Modelling Optimization of Energy Efficiency in Buildings for Urban Sustainability

D2.3. MOEEBIUS Energy Performance Assessment Methodology

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Glossary

Acronym	Full name
AHU	Air Handling Unit
BEPS	Building Energy Performance Simulation
BIM	Building Information Model
BMS	Building Management System
BSC	Business Scenario
CCT	Correlated Colour Temperature
CHP	Combined Heat and Power
CRF	Contrast Rendering Factor
CRI	Colour Rendering Index
DC	Direct Current
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
ECM	Energy Conservation Measures
EPBD	Energy Performance in Buildings Directive
ESCO	Energy Service Company
ET	Effective Temperature
EU	European Union
FEMP	Federal Energy Management Program
HHV	Higher Heating Value
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IPMVP	International Performance Measurement & Verification Protocol

KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCC	Life Cycle Costs
M&V	Measurement and Verification
MOEEBIUS	Modelling Optimization of Energy Efficiency in Buildings for Urban Sustainability
NPV	Net Present Value
NZEB	Nearly Zero Energy Building
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaic
RES	Renewable Energy Sources
ROI	Return on Investment
RTD	Resistance Temperature Detectors
SBS	Sick Building Syndrome
SET	Standard Effective Temperature
ToU	Time of use
USEF	Universal Smart Energy Framework
VOC	Volatile Organic Compounds
VPP	Virtual Power Plant
ZEB	Zero Energy Building

1 Executive summary

This document contains the work relative to task T2.3 "Building and District performance assessment specifications and Key Performance Indicators".

The objective of this task is to provide the basis for the MOEEBIUS Measurement and Verification (M&V) Protocol, which defines a novel methodology through the review, combination and extension of current methodologies and protocols.

This M&V framework will enable the holistic modelling activities in the project and the definition of the MOEEBIUS local and global energy performance models. Consequently, adequate Key Performance Indicators (KPIs) have been incorporated to assess the results achieved by MOEEBIUS, that is, the optimization of the energy performance at both building and district levels, addressing energy and economic savings, but always under user's comfort conditions. After selecting and improving existing indicators from international standards and other EU projects, the considered categories for the Key Performance Indicators will be energy, demand response, indoor environmental conditions, economic, and maintenance aspects, but also the MOEEBIUS simulation system. For each KPI, it will be defined the calculation method with the formulas used and monitoring needs to determine the performance of the parameters.

This report consists of the following parts: the measurement and verification methodology definition, the selection process of the key performance indicators carried out and the selected KPIs with corresponding assessment guidelines.

After an introduction to the objectives of the report (section 2 of this document), section 3 details the MOEEBIUS Measurement and Verification methodology, which is based on existing methodologies and is specifically developed for the MOEEBIUS deployment.

In section 4, the procedure followed to select the KPIs that are considered in each category applying to MOEEBIUS is described, and in the next sections (section 5 to section 11) the final KPIs considered for their use in the MOEEBIUS framework are described divided in different categories.

In section 5, the energy performance indicators are studied, reviewing the ones employed on the latest European projects and directives, listing the specific KPIs, detailing the monitoring aspects and the diverse diagrams depending on the granularity required by each Business Scenario.

The KPIs for DSM (Demand Side Management) and DR (Demand Response) are defined in section 6 since the analysis of the innovative business models for Demand Side Aggregators already reported in D2.2 "New Business Models and Associated Energy Management Strategies".

The KPIs for the categories related to the comfort of the occupants, addressing both thermal and visual comfort, and related to the Indoor Air Quality are explained in sections 7 and 8 respectively.

Finally, sections 9, 10 and 11 deal with the economic indicators and the KPIs considered for the implementation of the predictive maintenance and the assessment of the simulation system performance which is one of the business scenarios.

The definition of the measurement and verification protocol and the selected KPIs presented in this document corresponds to the methodology for the general MOEEBIUS framework. Nevertheless, this methodology and KPIs will be adapted for each case at each pilot site.

2 Objectives of the report

Deliverable D2.3 aims to establish the basis for the MOEEBIUS Measurement and Verification Protocol and define the most important Key Performance Indicators to fully characterize the performance of the systems where MOEEBIUS is going to be deployed, combining and extending existing methodologies and protocols to meet the requirements of EU-based stakeholders.

For the definition of these KPIs, the 5 business scenarios for MOEEBIUS defined in Deliverable D2.1 were taken into account. Thus, the definition of KPIs addresses the necessary indicators for the characterization of the buildings (and districts) performance in order to enable the deployment and evaluation of these business scenarios.

The optimization of the energy performance at both building and district levels, aiming at energy and economic savings, is closely linked with the requirements to maintain user's comfort conditions and the indoor air quality. Therefore, KPI categories for indoor environmental conditions and for indoor air quality have also to be considered in addition to the KPI categories for the energy and economic aspects.

Furthermore, a KPI category addressing the performance of the MOEEBIUS simulation system will be needed, in order to enable the assessment of the reduced gap between the predicted and actual performance of buildings and district.

The considered KPI categories will then comprise:

- Energetic issues
- Demand response issues
- Indoor environmental issues
- Indoor air quality issues
- Economic issues
- Predictive maintenance issues
- MOEEBIUS simulation system performance issues

For each selected KPI, its calculation method with the formulas to be used and the respective monitoring data that are required for the calculation are defined.

The definition of the measurement and verification protocol and the selected KPIs presented in this document corresponds to the methodology for the general MOEEBIUS framework. This general methodology will be later used and adapted for the deployment of the MOEEBIUS for each case at each pilot site (Tasks T7.3, T7.4 and T7.5) or implementation area of MOEEBIUS. The analysis starts with the presentation of MOEEBIUS Measurement and Verification methodology and further proceeds with the taxonomy of KPIs per category as presented above.

3 Measurement and verification methodology

The measurement and verification of systems is needed in order to verify that they are operating correctly and achieving the expected energy savings. Furthermore, MOEEBIUS aims to reduce the current gap between actual and predicted energy consumption by usual energy performance simulation tools. Therefore, MOEEBIUS deployment makes use of user's behaviour modules and energy performance models, which calibration will also require an evaluation of this performance gap.

Different existing methodologies and protocols have been consulted, as the International Performance Measurement and Verification Protocol (IPMVP) [1], FEMP (Federal Energy Management Program, 2015) [2], LEED and BREEAM. LEED M&V methodology is based on IPMVP. BREEAM requires, as part of the reporting and certification process, the confirmation of the existing measurement protocol used at each category (energy, pollutants, thermal comfort…), since there are a number of reporting protocols and initiatives to define monitoring and reporting protocols, as the BS, EN or ISO methods.

Therefore, the development of this Measurement and Verification (M&V) methodology has been based on the IPMVP [1] and FEMP [2].

M&V is defined as the *"Process of using measurement to reliably determine actual savings created within an individual facility by an energy management program. Savings cannot be directly measured, since they represent the absence of energy use. Instead, savings are determined by comparing measured use before and after implementation of a project, making appropriate adjustments for changes in conditions."* (IPMVP, 2012) [1].

Therefore, the main goals of M&V are to increase savings; document financial transactions; enhance financing for efficiency projects; improve design, operation and maintenance of efficiency projects; and account for variances in the utility budget.

FEMP (Federal Energy Management Program, 2015) [2] indicates the following six steps to measure and verify savings:

1) Allocate Project Risks and Responsibilities
2) Develop a Project-Specific M&V Plan
3) Define the Baseline
4) Install and Commission Equipment and Systems
5) Conduct Post-Installation Verification Activities
6) Perform Regular-Interval M&V Activities

In the following section International Performance Measurement and Verification Protocol (IPMVP) is presented providing the basis of M&V methodology. Then, the

defined methodology for MOEEBIUS is explained, separated in three parts: ex-ante analysis, implementation and verification.

3.1 IPMVP

IPMVP documents common terms and methods to assess energy performance of energy efficiency projects and provides methods, with different levels of cost and accuracy, to determine savings for a whole facility or for individual energy conservation measures. Moreover, it specifies the contents of an M&V Plan.

In order to calculate savings, a baseline period should be defined (period before the application of measures) and this baseline period might need to be adjusted if the initial conditions are changed during the reporting period (after measures applied). Adjustments are required to compare in similar conditions (e.g., introduction of a new production line). Thus, the baseline is adjusted to the same conditions of the analysis period in order to perform the comparison at the same conditions. The following equation (Equation 1) summarizes the calculation method (IPMVP, 2012) [1]:

$$\textit{Savings} = (\textit{Baseline-Period Use} \text{ or Demand} - \textit{Reporting-Period Use} \text{ or Demand}) \pm \text{Adjustments}$$

Additionally, adjustments can be routine (expected) or non-routine (unexpected):

- Routine adjustments. For any energy- governing factors, expected to change routinely during the reporting period, such as weather or production volume.
- Non-Routine adjustments. For those energy-governing factors which are not usually expected to change, such as: the facility size, the design and operation of installed equipment, the number of weekly production shifts, etc.

Table 1 presents the IPMVP options for the retrofit isolation method, i.e., for the evaluation of isolated energy conservation measures and considering only the affected equipment or system independent of the rest of the facility (options A and B). Table 2 presents IPMVP options for the whole facility method, which consider the total energy use and de-emphasize specific equipment performance (options C and D). Then, a simplified option selection process is presented in Figure 1.

IPMVP Option	How Savings Are Calculated	Typical Applications
A. Retrofit Isolation: Key Parameter Measurement *Savings* are determined by field measurement of the key performance parameter(s) which define the *energy* use of the *ECM*'s affected system(s) and/or the success of the project. Measurement frequency ranges from short-term to continuous, depending on the expected variations in the measured parameter, and the length of the *reporting period*. Parameters not selected for field measurement are *estimated*. *Estimates* can based on historical data, manufacturer's specifications, or engineering judgment. Documentation of the source or justification of the *estimated* parameter is required. The plausible *savings* error arising from *estimation* rather than measurement is evaluated.	Engineering calculation of *baseline* and *reporting period energy* from: ○ short-term or continuous measurements of key operating parameter(s); and ○ *estimated* values. *Routine* and *non-routine adjustments* as required.	A lighting retrofit where power draw is the key performance parameter that is measured periodically. Estimate operating hours of the lights based on *facility* schedules and occupant behavior.
B. Retrofit Isolation: All Parameter Measurement *Savings* are determined by field measurement of the *energy* use of the *ECM*-affected system. Measurement frequency ranges from short-term to continuous, depending on the expected variations in the *savings* and the length of the *reporting period*.	Short-term or continuous measurements of *baseline* and *reporting-period energy*, and/or engineering computations using measurements of proxies of *energy* use. Routine and non-routine adjustments as required.	Application of a variable-speed drive and controls to a motor to adjust pump flow. Measure electric power with a kW meter installed on the electrical supply to the motor, which reads the power every minute. In the *baseline period* this meter is in place for a week to verify *constant* loading. The meter is in place throughout the *reporting period* to track variations in power use.

Table 1. IPMVP retrofit isolation method - options A and B (IPMVP, 2012).

IPMVP Option	How Savings Are Calculated	Typical Applications
C. Whole Facility *Savings* are determined by measuring energy use at the whole *facility* or sub-*facility* level. Continuous measurements of the entire *facility's energy* use are taken throughout the *reporting period*.	Analysis of whole *facility baseline* and *reporting period* (utility) meter data. *Routine adjustments* as required, using techniques such as simple comparison or regression analysis. *Non-routine adjustments* as required.	Multifaceted energy management program affecting many systems in a *facility*. Measure energy use with the gas and electric utility meters for a twelve month *baseline period* and throughout the *reporting period*.
D. Calibrated Simulation *Savings* are determined through simulation of the *energy* use of the whole *facility*, or of a sub-*facility*. Simulation routines are demonstrated to adequately model actual *energy* performance measured in the *facility*. This Option usually requires considerable skill in calibrated simulation.	Energy use simulation, calibrated with hourly or monthly utility billing data. (Energy end use metering may be used to help refine input data.)	Multifaceted energy management program affecting many systems in a facility but where no meter existed in the *baseline* period. Energy use measurements, after installation of gas and electric meters, are used to calibrate a simulation. *Baseline* energy use, determined using the calibrated simulation, is compared to a simulation of *reporting period* energy use.

Table 2. IPMVP whole facility method - options C and D (IPMVP, 2012).

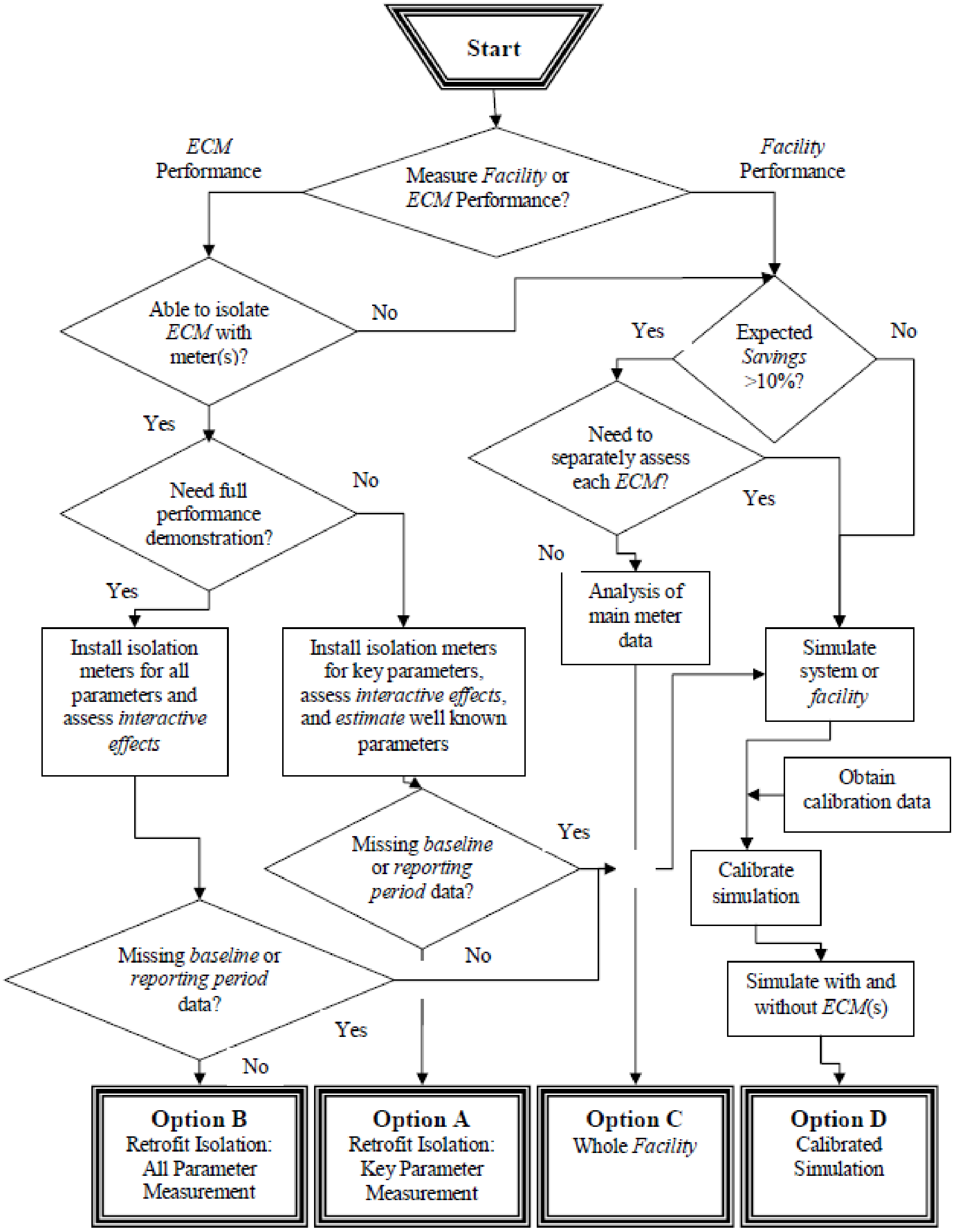

Figure 1. Option selection process (IPMVP, 2012).

3.2 M&V methodology for MOEEBIUS

The six steps defined in FEMP (2015) [2] to measure and verify savings are organized in the MOEEBIUS Measurement and verification (M&V) methodology in three phases: ex-ante analysis, implementation and M&V (Measurement and Verification). Furthermore, an additional step is considered in the Ex-ante analysis phase, comprising the analysis and comparison of the defined baseline.

Figure 2 represents the structure of these 7 steps distributed over the three phases of the MOEEBIUS M&V methodology.

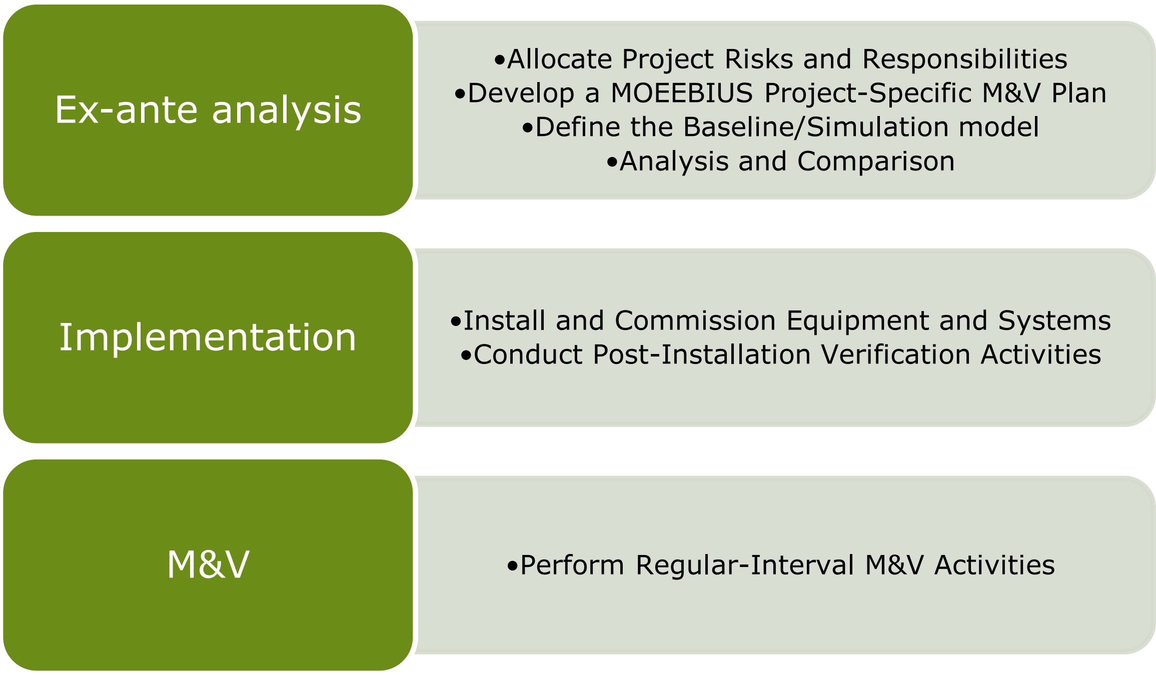

Figure 2. Scheme of the MOEEBIUS M&V methodology.

It has to be pointed out that the performance will be compared with two references:

- The Baseline period. This is the actual performance of the building measured in the period before MOEEBIUS implementation.
- The predictions obtained from the simulation models, in order to assess the gap between predicted and actual performance.

Thus, in the Ex-ante analysis phase, both comparison references have to be defined: the baseline and the simulation model.

3.2.1 Ex-ante analysis

3.2.1.1 Allocation of Project Risks and Responsibilities

As stated in FEMP [2], "the basis of any project-specific M&V plan is determined by the allocation of key project risks and responsibilities between the ESCO and the customer involved. A number of typical financial, operational, and performance issues must be considered when allocating risks and responsibilities. The distribution of responsibilities will depend on the customer's resources and preferences, and the ESCO's ability to control certain factors".

The design of the M&V and reporting process must run parallel to the Energy Conservation Measures (ECMs) design and implementation process (IPMVP [1]).

At this first stage of the M&V process, the following issues must be considered:

- Consider the needs of the user of the planned *M&V* report. If the user is focused on overall cost control, Whole-Facility methods may be most suited.

If user focus is on particular *ECMs*, Retrofit Isolation techniques may be most suited.

- While developing the ECMs, the IPMVP Option that best suits the ECMs, the needs for accuracy and the budget for M&V has to be selected. Furthermore, it has to be defined whether adjustment of all *energy* quantities will be made to the *reporting period* conditions or to some other set of conditions, and also the duration of the *baseline period* and the *reporting period* (These fundamental decisions must be written into the terms of an *energy-performance contract*).

3.2.1.2 Development of a MOEEBIUS Project-Specific M&V Plan

The first steps for the performance analysis consist in the collection of the necessary data to completely characterize the energy performance of the building:

- Define the type of measurement and data requirements.
- Gather relevant energy and operating data from the *baseline period* and record them in a way that can be accessed in the future.
- Identify significant energy uses.

After the development of these steps, an M&V Plan must be prepared containing the results of these steps and defining the subsequent steps.

3.2.1.3 Definition of the baseline

A first analysis must be carried out in order to establish the current performance of the system, before the implementation of any MOEEBIUS component or other manipulation with the system. This state of the building is defined as the Baseline, and its current energy consumption must be reported, in order to be able to evaluate the effect introduced by the deployment of MOEEBIUS and compare the performance of the system before and after the introduced changes. Thus, to enable the thorough validation of the MOEEBIUS framework, an ex-ante evaluation of the project pilot sites will take place before deployment to create a realistic and reliable performance baseline.

It is required also to define a calibrated simulation model that will be used for the evaluation of the gap between the expected (estimated by simulation) and the actual consumption.

For the analysis of the energy performance of a building with a specific configuration, a users' behavior and an equipment operation, it is necessary to ensure a proper collection of data followed by a thorough analysis of this data to get a full characterization of the energy performance of the building.

Therefore, it is necessary to define suitable Key Performance Indicators before any implementation of the MOEEBIUS framework.

3.2.1.4 Analysis and comparison

A model must be developed considering the collected data in the previous phase at each pilot site, constituting the Building Information Models. The BIMs of the buildings in the area for the MOEEBIUS implementation must be prepared to serve as the basis for the simulations to be performed through the Building Energy Performance Simulation (BEPS).

The Baseline, obtained before any intervention from MOEEBIUS with current building state and configuration and energy performance, will be used as reference data for comparing the final results after implementing MOEEBIUS framework in the area of deployment.

The energy baseline characterization will include the following elements:

- Analysis of the energy consumption over a sufficient period of time (about one year) and with sufficient resolution (hourly if possible) to identify variations in consumption.
- Estimated breakdown in energy consumption according to use (e.g. lighting, heating office equipment, servers, etc.).
- Independent and fixed variables that affect the energy consumption and the relevant values (i.e. degree days for heating or cooling, floor area for lighting, building opening hours, metering period length, etc.). This data must be measured at the same time as the energy consumption data.

As indicated before, it is then necessary to determine adequate Key Performance Indicators that reflect the parameters needed for the assessment of the energy performance at building and district levels. These KPIs will form the basis for routine comparison against the energy baseline, and to make results comparable, a monitoring of the KPIs and collection of all these data related to a determined time basis will be needed.

3.2.2 Implementation

3.2.2.1 Install and Commission Equipment and Systems

After the definition of the Baseline and the MOEEBIUS project-specific M&V plan, the next actions will aim to design, install, calibrate and commission any special measurement equipment that is needed under the defined M&V Plan.

