D1.5–KEY PERFORMANCE INDICATORS FOR PLATFORM PERFORMANCE ASSESSMENT

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DISCLAIMER

EXECUTIVE SUMMARY

This deliverable presents key performance indicators developed to assess the performance of the InBetween platform. The corresponding performance assessment addresses the issues of energy efficiency and thermal comfort, as well as user engagement and satisfaction.
The determination of key performance indicators presented here is primarily based on a literature review of research papers and surveys, project reports and relevant standards. Key performance indicators are selected based on the following criteria: relevance, completeness, availability, measurability, reliability, familiarity, non-redundancy, independence.
This selection leads to a total of twenty key performance indicators. In terms of energy consumption, final energy, both total and disaggregated, as well as source energy, energy costs and CO2 emissions, are considered. Savings against a baseline period are also calculated. Two indicators are also used to assess the corresponding loads, relevant for grid impact and renewable self-consumption. For thermal comfort, indicators based on international and European standards are used. In terms of user engagement, a recency index is assumed to be representative of the regularity of platform use, and another indicator makes it possible to assess to which extent users follow recommendations made by the system.

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1 INTRODUCTION

The InBetween project aims at inducing behavioural changes towards more energy efficient lifestyle by using ICT technologies to assist users in identifying energy wastes and learning how they can conserve energy, and to motivate them to do so. This is to be achieved with the development of a collaborative cloud-based platform offering advanced energy services, to which we refer as "InBetween platform" in the following. This document presents key performance indicators developed to assess the performance of the InBetween platform.

1.1 MOTIVATION

An important objective of the project is to evaluate how well the InBetween platform will fulfill its intended purposes in different conditions, in other words to assess its performance. As the aim of the InBetween project is to increase energy efficiency through changes in use behaviour, indicators are necessary to quantify energy efficiency. Besides, the user-centric approach applied in the project calls for an assessment of user engagement and satisfaction with the platform.

1.2 BACKGROUND

Key performance indicators can be defined as performance indicators on which emphasis is put because they reflect goals and allow the progress towards those goals to be measured [1].

As the InBetween project deals with energy consumption and user behaviour in buildings, the issue of building performance plays a significant role. Various domains of building performance may be distinguished, corresponding to different purposes of buildings. Rating schemes for "total quality assessment", for example, cover domains like energy efficiency (energy use, lighting efficiency, renewable energy), water efficiency, materials (reuse, embedded energy, durability), site (land use, landscape design, microclimate), indoor environment quality (thermal comfort, daylight, indoor air quality), waste and pollution [2].

Efficiency in general can be defined as the property of requiring less effort or producing less waste to achieve a certain effect, provide a certain service or produce a certain good. Energy efficiency consists in providing a service with minimum energy expenditure. The efficiency of certain technical components can be simply expressed as the ratio of useful energy output by the component to the energy supplied to the component. For complex systems such as those formed by buildings and building services interacting with human occupants, however, defining efficiency is a more difficult task, as the services provided are multiple and difficult to quantify. Among the services provided by buildings, thermal comfort is of primary importance in terms of required energy.

Thermal comfort is only one aspect of environmental comfort, which also comprises visual and acoustic comfort. Air quality also plays an important role, and is often enforced by the same heating, ventilation and air-conditioning (HVAC) systems as thermal comfort. Air quality as well as thermal characteristics of the built environment have an impact on well-being, health and productivity [3]. Energy-intensive services like domestic hot water may also be combined with HVAC systems. However, their interaction with building design is less direct.

1.3 OBJECTIVES

The expected outcome of the activity reported in this deliverable is a list of key performance indicators. The list should meet criteria defined below, which include that it should be as comprehensive but also as concise as possible. However, a first step is to determine for which purposes exactly the selected indicators shall be used.

The selected KPIs will be used:

- To evaluate the performance of the platform:
  - Comparing the performance of the platform on distinct cases;
  - Evaluating the performance of buildings/dwellings/apartments using the platform before and after its introduction;
  - Evaluating gains ascribable to the platform in terms of energy use and thermal comfort;
  - Evaluating engagement and satisfaction of end users with the platform.
- Indirectly, to support platform functions with indicators:
  - for optimization in advanced energy services,

- for monitoring in advanced energy services,
- used indirectly for feedback given to occupants,
- used for point calculation in an engagement strategy,
- displayed to, or accessed by end users.

The definition of KPIs for the InBetween platform interacts with other project activities. In particular, Task 2.3 (EE Performance Evaluation (Services) and User Benchmarking) and Task 5.1 (InBetween Platform Feasibility Assessment).

Before the definition of key performance indicators, the considered scope of performance should be specified. Building performance is as complex as the different uses of buildings. Environmental quality of buildings, which can be seen as one domain of performance, encompasses multiple aspects, including land use, atmosphere-related impacts, water resources, ecology, noise, visual impact, indoor air quality, energy, reuse and recycling potential and waste management [1]. Energy consumption is only one of the many environmental impacts of buildings. Still, the focus on it can be justified by its predominant relevance for the operation of existing buildings, as, in this case, a large share of environmental impacts can be attributed to energy use.

Apart from energy use, thermal comfort and air quality should also be considered, as they influence the health, productivity and satisfaction of occupants. Aspects of performance not considered here include building health, including the avoidance of mould, visual comfort, including illuminance level and glare, as well as acoustics and noise protection.

1.4 METHOD

The determination of key performance indicators presented here is primarily based on a literature review of research papers and surveys, project reports and relevant standards. Based on this, summary and analysis are carried out taking into account criteria described in the next paragraph. The main steps are thus the analysis of literature, the selection of appropriate KPIs from them, and their adaptation or the definition of additional KPIs to meet all requirements. It is acknowledged that metrics should be related to goals. A general approach for developing metrics is to start by stating goals, then identify signals sensitive and specific to these goals, and finally define how these signals are transformed into metrics [4].

1.5 CRITERIA

The criteria used for KPI selection follow those used in European initiative CIVITAS [5] and European project CITYkeys [6]: relevance, completeness, availability, measurability, reliability, familiarity, non-redundancy, independence.

- *Relevance* expresses the demand that each performance indicator should be significant for the evaluation process.
- *Availability* of data required for the calculation of each indicator is a prerequisite.
- *Measurability* refers to the possibility of producing values (objectively or subjectively) for the indicators.
- *Reliability* involves that indicators should be clearly defined and their calculation easy.
- *Familiarity* corresponds to the demand that the indicators should be easy to understand.
- *Completeness* requires the set of indicators to cover all aspects of the evaluated system relevant for the evaluation. Here, selected indicators should cover all the performance aspects on which the platform can have an impact. (holistic performance assessment)
- *Non-redundancy* of the set of indicators means that the same aspect of the system should not be measured by two indicators.
- *Independence* requires that the preferences regarding an indicator should not depend on the values of other indicators.

One may add broad applicability as an important criterion [7] which overlaps with availability and reliability, when considering different applications of the developed platform.

Another property to consider is sensitivity, which contributes to indicator relevance. The sensitivity of an indicator is its ability to reflect small changes of the measured performance. Indicators taking continuous values are likely to be more sensitive than indicators with discrete values, and granularity can play an important role for sensitivity of the latter indicators [2].

2 LITERATURE REVIEW

Task 1.4 was mainly intended as a "desk research". This chapter presents the literature review carried out to support KPI definition. After a general description of sources, it is structured according to the three domains of energy use, comfort indicators and user engagement.

2.1 SOURCES

2.1.1 Scientific literature

Scientific literature was used to frame the information found in existing standards and European projects with a broader perspective and, where needed, to provide deeper insight than could be found in standards or information regarding domains not yet standardized.

The review of literature was not confined to the performance of any one type of system. One may assess "building performance", or the performance of technical systems, or "the performance of an organization and its services" [7], whereby organizational performance is linked to a facility's performance [7]. In the context of facility management, one can distinguish between financial, functional, physical and survey-based KPIs [7].

Hitchcock [8] relates performance metrics to performance objectives, and proposes to organize them hierarchically, starting from performance objectives and following a metric (e.g. whole building energy use) at different levels.

2.1.2 Standards

Standards directly relevant to some of the performance aspects considered here have been published, as summarized in Table 1, for instance for thermal comfort and for the evaluation of energy performance.

Thermal comfort is covered by a series of standards on "ergonomics of the thermal environment published by the International Organization for Standardization (ISO).

Table 1: Selection of standards relevant to InBetween KPI definition.

