stated as very high. IFC interoperability enables seamless data exchange with other simulation and analysis tools, supporting the creation of a multi-tool energy performance ecosystem. On the other hand, the complexity of the software can be challenging and present a barrier to new users, and there is a risk of data loss during IFC exchanges, especially if models are not well-structured.

Table 9– Second questionnaire feedback received from Que Technologies

Category	Details
Tool/Technique Name	***Enter the name of the tool or technique being assessed*** ***Energy Simulation Tools (DesignBuilder, IESVE, IDA ICE)***
Developer/Owner *(If Available)*	***Specify the entity that developed or owns the tool/technique*** ***DesignBuilder Software Ltd. (DesignBuilder), Integrated Environmental Solutions (IES VE), EQUA Simulation AB (IDA ICE)***
Description	***Provide a brief description of the tool or technique, including its purpose and primary functions*** • Dynamic simulation software used to assess a building's energy performance, environmental conditions, HVAC design, and regulatory compliance. • Advanced energy modelling tools for EPCs, compliance, and retrofit analysis. DB is user-friendly, IESVE dominates UK SAP, and IDA ICE leads in EU Passive House/nZEB.
Technology Used	***Specify any technologies used (e.g., AI, IoT, mobile applications, drones, thermal imaging, etc.)*** • Energy Plus simulation engine (DesignBuilder), • proprietary engines (IES VE, IDA ICE); • 3D thermal simulation • daylighting analysis • interoperable file standards (IFC, gbXML)
Data Collection Method	***Describe how data is collected (e.g., manual inspection, automated sensors, remote monitoring, etc.)*** Manual entry or import of building geometry and systems data (often via IFC from BIM models) • BIM geometry (Revit/ArchiCAD via IFC/gbXML) • Weather files (EPW/TMY3)
Key Features	***List the main features of the tool/technique (e.g., real-time data capture, cloud storage, automated reporting, etc.)*** • Dynamic energy simulation • HVAC systems modelling • compliance checking • daylight and comfort analysis • support for importing building models via IFC for easier setup
Accuracy & Reliability *(If Available)*	***Indicate how accurate and reliable the tool/technique is compared to conventional methods***
Cost & Resource Requirements *(If Available)*	***Provide cost estimates (if available) and the resources required (hardware, software, skilled personnel, etc.)*** • DesignBuilder: €1,500/year • IESVE: €4,000/year • IDA ICE: €3,000/year
Advantages	***List the key benefits, such as efficiency gains, cost reduction, improved accuracy, etc.*** • detailed and customizable simulations; • support sustainable design and regulatory compliance; • benefit from streamlined workflow when models are imported via IFC
Limitations & Challenges	***Identify any drawbacks, such as high costs, complexity, regulatory barriers, etc.*** • Detailed data input is required; • model setup can be time-consuming; • outputs can be complex for non-specialists
Potential for Integration with Project KERNELS	***Assess how the tool/technique could complement or integrate with Project KERNELS, focusing on interoperability, data flow, and contribution to EPC assessment improvements*** Very high; IFC compatibility allows for easy connection between BIM-based modelling and dynamic performance analysis within KERNELS workflows

The second table provided is similar, but it is a comprehensive assessment of three energy simulation tools by Que Technologies: DesignBuilder, IESVE, and IDA ICE. These tools are used to assess a building's energy performance, environmental factors, and HVAC system design. IESVE is a leading SAP compliance solution in the UK, DesignBuilder is known for its user-friendly interface, and IDA ICE is extensively used throughout the EU, especially for projects that adhere to Passive House and virtually zero-energy building (nZEB) requirements [8].

These tools include advanced technologies such as, dynamic energy simulation engines (EnergyPlus in DesignBuilder and proprietary engines in IESVE and IDA ICE), 3D thermal modelling, and daylighting analysis. Additionally, they facilitate the effective integration of BIM models from platforms like Revit and Archicad by supporting interoperable file standards like IFC and gbXML. These technologies use a hybrid approach to data collection, combining data imports from BIM models with human entry of building geometry and systems information. Furthermore, they include environmental factors into the simulation process by using standardized meteorological datasets (such EPW and TMY3), allowing for comprehensive, context-aware performance modelling that supports both new building design and retrofit studies.