Thus, for the approach and implementation of the monitoring system, the following steps will be required:

- Identify the systems to measure
- Specify the metering points
- Track the energy consumption data

- Define the metering specifications

Identification of the systems to measure

All the sources of energy delivered to the building must be identified. These sources of energy include all the energy supplied by a utility company or campus central plant, such as the following:

- Electricity
- Natural gas, propane, fuel oil, diesel, other fossil fuels
- Biofuels
- District chilled water, steam and hot water.

A basic metering does not require the metering of locally generated sources of energy that are dedicated to the project building. However, in an advanced building metering, it is required to identify all energy sources that serve the project. Both renewable and nonrenewable sources of on-site energy generation have to be considered:

- Renewable sources include wind turbines, photovoltaic panels, solar thermal panels, and geothermal.
- Nonrenewable sources include fossil fuel-burning generators and microturbines. Both inputs and outputs of nonrenewable sources, including fuel input, electricity output, and recovery heat (if applicable), must be metered.

Metering point's specification

Metering points and sensors required for performance verification, and the number, type and location of all the meters must be specified.

If the project is not served by a utility company or if the project uses multiple sources of energy, additional meters may be required. The location of primary building-level meters for each energy source has to be identified. If the project shares utility meters with other buildings or include energy sources that are not metered by the supplier, the installation of submeters will be required to provide the required data.

The project M&V system may use a single meter at the utility entrance or multiple submeters that account for whole building energy use in aggregate, but the areas within the project boundary served by separate utility feeds must also be metered.

The scope of metering needs to be determined, by considering if the utility meters (of the energy provided to the building by one or more utility companies) meet the prerequisite requirements (providing periodic data). The building owner should

confirm the following with the utility company: location, accessibility and reporting (how the meter will be read). The performance characteristics to verify must be identified.

Locations with easy access for reading and maintenance are preferred to be selected.

There are no requirements for the type of meters except that they must be permanent.

Energy consumption data tracking

At this phase of implementation of the M&V system, the measurement and recording of the energy consumption must be done, with a time granularity that can vary depending on the needs (from real-time monitoring to time aggregation as day or month). Tracking of the building occupancy, use, and maintenance must be considered as well in order to provide context for the energy consumption data and explain possible anomalies in usage patterns.

Metering specifications definition

All the metering specifications, such as the type of metering equipment, the measurement frequency (preferred less than 1h for continuous performance characterization) and the expected accuracy associated with the measurement have to be defined. In the same way, also the communication protocols and data storage to fulfil the requirements have to be specified.

All the meters should be installed, calibrated and maintained according to the manufacturers' recommendations, and data loggers should be installed to setup trend through the BMS.

The responsibilities for reporting and recording the energy data will be at this point assigned.

3.2.2.2 Conduct Post-Installation Verification Activities

As IPMVP recommends for the ECMs, once the ECMs and the MOEEBIUS framework have been installed, it has to be ensured that they have the potential to perform and achieve savings by conducting operational verification. This may include inspecting the installed equipment and revising operating procedures as needed to conform to the design intent of the ECM, as also for the deployment of the MOEEBIUS framework. This requirement may be fulfilled by a formal "commissioning" process as part of the project.

Referring to the simulation model for the performance prediction, the simulation model will have to be adapted to accommodate the ECMs implemented in the building.

3.2.3 Measurement & Verification

The M&V of determined parameters will allow the calculation of the key performance indicators evolution. At this point, it is possible to develop different tasks in order to assess the performance of the monitored system in order to:

- Verify the savings relative to the baseline period
- Evaluate the gap between actual and expected building performance

This task involves:

- Analysis Procedure. Specify the exact data analysis procedures, algorithms and assumptions to be used.
- Analyse data to determine actual performance and make the comparison with baseline energy consumption.
- Compare actual performance to expected performance (savings calculations, accuracy of the reinforced EnergyPlus building energy simulation engine)
- Analyse the monitored data in order to evaluate the performance of the system and optimize this performance through:
    - Isolate deficiencies raised in the facilities in order to have an effective maintenance of the system. In this way, possible inefficient units or malfunctions can be located and either fixed or the unit can be replaced.
    - Investigate the performance of the equipment.
    - Correct the controls for optimizing the operation, defining alternative maintenance schedules.
    - Update the enhanced energy simulation tool, with refinements of the components since the observed actuations of the occupants.
- Define the resources required for the savings determination, both initial setup costs and ongoing costs throughout the reporting period.
- Specify the energy prices that will be used to value the savings, and how savings will be adjusted if prices change in future.
- Assessment of information provided by MOEEBIUS framework to the end users in order to define optimization needs and alternative maintenance schedules.

3.3 Using BMS for performance monitoring of commercial buildings

The BMS systems (Building Management System) are the automation systems installed in buildings responsible for monitoring and control of various types of building's mechanical and electrical equipment, such as lighting, ventilation or HVAC systems. Sophisticated BMS systems may encompass multiple subsystems for comfort, energy, security, life safety, asset location, digital video and others.

The following types of data can be extracted from BMS systems:

- Control system data – set points, schedules, alarms
- HVAC system data – temperatures, flows, humidity, IAQ (Indoor Air Quality)
- Lighting system data – light levels, presence
- Security system data – video streams, access logs
- Utility data – electricity, gas and water consumption, utility prices, Demand Response (DR) events
- User interaction data – people's locations, movements, comfort preferences, comfort adjustments

Most BMS systems provide information about control and HVAC systems, while the availability of other data types may differ quite significantly. User interaction data has not been typically available until recently when some BMS functions started to be offered as mobile phone apps.

The following groups of metrics can be calculated automatically from the collected data:

Energy metrics (energy use and costs)

- Lighting energy use (per occupant or floor area)
- HVAC energy use (pumps, fans, chillers, boilers, including purchased energy)
- Refrigeration energy use (for supermarkets and other relevant facilities)
- Other use of energy (plug loads, dishwasher, data center, cooking, etc.)
- Locally produced energy (thermal, wind, photovoltaics)

Operations and maintenance metrics (*some of them may require additional data, not listed above*)

- Equipment operation cost (repair, recommissioning, operation training, etc.)
- Preventive maintenance cost
- Work orders and service calls (percentage, volume, cost)
- Diagnostic maintenance cost (HVAC system diagnostics, envelope, lighting, refrigeration diagnostics costs)
- Janitorial services and outdoor maintenance cost

Indoor environmental quality metrics (*satisfaction metrics can be calculated only if occupants interact with mobile apps and/or fill out dedicated questionnaires*)

- Thermal comfort satisfaction by floor / zone - % of satisfied
- Indoor temperature by floor/zone
- Lighting satisfaction by floor / zone (illuminance)
- Air quality by floor / zone (CO_2, VOC levels, occupant satisfaction)
- Others – satisfaction with acoustic, cleanliness, safety and security, etc.

Performance monitoring process involves systematic comparison of actual metrics with baselines (reference data and/or baselines calculated from historical data).

4 KPIs selection Methodology

Following the detailed presentation of the MOEEBIUS M&V protocol, this document proceeds with the definition of the KPIs that complement the work for Energy performance assessment. The starting point of the work is the definition of the methodological framework that enabled the selection of the MOEEBIUS Key Performance Indicators.

4.1 Selection process

The selection process has consisted of the following steps:

- Initial proposal of partners for different KPIs categories
- Collation of inputs into a global list and rating
- Final selection in conference call

As a first approximation to the Key Performance Indicators list, an initial pre-selection of indicators was built up by the contribution of task T2.3 partners, each of them contributing with the definition of potential KPIs in their respective expertise areas. It was also considered the information from existing methodologies (e.g. LEED, BREEAM), R&D projects (CONCERTO [5], FASUDIR [47]) and Standards (EPBD, NZEB) on building and neighbourhood-level.

Initially five different KPIs categories were considered:

- Environmental aspects
- Energy aspects
- Demand response aspects
- Social aspects
- Economic aspects

Each category was composed by several issues which have been identified as important for MOEEBIUS.

Later, it was decided to consider only the CO_2 emissions as the key environmental KPI for the primary energy use. Additionally, the social category was renamed as indoor environmental conditions, and since one of the goals of the MOEEBIUS tool is to optimize the predictive maintenance diagnostics, a new category for predictive maintenance was created to assess HVAC systems performance.

The goal of the selection process was to select the most significant indicators to a manageable but still meaningful amount of Key Performance Indicators that are sufficient for conducting a solid sustainability assessment of building and district energy performance optimization projects. In order to reduce the number of potential indicators for conducting a detailed analysis it is necessary to pre-select the most suitable indicators for MOEEBIUS from the repository built-up.

The selected aspects were differentiated between building level (issues concerning the sustainability of single buildings) and district level (issues concerning the sustainability of the whole urban district), considering the issues at district level as an aggregation of the individual buildings issues composing the whole district.

The results of this first pre-selection phase are shown in the tables of the questionnaire for the KPI selection on Annex I. A detailed description of each KPI, the algorithms or formulas used for its calculation and the needed monitored parameters will be developed in the following sections of the deliverable.

To guide the final decision in the selection of the most suitable KPIs, a voting has been carried out including all task T2.3 partners. A questionnaire based on the pre-selected KPIs was prepared and filled in by each partner (Annex I). The role of the questionnaire was to rate the importance of the different issues for MOEEBIUS and to create a background for the discussion knowing previously the opinion of the partners on the carried out pre-selection. Each potential KPI was rated on a scale of 0-5 (0 not significant, 5 very significant) according to the significance and how suitable in the opinion of each partner they are for MOEEBIUS. Partners were asked to rate all the KPIs categories as possible, but in case they find not to have enough expertise in any category, they could leave it blank. The average of the evaluated ratings for each KPI was calculated. In the questionnaire the project partners were encouraged to use the following criteria for the ranking of the issues:

- The selection process for the Key Performance Indicators of the MOEEBIUS tool, not only of the building performance at the pilot sites of the project. In the same way, the tool developed on the MOEEBIUS framework will be applied to the pilot sites as an example of the capabilities for a potential commercial product to be developed. Therefore, the consideration of more general KPIs for covering a wider range of application cases could be necessary.
- For the assessment of the KPI ratings, task T2.3 partners have to be conscious of the main goals of the MOEEBIUS project:
    - Precise allocation of detailed performance contributions of critical building components, for directly assessing actual performance against predicted values and easily identifying performance deviations and further optimization needs.
    - Real-time building performance optimization and peak-load management optimization at the district level.
    - Optimized retrofitting decision making on the basis of improved and accurate LCA/ LCC-based performance predictions.

This optimization refers to the operation at building and district level with the minimum costs and/or energy consumption, which means the lower economic costs, energy depletion and environmental impact. Along with the definition of energy and economic KPIs, the scope of the project is to address the role of building occupants as an active element of the buildings. Therefore, this operation

optimization must be constrained to the satisfaction of the comfort and health requirements for the building occupants. Therefore, one of the main objectives is to enhance the MOEEBIUS performance evaluation framework with Key Performance Indicators related to occupants' preferences.

The goal of the voting was to identify which main issues are rated as relevant for MOEEBIUS by the project partners. The partners were also encouraged to add comments and suggestions. After gathering all the ratings and comments (results are shown in Annex I), the results were delivered to all the partners and discussed in a conference call in order to define the final list for the MOEEBIUS KPIs list.

4.2 Results

The poll results (presented in Annex I) had shown that a crucial environmental aspect to be considered is the global warming, especially the CO_2 emissions considered not only as an environmental indicator but also related to the primary energy use. Therefore a KPI for the CO_2 emissions as indicator of the environmental impact and simultaneously of the primary energy use is required. Other environmental aspects as the Ozone depletion, acidification, land use or water consumption are hardly to be considered in the MOEEBIUS framework. In one hand, due to the difficulties to monitor some of the involved parameters, but also due to the low influence of these indicators in comparison to the CO_2 emissions on the final decision making for the operation, maintenance and retrofitting actuations in the MOEEBIUS framework. Thus, a KPI for the CO_2 emissions is considered as indicator for both the primary energy use and the environmental impact.

All of the proposed KPIs for the energy performance got a good rating, since they are key in the MOEEBIUS project, and therefore all of them are considered for MOEEBIUS. These comprise the energy needs indicators, the indicators for the consumption and generation of energy, considering both renewable and non-renewable generation, and the final energy use indicators, which can be referred to the use of primary energy or, as mentioned before, referred to the KPI for the CO_2 emissions.

Among the KPIs in the social category, those for thermal comfort were also considered of significance, but some of them were considered to be redundant. Therefore, the most significant are considered. Nevertheless, some of these redundant indicators are by-products of other calculations, and no additional effort is needed for their assessment. Thus these KPIs are also considered. However, the "Noise level" and "Safety and security" KPIs were considered to be difficult to measure and due to the fact that they have low influence in the building operation and maintenance decisions in MOEEBIUS, these two KPIs will be not considered.

In the same way, among the economic issues, most of them got a quite good rating, showing the significance of these indicators in the MOEEBIUS project. However, the "Change in values of property" will not be considered also due to the

difficulty of measurement and determination and because not being addressed by MOEEBIUS in the decision making for the building operation, maintenance and retrofitting actions.

The results of the poll at district level were very similar to that at building level, therefore the same conclusions were obtained.

Results of the KPIs ratings of each task partner at both building and district level are presented in "Annex I: Vote Results for KPIs Selection". Based on these results of the poll and the comments and suggestions provided, the main KPIs to be considered in MOEEBIUS had been discussed.

Many KPI issues that were poorly rated in the pre-selection votes or were considered redundant are by-products of other calculations and require no additional effort in the assessment. For example, for the calculation of the Predicted Percentage Dissatisfied as indicator of the thermal comfort, it is necessary to calculate the Predicted Mean Vote, which is also an indicator for the thermal comfort. Therefore these KPI issues are selected additionally.

The finally selected KPIs at each category are described in the following document sections, comprising these categories:

- Energy KPIs
- Demand Response KPIs
- Occupants Comfort KPIs
- Indoor Air Quality KPIs
- Economic KPIs
- Predictive Maintenance KPIs
- MOOEBIUS Simulation system Performance KPIs

The detailed presentation of each category is described in the following sections, starting with the list of Energy Key Performance Indicators that consist of the skeleton of the MOEEBIUS performance framework.

5 Energy Key Performance Indicators

5.1 Introduction

5.1.1 Scope of the methodology

The MOEEBIUS solution will impact on *performance gap* reduction through a Holistic Energy Performance Optimization Framework. Diverse steps and processes of the framework will be based on evaluating the deviation between predicted (simulated) and actual energy consumption (measured).

Therefore, the methodology must establish diverse energy indicators and parameters obtainable through both methods (simulation and monitoring) for identifying deviations, quantifying energy gaps at varying level of detail inside a building, etc.

Simulation models will be detailed enough to study energy aspects at building subsystems or zones levels and to simulate their energy behaviour. In the same way, the presented monitoring methodology will allow the possibility of measuring energy performances at lowest aggregation levels like building's subsystems or even single critical equipment.

The level of monitoring reached in each application of MOEEBIUS at real cases will depend on the sensor deployment and specific end-user requirements.

5.1.2 Needs and requirements

End-user's requirements for MOEEBIUS implementation will determine the level of detail required or recommendable for monitoring deployment. 5 business scenarios were defined in MOEEBIUS Deliverable 2.1.

MOEEBIUS might be implemented in scenarios where a diverse grade of granularity or precision at aggregation levels is required and/or available. Therefore the methodology established for measuring energy parameters should face both district and building levels, and beyond it, lowest aggregation levels and equipment that might be critical for a building's energy performance.

For determining the following methodology, the state-of-the-art about Energy Indicators, M&V protocols and energy balance of buildings have been reviewed. The main consulted sources (ZenN, IEA, Concerto, IMVP and ASHRAE) are listed on the references.

5.2 Energy indicators

To make results comparable, buildings and districts energy performance values are usually referred to different basis or indicators. This point tackles with the key performance indicators related with buildings energy use on a yearly basis.

Main analysed sources include:

- Indicators from EU regulation related with the Energy Performance of Buildings Directive
- Potential indicators from initiatives like Concerto.
- Indicators from standards or harmonization works like for example Nearly zero energy buildings (PreEN 15603).

These points are further developed in the following subsections.

5.2.1 - Indicators from EPBD regulation.

The recast of Energy Performance in Buildings Directive (EPBD), the EU 2010/31/EU, in its article 9, states that Member State's shall include a detailed application in practice of the definition of nearly zero-energy buildings and including a numerical indicator of primary energy use expressed in kWh/m^2 per year.

In its 3rd article the EPBD recast states that Member States shall adopt a methodology for calculating the energy performance of buildings. Building energy performance shall be determined on the basis of the calculated or actual annual energy (monitored) that is consumed in order to meet the different needs associated with its typical use and this includes the heating and cooling energy needs to maintain the envisaged temperature conditions of the building, and domestic hot water needs. Since actual or operational energy performance includes users' behaviours and the potential malfunctioning of some equipment, (thus might not necessary reflect the typical use), 14 member states have not adopted this methodology, and rely only on the calculated energy performance.

In its article 4, it states that Member States shall take the necessary measures to ensure minimum energy performance requirements set with a view to achieving cost-optimal levels.

The comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings is further developed within the regulation EU244/2012.

And in its 11th article, the EPBD states that for selling or renting a building or building units, it needs to have an energy performance certificate.

The main building energy related indicators for the EU 244/2012 and for energy certification are the following ones:

<u>Energy building needs/use</u>

Energy need for heating (kWh/m^2·year)

Energy need for cooling (kWh/m^2·year)

Energy need for Domestic Hot Water (DHW) (kWh/m^2·year)

Energy need for other (humidification, dehumidification) - (kWh/m^2·year)

Energy use for ventilation (kWh/m^2·year)

Energy use for internal lighting - (kWh/m^2·year)

Energy use for other (appliance, external lighting, etc.) (kWh/m^2·year)

Energy generation at the building site

Thermal energy from Renewable Energy Sources (RES) (e.g. thermal solar collectors) (kWh/m^2·year)

Electrical energy generated in the building and used onsite (kWh/m^2·year)

Electrical energy generated in the building and exported to the market (kWh/m^2·year)

Energy consumption

Delivered electricity (kWh electricity /m^2·year)

Delivered fossil fuels (kWh fossil fuel/m^2)

Other delivered energy (biomass, district heating/cooling, etc.) (kWh/m^2·year)

Buildings final energy consumption/use:

Referred to primary energy kWh PE/m^2·year or Kg CO_2/ m^2·year

5.2.2 – CONCERTO databases indicators

CONCERTO is a European Commission initiative within the European Research Framework Programme which aims to support communities for the implementation of combined actions to increase buildings (either new or existing) and communities energy efficiency and the use of renewable energy sources.

To support the impact assessment of the CONCERTO initiative and the implemented local energy strategies, projects real energy use is monitored and data stored in a database that is being used by all the communities involved in the initiative.

CONCERTO Premium developed data collection sheets for new and refurbished buildings containing general data as well as aggregated monitoring data. There is a set of four groups of tables (1) Country, (2) Community, (3) Concerto Area and (4) Concerto Demonstration projects. *Country* and *Concerto area* related sheets, gather general information of the local circumstances related with buildings and energy balances. The Community and Concerto Demonstration project set of

tables are the ones which collect community and buildings energy performance related data as it is further explained bellow.

The following figure summarizes the main structure of data needed in the Concerto databases and collected in different sheets:

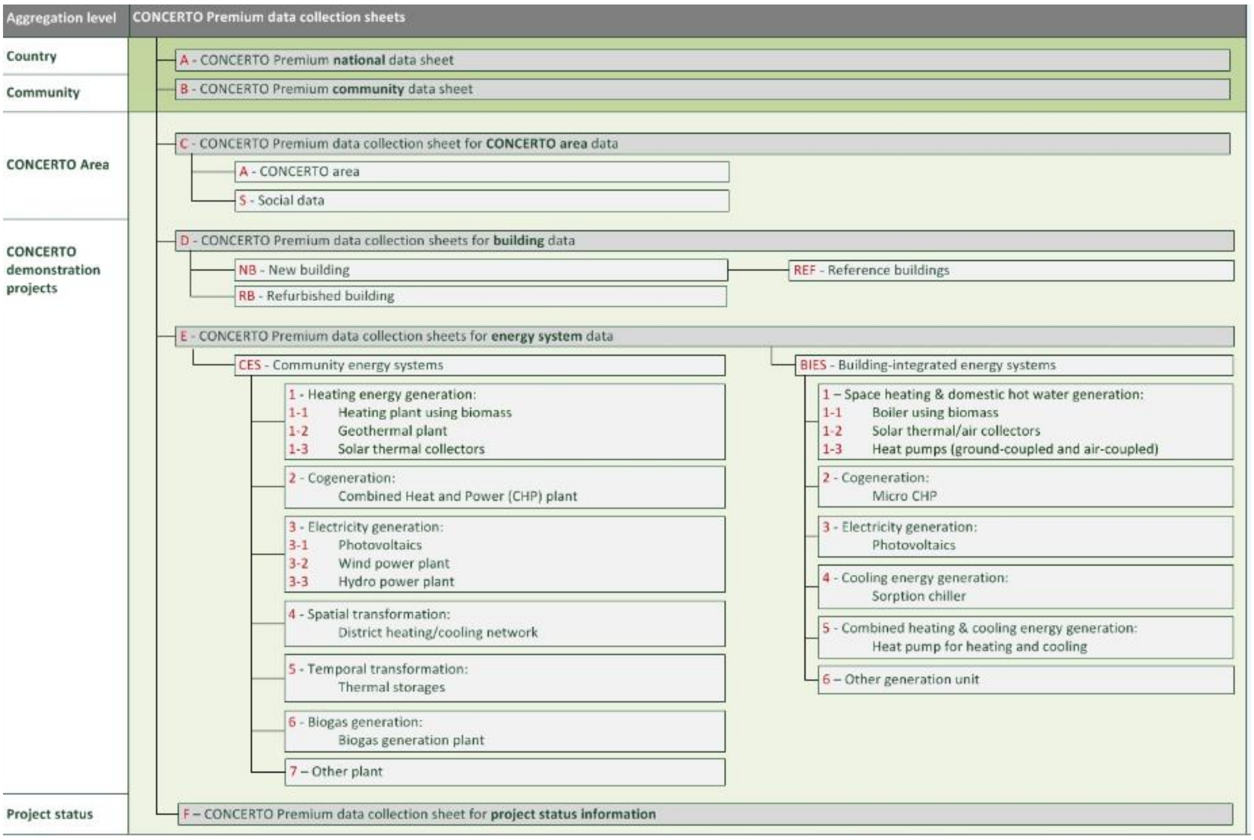

Figure 3. Main structure of Concerto Data Collection Sheets. (Source: Concerto 2011).

Concerto Guidelines define the minimum monitoring requirements in order to enable the analysis of the overall energy performance of a CONCERTO area and possible improvements. The overall generated, delivered and consumed energy of the whole energy system of a CONCERTO area needs to be metered and collected.

The monitoring data sheets included in the *Community* and *CONCERTO demonstration projects data sets* structure the monitored energy use information in two main parts: (1) the energy production part that is focused on the Community energy supply infrastructure (district energy systems and distributed energy plants), and (2) the consumption part that gathers all data related to energy use in buildings system (i.e. boilers, CHP, Photovoltaic, solar thermal).