Standard	Title
ISO 7730	Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
ASHRAE Std. 55	Thermal Environmental Conditions for Human Occupancy.
EN 15251	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
ISO 7726	Ergonomics of the thermal environment -- Instruments for measuring physical quantities
EN 13779	Ventilation for non-residential buildings. Performance requirements for ventilation and room-conditioning systems
EN 15217	Energy performance of buildings – Methods for expressing energy performance and for the energy certification of buildings
EN 15203	Energy performance of buildings - Assessment of energy use and definition of ratings
ISO 52003	Energy performance of buildings - Indicators, requirements, ratings and certificates
ISO 52018	Energy performance of buildings -- Indicators for partial EPB requirements related to thermal energy balance and fabric features
ASHRAE Standard 105	Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions
ASHRAE Guideline 14	Measurement of Energy and Demand Savings

ISO 37120	Sustainable development of communities -- Indicators for city services and quality of life
EN 15221-3	Facility Management. Guidance on quality in Facility Management
ISO 14031	Environmental management — Environmental performance evaluation

ISO 52003 is part of a series of international standards aimed at the harmonization of methodologies for assessing building energy performance, referred to as EPB (energy performance of buildings) standards [9]. It deals with calculated and measured energy performance, the latter being defined as "energy performance based on weighted measured amounts of delivered and exported energy". Performance indicators are used to assess building "features", which may relate to single building elements, combinations thereof, or whole buildings [9]. The assessment of the energy performance of specific technical building systems is handled in the appropriate part of EN 15241, EN 15243 and EN 15316 series. With regards to energy efficiency, a variety of national standards and guidelines are also defined at the national level.
Methods for the calculation of energy savings following interventions are specified for instance in ASHRAE guideline 14. These and other methods for recording energy savings are based on the International Performance Measurement and Verification Protocol (IPMVP) published by the Efficiency Valuation Organization (EVO).

2.1.3 European projects

The European Commission has funded many projects dealing with energy efficiency, the outcomes and methods of which can be reused.
In the CONCERTO initiative, demonstration activities at the city and neighbourhood levels were funded by the European Commission without specific technology targets and assessed with a common methodology. The unified assessment methodology developed for the CONCERTO initiative included rules defining system boundaries for performance assessment, performance indicators, ways to define baselines, and a structured method for data gathering and data processing [10]. Due to limitations in monitoring data availability, baseline definition was based on design data rather than measurements. As the demonstration activities spanned several European countries, a challenge was to harmonize the calculation of indicators, notably in terms of floor areas, heating and cooling degree days, and primary energy factors [10].
For the Smart City Information System (SCIS), successor of the CONCERTO initiative, KPIs were also defined and published in a guide [11].
The ICT-PSP (ICT-Policy Support Programme) energy efficiency projects proposed ICT-based services for the support of energy efficiency, and agreed on a common methodology to assess the energy savings achieved with these services [12]. The results are managed and displayed in the online software eeMeasure[1]. European projects Euroclass [14], Europrosper[15], Eplabel [16] and ENPER-EXIST[17] have studied the complexity associated with the elaboration of a database of building energy consumptions in Europe.

Table 2: List of relevant European projects

Project acronym	Project title	Relevant aspects
SCIS	EU Smart Cities Information System	Indicators for energy use, emissions, economic performance, mobility and others.
CONCERTO	CONCERTO initiative	Unified assessment methodology for multiple demonstration activities.
eeEmbedded	Collaborative holistic design laboratory and methodology for energy-efficient embedded buildings	KPI-based holistic multidisciplinary design.

[1] http://eemeasure.smartspaces.eu/

BECA	Balanced European Conservation Approach – ICT services for resource saving in social housing	Evaluation of savings achieved with resource management services and resource user awareness services for several pilot sites (common approach of ICT-PSP projects).
eSESH	Saving Energy in Social Housing with ICT	Evaluation of savings achieved with energy management and awareness services (ICT-PSP approach)
bestenergy	Built Environment Sustainability And Technology in Energy	List of indicators, including primary and delivered energy consumption.
DEEP	De-risking energy efficiency platform	Economic indicators such as payback time and avoidance cost (Eurocent/kWh).
ExcEED	European Energy Efficient building district Database	Key performance indicators to be developed to quantify and benchmark energy efficiency at building and district level.

In the context of design, projects like HOLISTEEC [13] and eeEmbedded[2] defined key performance indicators. The H2020-funded project CITYkeys delivered a list of indicators for smart cities and smart city project [6].
European tools dealing with building energy consumption on a large scale include the EU Building Stock Observatory[3], which aggregates monitored data on the energy performance of buildings in Europe. Common challenges encountered at all scales include the difficulty of harmonising data collection, for instance in defining floor area in the same way [14][4].

2.2 QUANTIFICATION OF ENERGY USE

This section reviews different methods used for the quantification of building energy use and efficiency, focusing on existing buildings.

2.2.1 Energy efficiency

The concept of energy efficiency is complex enough for its interpretation in specific cases to be subject to discussion. Patterson [15] argues that a series of indicators are needed to quantify energy efficiency, for which there does not exist one unequivocal quantitative measure. This can be related to the difficulty of defining precisely the useful output and the energy input in each case. According to the units in which energy input on the one hand and output are expressed, one can divide energy efficiency indicators into several groups [15]:

- Thermodynamic indicators, which are physical quantity ratios or measures relating actual energy usage to an ideal process;
- Physical-thermodynamic indicators, where the output is measured in physical units, for instance of mass or volume, and the input in terms of energy;
- Economic-thermodynamic, where the output is measured in monetary terms and the input in terms of energy;
- Economic indicators, where both input and output are measured in monetary terms.

For HVAC energy efficiency, Pérez-Lombard et al. [16] distinguish four levels (global, services, subsystems, equipment) and define efficiency indicators for each of them. The energy efficiency of services is expressed as the ratio of ideal energy

[2] http://eeembedded.eu/

[3] https://ec.europa.eu/energy/en/eubuildings

[4] Buildings Performance Institute Europe (BPIE): “EU Buildings under the microscope” p.25

demand for a service (e.g. space heating) to its actual energy use. Ideal energy demand cannot be measured and must be calculated. Subsystems efficiency can be defined for heat generation, cool generation, water transport and air transport [16]. The same article also advocates the use of demand ratios for heating and cooling, defined as the ratio of real thermal demand to ideal thermal demand of generation. In general, energy performance assessment requires not only the quantification of energy use, but also "benchmarking criteria and comparison scale" [17].

2.2.2 Energy classification instruments

Performance assessment methods for existing buildings may have two main purposes: performance classification and performance diagnosis [17]. While the InBetween project deals with a certain kind of performance diagnosis, in which occupant-related inefficiencies are detected, the objective pursued here is rather classification, that is the assessment and communication of relative energy efficiency between different buildings or building parts. Energy classification instruments include energy labelling, energy rating, energy certification and energy benchmarking [17].
We start by presenting energy rating as defined in European and international standards, review building codes and energy certificates in different countries, then present approaches to benchmarking, energy efficiency labels and finally total quality assessment schemes.
In general, energy quantification methods can be classified in three categories: calculation-based, measurement-based and hybrid methods [17], of which the first one is of less interest in our case.

Energy rating

Energy rating is defined in EN 15603 as "evaluation of the energy performance of a building based on the weighted sum of the calculated or measured use of energy carriers" [18].
EN 15603 proposes two main types of energy ratings for buildings: calculated and measured energy rating. It is acknowledged that these two ratings cannot be directly compared, but the difference between them "can be used to assess the cumulative effects of actual construction, systems and operating conditions versus standard ones and the contribution of energy uses not included in the calculated energy rating".
Depending on data used, EN 15603 further distinguishes between:

- standard energy rating calculated with actual building data and standard use data set;
- design energy rating calculated with design building data and standard use data set;
- tailored energy rating calculated with actual building data and actual climate and occupancy data;
- measured energy rating based on measured amounts of (delivered and exported) energy.

EN 15603 collates results and methods from other standards dealing with specific services, such as EN 15316 for heating systems and EN 15243 for ventilation systems. Considered services for a calculated energy rating are heating, cooling, ventilation, domestic hot water and lighting. Other energy uses, resulting from activities such as cooking, laundry or computer equipment, may be included or not, optionally, depending on a national decision. In 2018, EN 15603 should be replaced by EN ISO 52000-1.

Building codes and energy certificates

Building energy codes, or building energy regulations, establish minimum requirements for energy efficiency in new buildings or in renovated buildings. The approach used to define these requirements can be either prescriptive and performance-based. The prescriptive approach, also referred to as feature-specific [17], sets criteria for specific features, such as the thermal conductivity of wall constructions. Its simplicity explains that it was historically the first to be used [19]. The performance-based approach, on the other hand, uses performance indicators calculated for the whole building and compared against reference values which may be defined in a variety of ways. Building codes generally derive performance indicators from calculations rather than from measurements.
A paper of the International Energy Agency (IEA) [20] describes the variety of energy efficiency requirements found in building codes across the world and makes a finer distinction between approaches followed by building codes. Aside from prescriptive regulations setting separate requirements for building parts and system components, trade-off regulations exist, where a trade-off between values corresponding to different requirements is allowed. On the performance-based side, regulations may use a comparison of calculations carried out for a model (reference) building and an "actual" building,

or an energy frame (maximum of energy loss), or limits expressed in terms of final or primary energy consumption, and/or emissions. Finally, hybrid regulations may combine requirements of several of the above-mentioned types. For instance, the Austrian regulation sets prescriptive requirements in terms of U-values, as well as performance-based requirements in terms of maximum calculated specific energy demands [21].

The Energy Performance of Buildings Directive (EPBD) [22] makes it mandatory for EU countries to set minimum performance requirements for new buildings and major renovations, and requires energy performance certificates (EPC) to be issued for buildings to be sold or rented. In addition to this, it states that "all new buildings must be nearly zero energy buildings by 31 December 2020". However, the definition of NZEB and the formulation of performance indicators is up to the Member states. One may note that a revision[5] of the Energy Performance of Buildings Directive is in preparation, including updates supporting long term building renovation strategies and encouraging the use of information technologies for efficient building operation.