Moreover, DesignBuilder is priced at approximately €1,500 per year, IESVE at around €4,000, and IDA ICE at €3,000 annually. The effective use of these tools requires not only the software itself but also skilled professionals with expertise in energy modelling, as well as sufficient computational resources. They offer substantial benefits in terms of simulation accuracy, compliance support, and design optimization, despite their comparatively expensive costs. Additionally, it can take a lot of effort to set up comprehensive models, a significant amount of input data is needed, and the simulation results might be challenging for non-specialists to understand.

These tools have very high integration potential in the context of Project KERNELS. The project's objective of developing a multi-tool, interoperable energy performance ecosystem is supported by its conformance to IFC standards, which guarantees seamless communication with BIM platforms.

EUBAC Input from Stakeholders:

The questionnaire provided to EUBAC is designed to capture real-world stakeholder feedback from industry professionals engaged in building operations and energy performance evaluations. The questionnaire reached to users in France and Greece and gathered information about the tools that users are using for calculating EPCS. Its main goal is to compile information about real-world difficulties, accepted procedures, and particular requirements of energy system evaluations and EPC audits. From the perspective of users and stakeholders, feedback from Siemens France and Belimo is presented, highlighting field-level limitations like antiquated building systems, a lack of digital interfaces and standardized inspection tools, and the crucial role of on-site staff. The questionnaire also emphasizes the need for tools to deal with technological factors.

- ***Feedback provided from <u>Belimo:</u>***

General Information

Table 10 - Template regarding general information about the company Belimo

Category	Your Input
Organization Name	*Belimo - RetrFit+ Productmanagement tool*
Contact Person	*Juergen Maass*
Stakeholder Type	*Select one or more:* *☐ EPC Assessor* *☐ Building Owner/Operator* *☐ Certification Authority* *☐ Real Estate Professional* *☐ Technology Provider* *☐ Research Institution* *☐ Standards Organization* *x ☐ Other: _____*

Needs and Requirements Assessment

Table 11- Needs and requirements input received from Belimo

Category	Your Input
Current EPC Inspection Methods Used	*An ISO52120-based evaluation tool developed by Belimo is currently being used in projects of the Belimo partner organization [9]. This tool makes it possible to quickly record the existing actual situation and present the savings potential (energy, CO2 costs) based on a definable possible future situation.*
Challenges in EPC Assessments	*Often there are no documents or efficient digital interfaces to the property, which means that on-site inspections are often necessary. Many properties are very old and often have little or no building automation*
Desired Tool Features/Functionalities	*Inclusion of additional physical relationships. For example, hydraulic properties of assemblies (valves, pumps) or volume flow ratios in ventilation.* *Consideration of system properties such as single pipe heating systems or gravity heating systems. Both are particularly widespread in the DACH region and push pure automation solutions to their limits.*
Operational Constraints	*Great lack of knowledge about the status of the systems, inadequate qualifications of the operating personnel, and outdated automation and communication technology. Too little knowledge and confidence in possible methods, resulting in an extremely long decision-making process for measures.*
Best Practices or Recommendations	*Active involvement of the operating personnel on site in properties, even if documentation or technology is inadequate, then the employees in the property are a very good source of practical information. These people are also essential for the success of the implementation of measures.*

Belimo currently uses RetrFit and Productmanagement tool, an evaluation method based on ISO 52120 that they developed and employ in partner projects [9]. This tool calculates possible energy, CO_2, and cost savings based on future scenarios and makes it easier to swiftly record a building's existing status.

According to the feedback received, there are several challenges regarding the efficiency of EPC assessments. One major issue stated is the lack of documentation and digital interfaces for existing buildings, which often necessitates time-consuming on-site inspections. Additionally, many of these buildings are quite

old and lack any form of modern building automation, further complicating the assessment process. The stakeholder suggests that to overcome these constraints, future EPC tools should include more thorough system modelling, paying attention to the volume flow dynamics in ventilation systems and the hydraulic behaviour of pumps and valves. Crucially, it is mentioned that some heating systems that are typical in the DACH region, such as gravity and single pipe heating systems, require tools that consider them because they are frequently incompatible with conventional automation technology.