Going one step beyond, main data collected for Community energy performance monitoring data includes all the energy inputs by energy carrier and, where applicable, energy outputs like for example onsite RES production:

(1) Energy production or Community energy systems:

For each energy production or transformation technology the energy inputs and outputs by energy carrier in the monitored period [MWh EC/monthly in the monitored period].

(2) Buildings Energy input and output energy flows:

For each energy carrier, input energy flow into all buildings for the application area or for the following purposes: Space heating, DHW, Space cooling, Electrical appliances, Electricity export [MWh EC /monitoring period].

Differentiating the following data in the case of *communities:*

- Input and output energy flows of all residential buildings of the area
- Input and output energy flows of all commercial buildings of the area
- Input and output energy flows of all large-scale energy supply system located in the area considered; The building-integrated energy supply units are only considered in column "*(b) electricity for export (building-integrated)*"

In the case of buildings, information is similar, but information should be provided at building energy system included within the project (i.e. boilers, on site solar thermal panels, BIPV, CHP, chillers, lighting, etc.).

Timeframe for metering and to include data in CONCERTO Premium database: at least monthly metered values of energy production and energy consumption by energy carrier should be provided. Overall monitoring period should ideally last at least, two years after construction works have finished.

The monitoring stages of the Concerto initiative include:

- Before construction works start, *pre-retrofitting monitoring*:(1-3 years), all energy consumption data by energy carrier should be metered, including final energy demand for space heating, domestic hot water, cooling, electrical appliances in kWh/month.
- After construction works end, post-retrofitting monitoring (Project year 4): Monthly metered values of energy consumption and energy generation by energy carrier should be provided.
- Last stage, includes the second year of monitoring after retrofitting and overall data analysis, including climate and building operation adjustments, and referring data to unitary floor area since it allows for comparisons between buildings of different sizes.

Both project stage estimated energy performance and post-retrofitting metered real energy performance data are stored in the database. This allows a comparison between expected and actual community energy performance (ex-ante and ex-post evaluation) (Olivier Pol, 2009).

The overall process is further detailed in the figure below:

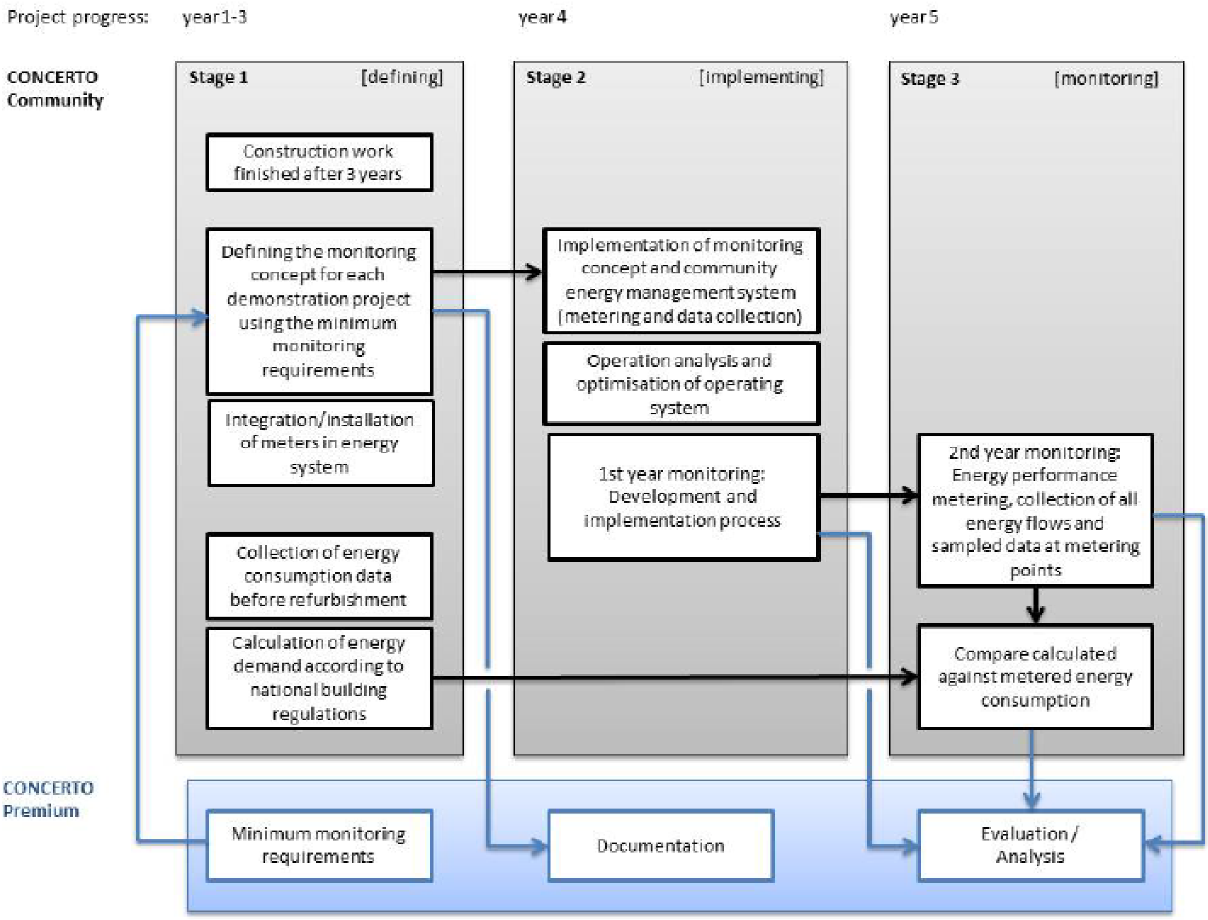

Figure 4. Three stages of monitoring within Concerto Initiative (Concerto 2011).

5.2.3 - Nearly zero energy buildings (NZEB) indicators.

In line with the energy balances for NZEB discussed in previous sections, there will be indicators of special interest for evaluating the performance of this type of buildings.

The system performance indicators should cover at least the services (sub-systems) included in the following table or a combination of such systems, but preferably a separate accounting is kept for each individual energy service.

Building services	Included in the energy balance of NZEB according to PreEN15603
Heating	Yes
Cooling	Yes
Ventilation	Yes
Humidification	Yes
Dehumidification	Yes
Domestic hot water	Yes
Lighting for non-residential buildings	Yes
Electric equipment of the central systems (pumps, burners, etc.), and the lighting consumption of common areas.	Yes
Lighting for residential buildings	Optional in residential building
Appliances	Optional

Table 3. Building services Included in the energy balance of NZEB.

5.2.4 List of energy KPIs at building level

As seen in previous descriptions of standards and regulations, different space and time references are considered in different system homologations. Nevertheless, since MOEEBIUS requires a continuous monitoring in order to develop the operation optimization and the gap reduction between predicted and actual performance of buildings and districts, a small time interval will be required, preferred hourly if possible. Related to the space granularity, the smallest enabled by the monitoring system will be desired, and an aggregation will be considered at buildings and district level.

At a building level, energy KPIs characterize the performance of the building inside the building boundary and the energy flows at the boundary with the exterior. Figure 5 shows a scheme of the energy flows considered at building level.

The physical boundaries concept will be further described on section 5.3.

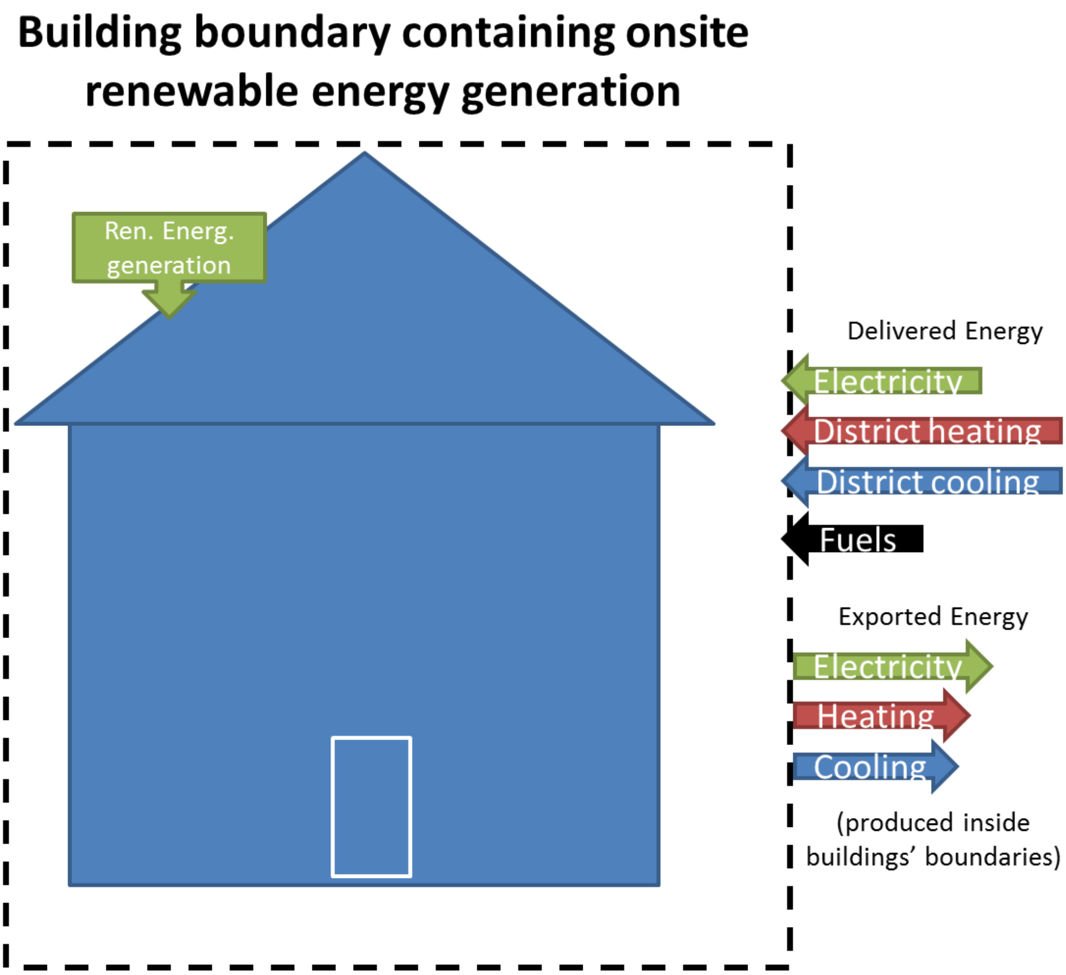

Figure 5. Energy flows at building level.

Main buildings energy uses that need to be included in the energy balance are the following ones:

Energy building needs/use

En.1 Energy need for heating

En.2 Energy need for cooling

En.3 Energy need for DHW

En.4 Energy need for other (humidification, dehumidification)

En.5 Energy use for ventilation

En.6 Energy use for internal lighting

En.7 Energy use for other (appliance, external lighting, etc.)

Energy generation at building site

En.8 Thermal energy from RES

En.9 Electrical energy generated in the building and used onsite

En.10 Electrical energy generated in the building and exported to the market

Energy consumption

En.11 Delivered electricity

En.12 Delivered fossil fuels

En.13 Other delivered energy (biomass, district heating/cooling, etc.)

Final energy consumption/use

En.14 Referred to primary energy

En.15 Referred to CO2

It has to be pointed out that the selection of KPIs is based on the capability of measuring the associated parameters. The next section presents a detailed framework for Energy KPIs monitoring and calculation.

5.2.5 List of energy KPIs at district level

At a district level, not only the aggregation of individual buildings comprising the district is considered, but also the energy generation plants and distribution grids. Energy KPIs will characterize the performance of the elements inside the district boundary and the energy flows at the boundary with the exterior. Figure 6 shows a scheme of the energy flows considered at district level.

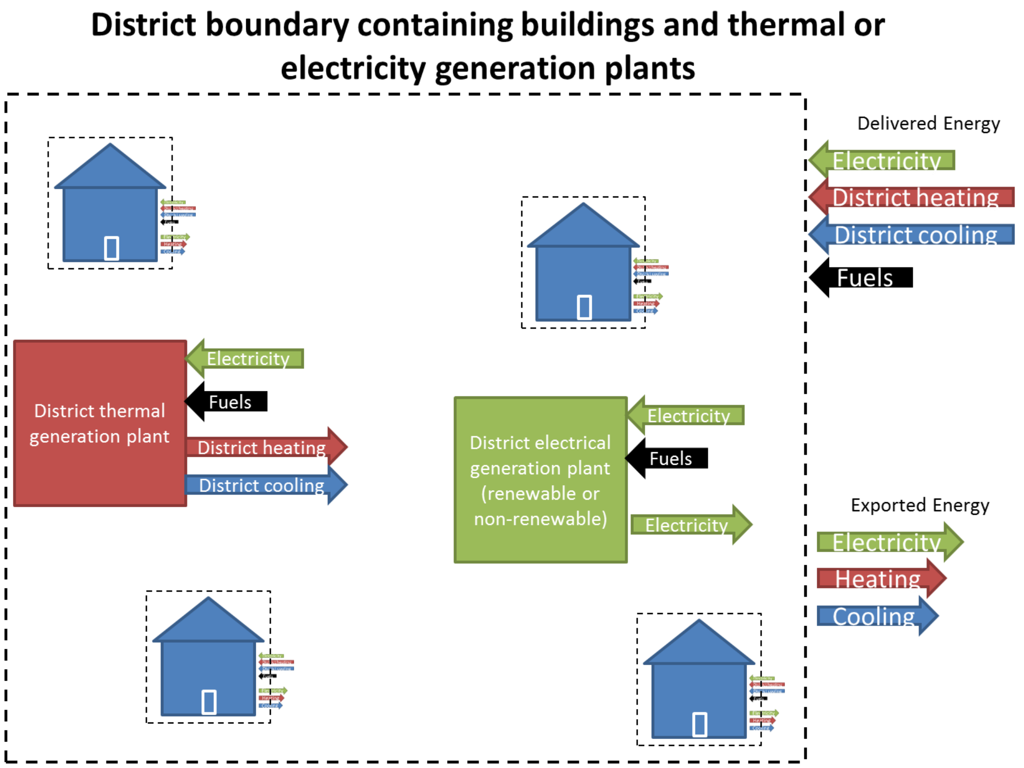

Figure 6. Energy flows at district level.

Therefore, on one hand, at district level all the energy KPIs considered at building level will be considered as an aggregation of all the individual buildings conforming the district. The aforementioned KPIs will be considered:

Energy needs/use

En.1	Energy need for heating
En.2	Energy need for cooling
En.3	Energy need for DHW
En.4	Energy need for other (humidification, dehumidification)
En.5	Energy use for ventilation
En.6	Energy use for internal lighting
En.7	Energy use for other (appliance, external lighting, etc.)

Energy generation at building site

En.8 Thermal energy from RES

En.9 Electrical energy generated in the buildings and used onsite

En.10 Electrical energy generated in the buildings and exported to the market

Energy consumption

En.11 Delivered electricity

En.12 Delivered fossil fuels

En.13 Other delivered energy (biomass, district heating/cooling, etc.)

Final energy consumption/use

En.14 Referred to primary energy

En.15 Referred to CO2

Furthermore, at district level it will be necessary to consider additional energy KPIs not related to the aggregation of the performance at individual buildings. These indicators are required for the characterization of common elements at the district level needed for the energy service but not considered at the building boundaries (such as the distribution pipes for district heating, central generation plants, etc.).

Energy indicators of the generation plants

These KPIs would be repeated for each plant and divided in RES and non-RES if necessary at each case.

Energy generation at district plants

En.16 Electrical energy generated in the district plants and used onsite

En.17 Electrical energy generated in the district plants and exported to the market

En.18 Thermal energy generated in the district plants and used onsite

En.19 Thermal energy generated in the district plants and exported to the market

Energy consumption of the district plants

En.20 Delivered electricity at the plant

En.21 Delivered fossil fuels at the plant

Distribution/Delivered fossil fuels

En.22 Energy losses from the plant to the building

Final energy consumption/use at district plants

En.23 Referred to primary energy

En.24 Referred to CO2

Energy indicators at district boundaries

These KPIs consider the aggregation of those energy flows that are common for the individual buildings and the generation plants inside the district boundaries. These KPIs are:

Energy generation at the district

En.25 Electrical energy generated in the district (buildings and plants) and used onsite

En.26 Electrical energy generated in the district (buildings and plants) and exported to the market

En.27 Thermal energy generated in the district (buildings and plants) and used onsite

En.28 Thermal energy generated in the district (buildings and plants) and exported to the market

Energy consumption at the district

En.29 Delivered electricity at buildings and plants

En.30 Delivered fossil fuels at buildings and plants

Final energy consumption/use at the district

En.31 Referred to primary energy

En.32 Referred to CO2

5.3 Monitoring diagrams

In order to monitor the energy performance of a system in MOEEBIUS, diverse topics are discussed in the following lines.

5.3.1 System's physical boundary

The energy parameters and indicators will be related to the processes and exchanges within the system's boundary and through it. That boundary is a virtual limit assumed, which can differ depending on the topic of interest for MOEEBIUS application in each case. It is necessary to agree the convention that will be employed in the present project for establishing the boundaries of a building and of a district (if needed). As an example, Figure 7 and Figure 8 represent the boundaries to be considered for evaluating NetZero energy buildings or neighborhood respectively according to PreEN 15603.

In any case, and in order to agree with the standards, MOEEBIUS methodology will consider on-site energy sources the ones generated inside the boundary (self-consumed or exported) and off-site the energy imported into system's boundary, whether being renewable or non-renewable.

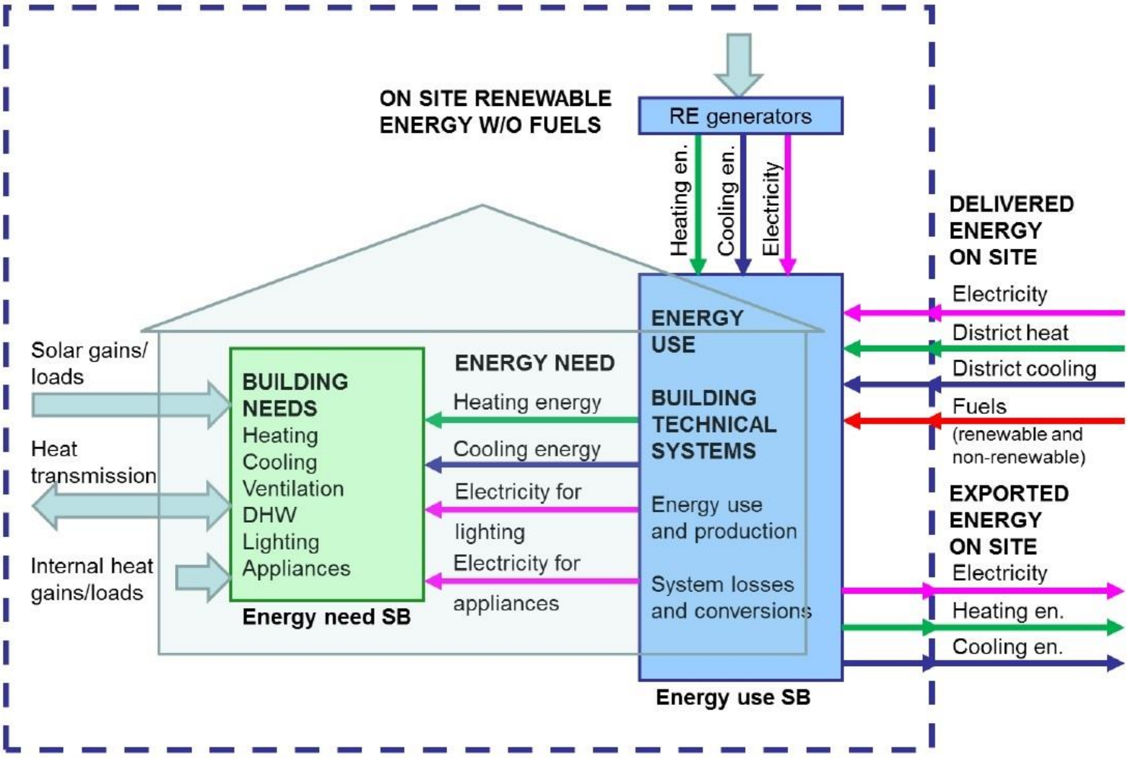

Figure 7. Scheme of the NetZero energy building concept understood under PreEN 15603.

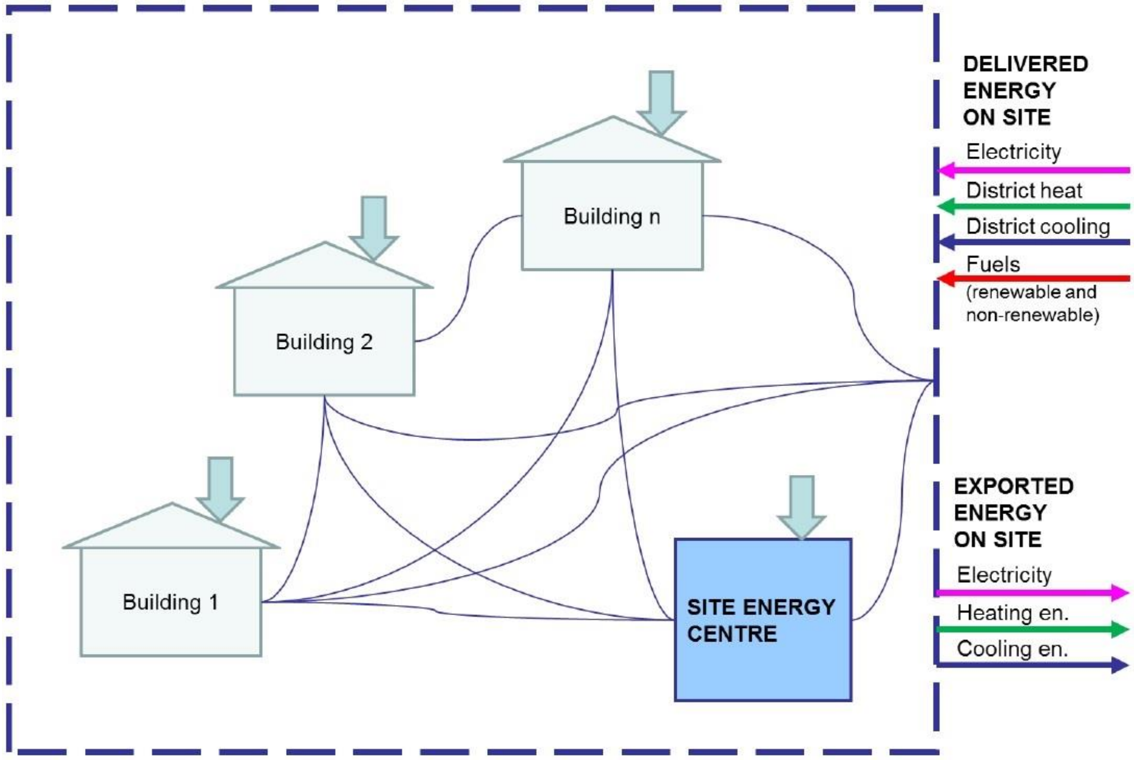

Figure 8. Scheme of the NetZero energy neighbourhood concept understood under PreEN 15603.