Certification usually implies an energy rating process and an energy labelling process [17]. National rules defining energy performance certificates (EPC) include a general calculation method, a scheme for labelling and displaying energy performance, and the setting of minimum requirements for existing buildings and major renovations [17]. Some of the national energy certification schemes are summarized in Table 3.

Table 3: Selection of national energy certificates.

Country	National name	Defining standards or laws
Germany	Energieausweis	Energieeinsparverordnung (EnEV)
Austria	Energieausweis	OIB RL6 ÖNORM H 5055 – Energieausweis für Gebäude ÖNORM B 8110 Wärmeschutz im Hochbau ÖNORM H 5055,5056,5057,5058,5059 – Gesamtenergieeffizienz von Gebäuden
Luxemburg	Energiepass[6]	Verordnung zur Energieeffizienz von Wohngebäuden vom 30. November 2007
France	Diagnostic de performance énergétique	Réglementation thermique 2012
Spain	Certificación de la eficiencia energética de los edificios	Real Decreto 235/2013
Italy	Attestato prestazione energetica	Legislative decree 19 August 2005, n. 192

For the setting of requirements, different energy-related parameters are used in different countries:

- Austrian energy certificates use:
  - Space heat demand;
  - Heating energy demand, including heat demand for space heating and hot water, as well as system losses;
  - Final energy demand, including heating energy demand, cooling energy demand, ventilation energy demand and typical energy needs for other equipment;
  - A coefficient for total energy efficiency f_{GEE} based on a ratio of final energy demand.
- The German energy certificate (*Energieausweis*) identifies primary energy demand, final energy demand and an energy use coefficient.
- French thermal regulations for buildings is based on:
  - Primary energy demand, with bounds based on building type, geographical location, height, floor area, and global warming potential of used energy;

[5] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016PC0765

[6] Energiepass was also the name of the first energy certificate prototype introduced by the German energy agency in 2004.

- A bioclimatic index expressing a building's performance in terms of insulation, orientation, solar gains, natural lighting etc.

Reference values and areas vary. As stipulated in EN 15603, factors used for instance for the calculation of primary energy use and CO2 emissions are defined at a local, typically national level [18].

Building energy benchmarking

According to the scope and depth of comparison, Wang et al. [17] distinguish between whole-building benchmarking and hierarchical classification. Methods for whole-building benchmarking can be grouped into statistical benchmarking, which presupposes the availability of performance data of a wide number of sample buildings, and calculated benchmarks [17]. Calculated benchmarks mostly imply the calculation (or simulation) of performance of a national/self-reference building.
In statistical benchmarking, features influencing building energy use can be used to define groups of comparable buildings [23] and/or to normalize energy use [17]. Examples of such features are building type and climate zone (usually used for grouping), and floor area (usually used to normalize energy use). Statistical benchmarking can use a simple normalized model, whereby the energy performance indicator is obtained by normalizing energy use with floor area, or a regression-based model using more building features [17].
An example of benchmarking with a simple normalized model is Cal-Arch[7], based on California's 1992 Commercial End Use Survey (CEUS). An example of benchmarking with a regression-based model is Energy Star.
The Energy Star label is developed by the US Environmental Protection Agency (EPA) [24]. Its aim is to provide a "peer group comparison". The 1-100 ENERGY STAR score calculation is based on the US Commercial Building Energy Consumption Survey (CBECS). For each peer group (of buildings of a given type), a least squares regression is carried out to predict source energy consumption using building features. Features used for regression are related to building operation, and include the number of opening hours and weather data, while features related to building technologies are not used.

Labels

Energy labelling involves energy rating, but more specifically it means assigning a performance label to a building, based on a well-defined scale [19]. Label schemes differ in the granularity of this scale, and on whether performance is measured or calculated.
Labels can be defined on the basis of benchmarking approaches, as mentioned in the previous paragraph. This is the case of the Energy Star label, or of ASHRAE's Building Energy Quotient rating programme[8]. The scale used for this building energy labelling program consists of a ratio of source Energy Use Index for the subject building, divided by median source EUI for that type of building in that climate zone.
Other labels are based on calculated values, with or without experimental verifications. The Swiss Minergie label defines three standards: Minergie, Minergie-P and Minergie-A [25]. The main characteristic number represents final energy use (for HVAC, hot water, lighting, appliances and other building services) minus on-site generated electricity, divided by a reference floor area. Minergie-P and Minergie-A require airtightness to be verified experimentally. Energy monitoring is required for large buildings, but not supposed to be used for the verification of calculated energy use.

Total quality assessment schemes

Total quality assessment schemes, also delivering certification, all consider the energy domain, along with other domains. Popular schemes are summarized in Table 4.

[7] https://hightech.lbl.gov/resources/calarch-california-building-energy

[8] *buildingenergyquotient.org*

Table 4: Popular total quality assessment schemes.

Name	Country	Focus on energy
LEED: Leadership in Energy and Environmental Design	United States, international	Main focus on energy performance optimization.
DGNB	Germany	5% of total score for life cycle primary energy, 8% for life cycle impact, 4% for thermal comfort, 4% for envelope quality, 10% for life cycle costs.
BREAM: Building Research Establishment Environmental Assessment Method	United Kingdom, international	Energy one of 10 assessment domains. For new buildings, 15 credits for reduction of energy use and carbon emissions.
Klima:aktiv	Austria	Climate protection the main goal. Maximum 600 of 1000 points for energy performance.

These assessment programmes generally offer different schemes for new buildings in the design phase and existing buildings. Most of these schemes are proprietary, and their assessment grids not freely available. Comparability at an international level is only given with LEED, which applies the same standards to buildings in all countries. The frequent use of discrete values for indicators and targets in total quality assessment schemes limits the sensitivity of comparisons [2].

To conclude this section, energy classification instruments differ in their range of application, their mandatory or voluntary character and the covered aspects of building performance. There seems to be a lack of methods for systematic multi-level energy performance assessment [17], which represents an issue in the InBetween context, as occupant behaviour is often not best assessed at the building level, but rather in smaller units, e.g. flats or offices.

2.2.3 Calculation of energy savings

More than the energy performance of buildings, building sections or systems, its evolution with the use of the InBetween platform is of interest, if the platform performance is to be assessed.

The energy savings of an intervention can be defined as the difference between the amount of energy used after the intervention and that which would have been used "had the intervention not been carried out" [12]. This fictitious reference means that energy savings cannot be measured directly.

The International Performance Measurement and Verification Protocol (IPMVP) represent a standard procedure for the evaluation of such energy savings [26]. The main steps involved by the protocol are as follows [26]:

- Determination of a measurement boundary
- Selection of two measurement periods:
  - baseline period which should encompass all operating conditions of the facility "one normal operating cycle";
  - reporting period which should also encompass at least one "normal operating cycle";
- The determination of methods of adjustment, which include
  - Routine adjustments (for factors expected to change during the reporting period);
  - Non-routine adjustments, for static factors, not expected to change but which should be monitored for change;
- The choice of an approach to account for savings:
  - Avoided energy consumption for the reporting period (in which case baseline period energy use is adjusted to reporting period conditions).
  - Normalized savings calculated with "normal" conditions differing from those in the reporting period.
- Operational verification ensuring that the energy conservation measure is installed and performs as intended.

Based on these steps, the International Performance Measurement and Verification Protocol proposes four options, depending on the measure to evaluate, the measurement boundary and available information. Options A and B isolate the equipment on which the measure was applied (narrow measurement boundary), while option C applies to a "whole facility", and option D uses calibrated simulation.

The issue of energy saving measurement was addressed by the European-funded projects of ICT for sustainable growth in the residential sector, leading to the publication of a common deliverable [12]. It was concluded that option C of the IPMVP was applicable [12]. This implied the use of baseline energy consumption data.

Alternatively, a control group approach was proposed [12]. The control group approach implies the challenge of finding a control building matching the characteristics of the intervention building "along all known independent variables", which include energy-related behaviour and social structure of households [12].

2.2.4 Dimensions of energy use quantification

Summarizing the reviewed literature, multiple dimensions can be considered for the quantification of energy use and are discussed in the following paragraphs:

- quantity of energy,
- assessment level, system limits and energy boundaries,
- end use,
- quality of energy.
- energy rate and load matching,
- energy sources (e.g. gas, solar energy) and carriers (e.g. gas, electricity, district heating),
- financial and environmental costs,
- life cycle.

Quantity

Energy is a physical quantity, expressed in joule (J) in the international system of units. For building-related applications, the unit mostly used in Europe is the kilowatt hour (kWh), with 1 kWh = 3.6 10^6 J. For fuels, a distinction is made between gross calorific value (higher heating value) including latent heat of vaporization against net calorific value (lower heating value) which assumes that water is in vapor state at the end of the combustion process. EN 15603 supposes the use of the gross calorific value to quantify amounts of delivered energy.

System limits

A prerequisite to the quantification of energy transfer is the definition of system limits. System limits naturally depend on the assessment level, which may for instance correspond to a building complex, a building, a dwelling, a building system or a single component [17]. ISO 52003-1 distinguishes between overall energy performance, concerning a whole building, and partial energy performance, concerning individual elements [9].