According to operational reports, there is a substantial knowledge gap among staff members, which is challenged by automation and communication systems. This leads to a general lack of trust and comprehension of assessment methodologies, which causes decision-making to take longer when energy-saving measures are considered.

Actively involving on-site staff in the inspection and decision-making process is a significant suggestion. It is noted that these people frequently possess important practical knowledge about building systems and are essential to the successful implementation of energy efficiency measures, even in situations where documentation or technology is missing. The significance of practical usability, system-specific functionality, and human-centric design in the creation of future EPC inspection tools is highlighted by this stakeholder input.

- ***Information provided by Siemens France:***

An overview of the Energy Performance Certificate (EPC) market in France is given by Siemens France, which also explains that the DPE (Diagnostic de Performance Énergétique) is the equivalent in France. A required assessment for determining a building's energy performance is the DPE. A certified diagnostician with professional liability must perform it. Crucially, the Ademe observatory, which is in charge of centralizing this data, must provide a 13-character identification number for the DPE to be considered authentic [10].

In terms of tertiary (non-residential) buildings, Siemens stated that France does not currently issue a true “certificate” that reflects ISO 52120-1 energy performance classes [9]. Instead, the regulatory framework consists of two major decrees: Décret Tertiaire and Décret BACS. The Décret Tertiaire applies to buildings over 1,000 m², requiring owners to reduce energy consumption compared to a chosen reference year (between 2010 and 2019) by:

- 40% by 2030
- 50% by 2040
- 60% by 2050

Additional technical improvements are required by the Décret BACS (Building Automation and Control Systems). Buildings with heating or cooling systems larger than 290 kW are required to install BMS and Class C regulatory systems by 2025. By 2027, this threshold is anticipated to be lowered to 70 kW. A specific maintenance contract and room-by-room smart control systems are also required for all new buildings and facilities replacing their generators starting in 2021. The BMS needs to be able to track and evaluate energy usage to spot inefficiencies and direct remedial measures.

A supporting regulation called the Arrêté introduced mandatory BMS inspections at least every five years and within two years of installation or replacement of a connected technical system. The regulated audit includes a functional analysis, verification of operation, compliance review, adjustment assessment, and improvement recommendations. The report must be submitted to the building owner within one month and retained for ten years.

According to the feedback statement, there is a regulatory gap in implementation practices because the French authorities have not yet established the precise procedures or equipment to be utilized for carrying out audits. To assess BEP in accordance with ISO 52120-1 [9], Siemens internally employs its own EPC Tool, which is openly accessible [11]. According to reports, this tool fills in the methodological gaps left by national rules and is widely used in France by experts looking for standardized energy performance assessments.

In summary, France's energy performance landscape is governed more by regulatory obligations for energy reduction and system upgrades than by formal EPCs in the ISO sense. While mandatory frameworks like the DPE, Décret Tertiaire, and Décret BACS set clear goals and requirements, the absence of standardized inspection tools leaves implementation largely to private solutions like Siemens' EPC Tool.

Comparative Analysis of Feedback from the Questionnaires

Across all of theinputs, including the analysis of BIM Authoring Tools, Energy Simulation Tools, Belimo and Siemens France response, several distinctions emerge. These inputs offer diverse perspectives ranging from tool capabilities to regulatory and operational gaps, providing a strong foundation for refining EPC audit procedures and tool development under Project KERNELS and OpenBEP4EU.

The evaluations of energy simulation tools and BIM both stress the value of interoperability through open standards like gbXML and IFC. Model interchange is supported by programs like Revit, Archicad, DesignBuilder, and IDA ICE, which facilitate smooth transitions from design to performance assessment. The Siemens solution used in France, which complies with ISO 52120-1 and bridges the gap where official methods are not offered, echoed this requirement for standardized data transmission [10].

Siemens France and Belimo also both draw attention to the absence of digital infrastructure in older structures. This leads to the necessity for on-site inspections, outdated automation systems, and manual data collection. Siemens France continues further clarifying that although there are legislative targets (such as Décret Tertiaire and Décret BACS), no national EPC certificate that complies with ISO 52120-1 exists, and no formal tools or procedures are established for audits [9].