5.3.2 Granularity level

As mentioned before, BEPS models developed in *EnergyPlus* will be precise enough to study in detail building subsystems and to simulate their energy needs and uses. Therefore, the MOEEBIUS methodology will allow to measure and simulate at lowest aggregation levels like building's subsystems or even single critical equipment. However, the level of granularity reached in each application of MOEEBIUS in real cases will be limited by the sensor deployment and that scenario's end-user requirements. In the same sense, diverse modules of MOEEBIUS (BEPS, Dynamic Assessment Engine at building level, Predictive Maintenance) will present their functionalities adjusted to the certain simulation/measurement granularity level of each scenario.

In summary, the considered methodology will be adaptable to diverse boundaries, which will be conditioned by measurement approach. In the following lines, the monitoring diagram for diverse cases will be described, from single elements or energy process monitoring to the case where the interest is on inputs/outputs at building level.

The definition of monitoring options will take as starting point the proposal for nearly zero energy neighbourhoods developed in the EU funded project ZenN [4] and the IEA document. MOEEBIUS will be applicable to any building or district, irrespective of their energy performance, so, for example, the diagram should be adaptable to buildings with or without Renewable Energy Sources.

Figure 9 presents the standard reference diagram for monitoring a building (ZenN, IEA), with the energy flows inside and through the building boundary. On-site energy sources will be considered the renewable ones generated within the building's boundaries, which might be consumed inside the building or exported. On the other hand, both renewable and non-renewable energies delivered through the building's boundary will be named off-site.

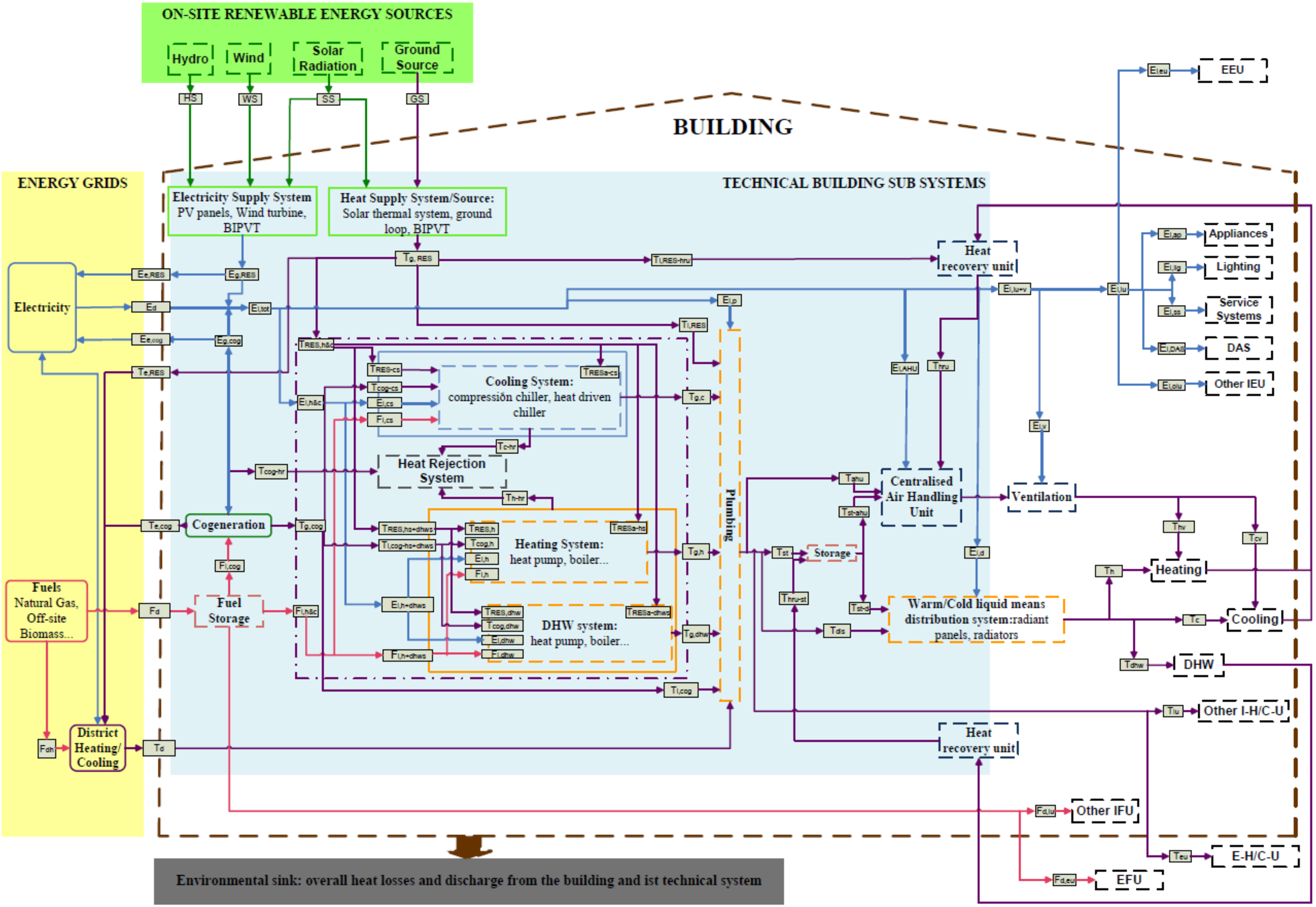

Figure 9. Itemized diagram for monitoring (Source: ZenN project, 2014).

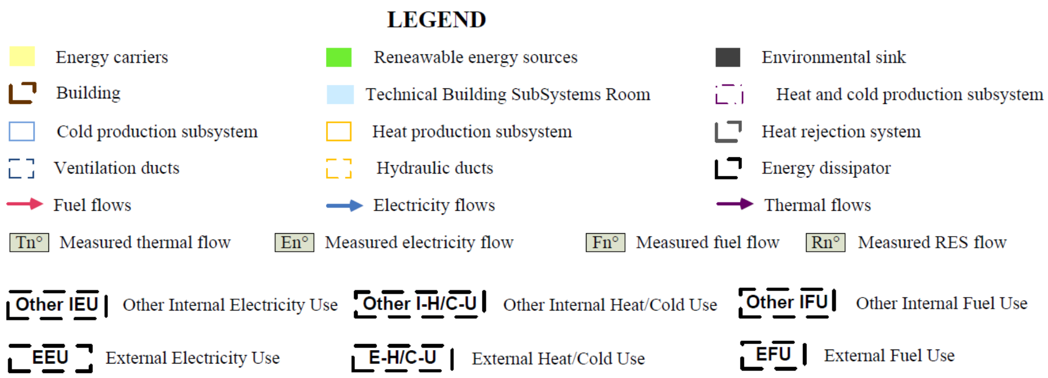

Table 4. Legend of monitoring diagram (Source: ZenN project, 2014).

The monitoring diagram schematizes the measurable energy flows and forms or carriers inside a building (thermal, electrical, fuel, renewable energy), and more in detail, the energy inputs and outputs of technical subsystems or final uses per needs.

Through this approach, all kind of technical subsystems can be monitored, irrespective of the energy forms of their inputs and outputs, such as:

- Gas boiler (fuel input / thermal output)
- Heat pumps and compression chillers (electricity input / thermal output)
- Thermally driven heat pumps and chillers (thermal+electrical input / thermal output)
- Solar thermal heating system (thermal+electrical input / thermal output)
- Cogeneration units (thermal+electrical inputs / thermal+electrical output)

It must be noticed that this methodology enables considering of multiple inputs and outputs per system, like it occurs for example with electrical consumption of pumps and fans at the thermally driver chillers.

Above the technical subsystem's boundaries, but still within the limits of building's boundary, the final uses of energy can be split (as shown in black dash line boxes) and monitored according to the energy inputs for that purpose, as following:

- Heating
- Cooling
- DHW
- Ventilation
- Lighting
- Appliances

Finally, in order to quantify the energy inputs for Renewable Energy generation systems and obtain their efficiencies through the outputs, primary sources like

wind speed or solar radiation would be necessary to measure using meteorological sensors or weather stations.

5.3.3 Energy balances

As stated before, the advances in nZEBs evaluation will be used as starting point for the present methodology. In this case, two methods for evaluating a building's energy balance will be discussed.

The topic of zero energy buildings (ZEBs) is gaining popularity in recent years, until becoming part of the energy policy in several countries. In the recast of the EU Directive on Energy Performance of Buildings (EPBD) it is specified that by the end of 2020 all new buildings shall be *"nearly zero energy buildings"*

However, despite the emphasis on the goals the definitions remains in most cases generic and are not yet standardized (Sartori 2011).

There is a conceptual understanding of a ZEB as an energy efficient building able to generate on-site electricity, or other energy carriers, from renewable sources in order to compensate part of its energy demand. Therefore, it is implicit that there is a focus on buildings that are connected to an energy infrastructure and not on autonomous buildings.

To this respect the term Net ZEB can be used to refer to buildings that are connected to the energy infrastructure. The wording 'Net' underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year.

However, an annual balance is not in itself a guarantee that the building is designed in a way that minimizes its (energy use related) environmental impact. In particular, Net ZEBs should be designed to work in synergy with the grids and not to put additional stress on their functioning.

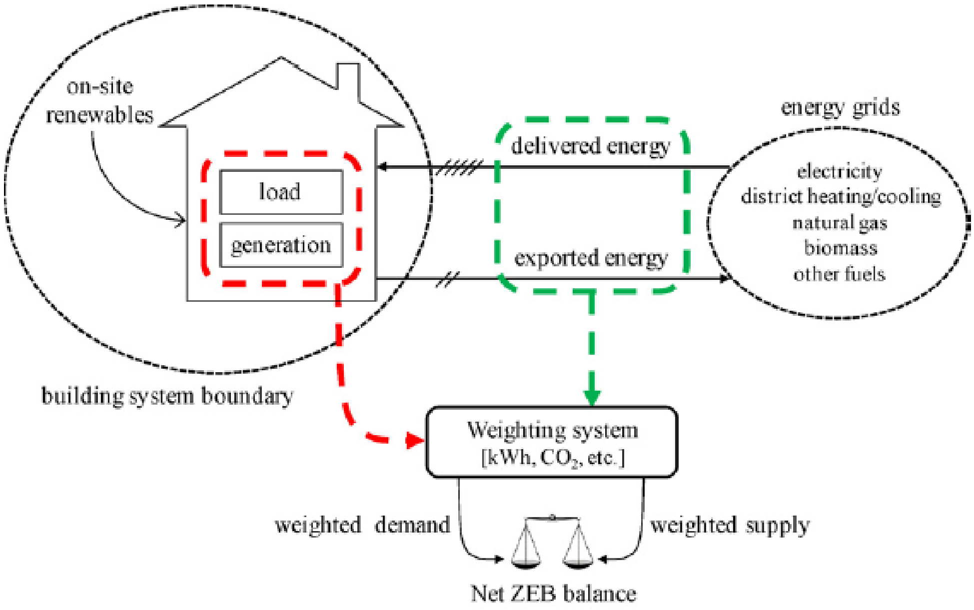

Figure 10. Net ZEB balance two methods (Source: ZenN project, 2014).

The common denominator for the Pre-EN 15603 framework Net ZEB definition is the balance between weighted demand and supply. The balance may be basically calculated in two different ways, (1) an import/export balance focused on the energy flows exchanged between the building and the grids comparing, energy delivered from and energy feed-in to the grids; or (2) to compare the energy use and on site renewable energy generation (load-generation balance).

Load to generation balance focuses on the gross load and generation quantities disregarding their interplay, and can be expressed as follows:

$E_p = \sum_{i=1} g_i * w_{e,i} - \sum_{i=1} l_i * w_{d,i}$ (load generation energy balance)

where *g* and *l* stands for generation and load, respectively; *e* stands for exported and *d* for delivered, *w* stands for weighting factor and *i* for energy carrier. Balance should be carried out in each time-step (recommended: 1hour) and figures should be expressed at least on a monthly basis.

Import-export balance or net delivered energy represents the exchanged energy flows between the building and the grids, and it is calculated as the delivered energy minus exported energy for each energy carrier

$E_p = \sum_{i=1} e_i * w_{e,i} - \sum_{i=1} i_i * w_{d,i}$ (export/import balance)

To convert these values into primary energy and have an overall indicator, weighting factors ($w_{e,i}$ and $w_{d,i}$) are used. In this sense two approaches can be followed:

(1) Use the symmetric National primary energy factors for both load and generation.

(2) Use the asymmetric energy factors for the generation and for the loads, following the calculation method in the prEN15603.

In MOEEBIUS symmetric factors will be prioritized.

BEPS models will allow implementing both energy balance methods described in this section. Therefore, and as stated previously, it will be the end-user requirements and priorities about MOEEBIUS framework (from peak load management for a group of buildings to precise management of a building and its critical equipment's performance) to determine the approach and required sensor deployment.

5.3.4 Simplified monitoring diagrams for building energy balance

Some of the functionalities of the MOEEBIUS tool do not require monitoring of each technical subsystem, but to obtain an energy balance of the building. In that sense, the outputs of the BEPS tool would be aggregated from units and zones to building level to face it with variables measured at building level.

If a load/generation approach is required, the overall diagram (Figure 9) can be simplified as shown on Figure 11:

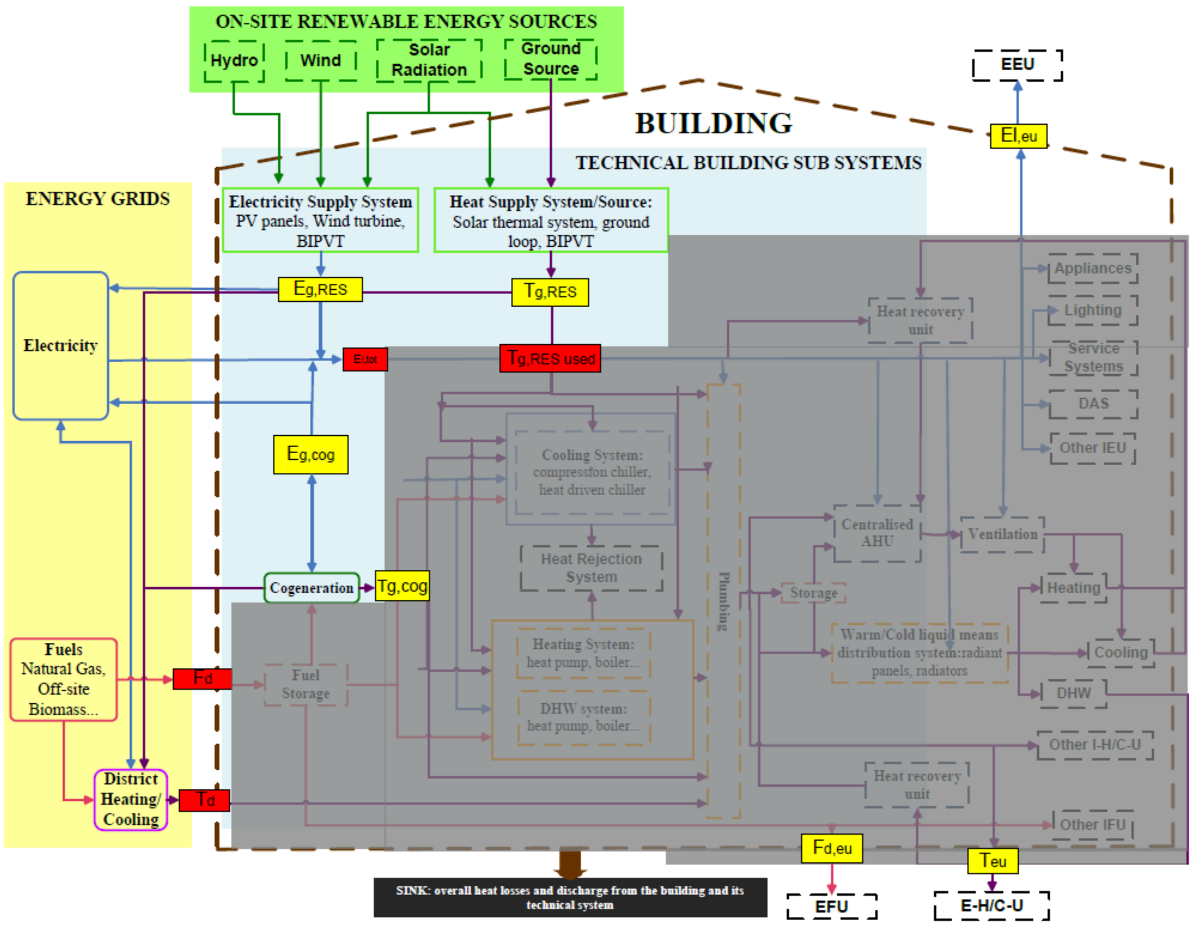

Figure 11. Load/generation balance diagram (Source: ZenN project, 2014).

For this balance, the on-site generated energy supplied to the building would be obtained from monitoring the electrical and thermal outputs of the RES and cogeneration units (if any). On the other hand, the loads at building level can be calculated monitoring four parameters: electrical load of the whole building, thermal energy delivered to the building, thermal on-site RES used (in case part of the production is exported off-site) and delivered fuels.

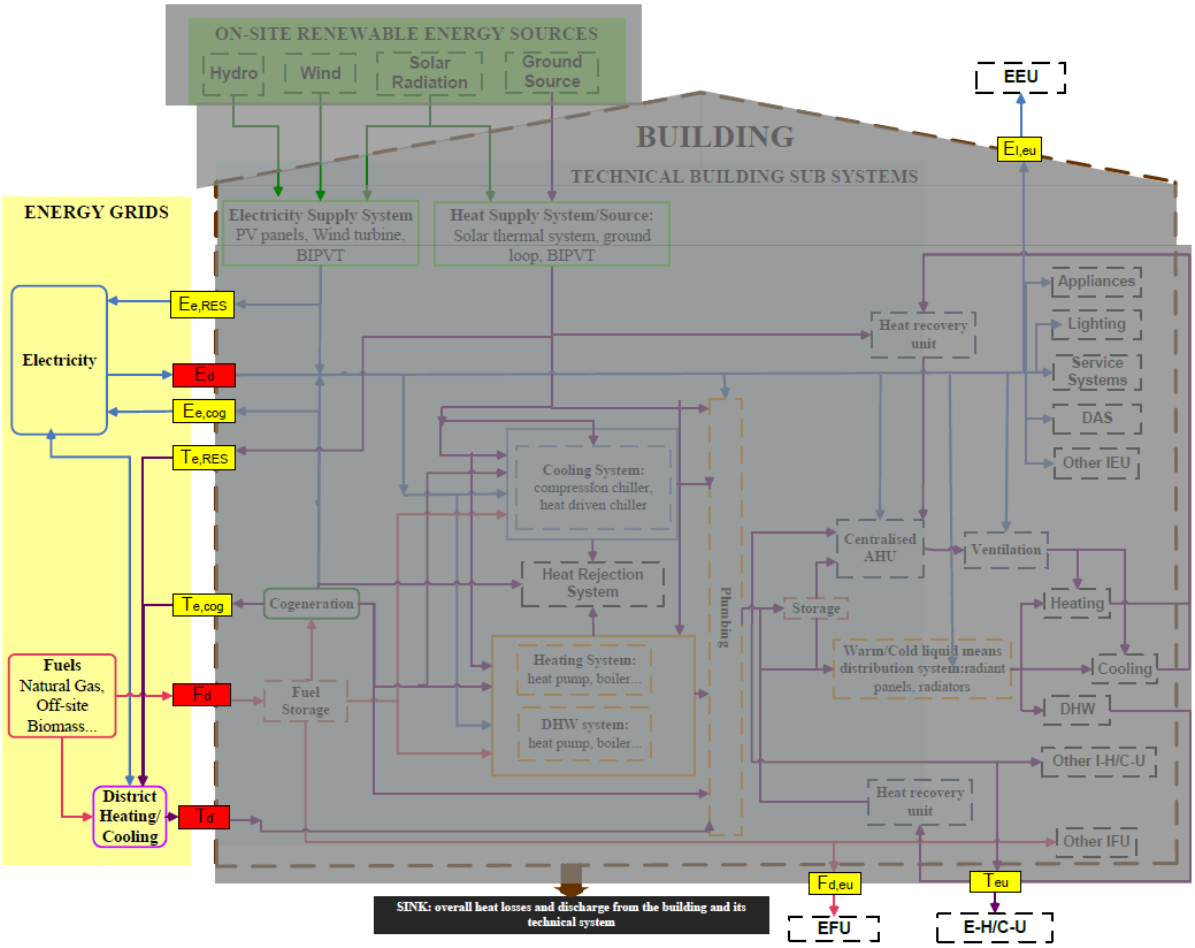

Figure 12. Import/export balance diagram (Source: ZenN project, 2014).

On the other hand, Figure 12 represents an import/export energy balance, which assumes the building boundary as a whole. In this case, the on-site energy generation is not monitored, but the surplus exported to the grid (in electrical or thermal form) and the off-site energy delivered into building's boundary. In case of external use (eu) of energy associated to the building (i.e. outdoor lightning in private parking), it will be measured in all the forms.

In summary, both balances can be applied at building level and the choice should be conditioned by the specific needs of that scenario.

5.3.5 Diverse monitoring approaches on MOEEBIUS

As stated before, the end-user's requirements for MOEEBIUS implementation will determine the level of detail required or recommendable for monitoring deployment. 5 business scenarios (BSC) were defined on MOEEBIUS Deliverable D2.1, which would put the focus on diverse aggregation levels and therefore the chosen monitoring detail and energy balance will be determined by them:

- BSC-01: **Real-time building performance** optimization towards the establishment of a sustainable environment
- BSC-02: Active Participation in **Demand Response Schemas** through the optimal management of consumers portfolio
- BSC-03: Optimized **Predictive maintenance** diagnostics and decision making tool to ensure high levels of business performance
- BSC-04: Optimized **retrofitting decision making** on the basis of improved and accurate LCA/ LCC-based performance predictions
- BSC-05: **Holistic Decision Support System** towards the establishment of a sustainable **building level and district level** environment

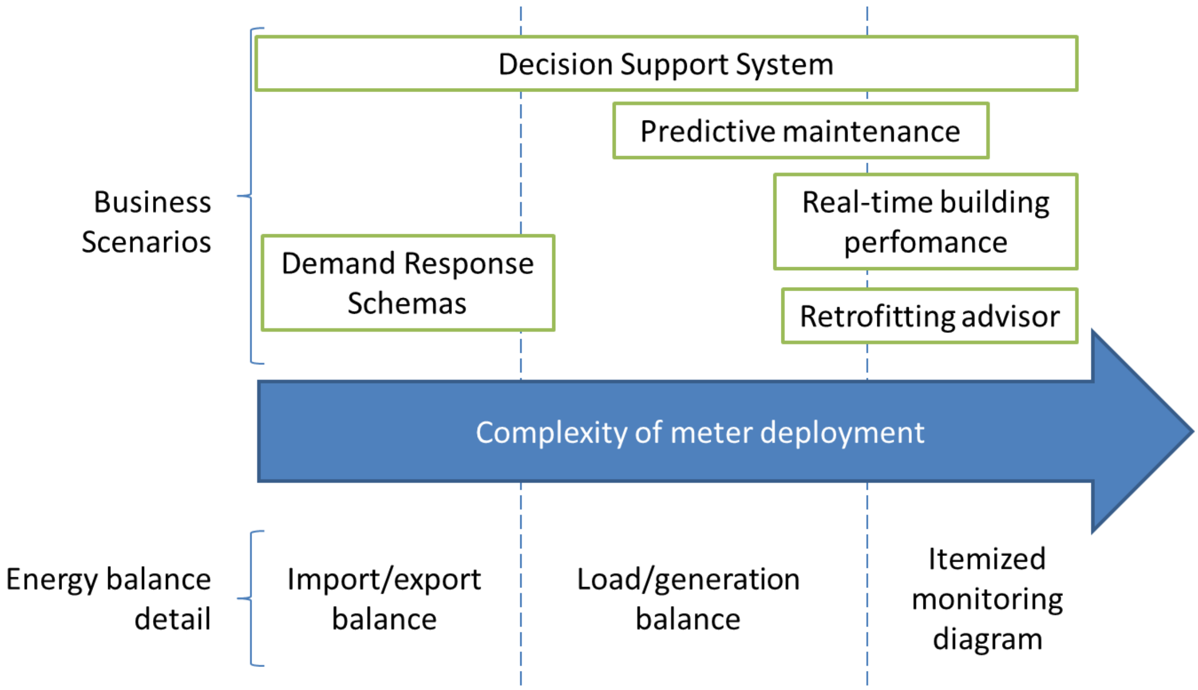

Figure 13. Diverse monitoring approaches for MOEEBIUS BSC.