Different boundaries can be drawn along the flow of energy from primary sources to various end uses. According to EN 15603 [18], system boundaries for energy carriers should be the meters (for gas, electricity, district heating and water). The boundary of "delivered energy" is generally quite clear in the case of commercial energy purchased from utilities, while cases of on-site renewable energy use are often more problematic [15]. Questions on system boundaries can arise in apartment buildings, where a distinction between tenant side and landlord side may be required [27].

IEA EBC Annex 53 on total energy use in buildings addressed the issue of system boundaries, inspired by standards ISO 16346 and ISO 12655 [28]. Three regions were defined, corresponding to energy demand E_B, energy delivered to technical systems E_T and delivered energy E_D. E_D is the energy delivered to the primary components (e.g. boilers, chillers, district heating) and to auxiliary equipment, while E_T accounts for efficiencies in converting E_D.

Beyond delivered energy, primary energy, which includes extraction, transformation and transportation losses, is often considered to be a better indicator of the true expense of energy use. However, the considerably larger system boundaries make primary energy more complex to assess than delivered energy, and dependent on local variables relative to energy supply and distribution.

Feedback can be provided for energy consumption at the building level or at the room level [29]. In case several dwelling units are often served by the same technical system, E_T cannot be used at the dwelling level, which calls for different energy boundaries downstream of central energy delivery. Several methods exist for the allocation of energy costs in central HVAC systems to individual tenants, but none of them is perfectly accurate [30].

End use

The end use of energy represents an essential aspect. Classifying end uses can be done in different ways. The Building Energy Specification Table (BEST) defined for European projects distinguishes the following end uses: heating, cooling, ventilation, lighting, domestic hot water and "other energy demand" [31], [32].
In cases where distinct systems serve different purposes, end use disaggregation corresponds to a disaggregation by system. However, allocating energy consumption to different end uses is sometimes difficult. For instance, combination boilers can be used for both domestic hot water and space heating. Discriminating between electricity use for lighting and appliances is often not possible. In the absence of separate metering, computational methods can provide estimates of load disaggregation [33].

Energy rate and load matching

Beside aggregated amounts of energy, rates of energy consumption can be of importance. Relevant aspects are load matching and interactions with the electricity grid. While this is especially relevant for near zero energy buildings [34], the rise of renewable energy sources with variable availability means that peak demand and load shapes gain significance for all buildings, even though this is often only perceived on the supply side.
Grid impact indicators include capacity factor, loss of load probability, dimensioning rate, one percent peak power, and peaks above limit (in the cited paper>5kW) [35]. ICT PSP European projects used the load factor metric (ratio of minimum power demand to maximum power demand) to assess peak shaving performance, with baseline periods of two weeks before intervention [12], as well as CO2 savings thank to load displacement, calculated as the displaced energy consumption multiplied by the difference of emission factors in peak hours and in off-peak hours. Load matching factors mostly refer to the fraction of the energy demand that can be covered by on-site generation during some time interval, or to the proportion of time during which on-site generation suffices to cover the demand [34].
Considering several consumers, the diversity of their energy demand curves plays a significant role in peak demand, which may be estimated with diversity factors. In the case of time-of-use tariffs, load matching becomes linked to energy costs.

Energy sources and carriers

Energy used to provide services in buildings can come from a variety of sources and be delivered in the form of a variety of energy carriers. Comparing the energy amounts corresponding to different carriers is not straightforward. Different aspects to consider are energy quality (thermodynamic view), costs of energy (economic view), environmental impacts and safety of supply. A significant distinction can also be made between renewable and non-renewable energy sources.

Energy quality

Especially in systems with multiple sources and uses of energy, the "quality" of energy represents a significant issue in quantifying energy use [15]. Indeed, amounts of low-quality energy such as waste heat and high-quality energy such as electricity are not commensurate.
A possible measure of energy quality is exergy, a thermodynamic quantity defined for a system in a given environment as the maximum useful work that might theoretically be extracted from it [36]. Methodological difficulties, which include the problematic choice of a reference environment, have until now prevented the exergy approach from being widely adopted for the assessment of energy use in buildings [36].

Energy costs

The costs of energy may also be considered to reflect energy quality. Energy-related costs may follow a variety of tariffs. Energy pricing is usually based on the sum of a fixed price and of a variable price proportional to energy consumption. Demand side management may involve more or less dynamic variations, from static time-of-use rates to (still uncommon) real-time pricing [37].

Environmental impacts

Environmental impacts can also be considered as costs, even if they are rather externalities in economic terms. Like financial costs, environmental costs are related to energy sources and may change in time. Electric power from the grid often has a higher emission factor during the peak hours [12].
Comparing the different aspects of environmental impact is far from straightforward. The reporting guidelines for UK business published by the Department for Environment, Food & Rural Affairs (DEFRA) define a set of 22 environmental key performance indicators. How relevant each KPI is depends on the sector. Fossil fuel combustion, used in building operation for thermal energy or electricity, affects several of these KPIs: greenhouse gases, acid rain, eutrophication and smog precursors, dust and particles, volatile organic compounds and metal emissions to air. In terms of resource use, the consumption of natural gas, oil, coal or wood is considered with specific KPIs. Nuclear-generated electricity would be priced with KPI “radioactive waste”.

Life cycle

Energy is used and transformed over the whole life cycle of buildings and systems, from the extraction of construction materials to destruction or recycling, over operation, maintenance and conversion. In terms of life cycle, the focus of the project is on operational energy use, as opposed to embodied energy. One may also distinguish between energy use before and after refurbishment and, in our case, before and after intervention with the platform.

Normalization

For an indication of energy performance, not only should energy use be quantified, but the corresponding figures should be normalized to make comparisons possible. Normalization can be done against a number of variables, related to space size (floor area, volume, envelope area), climate conditions, space use, number of occupants, or design energy consumption. The selection of a normalization factor can be related to the quantification of provided services, and depends on the comparisons which are to be carried out. Performance can be compared against earlier periods of use of the same building (including calculation of savings), or against similar buildings, or against any other building.
ISO 52003-1 uses the term “reference size” to describe metrics used to normalize energy performance to the size of a building or part of a building [9]. Such normalization variables encountered in the reviewed literature include the number of persons (at full occupancy, or multiplied by occupied hours), floor area in m^2 (according to various definitions), conditioned volume in m^3 (e.g. in OIB RL6 for non-residential buildings [21]), heating and cooling degree-days.
Equitable comparison may be difficult in cases where buildings are not equipped with the same services, for instance if a building is not equipped with cooling systems whereas cooling energy consumption is considered for other buildings.

2.3 COMFORT INDICATORS

Thermal comfort, defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [38], is determined by psychological as well as physical variables, and subjected to variations from person to person. However, the specification of air temperature, radiant temperature, humidity, air speed, metabolic rate and clothing insulation is often considered to be sufficient to estimate the average degree of satisfaction with given environmental conditions.
Indoor thermal assessment can be based exclusively on heat balance calculation, or consider additional adaptive mechanisms playing a role in thermal comfort (adaptive comfort models). According to the considered variables, one can distinguish between indicators reducing the thermal environment to temperature levels, and those in which other physical parameters like humidity and air velocity are also used. With regards to variations in time, one may distinguish steady-state and dynamic comfort assessment. Body position and spatial non-uniformities of the mentioned parameters may have an impact on thermal comfort.

2.3.1 Balance-based comfort indicators (PMV and PPD)

International standard ISO 7730 [39] defines indices regarding the “ergonomics of the thermal environment”. The main indicators defined in the standard are the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) originally developed by Ole Fanger [40]. The predicted mean vote (PMV) makes it possible to rate the thermal environment on a scale from -3 (cold) to +3 (hot). PMV values can be calculated with four equations based on a heat balance of the human body, with the following inputs:

- air temperature t_a [°C]
- mean radiant temperature t_r [°C]
- air vapor pressure p_a [kPa]
- air velocity v_{ar} [m/s]
- metabolic rate M [W/m²]
- external work W [W/m²]
- clothing insulation I_{cl} [clo]

Clothing insulation can be approximated from ISO 9920 Appendix C (depending on the season), or from ÖNORM ISO 7730 Appendix C, for typical clothing combinations. Metabolic rate and work can be estimated based on activity, for instance with ISO 8996. In most cases, work is negligible compared to metabolic rate. Default values for metabolic rate are also indicated in Appendix B of ÖNORM ISO 7730.

The PMV index corresponds to the average assessment of many persons exposed to the same thermal environment. Individual perceptions, however, will vary, and some individuals will be dissatisfied even with a perfectly neutral thermal environment (PMV equal to 0). The predicted percentage of dissatisfied (PPD) gives an estimate of the number of persons who will find the thermal environment too warm or too cold. It is a symmetric function of PMV.

An example computer program for calculating PMV is provided in ISO 7730. The calculation of the PMV is not analytical, as temperature of clothing is an implicit function of input variables, solved iteratively in the standard program.

ISO 7730 also provides criteria for local discomfort, for instance due to draught, vertical temperature gradient, warm or cold floors and asymmetric radiation. These logically require more detailed inputs. ISO 7730 does not provide a method for the long-term aggregation of discomfort indicators.

Occupant expectations, and consequently thermal comfort, depend on the way buildings are ventilated, with a mechanical system or natural ventilation.