Belimo additionally emphasize the importance of involving operational staff, especially in older buildings where formal documentation may be missing or outdated technologies are present. The response emphasizes that on-site staff frequently possess crucial informal knowledge, which is necessary for precise diagnosis and effective energy-saving strategy implementation. In keeping with operational realities, France's mandatory BMS inspections also demonstrate a rising regulatory emphasis on functional system evaluation and actionable recommendations that take a people-centric approach. Belimo also draws attention to technical requirements that are frequently missed by generic tools, such as the assessment of hydraulic characteristics, ventilation flow ratios, and support for legacy systems like gravity-based heating and single-pipe systems that are typical in the DACH region. These requirements are usually outside the purview of automated solutions and call for adaptable, context-aware tools.

The collective comments highlight a number of areas where innovation might greatly enhance EPC inspection practices and technologies. The possibility of creating a hybrid EPC inspection tool that combines manual inputs or annotations from on-site staff with automated model-based data from BIM is evident. Both conventionally managed facilities and those with digital equipment would benefit from this.

Given the emphasis on monitoring and analysis in BACS regulations, future tools should be able to connect with BMS platforms and IoT-based sensors. Real-time data could be visualized and benchmarked against predefined EPC classes, enabling both continuous performance assessment and regulatory reporting. Inspection tools and procedures should adhere to a uniform format that complies with national and EU regulations while also being sufficiently adaptable to accommodate the building's particular characteristics, incorporating compliance checklists, graphical summaries, and personalized recommendations to improve the evaluations' effectiveness and usefulness.

Inspection tools could include contextual assistance systems, diagnostic wizards, and on-site training to address the knowledge gap among operators and inspectors. These would facilitate the more widespread and independent use of EPC evaluation tools by assisting users in understanding legal obligations and navigating technical procedures. The innovation should concentrate on matching technical capabilities with

national decree needs (like BACS) and audit obligations [12] in all EU nations where gaps exist, such as in France with no officially approved tools.

Feedback from all four sources indicates a shared need for EPC solutions that are user-friendly, interoperable, and compliant with regulations. The next generation of EPC audit processes and tools can become both technically sophisticated and practically feasible by emphasizing hybrid data integration, technical specificity, user empowerment, and compatibility with smart systems. This will significantly advance the objectives of OpenBEP4EU and Project KERNELS.

The methods and tools established under WP3, especially through Tasks 3.1 and 3.3, will directly inform and improve the EU Kernel EPC Engine created under WP2 in order to guarantee project-wide coherence and practical application. In particular, WP3's automation-based measuring techniques, data gathering methods, and inspection protocols will provide the fundamental data sources for filling out and confirming the calculation engine.

Providing structured, high-quality input data streams from WP3 field assessments (such as building geometry, technical building system specifications, operational behaviour, and environmental conditions) to the data models and calculation routines specified in Tasks 2.2 and 2.4 of the EU Kernel is a crucial area of convergence. Buildings' physical attributes and real-world operational profiles are reflected in the EPC calculations carried out by the Kernel thanks to the creative use of dynamic and static data collecting technologies, including LiDAR, BMS/BACS integration, and digital twins.

Additionally, the WP3 pilots verify that the ontology-based data model supported under Task 2.4 is compatible with data formats and ontologies. Building performance data can be made machine-readable, traceable, and compliant with EU-wide interoperability goals by, for example, semantically uplifting and transferring building data obtained through the innovative inspection protocols to the Kernel's Data Space using common standards (e.g., IFC, gbXML, SAREF).

Furthermore, the reference guidelines for standardizing inputs into the Kernel engine across Member States will be the procedural templates and standardized checklists created under Task 3.3. As mandated by Task 2.3, the integration of SRI-related control functions into WP3 audits and conformity with ISO 52120 further enhance the data relevance for the EPC Kernel and guarantee that computed outcomes take smart readiness variables into account.