Figure 13 represents the granularity level or energy balance that should be adopted in each business scenario. For a certain scenario, if the only objective of MOEEBIUS implementation is Demand Response Schemas at district level or peak-load management, simple metering schemes can be deployed at building level (as the one required for import/export balance). Predictive maintenance module could detect unexpected deviations at building/subsystems level or go down to the

critical equipment level to detect mechanical failures or discrepancies; the functionalities of this module will be limited by sensors deployment granularity. In a same way, real-time building performance optimization and retrofitting advisor could enable building managers, ESCOs or retrofitting advisory companies to focus those business scenarios with all the possibilities if the metering complexity is increased. Finally, Holistic Decision Support System involves, in a global framework, all the previously mentioned business scenarios and all possible actors, so depending on the interest on going deep into lowest aggregation level or understanding the behaviour of the system at district level, the adopted energy balance and sensors deployment approach will be one or another.

In the following subsection, specific MOEEBIUS' modules focus and required monitoring are listed.

5.3.5.1 Retrofitting advisor and Investment Evaluation Module

In order to support retrofitting decision-making, diverse applicable projects should be evaluated in terms of economics aspects of the investment and performance benefits (energy savings) of the retrofitting action.

If any Energy Conservation Measure (EMCs) is implemented to improve energy efficiency, to conserve energy or to manage demand, its results should be quantified following the International Performance Measurement and Verification Protocol (IPVMP).

Energy savings cannot be directly measured, but through the comparison between measured consumption or demand before and after the EMC implementation (Figure 14), based on an equation like:

$$Savings = (Baseline\ Period\ Energy - Reporting\ Period\ Energy) \pm Adjustements$$

As already seen in section 3.1, the baseline period energy must be adjusted to the conditions after ECM for a fair comparison with the reporting period measured energy or both lines can be normalized to some other fixed set of conditions.

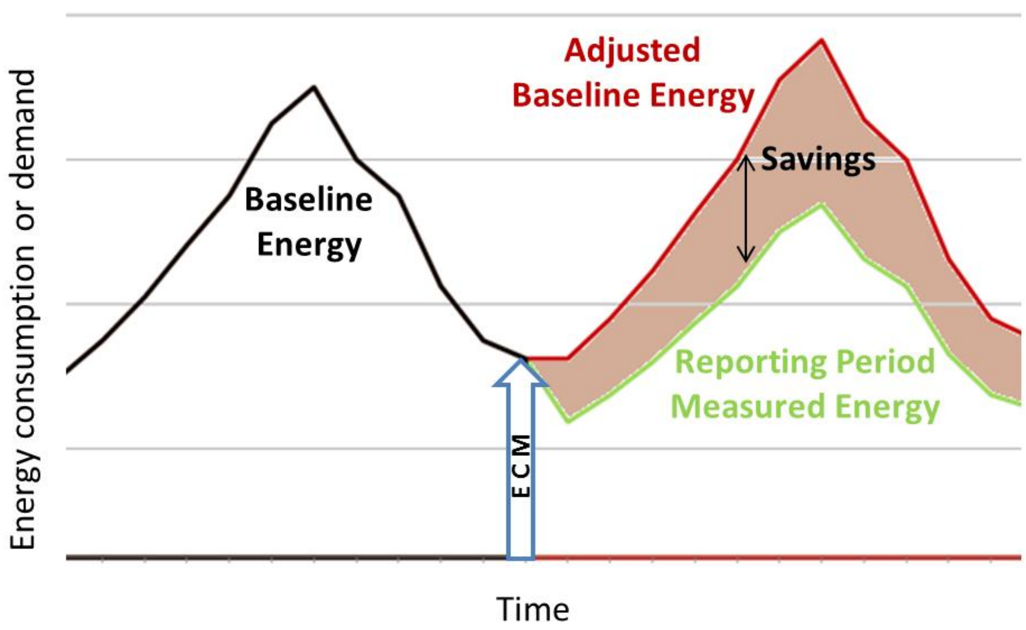

Figure 14. Savings or avoided energy consumption or demand.

The comparison between before and after EMC implementation can be carried out following 4 different options, as before seen in section 3.1:

(A) Retrofit Isolation: Key Parameter Measurement
(B) Retrofit Isolation: All Parameter Measurement
(C) Whole Facility
(D) Calibrated Simulation

Additional information of each option is listed on Table 1 and Table 2. In any case, the first 3 options imply the use of pre and post-retrofitting monitoring, so the energy savings can be only quantified once the retrofitting action have been physically implemented. On the other hand, option D approach, allows determining the energy savings of multiple hypothetical retrofitting actions before starting any EMC action.

For a sharp prediction of energy savings through simulation, the models have to be calibrated. This purpose will be enabled by overall MOEEBIUS framework implementation, where the BEPS tool will manage building's detailed models. Nevertheless, the more exhaustive sensor deployment is, the more itemized calibration of the models will be possible.

In summary, aligned with BSC-04 (Optimized retrofitting decision making on the basis of improved and accurate LCA/ LCC-based performance predictions), MOEEBIUS *Retrofitting Advisor and Investment Evaluation Module* will be based on IMVP's option D: Calibrated Simulation.

According to IPMVP, building simulation softwares evaluated by ASHRAE Standard 140 are preferred for this option. This preference will be fulfilled, as simulations will be carried out in EnergyPlus.

5.3.5.2 Predictive Maintenance Advisor Module

The functionalities for predictive maintenance will be conditioned by monitoring deployment (Figure 13). If the meters are deployed at building boundary level or in a load/generation balance diagram, the advising functionalities would be generic and limited.

The predictive maintenance module should likely provide fault detection and diagnostic functionalities for the main subsystems/equipment of the HVAC system of complex buildings, in order to enable fault and suboptimal operational status early detection and diagnostics.

The module should take advantage of the information provided by the sensor networks existing or deployed on the main subsystem/equipment of the HVAC system, and additionally use the output provided by the existing building level simulation model.

This module should provide 2 different levels of information/diagnostics/alarms.

- High level alarms based on the detection of modifications on the behavior of complete systems. The module should be able to detect modifications on the total consumption disaggregated by functional systems (heating, cooling, etc.) that are not consistent with the evolution of external climatic conditions or usage intensity (user behavior).
  Additionally, when the detail level of the available building model allows it, the thresholds depicted by model outputs could be used as additional information to detect inconsistencies between the monitored consumption, climatic conditions and user behavior.

  These functionalities will be relevant to all type of buildings.

- Low level alarms and diagnostics focused at equipment level including the identification of the possible causes of the problems, using the information provided by the sensor networks and expert rules.
  These functionalities will require a more complex sensor network to monitor the necessary operational variables of the subsystem/equipment included in the scope of the low level predictive maintenance functionalities.

  The monitored data will be used in fault detection and diagnostic expert rules and will enable the early detection of operational faults and sub-optimal performance values at subsystem/equipment level.

  As in the precedent case, if a detailed E+ building model is available the thresholds provided by the outputs of the model for the main

subsystem/equipment will provide useful input to complete the conclusions obtained through the application of the expert rules.

5.3.6 Measurement and registration: practical issues

For implementing the monitoring diagrams in real scenarios some practical issues must be considered:

- How often should each parameter be measured?
- Which are the types of meters employed for monitoring each carrier or flow?
- Where are technical equipment's parameters measured?

5.3.6.1 Time extension

The measurements types can be divided in 3 categories (IEA), depending on their duration:

- Spot and one time measurements (up to one day): useful to check the functioning of a certain subsystem, detecting permanent failures or operational characteristics curves, etc. Portable and likely non-invasive metering units would be used. Even for U-value of constructive elements.
- Short time measurements (days to months): useful to assess the energy savings resulting from the implementations of an efficiency measure, to evaluate seasonal performance of HVAC equipment, etc. Sub-metering or whole building metering units can be used.
- Long-time measurements (min 1 year): useful to assess metrics influenced by variations in weather, occupant behaviour or other operating conditions. Permanent metering units are preferable for these cases.

MOEEBIUS framework will require, in most of the cases, long time measurements, likely with electronic metering and sub-metering devices that enable an on-line monitoring of energy consumption and performance of building, subsystems and equipment.

5.3.6.2 Monitoring techniques and equipment

Commonly, flows into the building could be consulted from energy suppliers, ESCOs or building managers, which might be obtained through monthly or even bi-monthly bills. In case of smart metering deployment, imported energy could be consulted on-line. However, in case of requiring a deeper knowledge of technical subsystems, indoor energy uses' distribution, etc. sensors should be installed to measure energy flows within and through a building's boundary.

Common sensors for measurement of energy flows (IEA) are listed on Table 5.

Type of meter	Technique
Electricity	Electronic meters Electromechanical induction meters
Gas	Positive displacement flowmeters: diaphragm or bellows meters Coriolis flowmeters Thermal mass flowmeters
Solid flow	Conveyor based methods Free fall solid measurement Detectors of the level of solids in tanks (radar, microwaves, acoustic sensors)
Liquid flow	Electromagnetic flowmeters Ultrasonic flowmeters Vortex-sheeding flowmeters Differential pressure (obstruction-type) meters: orifice plate, Venturi tube, flow nozzle and Dall flow tube, Pitot static tube Turbine meters
Heating and cooling	Liquid flowmeters Temperature sensors: • Thermoelectric effect sensors (thermocouple) • Varying resistance devices: resistance thermometers, thermistors

Table 5. Measurement common sensors.

5.3.6.3 *Monitoring critical equipment*

As mentioned previously, each technical subsystem or equipment's input and output energy flows should be metered separately in case of interest. For each item, the criteria of monitoring should be defined in detail. The metering points for some of these systems [5] can be as follows:

- Photovoltaic (PV): the amount of electrical energy delivered by the inverter.
- Solar thermal collectors: the amount of energy delivered directly by the collectors to the primary circuit (and not at the output of the storage unit).
- Boilers and combined heat and power (CHP): input of final and auxiliary energy and amount of thermal energy delivered directly at heat exchanger level and electrical energy at output of CHP.

- Heat pumps: auxiliary energy input, the input of a renewable energy source and the amount of thermal energy delivered by the condenser (heating mode) or dispersed in the evaporator (cooling mode).
- Sorption chillers: input of electrical and heating energy and the amount of thermal energy dispersed in the evaporator.

The physical measurement of the variables will based on the specifications of *ASHRAE Guideline 14, Measurement of Energy Demand Savings.*

5.3.6.4 Physical measurements

The proposal for monitoring in MOEEBIUS framework will be based on the following methods and meters:

Electrical consumption

In order to monitor the electrical consumption of a whole building or a technical subsystem, electronic meters measure the diverse components of AC power (total, true and reactive power). For this purpose, variables such as voltage, current, frequency and phase angle are internally measured by the meters.

Commonly, electric energy is metered in kWh.

Thermal flows for Heating and Cooling equipment

The thermal outputs of heating and cooling equipment can be calculated through the following equation:

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T$$

Where:

$\dot{Q}$ is the thermal power (W)

$\dot{m}$ is the mass flow (kg/s)

C_p is the specific heat of the thermal fluid at a constant pressure (J/kg K)

ΔT is the difference between inlet and outlet fluid temperature (K)

Monitoring the thermal power for a certain time period, the thermal energy is obtained for that period.

Therefore, the mass flow needs to be metered through a liquid flowmeter and its temperatures on the go and return through resistance temperature detectors (RTDs). Both meters can be installed around the surface of pipes (non-invasive) or through an injection into the pipes (invasive). The first option would require more expensive ultrasonic flowmeters, while the invasive one presents a more complicated replacement to time and corrosive damages.

Fuel energy uses

Diverse type of fuels can be delivered into the building for multiple energy uses. Depending on the chosen monitoring detail, fuel meters will have to be deployed at building's boundary or at inlet points of critical equipment (i.e. boilers).

Gas in pipes

Commonly natural gas is delivered into buildings through pipes grid for heating, DHW and cooking.

Consumed gas amount in a certain period of time is commonly measured through a diaphragm meter. The amount of gas can be translated to energy, multiplying by a conversion factor related to this carrier's energy density (higher heating value):

$$Energy = m_{gas} \cdot HHV_{gas}$$

Where:

m_{gas} is the mass of gas consumed during a period of time (kg)

HHV_{gas} is the Higher Heating Value of gas (J/kg).

Other fuels

Other fuels can be delivered into the building in packages, bottles, etc. In this case, the energy consumed during a certain period will be determined by the changes on building's fuel stock changes and the balance between the imported and exported fuel amount:

$$Energy = [\Delta Stock_{fuel} + (Imported_{fuel} - Exported_{fuel})] \cdot HHV_{fuel}$$

This calculus is adaptable to any type of fuels, once its HHV is known.

Weather station

Meteorological conditions have to be monitored, as they affect strongly on energy performance of a building, i.e. on its energy demand and the generation of renewable energies. For an accurate monitoring diagram of a building in MOEEBIUS framework, the following parameters should be measured:

- Solar radiation (W/m^2), by pyranometers.
- Outdoor and indoor dry bulb temperatures (ºC), by RTDs.
- Wind speed (m/s) and direction (º), by an anemometer.
- Relative humidity (%), by an hygrometer.
- Pressure (atm), by a barometer.

On-site renewable energy production

A building can present diverse types of RES. The most common ones in Europe are solar thermal collectors and photovoltaic panels.

Solar Thermal collectors' thermal generation

In this case, the thermal production of the collectors should be metered at the output and return pipes of the collector through a flowmeter and RTDs, employing the previously stated equation for thermal flows.

Solar Photovoltaic panels electrical generation

Likely the electrical production of a PV array will be measured in DC before entering any transformer, controller or inverter, through a shunt meter which will register the voltage (V) and intensity (A) of the array. Therefore, PV power (W) will be calculated as following:

$$Power_{array} = I_{array} \cdot V_{array}$$

Ground source heat pumps

In case of employing a heat pump with ground exchange, that renewable energy can be quantified by installing a flowmeter and RTDs at the secondary circuit.

Micro-hydropower system

For the buildings with a micro-hydropower system, the electrical production will be measured at the output of the turbine.

5.3.6.5 Focus of predictive maintenance module

The predictive maintenance functionalities should be focused on the subsystems/equipment of the HVAC system that have the highest impact on the energy behavior of buildings, in order to keep the complexity level and the size of the required sensor network inside sustainable limits.

The deployment of the predictive maintenance module (at least regarding the availability of low level alarm and diagnostic capabilities) will only be relevant to buildings with centralized systems with a complexity level consistent with these functionalities.

In principle, in this type of buildings, the availability of a relatively rich sensor network can be expected before the deployment of the MOEEBIUS system. This will increase the feasibility of the implementation of the advanced (low level) predictive maintenance functionalities as the cost of the necessary additional sensors will be reduced.

The complexity level of the existing HVAC system in any specific building, considered in the frame of the MOEEBIUS project will be affected by the following factors:

- Presence/lack of a connection to a thermal network (district heating, district cooling or district heating and cooling).
- If any, type of the connection to the thermal network
    - Direct/indirect connection
    - Single substation per building/multiple substations (in the case of residential buildings)
    - With/without integrated DHW production
- If connected to a thermal network, presence/lack of local heating/cooling generation
- Type of building: Residential/non-residential
- Type of HVAC system: Individual/centralized
- Presence/lack of a mechanical ventilation system
- Presence/lack of distributed generation systems (RES, etc.)

Before the final selection of the subsystems/equipment to be included inside the scope of the predictive maintenance module, the typologies of the HVAC systems that will be typically found in the buildings to be considered in the frame of the project, and their relative impact on the performance of the buildings should be further analyzed considering all the aspect listed above.

However, at this stage of the project it can be accepted that, for the most general case, the following sub-systems/equipment will be typically present and will have a strong impact on the thermal performance and the maintenance costs of any building:

- Connection to a thermal network (Heating/cooling substation)
- Local heating/cooling back-up generators (boilers, etc.)
- Heating/cooling storage subsystem
- Heating/cooling distribution subsystem (typically hydronic distribution systems)
- DHW production subsystem
- Ventilation subsystem
- Heating/cooling emission subsystem

Therefore, it seems reasonable to define the following subsystem/equipment as the preliminary candidates to be included inside the scope of the predictive maintenance module.

- Heating/cooling substations
- Locally deployed heating/cooling plants (Boilers, chillers, etc.)
- Heating/cooling storage tanks
- Heating/cooling main distribution hydraulic circuits (focusing on heat exchanger and pumps)
- AHU-s.

Diverse examples of module’s expectable functionalities for diagnostic and fault detections are depicted in Annex II.

6 Demand Response Key Performance Indicators

The goal of this section is to document the list of KPIs related to DSM (Demand Side Management) and DR (Demand Response) scenarios implementation as examined in the MOEEBIUS project as the main objective of the MOEEBIUS project is to address the role of Demand Side Aggregator as a new entity in the deregulated market environment. There are different types of commercial DSM and DR programmes but the analysis is mainly focusing on the Aggregator specific business models to be examined in the project.

A detailed analysis of Aggregator business role, and the innovative business models examined in the MOEEBIUS project are reported in D2.2 "New Business Models and Associated Energy Management Strategies". Hence, a summary of MOEEBIUS business models is reported, focusing on the identification of the associated indicators to be considered at the evaluation process.

Predictive analytics is an extension of the traditional DR aggregation service. The cloud based predictive analytics solution will enable dynamic real-time energy management across the globe and witness all around improved efficiency for the customers. In this case, *outliers' detection* in portfolio performance leads to the implementation of DSM strategies from Aggregator, enabling that way the smooth performance management of the portfolio. This is a business model mainly implemented with Automated Demand Response strategies, fully preserving building occupants' needs and preferences.

Peak demand management is a solution for energy consumers to control their peak demand and reduce annual energy bills by 30-50%. It is observed that for many large energy users in the USA, a single peak demand at any point in time can impact electricity bills for the next 12 months. This can be achieved by utilising a DR aggregator's metering and controlling asset hardware. In addition, the software automatically (in advance) notices a potential peak load (kW_{max}) and directs the energy management system for cutting functionality without intruding the end-user comfort.

This business model is similar to ToU optimization business model where an optimization process is considered taking into account differences on electricity prices (in most of the cases high electricity prices are associated with peak demand). This enables customers to lower energy costs by shifting energy consumption during low price hours. In this case, price based DR strategies are considered as the way for implementing ToU optimization process.

Finally, the typical business role of Demand Side Aggregator is also examined in the project. The Demand Side Aggregator performs co-ordinated optimisation at the district level and can actively take part in energy trading with external parties on behalf of the district members, who are not allowed for direct participation in energy trading. The Demand Side Aggregator operator decides on the activation of the resources offered by each costumer of the portfolio. This is the definition of

VPP (Virtual Power Plant) setup by utilizing the aggregated flexibility of DERs (Distributed Energy Resources) under diverse DSM strategies launched by the aggregator. There are different external factors that may lead to the activation of DR strategies (Congestion Management, Grid Capacity Management, etc.). While no integration with external parties is expected in the project, the integration of a Dynamic Pricing Simulation Engine will facilitate the simulation of external parties' role. The engine will constantly collect and analyse energy price data, following market dynamic fluctuations and will feed this data to the MOEEBIUS platform, triggering that way the associated DSM strategies. While both automated DR and price based DR strategies may be considered for the implementation of this business model, the focus is on the evaluation of price-based control strategies for district management process.

Following the brief description of DSM Aggregator Business Models, a list of KPIs that are normally used to evaluate DSM and DR strategies performance was compiled. It has to be pointed that the analysis covers both building (building occupants) and district level (Aggregators) as both sides are participating on DSM strategies implementation. A high level taxonomy in business and technical KPIs is also considered.

6.1 Generic Business KPIs

We are starting the analysis with the list of business KPIs mainly affecting the business role of Aggregator and the contractual parameters with portfolio participants. KPIs about the size and the potential capacity of the portfolio are covered by this list:

- **Average aggregated capacity per customer** (kW or kWh within time-period): This is the amount of *potential flexibility* that each costumer/site may offer to the aggregator.
- **Average aggregated capacity in operation** (overall and per DSM programme): This is the total amount of *potential flexibility* that the portfolio may offer to the aggregator.
- **Average revenue** (per kW or kWh) **managed for DR participation** (in total, per DSM programme and per customer): This the amount of remuneration of each costumer/site for participation on DR programmes (in total and per programme)

6.2 Technical KPIs

Following the definition of high level business KPIs associated to the different DSM programmes examined in the project, technical KPIs are identified related to the actual implementation of DR strategies. Therefore, the following list of KPIs highlights the actual performance of customers during DSM programmes:

- **Potential turndown (per site / asset)** [kW or kWh]: This is a metric which shows the specific turndown potential for that asset. This is the potential

amount of demand flexibility that each customer of the portfolio will offer to the Aggregator, during a DR strategy.

- **Enrolled turndown (per site / asset)** [kW or kWh]: This is what requested by Aggregator during a DR strategy implementation. This is actually, the lower to potential turndown value, taking into account the reliability level of each customer of the portfolio.
- **Measured turndown (per site / asset)** [kW or kWh]: This is what is actually measured when a DR strategy is performed. In other words, this is the amount of actual flexibility offered during a DR strategy.
- **Delivered capacity (per site/asset)** [%]**:** This is the measured capacity delivered by an asset in a live dispatch event. This is the *"ratio of measured to enrolled capacity"*, thus this is the reliability level of each customer of the portfolio.
- **Turndown/Energy Consumption, (per site / asset)** [%]: This is a ratio defining the flexibility that each asset may offer to the Aggregator, compared to the total amount of energy consumption.
- **Delivered capacity (per contract)** [kW or kWh]: This is a district specific KPI with the measured capacity delivered to external parties, *aggregated at contract level*. Each contract is a settlement unit and therefore is important to size and declare them carefully as negative performance (delivered capacity < 100%) will attract reduced payments or penalties for the aggregator and subsequently non-payment (or reduced payment) for the contract participants.