2.3.2 Temperature-based indicators

European Standard EN 15251 specifies diverse criteria for the indoor environment [41]. Several classes of requirements are specified, as summarized in Table 5.

Table 5: Applicability of categories used in EN 15251.

Category	Applicability
I	High level of expectation, recommended for spaces occupied by very sensitive persons.
II	Normal level of expectation, to be used for new buildings.
III	Moderate level of expectation, acceptable for existing buildings.
IV	Only acceptable for limited time.

European Standard EN 15251 specifies acceptable indoor operative temperatures for buildings without mechanical cooling systems, as a function of the exponentially-weighted running mean of the outdoor temperature. One should note that, for mechanically cooled buildings, EN 15251 refers to the comfort criteria of ISO 7730.

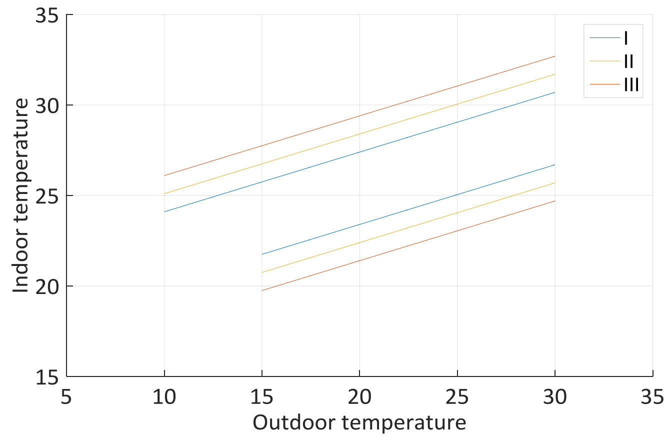

Figure 1: Comfort ranges of operative indoor temperature according to EN 15251.

It is assumed that the criteria of a given category (A,B,C) are met if the room temperature in rooms representing 95% of the occupied space is not more than 3% of occupied hours outside the temperature limits of the category [42]. For long term evaluation of thermal comfort conditions, EN 15251 (Annex F) offers several methods:

- Percentage or number of occupied hours when criteria (PMV or operative temperature) are not met;
- Degree hours criteria, consisting in a sum of degree hours outside the specified range;
- Weighted PMV criteria. With this method, time with PMV outside the comfort boundaries is weighed with a ratio of the PPD to the PPD corresponding to the limit PMV.
- An alternative method is to calculate the average (or the sum) of PPD during occupied hours.

1. In general, "performance of the buildings or rooms with different mechanical or electrical systems can be evaluated by calculating the number of actual hours or % of time when the criteria are met or not." For measurements, EN 15251 requires that standard ISO 7726 should be followed.

2.3.3 Air quality

Indoor air quality may be affected by a variety of contaminants with potential impacts on occupant health, well-being and productivity. Among these, carbon dioxide is often used as an air quality indicator, because of the correlation between the concentrations of CO2 and other contaminants [43].
For non-residential buildings, standard EN 13779 [44] gives air quality requirements in terms of maximum CO2 levels for various categories, as summarized in Table 6. These recommended CO2 concentrations (above outdoor concentration) are also referred to in EN 15251. The Austrian standard H 6038 for mechanical ventilation systems in residential buildings mentions limit CO2 concentrations of 1000 ppm (1400 ppm), which corresponds to category IDA 2 (IDA 3) for an assumed outdoor CO2 concentration of 400 ppm. A limit value of 1000 ppm is also frequently found in guidelines and published works, for instance in the context of demand controlled validation [43].

Table 6: EN 13779 indoor air quality categories in terms of CO2 concentrations and outdoor air volume flow rates.

Category	**CO2 concentration above outdoor concentration (ppm)**		**Outdoor air volume flow rate per person ($l.s^{-1}.Person^{-1}$)**	
	Range	Standard value	Range	Standard value
IDA 1	≤ 400	350	>15	20
IDA 2	400 - 600	500	10 – 15	12.5
IDA 3	600 - 1000	800	6 – 10	8
IDA 4	> 1000	1200	<6	5

Total volatile organic compound (TVOC) concentrations can also be used as an indicator of air pollution, although the wide variety of volatile organic compounds and their possible sources means this can only represent a rough indicator [45].

2.4 USER ENGAGEMENT AND SATISFACTION

2.4.1 User satisfaction

Satisfaction can be defined as "the fulfilment or gratification of a desire, need, or appetite"[9]. As far as the need for an appropriate thermal environment is concerned, satisfaction may be quantified with objective measurements. When it comes to satisfaction with the InBetween platform, we need to determine in which measure the need or desire for information or feedback - or whatever individual users may expect from the platform - is fulfilled, which is much more subjective and difficult to measure.

Surveys represent the most frequent method used to assess satisfaction with services. In the context of surveys, the Likert scale, whose purpose is to measure "attitude", is often used to report and quantify satisfaction [46].

2.4.2 User engagement

User engagement can be defined as "the quality of the user experience that emphasises the positive aspects of the interaction" [47]. The interaction involves emotional, cognitive and behavioural factors [48]. However, a more limited and quantifiable view of engagement is "the user's level of involvement with a product" [4].

Aspects of user engagement mentioned in the literature [47] [48] [49] include the following: intensity of use, activity, focused attention, captivation, enjoyment, loyalty (retention of users from the service provider side), trust, novelty, endurability, perceived user control, motivation to use the tool, system feedback, user-perceived utility of system, positive affect, and system accuracy in providing relevant recommendations. Characteristics of user engagement at macro level include popularity, adoption (the ability to gain new users) and reputation.

Attfield et al. [48] divide user experience evaluation metrics into subjective and objective measures. Subjective measures generally involve self-reporting. Advantages of objective measures are that they do not put a burden on users, and are well-suited to measure temporal changes in interaction [48]. Apart from online behaviour, objective measures include physiological measures, follow-on task performance and the reported subjective perception of time [48]. A drawback of objective metrics is that they can only target "a very specific aspect of engagement" [48]. Claiming the need for "a science of user engagement", Attfield et al. [48] see the need for future work on correlations between subjective and objective measures of user engagement.

User engagement on web sites is commonly measured with *engagement metrics* including number of page views and time spent on site [47]. User engagement differs qualitatively according to the type of web application, and as a consequence it may be discussed what the metrics used for each type of application should be [47].

Metrics proposed for measuring website visitor engagement include: a click depth index scoring session only when the number of clicks exceeds a predefined threshold, a duration index (also with threshold), a recency index measuring the rate at which visitors return to a site, a loyalty index accounting for the number of visits of a visitor during a time frame [50]. Absence time – measured as the time between two visits - represents an easy metric which has been argued to represent a good indicator of engagement [51].

European project ENTROPY (Design of an Innovative Energy-Aware IT Ecosystem for Motivating Behavioural Changes Towards the Adoption of Energy Efficient Lifestyles) uses gamification to foster behavioural change towards energy efficiency [52]. In this context, data on logins and interactions with content are used to calculate behavioural metrics. An engagement metric is calculated as sum of click-depth index, recency index, duration index, feedback index, interaction index and loyalty index, as proposed by [50].

As the InBetween platform will make recommendations, methods for the evaluation of recommendation systems may be of interest. Properties of recommendation systems assessed in the corresponding literature include [53]:

- User preference, generally assessed directly by asking users;
- Accuracy in predicting ratings, rankings or usage, which does not really apply to the InBetween platform;
- Utility, generally easy to define in monetary terms for the service provider, but difficult to measure for users;

[9] *https://www.thefreedictionary.com/satisfaction*

- Confidence, trust, novelty, serendipity, diversity, risk, robustness, privacy, adaptivity and scalability.

Information retrieval represents another relevant adjacent domain. In this context, correlations can be established between document relevance and satisfaction, but user satisfaction is arguably more complex [54]. Rodden et al. [4] group business-related metrics under the acronym PULSE (page views, uptime, latency, seven-day active users and earnings), argue that they are too limited in terms of assessing user experience, and propose a complementary metrics framework under the acronym HEART (happiness, engagement, adoption, retention and task success).

An interesting possibility is to relate satisfaction to the measurable online behaviour of users. For instance, dwell time on a clicked page is often considered as an indicator of user satisfaction with a search result [55]. Going further, Hassan et al. [54] trained a model of user behaviour including the sequence of queries and clicks in a search session, making it possible to predict the success of search based on them. Periodicity is an important aspect of engagement, which can be assessed with spectrum analysis methods [56]. Another correlation between subjective values and objective online metrics is the correlation between quality of service (in this case search relevance and search success) and service reuse, which has been investigated in the context of search engines [55].

2.4.3 Satisfaction with building automation systems

User satisfaction and engagement is particularly important in the context of building automation or home energy management systems, as it largely determines their possible impact.

A review of the literature on the effectiveness of metering, billing and direct displays showed that the impact of such feedback was variable and often disappointing, but highlighted a link between user disengagement and negative feedback [57]. It has been argued that user-centred design holds the key to making home energy management systems attractive for users and thus effective in terms of energy saving [58]. In the same piece of work, a co-creation approach was validated by investigating user experience with a questionnaire and usage statistics (evolving over time) [58]. It has been argued that socio-technical studies are necessary in this context because the roles of technologies are not entirely determined by technology itself [59].