A two-way validation loop supports the continuous interaction between WP3 and WP2: WP2's modelling assumptions and parameters are improved by field data and insights from WP3, and the consistency and significance of the inspection data are confirmed by computational outputs from the Kernel. A more dynamic, data-driven, and future-proof EPC framework is made possible by this mutually reinforcing relationship, which ensures that the EPC engine is not only in compliance with EPBD and ISO standards but also supported by solid empirical evidence from real-world assessments.

A2. Technical Specifications of Tools

Table 12 - Technical Specification Tables for EPC Inspection Tools for Building Elements

Tool	What It Measures	Key Specifications
LiDAR Scanner [48]	3D geometry of building exteriors	**Accuracy:** 2 cm at 10 m; 3 cm at 20 m; 5 cm at 40 m
Range	Up to 140 m	
FOV	360° H / ≥59° V	
Output	LAS, E57, IFC	
Standards	Class 1 - IEC 60825-1 [13]	
Power	Li-ion battery	
Connectivity	USB, Wi-Fi	
Thermal Camera [49]	Surface temperature, heat loss	**Accuracy:** ±2 °C or ±2%
Thermal Sensitivity	<80 mK (0.08°C)	
Temp Range	-30 to +650 °C	
Resolution	160×120 to 320×240	
Standards	EN ISO 6781-1 [5], ISO 18436-7 [15]	
Power	Battery/USB	
Calibration	Annual	
3D Scanner [50]	Interior spatial data	**Accuracy:** ±0.4 at 10m
Range	0.5–45 m	
FOV	360° H / ≥59° V	
Output	OBJ, STL, IFC	
Standards	Class 1 - IEC 60825-1 [13]	
Power	Battery	
Connectivity	USB, Wi-Fi	
Virtual Reality [51]	Immersive simulation of geometry/energy	**Input:** IFC, OBJ, gbXML
Resolution	5K resolution	
FOV	120° wide field of view	
Platforms	HTC Vive	
Standards	IEC 5927	
Drone [52]	Roof/ façade geometry and temperature	**Payload**: LiDAR, IR cameras

Flight Time	40 -50 min	
Standards	ISO 21384-3 [24], EASA [26]	
Battery	Li-ion battery	
Thickness Gauge [53]	Insulation or material layer thickness	**Accuracy:** ±0.3 mm
Range	0.2–120 mm	
Output	Digital display/logging	
Standards	ISO 2808 [28], ISO 16809 [29]	

Technical Building Systems

Table 13 - Technical Specification Tables for EPC Inspection Tools for TBS

Tool	What It Measures	Key Specifications
Temperature Sensor [54]	Pipe or air temperature	**Accuracy**: ±0.2–0.5 °C
Range	-30 to +150 °C	
Mounting	Clamp, probe	
Output	0–10V, 4–20 mA, Modbus	
Standards	EN ISO 7726 [31], EN 1434-2 [3]	
CO_2 Meter [55]	IAQ, occupancy level	**Accuracy**: ± 3%
Range	0–50000 ppm	
Output	Analog/digital	
Mount	Wall mount	
Standards	ISO 16000-26 [33], EN 50543 [32]	
Flow Meter [56]	Volume of water/fluid in heating systems	**Accuracy**: ±1–4%
Range	0.7–285 m³/h	
Flow speed m/s:	For flow speed range: 0.1-10 m/s	
Standards	EN 1434 [3], ISO 4064 [37]	
Heat Meter [57]	Energy transferred via heating/cooling fluids	**Accuracy:** ±2–3%
Temperature Range	2 °-180 °C	
Output	M-Bus, Modbus	
Standards	EN 1434	
Lux Sensor [58]	Indoor light levels in lux	**Accuracy:** ±4%
Range	200–100,000 lux	
Output	Analog, Digital, Wifi,	
Resolution	0.1 Lux	
Standards	EN 12464-1 [38], ISO 8995-1 [39]	
Irradiance Sensor [59]	Incoming solar radiation on surfaces	**Accuracy**: ±2%
Range	0-2000 W/m2	
Spectral Range	0,3µm - 3µm	
Class	Class A – Class B – Class c	
Output	Analog, Digital, Wifi	

Standards	ISO 9060:2018 [42], IEC 61724-1[43]