The aforementioned analysis highlights the DSM related KPIs, associated with the different phases of DSM implementation. There are 3 intertwined phases highlighted also in USEF framework that standardizes the DR operational process in Europe:

- FlexPrognosis: First the FlexPrognosis message is send from the prosumer to Aggregator to offer flexibility for sale. It contains the potential demand flexibility is available to Aggregator.
- FlexOrder: The FlexOrder message is used for buying the flexibility from customers. It has a close relation with the original FlexOffer message. The FlexOrder is used to signal the acceptance of the offer.
- FlexOffer: This is the amount of flexibility actually offered by the customers to the Aggregator. In the same way, FlexOffer is the amount of flexibility offered by Aggregator to external parties (Delivered capacity).

The next schema presents the overall flow of DSM strategies. The detailed operational process reveals the list of DSM KPIs as presented above, associated with the different phases of DSM implementation.

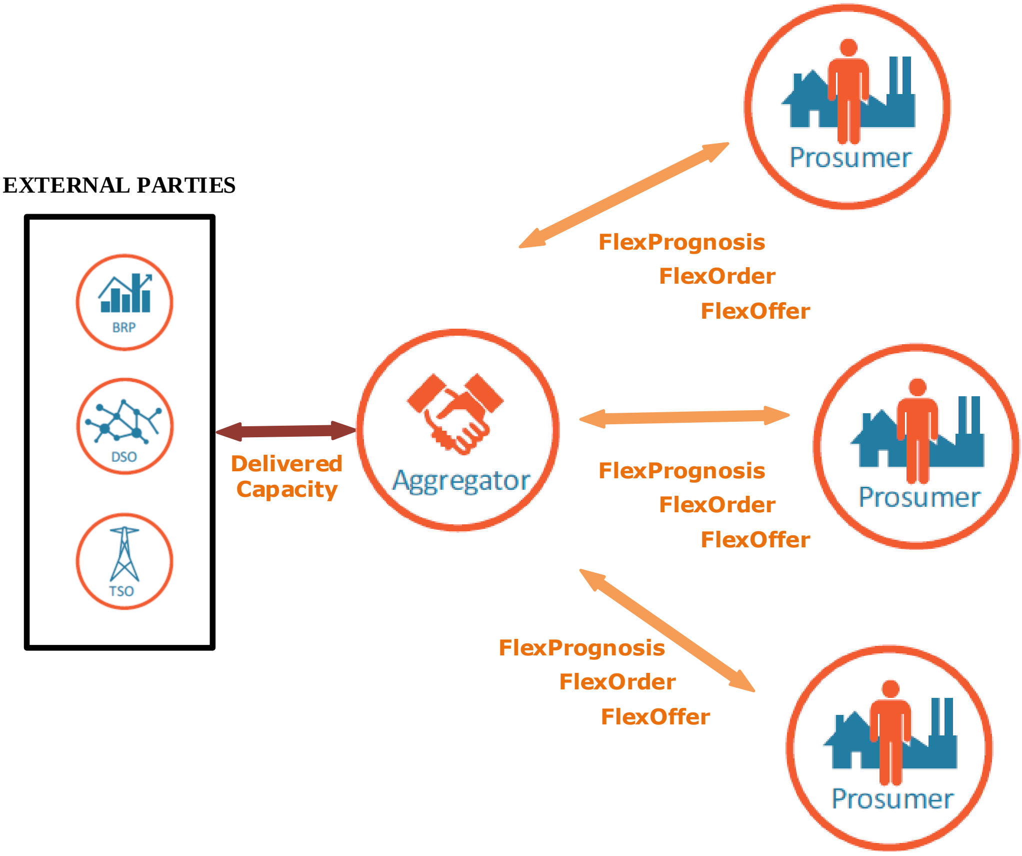

Figure 15. Demand Side Management Strategies Implementation.

The aforementioned analysis presented the detailed list of DSM KPIs of the MOEEBIUS project. The analysis covers both the business analysis for the role of Aggregator and the technical implementation of DSM scenarios as examined in the project. It has to be highlighted that DR KPI calculation is derived from energy metrics as presented above. Demand Response KPIs are associated with the term of flexibility which is the dynamic variation of energy consumption through time.

Time and space granularity

Regarding the granularity, potential flexibility is assessed in intervals of 15 minutes (and any aggregation of this: hourly/daily/monthly) taking into account business requirements as extracted from business scenarios and business models definition. This time granularity will enable clustering of prosumers at groups that can further participate on the different business models defined in MOEEBIUS framework.

For the KPIs associated with the actual implementation of DSM strategies, the time granularity is the time period of the DR strategy itself (calculation is event based and not time driven). The technical implementation of MOEEBIUS platform will enable real time evaluation of DR strategies at the minimum of time granularity as specified by the different strategies implemented.

Further defining the spatial granularity for Demand Response KPIs, once again the business framework for DR implementation is considered. Towards this direction KPI calculation is considered per:

- Total building, as an entity that provides demand flexibility to Aggregators towards participating in DSM programmes.
- Portfolio (aggregation) of customers that participate at a specific contract/DSM programme or consist of the total portfolio of the DSM Aggregator.

Therefore, considering the building as the low level entity at district level, different types of groups for aggregation are defined taking into account also the business perspective of DSM Aggregators.

7 Occupants Comfort Key Performance Indicators

Following the definition of energy and Demand Response KPIs, the scope of the MOEEBIUS project is to address the role of building occupants as an active element of the buildings. Therefore, one of the main objectives is to enhance the MOEEBIUS performance evaluation framework with Key Performance Indicators about occupants' preferences and non-preferences. As the main focus of the MOEEBIUS project is the incorporation of HVAC and Lighting devices in MOEEBIUS platform, special interest is on the definition of:

- Thermal Comfort KPIs associated with HVAC operation
- Visual Comfort KPIs associated with Lighting devices operation

The next section highlights the key performance indicators related to the aforementioned profiles. The analysis starts with a review of the standardization towards the selection of KPIs that fit in the scope of the project. Then an extended list of thermal/visual KPIs is considered addressing also MOEEBIUS project specific requirements and describing the monitoring requirements for each of these KPIs. The overall analysis takes into account the selected business scenarios and the associated project use cases that pose the occupants comfort as a main objective of the proposed MOEEBIUS platform. At the end of each subsection for the thermal and visual comfort, the impact of each described KPI and its suitability in the MOEEBIUS project is evaluated.

7.1 Thermal Comfort KPIs Overview

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. Because there are large variations, physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space. Thus, the environmental conditions required for comfort are not the same for everyone (ASHRAE 55, 2013).

Human's thermal sensation is mainly related to the thermal balance of the body as a whole. This balance is influenced by physical activity and clothing, as well as environmental parameters such as air dry bulb temperature, surrounding surfaces radiant temperature, air speed and humidity. The first two factors are characteristics of the occupants, and the remaining four factors are conditions of the thermal environment. These parameters are combined in thermal models defined in bibliography to express thermal comfort and discomfort settings (Figure 16).

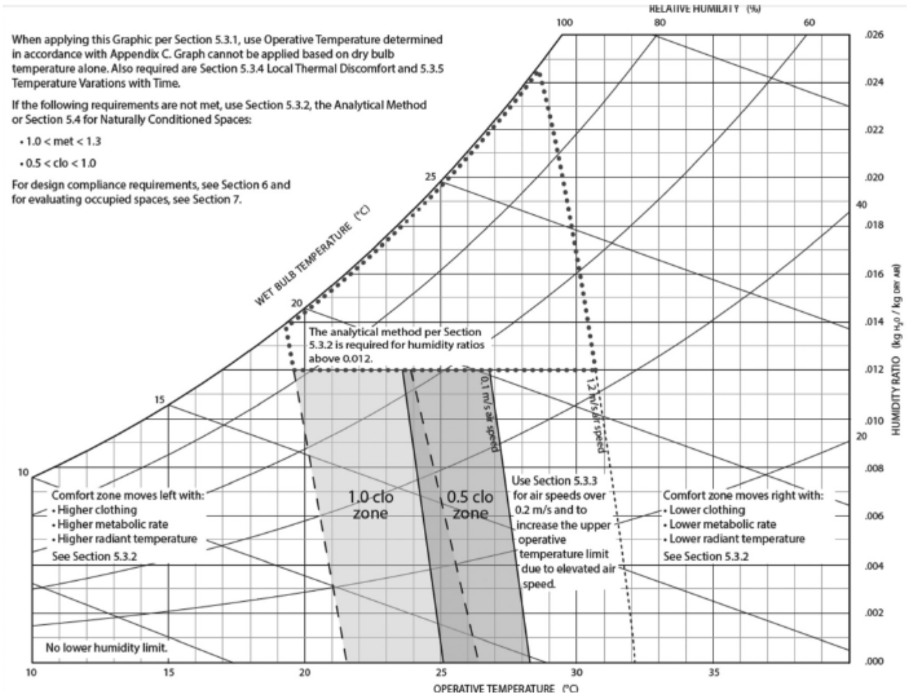

Figure 16. Acceptable range of operative temperature (to) and humidity for activity levels between 1.0 ≤ met < 1.3 and cloth insulation levels of 0.5 < clo < 1.0 (Source ASHRAE 55, 2013).

Numerous indices for the assessment and design of thermal comfort conditions have been developed during the past 50 to 60 years. One of the most widely used indices in moderate thermal environments, the PMV index (predicted mean vote), predicts the mean value of the overall thermal sensation of a large group of persons as a function of activity (metabolic rate), clothing insulation, and the four environmental parameters: air temperature, mean radiant temperature, air velocity, and air humidity [9]. Alternatively, other methods for the assessment of moderate thermal environments could be used, such as the new effective temperature (ET) and the standard effective temperature (SET) [10].

We have to point out that thermal comfort assessment process includes a part of ambiguity on the defined performance indicators (PI). Several researchers, such as Park et al. [11], examine the theoretical derivation of indicators for the normative assessment of thermal comfort in buildings and their relevance in building design. Furthermore, in some cases it is not possible to achieve an acceptable thermal environment for all occupants of a space due to individual differences, including activity and/or clothing. Even in laboratory settings, it is not possible to satisfy more than 95% of occupants by providing a single uniform thermal environment (Fanger 1970) because thermal preferences vary among people. Therefore, it is of high importance to define adaptive models that address the specific characteristics of the end users involved on building activities. These issues are addressed in literature and thus an extensive analysis is required for the selection of best fitted Thermal KPIs. Overall, the goal of this section is twofold:

- To review existing assessment methodologies for sustainable buildings (IPMVP, BREEAM, LEED), other EU projects (recent or on-going), and also standardization or harmonization towards the definition of Thermal comfort KPIs.
- To present the most indicative Performance Indicators related to Thermal Comfort in order to further select the final list of project needs.

7.1.1 Thermal Comfort KPIs Literature Review

Apart from ASHRAE which defines models and parameters related to Thermal comfort in buildings, additional EU and national legislations are addressing thermal comfort related parameters through the associated KPIs. The analysis covers the main M&V methodologies as presented above.

"Hea 04 Thermal comfort" of BREEAM, specifies the thermal comfort KPIs examined by the proposed methodology. *"To ensure that appropriate thermal comfort levels are achieved through design, and controls are selected to maintain a thermally comfortable environment for occupants within the building."*

Thermal modelling results demonstrate that thermal comfort levels in occupied spaces should meet the requirements for both PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) indices as specified in Table A.1 of Annex A in ISO7730:2005. When assessing free-running buildings, parameters for the hours of exceedance, daily-weighted exceedance and upper limit temperature, as outlined in CIBSE TM52, should be used to establish the risk of overheating. The PMV and PPD indices are reported via the BREEAM assessment scoring and reporting tool, based on the modelling undertaken above.

The strategy for proposed heating/cooling systems is also specified by BREEAM, highlighting the need to define zones within the building and how building services could efficiently and appropriately heat or cool these areas.

LEED - Leadership in Energy and Environmental Design (LEED) is one of the most popular green building certification programs. Developed by the non-profit U.S. Green Building Council (USGBC) it includes a set of rating systems for the design, construction, operation, and maintenance of green buildings, homes, and neighbourhoods. Towards this direction, guidelines to meet the requirements for both thermal comfort design and thermal comfort control are defined. More specifically, EQ6.1 defines the following:

<u>Option 1. ASHRAE Standard 55-2010</u>

Design heating, ventilating, and air-conditioning (HVAC) systems and the building envelope to meet the requirements of ASHRAE Standard 55–2010, Thermal Comfort Conditions for Human Occupancy, with errata or a local equivalent.

Option 2. ISO and CEN Standards

Design HVAC systems and the building envelope to meet the requirements of the applicable standard:

- ISO 7730:2005, 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; and
- CEN Standard EN 15251:2007, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings, addressing indoor air quality, thermal environment, lighting, and acoustics, Section A2.

About thermal comfort control, LEED standard defines the need for individual thermal comfort controls for at least 50% of individual occupant spaces. In addition, group thermal comfort controls for all shared multi occupant spaces and for any individual occupant spaces without individual controls should be considered.

Thermal comfort controls allow occupants, whether in individual spaces or shared multi occupant spaces, to adjust at least one of the following in their local environment: air temperature, radiant temperature, air speed, and humidity.

IPMVP protocol (International performance measurement and verification protocol), through concepts and practices for Improved Indoor Environmental Quality, defines guidelines for thermal comfort related aspects. Again, the protocol identifies ASHRAE thermal comfort models as the ones to be addressed during the evaluation process.

Following the high level review of existing methodologies, we further describe the list of Thermal Comfort KPIs selected for the MOEEBIUS project.

7.1.2 List of Thermal Comfort KPIs

There are different types of KPIs examined for thermal comfort evaluation. A high level taxonomy is considered about non-adaptive and adaptive models, focusing on the later as indicated also in ASHRAE standards. We are starting the analysis with the most commonly adopted thermal model/KPI and further present the list of potential KPIs to be considered in the project.

7.1.2.1 Predicted Mean Vote

The predicted mean vote (PMV) is determined based on the estimated metabolic rate and the clothing insulation, and additional environmental indicators: the measured or predicted air temperature, mean radiant temperature, relative air velocity, and air humidity. The PMV integrates the effects of the two personal parameters and the four environmental parameters on the thermal balance, and it predicts the mean thermal sensation on a seven-point thermal sensation scale. The next table presents the seven-point thermal-sensation scale, which serves as a basis for the predicted mean vote.

PVM Index	Thermal Sensation
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 6. PMV Indicator Values.

As mentioned above, the Predicted Mean Vote model is based on two personal parameters: the metabolic rate of a person and the clothing insulation which are further defined:

Metabolic rate

The metabolic rate (M) is the rate of energy production of the body by metabolism, which varies with activity. Metabolic rate can be quantified by the met unit, where 1 met is defined as the metabolic rate of a sedentary person (seated, quiet) (1 met = 58.2 W/m^2).

Metabolic rate varies over a wide range, depending on the activity, the person, and the conditions under which the activity is performed. It can be very roughly assessed from knowledge of the occupation or from analysis of a task or activity. A more precise method, as defined in ISO/WD 8996-2004 [12], involves observation of the activity and the use of tabulated values of metabolic rates for specific activities.

The data for metabolic rate are based on measurement of metabolic rates (oxygen consumption) performed on human subjects continuously occupied with a specific activity. A detailed description of the evaluation and measurement of metabolic rate as well as a comprehensive collection of metabolic rates for typical activities can be found in ISO 8996- 2004.

Thermal Insulation of Clothing

Clothing insulation varies between occupants due to differences in clothing preferences, season, etc. Clothing insulation can be measured with a heated thermal manikin or with human subjects, but in practice, thermal comfort estimates based on tables may be sufficiently accurate. Additional information on the insulation provided by clothing ensembles composed of some typical combinations of garments can be found in ISO 7730-2005. If no matching clothing ensemble can be found in ISO 7730-2005 [13], tabulated insulation values of a wide variety of individual garments are provided in ISO 9920-2007 [14]. Summation of these partial insulation values for individual garments can be used as an estimate of the insulation of the entire clothing.

Following the definition of personal parameters, requirements about measuring environmental conditions are provided. Measurement of the thermal parameters of

the environment should be made in occupied zones of the building at locations where the occupants are expected to spend their time. Olesen (1995) [15], ISO 7726-2005 [16], and ASHRAE 55-1992R [17] provide detailed descriptions of the requirements for the measuring instruments and for thermal comfort measurement procedures.

Overall, PMV is expressed as a function of the personal parameters of metabolic rate and clothing insulation and the thermal environment parameters as input variables.

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

With:

1. $t_{cl} = 35.7 - 0.028(M - W) - I_{cl}\{3.96 \cdot 10^{-8}\,[(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl} - t_a)\}$
2. $hc = \max\,(2.38\,|t_{cl} - t_a|^{0.25}\,,\ 12.1\sqrt{v_{ar}})$
3. $f_{cl} = \begin{matrix} 1.00 + 1.290 I_{cl} \text{ for } I_{cl} < 0.078 m^2 K/W \\ 1.05 + 0.0645 I_{cl} \text{ for } I_{cl} > 0.078 m^2 k/W \end{matrix}$

Where:

- PMV is the predicted mean vote [-]
- M is the metabolic rate [W/m^2]
- W is the external work (zero for most indoor activities) [W/m^2]
- f_{cl} is the ratio of the clothed surface area to the nude surface area [-]
- I_{cl} is the thermal resistance of the clothing [$(m^2K)/W$]
- t_a is the air temperature [ºC]
- t_r is the mean radiant temperature [ºC]
- v_{ar} is the air velocity relative to the human body [m/s]
- p_a is the partial water vapour pressure [Pa]
- h_c is the convective heat transfer coefficient [$W/(m^2K)$]
- t_{cl} is the surface temperature of the clothing [ºC]

We have to point out that though PMV is a common indicator, deviations are expected in specific case studies. For example, in non-air-conditioned buildings in warm climates, the occupants may sense warmth as being less severe than PMV predicts. For such cases, an adaptation of the PMV model to local conditions is considered [18]. This adaptation process is considered as the anchor point for the definition of innovative KPI thermal models in MOEEBIUS project.

7.1.2.2 Predicted Percentage Dissatisfied

The PPD index (predicted percentage dissatisfied) is derived from the PMV index and predicts the percentage of thermally dissatisfied persons among a large group

of people. Occupants of buildings are not alike, and therefore the individual thermal-sensation votes of the occupants of a given environment will be scattered around the mean. The PPD index predicts the number of people likely to feel uncomfortably warm or cool. When the PMV value is known, the PPD index can be calculated.

Typically, a 10% dissatisfaction criterion for thermal comfort is used for the determination of acceptable thermal conditions [13]. This corresponds to a PMV in the range -0.5 to +0.5. Note that the minimum attainable PPD is 5%, even when the result is a neutral thermal sensation (PMV = 0). Because of inter-individual differences, it is not possible to satisfy everyone. The next figure presents the PPD index curve:

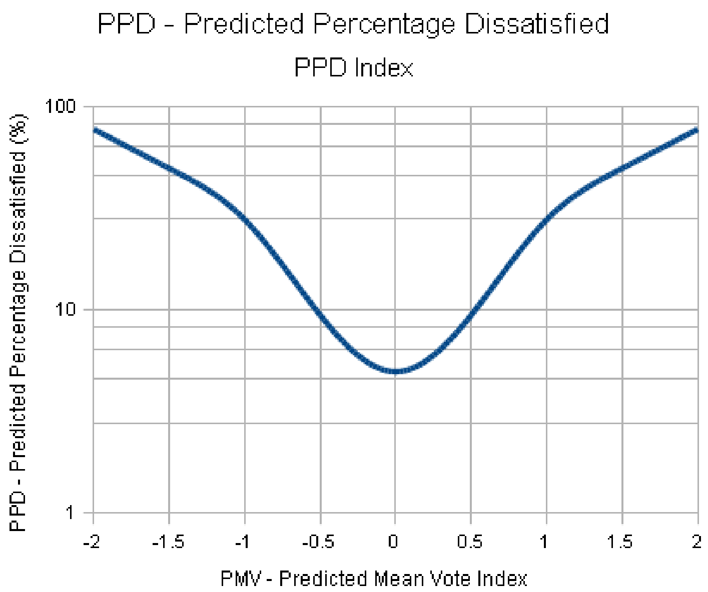

Figure 17. Predicted Percentage Dissatisfied Indicator.

The next equation provides the correlation among PPD and PMV values.

$$PPD = 100 - 95e^{[-(0.3353PMV^4 + 0.2179PMV^2)]}$$

The PMV index has been validated as a predictor of thermal sensation in numerous comprehensive field studies and thus an extension of the PMV model for buildings is now proposed [18].The next Table presents the PMV and PPD values, taking indicative input parameters.

Run no.	Air temperature °C	Mean radiant temperature °C	Air velocity m/s	RH %	Metabolic rate met	Clothing insulation clo	PMV	PPD
1	22,0	22,0	0,10	60	1,2	0,5	−0,75	17
2	27,0	27,0	0,10	60	1,2	0,5	0,77	17
3	27,0	27,0	0,30	60	1,2	0,5	0,44	9
4	23,5	25,5	0,10	60	1,2	0,5	−0,01	5
5	23,5	25,5	0,30	60	1,2	0,5	−0,55	11
6	19,0	19,0	0,10	40	1,2	1,0	−0,60	13
7	23,5	23,5	0,10	40	1,2	1,0	0,50	10
8	23,5	23,5	0,30	40	1,2	1,0	0,12	5
9	23,0	21,0	0,10	40	1,2	1,0	0,05	5
10	23,0	21,0	0,30	40	1,2	1,0	−0,16	6
11	22,0	22,0	0,10	60	1,6	0,5	0,05	5
12	27,0	27,0	0,10	60	1,6	0,5	1,17	34
13	27,0	27,0	0,30	60	1,6	0,5	0,95	24

Table 7. PMV and PPD Values (ISO 7730: 2006- Annex D).

The variables examined for the simulation process are further presented:

Variables	Metric
Clothing	clo
Metabolic rate	met
External work	met
Air temperature	°C
Mean radiant temperature	°C
Relative air velocity	m/s
Relative humidity	%
Partial water vapour pressure	Pa

Table 8. PMV and PPD Indicator Input parameters.

7.1.2.3 Local Thermal Discomfort

The PMV and PPD indices can be used to assess overall thermal comfort in a wide range of buildings with differing HVAC (heating, ventilation, and air-conditioning) systems as well as for different combinations of activity, clothing habits and environmental parameters. The indices are used widely for the evaluation of indoor thermal comfort. However these are considered as generic indicators not addressing the local characteristics in buildings. Local thermal discomfort due to draft, vertical temperature gradient, radiant asymmetry, or warm or cold floors may cause variant thermal discomfort level. The most common cause of complaint is draft, which is defined as an unwanted, local cooling caused by air movement. Criteria to assess local thermal discomfort are provided in standards and guidelines [17].

In that case, the percentage of people predicted to be bothered by the specific conditions is defined. This is an abstraction of PPD indicator, focusing on specific building characteristics that affect the comfort and discomfort boundaries of building occupants. By defining the PPD specific indicators, the desired thermal environment for a space may be selected from among three different categories defined by the standard [13]. Each category prescribes a maximum percentage dissatisfied as a whole (PPD) and a PD for each of the four types of local

discomfort. The categories of the thermal indoor environment are presented in Table 9.

Category	Thermal neutrality		Local discomfort			
	PPD %	PMV	DR %	PD % warm or cold floors	PD % vertical air temperature	PD % asymmetric thermal radiation
A	< 6	– 0,2 < PMV < + 0,2	< 10	< 3	< 10	< 5
B	< 10	– 0,5 < PMV < + 0,5	< 20	< 5	< 10	< 5
C	< 15	– 0,7 < PMV < + 0,7	< 30	< 10	< 15	< 10

Table 9. Categories of thermal indoor environment.