A widely accepted definition of thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" [38]. Thus, user satisfaction and thermal comfort are obviously linked. However, the interactions between thermal comfort, perceived control upon a system and user satisfaction are complex and not fully understood yet. Not only does reported user satisfaction tend to be higher when the possibility of manual control is given, but "lower control over building elements can increase the occupant's consciousness of environmental factors" [60].

The definition of user satisfaction and engagement in specific cases should take into account the respective levels of automation. An example of system with a high level of automation was presented in a thesis in which genetic algorithms were used to take into account user wishes in an advanced building control system [61]. "Wishes" were assumed to correspond to user interactions (e.g. raising or lowering a blind). Evaluation of user acceptance was carried out using three types of questionnaires: one-time personal questionnaire, twice-monthly user satisfaction questionnaire, and twice-daily comfort questionnaire. A decrease in the number of interactions with the controlled system (e.g. the blinds) was seen as an indication that "user adaptation is working efficiently" [61]. Personal preferences for automation level in building energy domain, though not completely understood yet, can be shown to depend on the context, but also on personality traits [62].

3 SELECTION OF KEY PERFORMANCE INDICATORS

3.1 CRITERIA APPLICATION

As mentioned above, the selection of KPIs follows criteria used in the CITYkeys project [6]: relevance, completeness, availability, reliability, familiarity, non-redundancy, independence. The following paragraphs discuss these criteria in the context of the InBetween platform.

3.1.1 Relevance

The project-specific relevance of performance indicators is ensured by checking that they fall into the scope defined in the introduction. The general relevance of performance indicators for given performance aspects is, mostly, ascertained by their presence in published standards and scientific literature.

3.1.2 Availability

Availability of data required for indicator calculation plays a key role for the selection of key performance indicators.

Indicators relative to thermal comfort all depend on measurements of the thermal environment. In particular, the indicators identified in the literature review all require at least measurements of air temperature and mean radiant temperature. In many cases, it may be expected that air temperature is monitored, but not mean radiant temperature. Mean radiant temperature, which is required by both ISO 7730 and EN 15251, may thus represent a bottleneck for the calculation of thermal comfort KPIs. The availability criterion means that temperature-based indicators should be favoured against the PMV and PPM indicators, which additionally require values of wind velocity, humidity, clothing and activity.

Energy efficiency indicators considered in the project all depend on energy use data. Available data may be characterized in terms of time resolution, and level of disaggregation (spatial, by system or by end use). A key consideration for the calculation of indicators relative to energy savings is that there should be enough time for a baseline period against which energy savings can be evaluated. The baseline period should ideally last at least one year, in order to cover all possible load situations. Privacy issues may have an impact on data availability, as high-resolution energy use data can raise privacy concerns [63].

The availability of data on the energy supply side also matters. Load matching indicators like mismatch compensation, market matching require such data [34]. The calculation of indicators relative to energy costs and primary energy depends on the availability of data on the local energy mix (and its time variations), and the corresponding primary energy factors.

Indicators based on statistical benchmarking, implying the comparison with aggregated values for many comparable buildings, have to be excluded for lack of available data.

Calculated values based on design data or building documentation may also be used for benchmarking. Available building data include: building geometry (as two-dimensional plans), conditioned floor area (“living space”), method of construction and insulation thickness for wall, floor and roof. Assumptions may be needed for material properties (thermal conductivity of insulation and other materials) and internal gains.

For user engagement and satisfaction, availability is a fundamental reason for choosing objective measures over subjective measures. Also, physiological measures such as eye trackers will not be available, so indicators based on them are not selected.

Availability of data for measuring user engagement with the proposed platform will depend on the level of automation of the services provided. Data on the state of active systems (thermostat set points, radiator valve position) or passive systems (position of windows) is needed to determine user behaviour and find out how it is influenced by the system. These data may be obtained directly (e.g. from control system) or indirectly through measurements.

In relation with data availability, data privacy should be taken into account. In particular, compliance with the new European General Data Protection Regulation[10] enforced in May 2018 should be observed.

3.1.3 Reliability

Reliability is ensured by the detailed definition of each indicator. KPIs should be easy to define, as far as possible. For instance, KPIs whose calculation would involve the use of dynamic simulation methods are avoided, because of the time-intensive and error-prone model creation process.

3.1.4 Familiarity

Indicators should be easy to understand, and kept as simple as possible. For energy efficiency indicators, this means that complicated normalization schemes should be avoided. Familiarity is an argument for the rejection of thermodynamic indicators which could have been used to reflect the quality of energy used, as these indicators have yet not been widely adopted in the building performance domain outside of research.

[10] https://www.eugdpr.org/

3.1.5 Completeness

Completeness is ensured by comparison of the selected KPIs with aspects identified in the literature review. The proposed KPIs will cover the three main domains of energy performance, thermal comfort and user engagement. More specifically, the indicators will provide answers to the following questions:

- How does energy use evolve with the use of the platform?
- How is the energy consumption for each end use affected by the platform?
- How much energy can be saved using the platform?
- What are the environmental impacts of platform energy savings?
- Is shifting and shaving of loads made possible by the platform?
- Can uncomfortable conditions be avoided with platform use?
- How regularly do users engage with the platform?
- In which measure do users comply with recommendations given by the platform?

3.1.6 Non-redundancy

In other to ensure non-redundancy, it should be justified that indicators concerning the same domain refer to distinct aspects of performance. For instance, the selection of several energy-related performance indicators is justified by the need to account for various aspects of energy use, such as end use and energy quality.

3.1.7 Independence

Independence is ensured by stating, for each indicator, its preferred values and/or whether it is to be minimized or maximized, independently of the values of other indicators (see column "objective" in KPI matrix).

3.1.8 Generality

A further criterion for the selection of indicators is that they should be applicable not only to the demonstration buildings, but more widely to a large share of possible applications of the developed platform.
Some indicators are not retained because of their limited range of application. For instance, assessing loss of productivity due to thermal discomfort may be interesting, but mostly for office buildings. Some of the selected indicators only apply to certain cases. For other cases, it is ensured that the corresponding aspect is either irrelevant (e.g. load matching for buildings without on-site generation) or covered by another indicator. Temperature-based indicators for thermal comfort defined in EN 15251 only apply to buildings without mechanical cooling. For buildings with mechanical cooling, an indicator based on the predicted percentage of dissatisfied is used instead.

3.2 OVERVIEW OF SELECTED KEY PERFORMANCE INDICATORS

The selected key performance indicators are summarized in Table 7. Reference is made to the high-level goal corresponding to each indicators, as goals can be seen as the starting point for indicator definition [1], [4], [9]. Detailed characterization of the selected indicators can be found below.

Table 7: Summary of selected KPIs. Note indirect link: thermally comfortable environment may

Goal	Indicator
Reduce amounts of energy used by occupants	Energy consumption by person – total
	Energy consumption by floor area – total
	Energy savings
Assess and reduce energy consumption for each end use	Energy consumption by person – disaggregated: space heating, cooling, ventilation, lighting, hot water, others
Reduce impacts of energy consumed by the occupants	Source energy consumption
	CO_2 emission savings
Reduce costs of energy for occupants	Energy cost savings

Assess potential for heating energy savings	Energy consumption % of ideal demand
Reduce stress for grid and minimize costs of electricity generation	Peak load indicator
Optimize self-consumption of renewable energy	Load match index
Provide thermal environment as comfortable as possible	Temperature discomfort indicator
Limit number of occupied hours with uncomfortable thermal environment	% uncomfortable hours
Minimize thermal dissatisfaction of occupants with variety of tasks	Thermal discomfort indicator
Provide good air quality	Stale air indicator
	Volatile organic compound levels
Engage users in a sustained way	Recency index
Provide users with interesting information	Message opening rate
Convince users to adopt energy-efficient behaviour	Compliance indicator

3.3 DETAILED KPI DESCRIPTIONS

Energy efficiency

Energy consumption by person – total (kWh.person^{-1}.a^{-1})

Final energy consumption per person per year for all uses.

Final energy is the energy consumed by all devices in the building or building part. It traditionally corresponds to purchased energy, to which on-site generated and consumed energy should be added if applicable. Final energy is relevant because occupants have direct control over it.

As occupant behaviour is the focus of the project, a normalization per person is assumed to be a relevant way of normalizing energy consumption in a simple way. Although defining the number of persons may in some cases present difficulties, so does determining the served floor area. For simplicity, all human occupants are counted equally, without difference of, for instance, age. Distinctions in terms of occupancy patterns on a short time scale (weeks or days) are also avoided, by taking the nominal (maximal) number of occupants in usual conditions. In the case of regularly variable occupancy (e.g. children present each other week), part-time occupants may be counted on a pro rata basis.

The spatial scale used for this indicator and the following ones is the unit of use defined in the project, e.g. the apartment for apartment buildings and the whole building for smaller buildings. Energy consumption for each of these units is then divided by the corresponding number of occupants. Energy consumption is not attributed to occupants in specific rooms or zones inside of units, as this would raise data availability and privacy issues.

Energy consumption by floor area – total (kWh.m^{-2}.a^{-1})

Final energy consumption per conditioned gross floor area per year for all uses.

Final energy is the energy consumed by all devices in the building or building part. It traditionally corresponds to purchased energy, to which on-site generated and consumed energy should be added if applicable. Final energy is relevant because occupants have direct control over it.