7.1.2.4 Operative temperature

An abstraction of PMV model is the "Operative temperature" comfort model. The operative temperature, t_o, is defined as the uniform temperature of an imaginary black enclosure in which an occupant feels totally comfort. The optimal operative temperature in a zone can be expressed as a function of the activity and clothing. For a given space, an optimum operative temperature, depending on the activity and the clothing of the occupants is defined based on ISO 7730-2005 as depicted in the following figure:

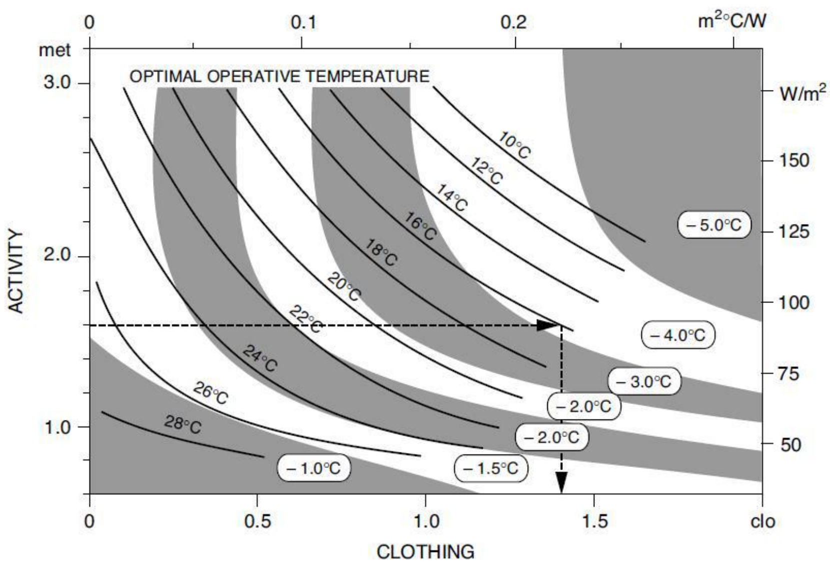

Figure 18. Optimal operative temperature as a function of the activity and clothing.

The operative temperature is a variable that can be measured with a 0.04-0.1m diameter black globe temperature sensor and set an indicator to quantify thermal comfort and discomfort levels.

7.1.2.5 Other Thermal Key Performance Indicators

Other methods for the assessment of moderate thermal environments include the new effective temperature (ET) and the standard effective temperature (SET).

Effective temperature (ET) is defined as the temperature of a still, saturated atmosphere, which would, in the absence of radiation, produce the same effect as the atmosphere in question. It thus combines the effect of dry air temperature and humidity. It became the most widely used index for the last 50 years, but it is now superseded. The next schema provides the Effective temperature model.

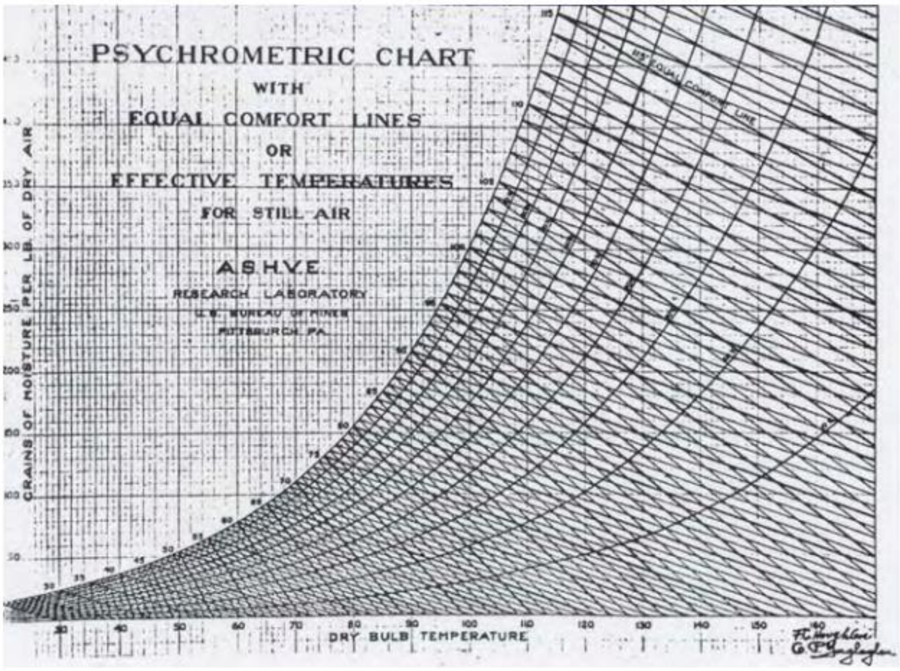

Figure 19. Effective temperature Psychrometric Chart.

Standard effective temperature (SET) is an additional model of human response to the thermal environment. (Developed by A.P. Gagge and accepted by ASHRAE in 1986). It is also referred to as the Pierce Two-Node model. Its calculation is similar to PMV because it is a comprehensive comfort index based on heat-balance equations that incorporates the personal factors clothing and metabolic rate. Its fundamental difference is it takes a two-node method to represent human physiology measuring skin temperature and skin wettedness. ASHRAE 55-2010 defines SET as "the temperature of an imaginary environment at 50% relative humidity, <0.1 m/s average air speed, and mean radiant temperature equal to average air temperature, in which total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level." In addition, even combined temperature and humidity metrics can be considered as rough indicators for expressing thermal comfort levels.

Today, advanced models are available that allow for the transient prediction of very detailed thermal parameters, focusing mainly on the adaptability for specific building cases examined. The concept of adaptive thermal comfort can be described as:

When a change occurs causing thermal discomfort, people react in such a way that their thermal comfort is re-established. This description refers to behavioural adaptation that can be discerned in personal, technical, environmental, cultural and organizational adaptation [19].

Adaptive models of comfort take human's adaptation to thermal comfort in such a way into account that indoor climates, which would be regarded as uncomfortable in specific buildings, are actually acceptable to the occupants. Focusing on the performance indicators, which serve as a basis for the adaptive thermal comfort models, the main performance indicator is the operative temperature in the building. This mainstreaming of adaptive comfort was further supported by the introduction in 2007 of a European standard (EN 15251 [20]). This is the starting point of the MOEEBIUS thermal comfort performance framework, as the goal is to provide dynamically adaptive thermal comfort models to address building occupants' thermal preferences and needs.

The analysis shows that the thermal comfort level in a building is determined by the influence of the indoor environmental parameters on human's thermal sensation. There are different input parameters and models that define the thermal comfort and discomfort levels. While PVM remains the indicator for thermal comfort management, there is an ongoing discussion for the importance of adaptive models that cover personalized preferences and needs. This is the main focus of MOEEBIUS project, towards the definition of adaptive thermal models that incorporate the specific building operational conditions. The next table presents a summary of the defined KPIs along with their impact in the MOEEBIUS project:

Thermal Effect	Indicator	Short Description	MOEEBIUS Impact
PMV	PMV	Combination of different context parameters	√√
PPD	PPD	Predicted percentage dissatisfied as extracted from PMV	√
Local Thermal Discomfort	Category	Extension of PMV addressing local factors	x
Operative Temperature	°C	Typical temperature preferences under specific conditions	√
Effective Temperature	ET	Defined as the temperature of a still, saturated atmosphere, which would, in the absence of radiation, produce the same effect as the atmosphere in question	x

	SET	A comprehensive comfort index based on heat-balance equations that incorporates the personal factors clothing and metabolic rate.	x

Table 10. Thermal Comfort Related Key Performance Indicators.

We have to point out that PMV, PPD and Operative Temperature are considered as the different viewpoints of the same model. The same input parameters are incorporated for calculation and thus we are selecting PMV as the indicator to be adopted in MOEEBIUS performance framework. PMV calculation is straightforward compared to PPD, and in buildings under use, measuring representative operative T_o is difficult since the sensor has to be located in certain position that can interfere with day to day activities.

7.1.3 Monitoring techniques

In order to proceed with the calculation of thermal comfort indicators, real time metrics and configuration parameters will be considered. Therefore, different types of sensors will be installed to gather real time context environment data (temperature sensor, humidity sensor) while also specific values (following ex-ante pilot analysis and selection of typical thermal zones) will be selected for the definition of thermal model configuration parameters (External work, Metabolic rate, Clothing, Relative air velocity, etc.) (Table 11). The main objective is to incorporate in the "MOEEBIUS measurement and verification protocol", typical and innovative thermal comfort indicators that highlight human's comfort and discomfort levels.

Variable	Monitoring technique
Clothing	Typical values
Metabolic rate	Typical values
External work	Typical values
Air temperature	***Temperature sensor***
Mean radiant temperature	***Temperature sensor***
Relative air velocity	Typical values
Relative humidity	***Humidity sensor***
Partial water vapour pressure	Typical values

Table 11. Monitoring techniques for thermal comfort variables.

Once again to point out that the main focus in MOEEBIUS project is on the definition of adaptive thermal models taking into account building operational conditions (see Section 7.3).

7.2 Visual Comfort KPIs overview

Following thermal comfort models analysis, we proceed with the definition of Visual comfort performance framework. Almost all aspects of human behaviour depend heavily on the light exposed to. Apart from the role of light in visual

processes, light also turns out to play a major role in a wide variety of non-visual processes as well (e.g. Health and safety, aesthetics). The focus of this section is to address specific parameters related to visual comfort of building occupants (The visual performance defines whether the lighting solution in a room is suitable for the performed tasks).

Overall, for the area in which a specific task is performed, the lighting level should fulfil the maintained illuminance, the uniformity of illuminance, the colour rendering, and the absence of glare. The arrangement of the lighting should avoid distracting hard shadows, discomforting sources of glare and reflections. The lighting should not flicker, should avoid larger dark zones in the room, and should meet the conditions of uniformity of illuminance in the area in the surroundings of the visual task. Regarding the visual performance, the recommendations and standards for lighting design in workplaces adequately address visual needs and visual comfort. The European standard NEN-EN 1264-1 [21], presents the requirements for lighting in the task areas of a building concerning intensity level, colour, glare, luminance ratios, and daylight entrance. Along with this standard additional methodologies provide guidelines for accepted luminance levels. Again, the role of this section is twofold:

- To present an overview of existing methodologies and EU initiatives that promote visual comfort related guidelines
- To provide an indicative list of KPIs related to visual comfort for the MOEEBIUS project

7.2.1 Visual Comfort KPIs literature review

The goal of this section is to provide a high level review on existing methodological frameworks towards the definition of aspects that affect visual comfort parameters. The selection of M&V methodologies at the very early stage of this deliverable further leads to the analysis in this section.

“Hea 01 Visual comfort” of BREEAM methodology, specifies the criteria to be addressed related to visual comfort. The goal is *“to ensure that daylighting, artificial lighting and occupant controls are considered at the design and operational stage to ensure best practice in visual performance and comfort for building occupants”*

This issue is split into five parts:

- Glare control
- Daylighting
- View out
- Internal and external lighting
- Reflectance Ratio

Indicative tables and limitations are defined to address the different aspects of the buildings examined. Special interest is delivered for zoning and occupant control where internal lighting should be zoned to allow for occupant control taking into account building activities:

- In office areas, zones of no more than four workplaces
- Workstations adjacent to windows/atria and other building areas separately zoned and controlled
- Seminar and lecture rooms: zoned for presentation and audience areas
- Library spaces: separate zoning of stacks, reading and counter areas
- Teaching space or demonstration area
- Whiteboard or display screen
- Auditoria: zoning of seating areas, circulation space and lectern area
- Dining, restaurant, café areas: separate zoning of servery and seating/dining areas
- Retail: separate zoning of display and counter areas
- Bar areas: separate zoning of bar and seating areas
- Wards or bedded areas: zoned lighting control for individual bed spaces and control for staff over groups of bed spaces
- Treatment areas, dayrooms, waiting areas: zoning of seating and activity areas and circulation space with controls accessible to staff

Therefore, it is clear that we need to examine the context environment of the buildings towards establishing high visual quality levels.

Related to Interior lighting quality, IEQpc22 of LEED methodology specifies the guidelines for visual comfort. KPIs about illuminance levels, CRI, Reflectance ratio, ceiling illuminance (excluding fenestration) to work surface illuminance are defined, highlighting that way the role of visual comfort in LEED methodological framework.

In addition, IPMVP measurement and verification protocol specifies visual comfort related guidelines. "The quality of the indoor environment depends significantly on several aspects of lighting (IES 1993, Veitch and Newsham 1998) including the *illuminance* (intensity of light that impinges upon a surface), the amount of *glare*, and the *spectrum of the light"*. There is evidence that a decrease in the amount of *flicker* in light, i.e., the magnitude of the rapid cyclic change in illuminance over time, may be associated with a decrease in headache and eyestrain (Wilkens et al. 1988) and with an increase in worker performance (Veitch and Newsham 1997).

The methods of lighting control, such as no control, automatic dimming of artificial light and manual control of overhead or task lighting may also influence lighting quality. The recommended range of illuminance is a function of the type of visual activity and the age of the occupants. Different guidelines provide recommendations for the maximum luminance ratio, i.e., range of luminance in the visual field etc... Occupant's satisfaction with lighting may vary with

illuminance and with the characteristics of the lighting system, leading to the need for definition of an adaptive model that addresses personalized preferences and needs of building occupants.

Following the state of the art analysis on existing methodologies, performance indicators for visual comfort as met in standardization and further adopted in the project are presented in the next section.

7.2.2 List of Visual Comfort KPIs

7.2.2.1 Illuminance

The main requirement in terms of visual performance is a sufficient illuminance for the specific visual task(s) which carried out in a zone. The illuminance metric is *"the amount of light falling on a given surface area, i.e. the luminous flux per unit area".* Regarding the lighting quality, which is necessary for performing the visual task in a work situation, illuminance is used as the main indicator.

In a typical office, the European standard [21] requires a maintained illuminance level of 500 lux on the working plane for activities such as writing, reading and typing. In the surroundings of the desk, up to 0.5 meter around it, the lighting level should be at least 300 lux. In the remaining area of the workspace an illuminance level of 200 lux is recommended. The next figure presents the typical illuminance levels as defined in the standard

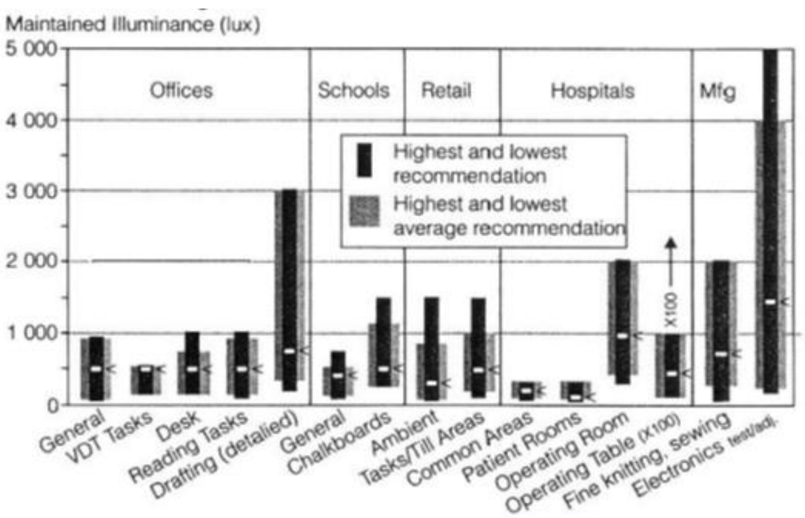

Figure 20. Range of (horizontal) illuminance levels recommended by the European Standard.

While, the previous analysis defines specified illuminance levels for building zones, this is not the case in practise as it is difficult to measure illuminance levels in a unified way. What we need is a dynamic model that adapts illuminance levels to building specific conditions. This is the main objective of the MOEEBIUS project, to define an adaptive model that aligns illuminance values, as captured by illuminance sensors, to actual building conditions.

7.2.2.2 Luminance

The amount of light falling on a point on the wall is its illuminance, and the amount of reflected light coming back from the wall is its luminance. Illuminance and luminance are closely linked. If all of the light that fell on the wall was reflected, then the values of the illuminance and the luminance would be the same, using appropriate units. If some of the light was absorbed or transmitted, then the values would differ. Therefore, the reflectance of the wall may be found by comparing the illuminance and the luminance values.

A number of lighting-related visual problems have been grouped together under the heading of 'glare'. These problems have in common the fact that they are all associated with light levels that are relatively high compared to the ambient light levels. A detailed analysis of luminance related discomfort factors are defined:

Discomfort glare

Although the mechanism of discomfort glare is unknown, the conditions under which discomfort occurs have been well established for a number of years [22]. Generally, discomfort increases with an increase in the luminance of the glare source, and/or an increase in the angular size of the glare source at the eye. By definition discomfort is subjective, and discomfort glare is not easily quantified. Towards this direction, and while discomfort glare from daylight and artificial origin has been the subject of extensive research in the past, there is no unique reliable prediction model, accepted as standard worldwide. Several different indexes have been proposed as a result of experimental studies relating subjective evaluation to the relevant (measurable) variables affecting the glare phenomenon. Most of these empirical formulas quantify the subjective glare sensation by calculation of a Glare Constant, which is expressed in terms of the measurable physical parameters through equations having the following general structure [23]:

$$G = \frac{L_s{}^p \omega_s{}^q}{L_b{}^r f(\psi)}$$

Where:

- L_s is the glare source luminance
- $\omega_s{}^q$ is the solid angle subtended by the source at the observation point
- L_b is the background luminance excluding the glare source
- $f(\psi)$ is a function of the displacement angle j of the source from the observer line of sight
- p, q and r: are constant weighting exponents.

The Visual Comfort Probability (VCP) method [24], the CIE Glare Index (CGI) [25] and the Unified Glare Rating (UGR) system [23] are well known methods. Despite the apparent validity of these studies in carefully-controlled experimental conditions, the evaluation of the glare indices in practice is complicated. While the

luminance and size of the glare source(s) are easily measured, there are real difficulties in determining the value of both the background luminance and the glare source position. Therefore, it is difficult to define a unique framework that addresses real time estimation of glare phenomenon. The glare phenomenon is mainly related and affected by the actual zone topology and thus further analysis of this index is out of the scope of the MOEEBIUS project.

Uniformity and contrast

The relative positions of the light source, the visual task, and the observer determine how effectively the task contrast is rendered, and recently a measure of lighting effectiveness, the **Contrast Rendering Factor** (CRF) has been devised [22]. The CRF has been used mainly in regard to paper-based tasks, which is where it is at its most useful. If the task lighting in an office is deficient, then measurement of the CRF would be the way to investigate this issue. Ideally, the CRF is measured by comparing the contrast of the object under the ambient lighting with its contrast under reference lighting (completely diffuse, unpolarised illumination). Generally, the higher the CRF, the more acceptable the visual performance is.

A further consideration in lighting uniformity is the **illuminance** distribution over a workplace. The arrangement of the lighting in a room should avoid distracting hard shadows, discomforting glare sources, and distracting reflections. Large differences in illuminance in a room may lead to visual stress and uncomfortable situations. The luminance ratio is the luminance of one area divided by the luminance of another area. Luminance ratio limits are recommended to prevent excessive contrast between light and dark.

The Uniformity and contrast of luminance levels are aspects directly affecting users' visual comfort and therefore should be examined within the context of MOEEBIUS framework. A main prerequisite is the segmentation of building zones and further the installation of the specialized equipment needed for gathering data.

7.2.2.3 Flicker

Flicker, noticeable rapid fluctuations in light level, can be a serious problem in artificial environments. Unfortunately, objective measurement of flicker is not simple because it requires rapid-response equipment, normally available only to a lighting specialist. Therefore, the evaluation of this parameter is mainly based on subjective assessment. There are different criteria defined in the bibliography that specify the different factors that affect the evaluation process, though as this factor is out of the scope of the project no detailed reference is provided.

7.2.2.4 Colour aspects

With respect to the colour aspects of lighting, the performance can be described by the colour temperature and colour rendering of the lighting.

Colour rendering

Colour rendering is the effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant. Different light sources have different colour rendering properties, and the colour of an object is determined both by the spectral composition of the light source, and by the spectral reflectance properties of the object and its surround.

The European standard [21] defines a colour rendering index (CRI) for lighting. The colour rendering is a measure of the effect a light source has on the perceived colour of objects and surfaces. Daylight coming from a northern sky is broad-band and is used as a reference illuminant. The lighting in a building is evaluated based on a 100 point scale colour rendering index (CRI) for lamps. Lighting with a relatively high colour rendering index represent virtually all colours natural and vibrant, while low CRI lighting causes some colours to appear washed out. In general, the higher the value of the CRI the better the lamp performs. The European standard advises a colour rendering index (CRI) of at least 80, which means good (50 is bad, 100 is excellent).

Colour temperature

The colour temperature (CCT, correlated colour temperature) of an artificial light source is determined by comparing its chromaticity with that of an ideal black-body radiator. The temperature (usually measured in Kelvin (K)) at which the heated black-body radiator matches the colour of the light source is that source's correlated colour temperature. For the description of colour the CIE (Commission Internationale de l'Eclairage) created in 1931 a mathematical model of a colour space. Since the retinal colour receptors in the human eye, cones, are sensitive to short, middle and long wavelength of light, the colour space model is characterized by three parameters (X,Y,Z), which are related to these three basic colours. Using these parameters it is possible to create an additive colour space based on three colours as depicted in the figure

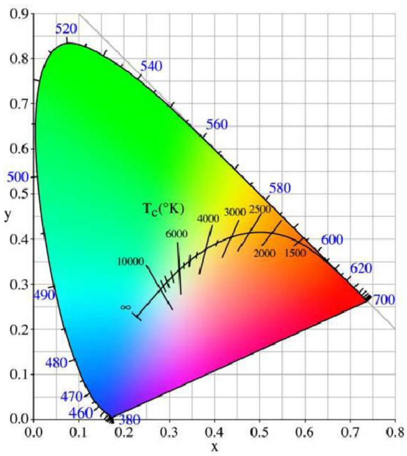

Figure 21. Colour temperature model.

Concerning the quality of colour properties of lighting, no colour temperature recommendation is given by the European standard [21]. The choice of the lighting colour is psychological and esthetical, and is dependent of other aspects as well, such as the illuminance in a room, the furniture, indoor and outdoor environment. The human perception of the correlated colour temperature is presented in the Table 12. Moreover, The CIE (Commission Internationale de l'Eclairage) recommends a colour temperature (CCT) for interior lighting in the range of 3000-6500K.

Lighting Colour	Correlated Colour Temperature
Warm	<3300K
Intermediate	3300-5300K
Cool	>5300 K

Table 12. Lighting Colour.

The analysis on colour impact is provided as part of the State of the Art analysis. The scope of the project is to examine the visual comfort of occupants addressing current building conditions. Therefore, the analysis is performed taking into account the existing installations and thus colour aspects and parameters are predefined in the MOEEBIUS framework and thus not part of the examination.

There are different factors that affect visual comfort parameters. The next table summarizes the list of indicators and further the correlation of them with aspects examined in MOEEBIUS project. This analysis will show the list of visual comfort indicators that set the baseline for MOEEBIUS Visual Comfort Performance Evaluation framework.