Normalization by floor area is commonly used for building energy performance rating, especially for heating, ventilation, air-conditioning and lighting. Compared with the normalization per person used in the previous indicator, it tends to favour buildings with more space per occupant. Considering both indicators makes it possible to assess energy use in relation to different determining factors, thus providing a basis for fair comparison.

Attention should be paid to the floor area definition used for normalization, as such definitions may vary with each country and application. The conditioned gross floor area is assumed to be easier to define and calculate than net floor area or useful floor area.

Energy consumption by person – space heating ($kWh.person^{-1}.a^{-1}$)

Final energy consumption per person per year for space heating.

A disaggregation of final energy use by end use is of high value both for the occupants and for platform operation, as it allows potential savings to be estimated.

Disaggregation, for this indicator and the following ones, can be ensured by separate metering or by numerical methods, for instance with the non-intrusive load monitoring (NILM) approach [33].

This indicator accounts for the energy consumption for space heating. Final energy consumption for space heating should be distinguished from energy consumption for domestic hot water.

Energy consumption by person – lighting ($kWh.person^{-1}.a^{-1}$)

Final energy consumption per person per year for lighting.

This indicator accounts for the energy consumption for lighting. Disaggregation by submetering may present difficulties for this indicator, as luminaires may use electricity from the same sockets as other appliances.

Energy consumption by person – mechanical ventilation ($kWh.person^{-1}.a^{-1}$)

Final energy consumption per person per year for mechanical ventilation.

This indicator accounts for the energy consumption for mechanical ventilation. This is equal to zero unless a mechanical ventilation system is installed. Note that air heat recovery may make this energy consumption slightly higher, while decreasing heating energy consumption.

Energy consumption by person – space cooling ($kWh.person^{-1}.a^{-1}$)

Final energy consumption per person per year for space cooling.

This indicator accounts for the energy consumption for space cooling. This is equal to zero unless a mechanical cooling system is installed.

Energy consumption by person – hot water ($kWh.person^{-1}.a^{-1}$)

Final energy consumption per person per year for hot water preparation.

This indicator accounts for the energy consumption for hot water preparation, which is mostly relevant for residential buildings.

Source energy consumption (kWh.person^{-1}.a^{-1})

Primary non-renewable energy use per person per year.

This is calculated based on final energy demand with local conversion factors for each energy carrier. We include only non-renewable energy here, for which it represents the total energy expenditure from energy extraction.

CO2 emissions (g$_{CO2}$.person^{-1}.a^{-1})

Energy-related carbon dioxide emissions per person per year.

This indicator accounts for the carbon dioxide emissions induced by the energy consumption for all previous end uses. This is calculated based on final energy demand with local conversion factors for each energy carrier.

Energy savings (%)

Savings in terms of final energy.

Energy savings are calculated following option C of the International Performance Measurement and Verification Protocol (IPMVP), using normalization to estimate the energy consumption that would have occurred without intervention. The selected normalization factors are heating degree days (in Kelvin days or °C days) and estimated or measured occupancy hours (in person hours), as well as cooling degree days in case of mechanical cooling.

Regression analysis is used to correlate daily energy consumption to these independent variables. The coefficient of determination R^2 and t-statistics are used to validate the correlations.

According to the IPMVP, it should be checked that static factors (e.g. characteristics of the building envelope or technical systems) indeed do not change during the reporting period. In the case of such changes, non-routine adjustments should be applied to account for them.

CO2 savings (%)

Savings in terms of greenhouse gas emissions.

Savings in terms of greenhouse gas emissions are calculated with the same methodology as for final energy savings and using conversion factors.

Heating energy consumption % of ideal demand (%)

Ratio of heating energy consumption to calculated heating energy demand.

Heating energy demand is calculated with a monthly energy balance, based on building design data. Calculation is based on a quasi-steady state method according to EN ISO 13790, which means dynamic effects are accounted for with empirical gain utilisation factors.

Ideal heating energy demand for each month $Q_{D,H}$ is expressed as:

$$Q_{D,H} = Q_{L.H} - \eta_{G,H}\, Q_{G,H}$$

Where $Q_{L.H}$ are the heat transfer losses, $\eta_{G,H}$ is a utilisation factor for internal and solar heat sources $Q_{G,H}$.

One single thermal zone is assumed for the building or part of building under consideration. Default values mentioned in ISO 13790 may be used for internal loads.

Peak load indicator (kW/person)

One percent peak of electric load (normalized by person).

Electric load is assumed to be monitored on a sub-hourly basis. Given loads measured at regular intervals $\dot{Q}(t)$ for $t = 1..n$, with $n \gg 100$, one may sort them by decreasing values. The peak load indicator is then the k^{th} of these values, with $k = [0.01\, n]$. Values of the indicator can only be compared if the measurement interval is the same.

Load match index

Minimum on interval of generation to load ratio.

The load match index is only relevant in the case of on-site energy generation, and especially for near zero energy buildings. Given loads $\dot{Q}(t)$ and on-site generation energy rates $G(t)$ for $t = 1..n$, the load match index is defined as $\min_{t=1..n}(\min(1, G(t)/\dot{Q}(t)))$.

Thermal comfort and air quality

Uncomfortable hours (%)

Percentage of hours outside of comfortable range according to EN 15251 with category III.

The selection of category III of EN 15251, corresponding to a moderate level of expectation, means that the non-complying hours are likely uncomfortable.

Temperature discomfort indicator (K)

Degree-hours outside of comfortable range according to EN 15251 with category II.

The selection of category II of EN 15251 for this indicator allows the indicator to express the deviation from a better level of expectation (than category III, used in the previous indicator). Although more sensitive than the previous indicator, this indicator alone would not make it possible to distinguish between short episodes of highly uncomfortable conditions and long periods of slightly uncomfortable conditions. The two indicators are assumed to be complementary.

Thermal discomfort indicator (%)

Average predicted percentage of dissatisfied (PPD) in occupied hours.

As opposed to the two temperature-based indicators, this indicator is also applicable to mechanically cooled buildings, but it also requires more input data. The required inputs are as follows:

- air temperature t_a [°C]
- mean radiant temperature t_r [°C]
- air vapor pressure p_a [kPa]
- air velocity v_{ar} [m/s]
- metabolic rate M [W/m²]
- external work W [W/m²]
- clothing insulation I_{cl} [m²K/W]

For each time step, the PPD is calculated based on the PMV:

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

PMV values can be calculated with four equations based on a heat balance of the human body, with intermediate variables for surface temperature of clothing t_{cl}, surface heat transfer coefficient h_c and clothing area factor f_{cl}:

$$\begin{aligned} PMV = {} & (0.303\exp(-0.036\,M) + 0.028)\big((M-W) - 3.05\,10^{-3}\,(5733 - 6.99(M-W) - p_a) \\ & - 0.42(M-W) - 58.15 - 1.7\,10^{-5}\,M(5867 - p_a) - 0.0014\,M\,(34 - t_a) \\ & - 3.96\,10^{-8} f_{cl}((t_{cl}+273)^4 - (t_r+273)^4) - f_{cl}\,h_c(t_{cl} - t_a)\big) \end{aligned}$$

$$t_{cl} = 35.7 - 0.028(M-W) - I_{cl}(3.96\,10^{-8}\,f_{cl}((t_r+273)^4 - (t_c+273)^4) + f_{cl}\,h_c(t_{cl} - t_a))$$

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

$$f_{cl} = \begin{cases} 1 + 1.29\,I_{cl} & \text{for } I_{cl} \leq 0.078\ \mathrm{m^2K/W} \\ 1.05 + 0.645\,I_{cl} & \text{for } I_{cl} > 0.078\ \mathrm{m^2K/W} \end{cases}$$

The calculation of the surface temperature of clothing t_{cl} can be done out iteratively, starting from a first guess [38].

See appendix for metabolic rates and clothing values which are required for the calculation of the predicted percentage of dissatisfied.

Hours with bad air quality (%)

Percentage of hours with CO2 concentration above 1000 ppm

This corresponds to hours not compliant with category IDA2 in standard EN 13799, assuming an outside CO2 concentration of 400 ppm. Only occupied hours should be considered.

Stale air indicator (ppm) Sum of in occupied hours of CO2 concentrations exceeding 1000 ppm, divided by occupied hours.
The stale air indicator is defined in the following formula $$s = \frac{\sum_{t=1}^{n} o_t (c(t) - c_{max}) \mathbb{1}_{c(t)>c_{max}}}{\sum_{t=1}^{n} o_t}$$ With time t, o_t indicating occupancy (1) or not (0), c the CO2 concentration, and $\mathbb{1}_{c(t)>c_{max}}$ the characteristic function equal to 1 when $c(t) > c_{max}$ and 0 otherwise. For c_{max}, one uses the 1000 ppm limit, corresponding to the higher limit of category IDA2 in standard EN 13799.

Volatile organic compound levels (mg/m³) Mean total volatile organic compounds values.
Total volatile organic compound (TVOC) concentrations can be used as an indicator of air pollution, correlated with the likelihood of complaints and adverse health effects, even though this correlation should be relativized by the wide diversity of volatile organic compounds and the yet unexplored complexity of their individual and combined impacts. It is considered that TVOC values under 0.3 mg/m³ are unobjectionable, and that relevant health-related concerns arise with TVOC values above 1 mg/m³ [45], [64].

User engagement and satisfaction

Recency index (days) Median time between sessions.
The recency index simply corresponds to the time elapsed between user interactions with the system. This requires the times of sessions to be determined. As in related literature [51], a session is defined as a series of interactions with the system taking place with less than 30 minutes between them.

Compliance indicator Differential of squared difference between user-selected value and recommended value.
This indicator expresses the degree to which a user complies with a given recommendation. The indicator refers to a value which would typically represent a temperature setpoint, but could also be a status value (e.g. window opening) varying between 0 and 1. For initial value p_i, recommended value p_r and new value p_n, the indicator is calculated as: $$C = \frac{(p_i - p_r)^2 - (p_n - p_r)^2}{(p_i - p_r)^2}$$

For it to be well-defined, the recommended value should differ from the initial value. The indicator would take a value of 1 if the user follows the recommendation, a value of 0 if the user does not do anything, and negative values if the user makes a change contradicting the recommendation.

Message opening rate (%)

Percentage of platform messages opened by users.

This indicator corresponds to the click-through rate, which is a very widespread metric in the field of online information retrieval and advertisement [47], [51]. The message opening rate may take on various meanings according to the aspect and nature of the assessed messages, e.g. whether they correspond to recommendations or items of information.

3.4 REFERENCE VALUES

Reference values, for instance for energy consumed for space heating in the residential sector, can be obtained at the national level.
In France in 2016, final energy consumption in the residential and tertiary sector was around 60 Mtoe[11], which amounts to approximately 10 MWh per person.
Similar statistics in Austria give a final energy consumption of 419 PJ for the residential and tertiary sector[12], which amounts to approximately 13 MWh per person.
Statistics for the residential sector only are also available from Eurostat[13]. These give a residential final energy consumption of 6550 $kWh.person^{-1}.a^{-1}$ for France and 7950 $kWh.person^{-1}.a^{-1}$ for Austria. For the whole European Union, the average residential final energy consumption amounts to 6450 kWh per year per person.

Table 8: Average residential final energy consumption in the European Union (EU 28) in 2016.

End use	Total (TJ)	Per person ($kWh.person^{-1}$)
Space heating	7634	4174
Space cooling	32	17
Water heating	1714	937
Cooking	642	351
Lighting and appliances	1629	891
Other end uses	154	84
Total	*11805*	*6455*

3.5 KPI VALIDATION

Particularly for user engagement and satisfaction, the defined KPIs may be validated by crossing them with survey results. The surveys planned in Tasks 3.1, 3.2 and 5.2 may be used for this.

4 CONCLUSIONS

[11] http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Datalab_essentiel/2017/datalab-essentiel-129-bilan-energetique-France-2016-decembre2017.pdf

[12] https://www.oegut.at/en/projects/energy/energy-consumption-service-sector.php

[13] http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households

Twenty key performance indicators were selected. Together, they cover performance aspects related to energy efficiency, comfort and user engagement. These KPIs are the result of a selection based on criteria of relevance, availability, reliability, completeness and non-redundancy, following a broad literature review. While this selection took into account project-specific aspects, it was attempted to reuse existing and widely accepted indicators where possible.

Defining KPIs early in the project, as it has been done here, is good practice, as it will allow the performance of the developed systems to be assessed more objectively. On the other hand, uncertainties about the developed systems and about available data mean that the calculation of some indicators may eventually not be possible, or require additional assumptions or approximations.

As opposed to performance indicators for thermal comfort, which are defined in international standards, indicators for energy efficiency exist in multiple forms, with differences between national standards. Several indicators address energy consumption, providing a disaggregation of final energy consumption by end use, and making it possible to assess primary energy use, CO2 emissions, energy savings as compared to a baseline, as well as grid impact and, if applicable, self-consumption of renewable energy. With regards to user engagement, the lack of recognized standards made it necessary to define new indicators based on scientific literature.

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6 APPENDICES

6.1 ACRONYMS

EPB: Energy performance of buildings
ICT: Information and communication technology
InBetween: ICT enabled BEhavioral change ToWards Energy EfficieNt lifestyles
IEA EBC: International Energy Agency's Energy in Buildings and Communities Programme
KPI: Key performance indicator
NILM: Non-intrusive load monitoring

6.2 DEFINITIONS

Final energy: amount of energy made available to building services
CO2 emissions: Carbon dioxide is not the only gas responsible for the greenhouse effect. However, for common fuels used in buildings, CO2 is indeed the main greenhouse gas, so that conversion factors in and are very similar, as illustrated in Table 9. CO2 emissions are used rather than CO2-equivalent global greenhouse gas emissions, because most standards and data sources give conversion factors for the first.

Table 9: Conversion factors for CO2 emissions (kgCO2/kWh) and greenhouse gas emissions (in kgCO2e/kWh) for the United Kingdom in 2017[14].

Energy carrier	CO2 emissions (g_{CO2}/kWh)	Greenhouse gas emissions (g_{CO2e}/kWh)
Electricity	348.9	351.5
Natural gas	183.8	184.2
Wood pellets	0	12.7

[14] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017

6.3 CALCULATED ENERGY DEMANDS

Appendix G of DIN EN 13790 mentions average internal gains for people and equipment, average of 9 W/m² for living room and kitchens, 3 W/m² for other rooms in residential buildings. 7.4 W/m² for office rooms, and 3.1 W/m² for other rooms in office buildings, in average 5.7 W/m².

6.4 INPUTS FOR THERMAL COMFORT INDICATORS

6.4.1 Metabolic rates

Table 10: Metabolic rates in various standards. 1 met = 58 W/m². Average body surface area 1.8 m²/person.

Source	Space or activity	Metabolic rate	Heat gain
EN 15251	Residential buildings: living spaces	1.2 met	
EN 15251	Residential buildings: other spaces	1.6 met	
EN 15251	Kindergarten	1.4 met	
EN 13779	Sitting activity (office, school)	1.2 met	125 W/person

6.4.2 Clothing values

EN 15251 generally uses a value of 1.0 clo for the winter season and 0.5 clo for the summer season.

6.4.3 Mean radiant temperature

The mean radiant temperature is defined referring to the position of the occupant, as the temperature of an imaginary enclosure with uniform temperature, in which radiant heat transfer from the body is equal to that in real (non-uniform) conditions. Mean radiant temperature can be measured in several ways:

- based on a calculation using surface temperatures of the enclosures and angle factors;
- more directly, for instance with a globe thermometer, whereby the measured value is a globe temperature, from which the actual mean radiant temperature can be deduced (with knowledge of air temperature and velocity), as described in ISO 7726.

Measuring radiant temperature is expensive. Approximating radiant temperature with air temperature is not always acceptable. In the case of thermally activated building systems, they should be taken into account. Large glazing areas should also be taken into account.

6.4.4 Requirements for measurements

For the determination of thermal comfort, ISO 7726 specifies tolerances of ±0.5 K for air temperature and ± 2 K for mean radiant temperature.
For the measurement of air temperature, the thermometer should not be exposed to radiation from the sun or local heat sources.

6.4.5 Running mean of external temperature

The running mean of external temperature on day d $\theta_{rm,d}$ is defined as follows, with $\theta_{e,i}$ the daily mean external.

$$\theta_{rm,d} = (1-\alpha)\sum_{k=1}^{\infty} \alpha^{k-1}\ \theta_{e,d-k}$$

α is a constant between 0 and 1, for which a value of 0.8 is recommended [42].
EN 15251 suggests following approximation:
$\theta_{rm,d} = (\theta_{e,d-1} + 0.8\ \theta_{e,d-2} + 0.6\ \theta_{e,d-3} + 0.5\ \theta_{e,d-4} + 0.4\ \theta_{e,d-5} + 0.3\ \theta_{e,d-6} + 0.2\ \theta_{e,d-7})/3.8$
Otherwise, a consistent definition of the running mean for a limited number of days would be:

$$\theta_{rm,d} = \frac{\sum_{k=1}^{n_d} \alpha^{k-1} \; \theta_{e,d-k}}{\sum_{k=1}^{n_d} \alpha^{k-1}}$$

6.5 CONVERSION FACTORS

6.5.1 Primary energy factors

Primary energy factors are defined at the national level.
In Austria, they are defined in OIB Richtlinie 6.

Table 11: Primary energy conversion factors for Austria.

Energy carrier	f_{PE}	$f_{PE,nr}$
Natural gas	1.17	1.16
Biomass	1.08	0.06
Electricity	1.91	1.32
District heating (non-renewable)	1.52	1.38

In France, they are specified in the *règlementation thermique*, with a primary energy factor of 2.58 for electricity, and 1 for other energy carriers[15].

6.5.2 CO2 emissions

Table 12: Conversion factors for CO2 emissions for Austria.

Energy carrier	f_{CO2} (g_{CO2}/kWh)
Natural gas	236
Biomass	4
Electricity	276
District heating (non-renewable)	291

The French electricity transmission operator RTE provides high-resolution of the average CO2 emissions by kWh of electricity[16].

[15] http://www.rt-batiment.fr/index.php?id=144&faqid=9

[16] http://www.rte-france.com/fr/eco2mix/eco2mix-co2