Visual Effect	Indicator	Short Description	MOEEBIUS Impact
Illuminance	Illuminance	Amount of light falling on a surface area	√
Discomfort glare	Daylight Glare Probability	Subjective discomfort due to glare	x
Uniformity and Contrast	Contrast Rendering Factor	Effectiveness of contrast rendering	√
	Luminance ratio	Luminance contrast on different subzones	√
Flicker	Number of flickers	Rapid fluctuations in light level	x
Colour Aspects	Colour Temperature	Colour Temperature between standardized boundaries	x
	Colour Rendering	The effect of a light source on the perceived colour of objects and surfaces	x

Table 13. Visual Comfort Related Key Performance Indicators.

7.2.3 Monitoring techniques

Different types of sensors will be installed in order to gather data related to visual comfort. More specifically, different types of luminance sensors should be considered to gather the input values required for calculation of visual comfort KPIs. Different sensor installation topologies (Table 14) will further enable the calculation of illuminance level, Contrast Rendering Factor and Luminance ratio as the Visual Comfort KPIs selected in MOEEBIUS project.

Variable	Monitoring technique
Illuminance	Lux meter
Luminance ratio	Luminance meters

Table 14. Monitoring techniques for visual comfort variables.

7.3 Extended framework for MOEEBIUS Comfort KPIs

The literature review highlights occupants' comfort KPIs as defined in standardization. A high level taxonomy of comfort KPIs to thermal comfort and visual comfort has been provided focusing on the main objectives of the project. The aforementioned analysis highlights which KPI parameters will be examined as part of the MOEEBIUS performance framework and further set the baseline for the extension of MOEEBIUS comfort assessment framework.

The scope of this section is to start from state of the art analysis and further extend the identified Comfort KPI framework with additional aspects that complement the MOEEBIUS performance assessment analysis. As explicitly highlighted in previous sections, the goal of the MOEEBIUS project (by integrated Occupants' Behaviour Engine) is to enable the extraction - in real time - of personalized comfort and discomfort parameters. We have defined in previous sections the important role of adaptive models that localize the generic comfort models to specific conditions. Generic models are considered as parametric models with a limited flexibility on modification. Though, we need to define models that are dynamically adaptive taking into account the context conditions of building premises. Therefore, the main objective in the project is to define non-parametric indicators that take into account the context conditions and further (through learning process) define the comfort and discomfort boundaries for the users. A detailed analysis of the proposed framework is provided.

For the application of a personalized and adaptive comfort models, a sensation model taking into account the specificities of each occupant through one or several personal parameters is considered. This approach calculates for a considered person in an indoor environment, a statistical sensation according to measurable environmental parameters. Towards the combination of real time context

parameters in non-parametric models we need to define a KPI metric that translates the personal parameters to meaningful information.

In order to translate personalized parameters that dynamically characterize the individual user preferences, the term "Utility Function" is adopted. Utility function [26] is mentioned as the function that specifies the utility (well-being) of a consumer/individual for all combinations of goods consumed (and sometimes includes other considerations).

In the behavioural analysis of individuals, each customer operates a set of appliances such as air conditioner, refrigerator, plug-in hybrid electric vehicle (PHEV), etc. For each appliance of the customer, an amount that models how much a customer values the consumption vector of a device is delivered as well as a set of constraints on the consumption vector {Consumption vector: (User, Appliance)}. The willingness to use a specific device under specific conditions is transformed to the utility function value. This terminology is independent from environmental conditions and thus a holistic approach is considered for all operational devices. An abstract approach of the utility function estimation is provided [27].

"Each customer $i \epsilon N$ operates a set $A_{i,i} \epsilon N$ of appliances such as air conditioner, refrigerator, plug-in hybrid electric vehicle. For each appliance $\alpha \epsilon A_i$ of customer i we denote by $q_{i,a}(t)$ its power draw at time $t \epsilon T$, and by $q_{i,a}(t)$ the vector $(q_{i,a}(t), t \epsilon T)$ of power draws over the whole period examined."

A high level representation of the Utility function format is given in the next figure

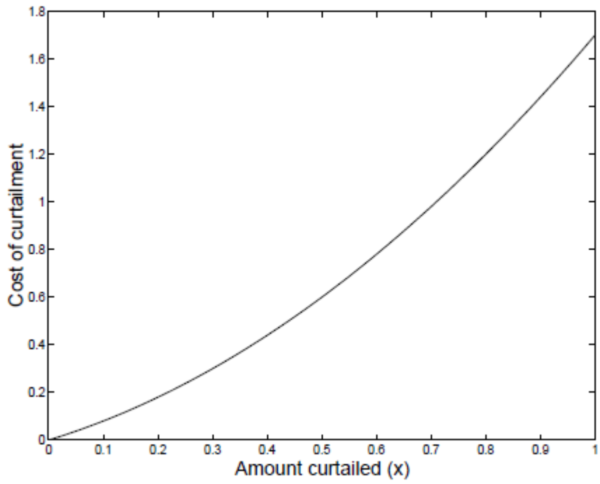

Figure 22. Utility Function Curve.

Overall, the utility function quantifies the preferences and non-preferences under specific conditions in a scale [0-1]. Based on the state of the art analysis [27], a high level taxonomy of the Distributed Energy Resources is considered in order to

provide fitted utility functions that optimally characterize the behavioural operation of the individual users:

- Type 1*:* The first type includes those appliances such as air conditioner and refrigerator which control the temperature of customer's environment. The value of the Utility function is maximized out of the technical operational limits of the devices.
- Type 2: The second category includes appliances such as PHEV, dish washer, clothes washer. For these appliances, a customer only cares about whether the task is completed before a certain time. This means that the cumulative power consumption by such an appliance must exceed a threshold by the deadlines. These devices are characterized as demand shiftable devices and thus the total value of utility function is increased at the end period of the scheduled operation.
- Type 3: The third category includes the appliances that must be on for a certain period of time, such as lighting. A customer cares about how much light they can get at each time t but different operational states can be considered on the time period. Type 3 devices combine the environmental and operational conditions in an integrated framework and the utility function is delivered as the performance indicator of the holistic model.
- Type 4: The fourth category includes the appliances that a customer uses in a non-continuous essential mode, such as TV and computers. The status of these devices is considered as on/off and thus an extra parameter (e.g. price) has to be examined in order to estimate the utility preferences of end users. The overall potential of Type 4 DERs on Demand Side Management Strategies is considered as significant one, and thus a special interest is delivered on the extraction of the utility function of individual devices.

This framework combines the operational characteristics of the devices along with the associated contextual conditions (environmental conditions) towards the establishment of a unified comfort performance framework. The goal of this section is to consider as part of the proposed comfort model, the contextual parameters that characterize the utility function levels of building occupants.

The main focus of this section is on defining the performance indicators for Thermal and Visual Comfort, by incorporating environmental conditions and user control actions on devices under a single model. As mentioned above, these personalized input parameters are combined in a non-parametric model towards the extraction of Thermal Utility Function and Visual Utility Function that define the comfort and discomfort boundaries in a dynamic way. This correlation is expressed through the following equation:

$$DiscomfortValue = f(\text{environmental conditions})$$

It has to be pointed out that end users control actions are indirectly integrated in the proposed framework, as the control settings lead to changes on environmental

conditions. The $f(function)$ is not extracted as a single value, but as the synthesis of different input parameters towards the extraction of user preferences and non-preferences under specific environmental (luminance, temperature, humidity etc...) conditions. More specifically we define the following KPIs:

Thermal Discomfort Factor: This indicator defines thermal level user references and non-preferences in a scale of [0-1].

$$Thermal\_Discomfort\_Value = f(Temperature, Humidity)$$

Where input parameters:

- Temperature: Real time temperature values from sensor devices (dry bulb air temperature and operative temperature)
- Humidity: Real time humidity values from sensor device

Visual Discomfort Factor: This indicator defines visual level user references and non-preferences in a scale of [0-1].

$$Visual\_Discomfort\_Value = f(luminance)$$

Where input parameters:

- Luminance: Illuminance values from sensor devices

The aforementioned analysis goes beyond the existing standards and defines (user and zone specific) comfort KPIs that incorporate in the model building actual conditions. The main innovation of the proposed framework is that we are taking into account the environmental conditions through a non-parametric model and we define personalized and adaptive thermal and visual comfort/discomfort levels expressed in terms of "utility function".

By further extending the list of standards based comfort KPIs, with dynamically adapted KPIs as defined in this section we can further set the final list of MOEEBIUS comfort KPIs for the project. A detailed modelling framework of the selected KPI parameters will be provided in T3.6 Local and Global Energy Performance Modelling.

Time & space granularity and gender issues

For occupants' comfort KPIs (both thermal and visual comfort KPIs), there is no time granularity explicitly defined for comfort values, as these values are directly associated to real time environmental conditions. MOOEBIUS will provide real time calculation of comfort metrics and further aggregation of these values at any time granularity (average comfort level), setting that way the KPI values for the associated comfort parameters.

Special interest is delivered on the definition of spatial granularity for comfort KPIs. As the goal of the MOEEBIUS framework is to provide a user oriented

framework, adaptive to building occupants preferences and needs, the spatial granularity is defined at any virtual zone (thermal or visual) associated to users' vicinity. This definition of virtual zones will be part of BIM model of the project, considering that way the physical boundaries for comfort KPIs calculation. We have to point out that user centric comfort KPI analysis will be possible if the required hardware equipment is available at each specific virtual zone (thermal or visual) defined. Therefore, sensors (commercial sensors and the MOEEBIUS prototype device - MOEEBIUS NOD-) for measuring temperature/humidity/luminance levels will be installed to enable KPI calculation.

The individual differences in thermal comfort responses are well known, but the differences between male and female subjects are considered to be small. Although gender differences in preferred temperature and thermal comfort are generally considered to be small, there are several studies in the literature in which gender differences have been found:

- Fanger found no significant difference in preferred temperature between the genders in climate chamber studies, but notes that females seem to be more sensitive to a deviation from the optimum.
- In a laboratory study [28], only small differences in the thermal comfort between male and female subjects were found, but in cool conditions females tended to be cooler than males.
- Although there was little difference (particularly in summer) between the genders in terms of thermal sensations in a large field study in Australia [29], females expressed significantly more thermal dissatisfaction than males.
- When draft discomfort was studied by a laboratory study with 179 participants [30], it was found that women felt uncomfortable and preferred a higher temperature significantly more often than men.
- In a laboratory study [31], females tended to feel more uncomfortable than males at both high and low temperature extremes.
- A field survey conducted in an office [32] showed that the neutral temperature was 3.1 ^{o}C higher in a Japanese female group than in a non-Japanese male group. In Japan, it has been found that more than 30% of women in all age groups feel unusual coldness in thermal environments in which most people feel thermally comfortable.

Usually, the differences, if they have been found, have been explained in terms of clothing differences. Within MOEEBIUS project, we will try to examine possible gender differences in thermal comfort (by setting up test cases in pilot premises) towards the establishment of a personalized and adaptive thermal comfort management framework.

8 Indoor Air Quality

Even though the significance of ensuring thermal comfort during building operation by incorporating more advanced thermal comfort indices – in contrast to the widely-used practice of monitoring only the indoor air temperature – in the design and operation of building energy management systems is becoming more apparent, the topic of Indoor Air Quality (IAQ) is rather overlooked in current practice or, at best, it is simplified to a set of designed minimum air flow rates.

This is in part due to the inability of the occupants of a building to quantify their discomfort due to reduced IAQ, compared to thermal or visual perception; it is much easier to understand the impact of a too dark or too bright working space to our productivity or the effect of a cold, hot, too humid or too dry space to our thermal sensation. Nevertheless, many studies have tried to correlate the effect of reduced IAQ to a cost-related index, such as office productivity, with tangible results, as shown in Figure 23 (Wargocki et al., 2000 [33]).

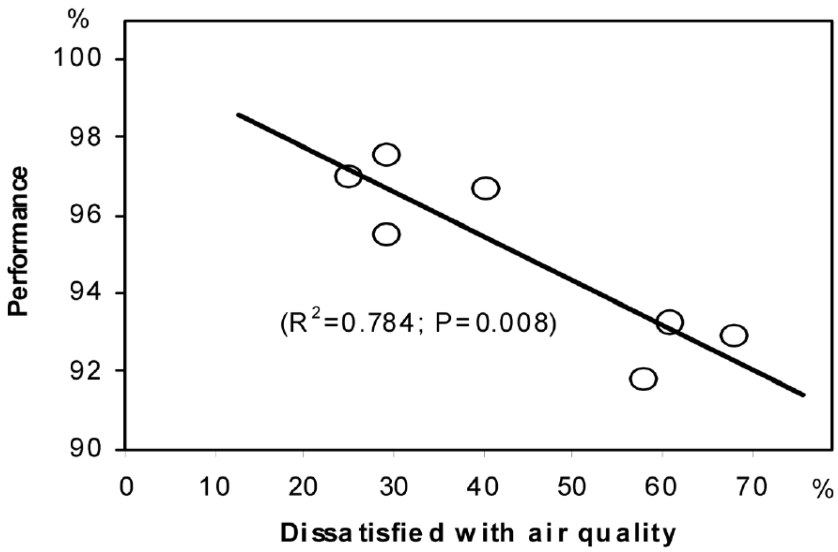

Figure 23. Relative performance in office work depending on the perceived air quality (Wargocki et al., 2000 [33]).

Within MOEEBIUS, we take the stance that the overall Indoor Environmental Quality (IEQ) is defined in a holistic manner, based on three pillars: thermal comfort, visual comfort and IAQ. These three IEQ aspects act as constraints defining a theoretical and practical upper bound on potential energy savings in buildings (i.e. the most energy-efficient strategy is to close the HVAC system).

In contrast to thermal and visual comfort, IAQ definitions include long lists of different pollutants, accompanied by reference values guidelines for each of them. Many standardisation efforts have been undertaken, often providing different views and categorizations of the various substances. Since the task at hand here is not to provide an exhaustive list of all available guidelines worldwide, but rather to conclude to a set of meaningful and applicable KPIs, we include in our analysis

only a part of the available standards (for a detailed discussion refer to Steskens & Loomans, 2010 [34] and Schuh, 2000 [35]).

A good starting point for defining the MOEEBIUS IAQ KPIs are the World Health Organization (WHO) air quality guidelines (World Health Organization, 2000 [36], 2005 [37], 2010 [38]), which are issued for the protection of public health from health risks due to a number of chemicals commonly present in indoor air. The guidelines are based on a comprehensive review and evaluation of the accumulated scientific evidence by a multidisciplinary group of experts studying the toxic properties and health effects of these pollutants and they have been adopted by several European Projects in an effort to provide a unified KPI framework (PERFECTION project, 2009 [39]).

Table 15 provides an overview of the WHO guidelines for various air pollutants, along with limit values for each one.

Performance Indicator	Parameter	Guidelines
Organic Pollutants	Acrylonitrile	As low as possible
	Benzene	As low as possible
	Butadiene	No guideline value available
	Carbon disulfide	annual average – 100 $\mu g/m^3$
	Carbon monoxide	15 minutes – 100 $\mu g/m^3$ 1 hour – 35 $\mu g/m^3$ 8 hours – 10 $\mu g/m^3$ 24 hours – 7 $\mu g/m^3$
	1,2-Dichloroethane	Annual average – 0.7 mg/m^3
	Dichloromethane	Annual average – 3 mg/m^3
	Formaldehyde	30 minutes – 0.1 mg/m^3
	Polycyclic aromatic hydrocarbons	As low as possible
	Polychlorinated biphenyls	No guideline value available
	Polychlorinated dibenzodioxins and dibenzofurans	No guideline value available
	Styrene	Weekly average – 0.26 mg/m^3
	Tetrachloroethylene	Annual average – 0.25 mg/m^3
	Toluene	30 minutes – 1 mg/m^3
	Trichloroethylene	As low as possible
	Vinyl chloride	As low as possible
Inorganic Pollutants	Arsenic	As low as possible
	Asbestos	As low as possible
	Cadmium	Annual average – 0.5 ng/m^3
	Chromium	As low as possible
	Fluoride	Annual average – 1 $\mu g/m^3$
	Hydrogen sulfide	30 minutes – 7 $\mu g/m^3$
	Lead	No guideline value available

	Manganese	Annual average – 0.15 $\mu g/m^3$
	Mercury	Annual average – 1 $\mu g/m^3$
	Nickel	No guideline value available
	Platinum	No guideline value available
	Vanadium	Annual average – 1 $\mu g/m^3$
Classical Pollutants	Nitrogen dioxide	Annual average – 40 $\mu g/m^3$
	Ozone and other photochemical oxidants	8 hours – 100 $\mu g/m^3$
	Particulate matter (PM_{10})	Annual average – 20 $\mu g/m^3$ 24 hours – 50 $\mu g/m^3$
	Particulate matter ($PM_{2.5}$)	Annual average – 10 $\mu g/m^3$ 24 hours – 25 $\mu g/m^3$
	Sulfur dioxide	24 hours – 20 $\mu g/m^3$ 10 minutes – 500 $\mu g/m^3$
Indoor Air Pollutants	Environmental tobacco smoke	As low as possible
	Man-made vitreous fibres	As low as possible
	Radon	As low as possible
Bioaerosols	Bacteria Fungi Viruses Plant and Animal Matter	Total number of bioaerosol particles < 1000 CFUs/m^3 Culturable count for total bacteria < 500 CFUs/m^3

Table 15. Summary of indoor air quality guidelines for selected contaminants according to the WHO.

8.1 MOEEBIUS Indoor Air Quality KPIs

Despite the fact that the enumeration of pollutants in Table 15 is quite complete, measuring all these substances at high spatial and time granularity can be a formidable task, requiring a complex and expensive monitoring solution. In an effort to balance the trade-off between ensuring acceptable IAQ and minimizing the associated sensing infrastructure cost, we identify (as in Schuh, 2000 [35]) a small set of IAQ KPIs, namely Carbon Dioxide (CO_2), Carbon Monoxide (CO), Particulate Matter (PM) and Volatile Organic Compounds (VOCs).

We have to emphasize here that measuring and calculating all four KPIs in a building is not a prerequisite for ensuring IAQ. Each building is unique and is subjected to different disturbances affecting indoor air quality. The initial selection of the evaluation metrics should be performed by the building Stakeholders based on the particularities of each target building. In case IAQ proves to be inadequate (e.g. by direct complaints from the occupants), more KPIs can be measured and calculated either for the entire building either targeted to specific spaces that are identified as problematic.

8.1.1 Carbon Dioxide

CO_2 at very high concentrations (e.g. greater than 5000 ppm) can pose a health risk. However, in most buildings, concentrations almost never rise to these levels, but CO_2 concentrations can be used as an indicator of occupant odours (odorous bioeffluents) and occupant acceptance of these odours. In addition, CO_2 concentrations can serve as an appropriate air quality measurement because of the potential to predict the amount of outdoor air supplied to a space. For example, ASHRAE suggests that a level of 1000 ppm or 650 ppm above ambient levels would be equivalent to a delivery rate of 10 L/s per person of outside air (ASHRAE, 2010 [40]).

According to (DIN EN 13779, 2007 [41]) the recommended criteria for calculating the design ventilation rates in non-residential buildings, based on CO_2 concentrations are the following:

Indoor Quality Category	**CO_2 – level above level of outdoor air in ppm**	
	Typical Range	Default Value
I	<400	350
II	400 – 600	500
III	600 – 1000	800
IV	>1000	1200

Table 16. IAQ categories based on CO2 limit values.

These levels also serve as CO_2 concentration guidelines. Based on the above values, and taking into account that CO_2 concentrations in outdoor air typically range from 300 to 500 ppm, indoor CO_2 concentrations of 1000 ppm in spaces housing sedentary people is an indicator that a substantial majority of visitors entering the space will be satisfied. A recent study (Satish et al., 2012 [42]) revealed a connection between CO_2 concentrations and human decision making performance and verified the suggested limit values, as shown in Figure 24.

Measurements of CO_2 concentrations for purposes of assessing the adequacy of ventilation need to be made after an extended period of steady occupancy and ventilation – in schools at least 2 hours, and in offices at least 3 hours – for concentrations to be a reasonable indicator of ventilation adequacy, while the sensors should be spread out through many areas in a building to ensure that air is distributed evenly. If CO_2 measurements are used for CO_2-based demand control ventilation in large spaces, like e.g. lecture halls, gyms, etc., proper care should be taken, to avoid false readings due to local CO_2 concentrations (Stipe, 2003 [43]).

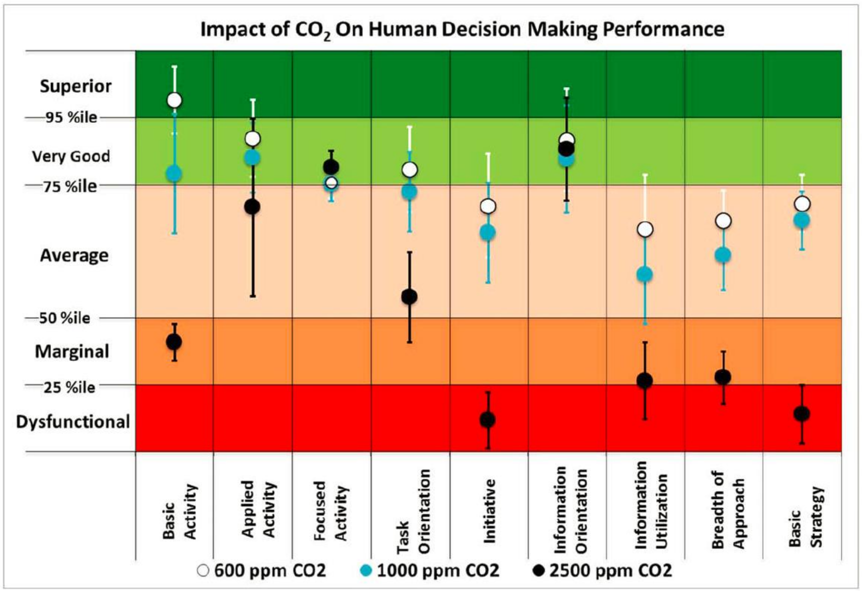

Figure 24. Impact of CO_2 on Human Decision-Making Performance. Error bars indicate one standard deviation (Satish et al., 2012 [42]).

The *long-term* IAQ evaluation of CO_2 concentrations KPI for a monitored space i for a time-period T, is performed by evaluating the specific percentage of time the space was in each of the four categories shown in Table 16 during occupied time. More formally, if T_{occ}^{i} is the total amount of time that space i was occupied and T_{I}^{i}, T_{II}^{i}, T_{III}^{i} and T_{IV}^{i} are the total amounts of time the CO_2 levels measured during occupancy where in the limits defining the categories I – IV of Table 16 respectively, then the *long-term evaluation vector* for the of CO_2 KPI for space i during occupancy is:

$$LT\_KPI_{co_2}^{i} = \begin{pmatrix} \frac{T_I^i}{T_{occ}^i} \\ \frac{T_{II}^i}{T_{occ}^i} \\ \frac{T_{III}^i}{T_{occ}^i} \\ \frac{T_{IV}^i}{T_{occ}^i} \end{pmatrix} \times 100\%.$$

8.1.2 Carbon Monoxide

According to Schuh (2000), carbon monoxide is identified as an appropriate air quality measure because of the significance of the health effects and associated risk and liability of this contaminant. Sources of carbon monoxide are carbon based fuel sources.

A carbon monoxide indicator would assist towards identifying any IAQ problems in buildings with fuel-based heating systems and smoking areas, as well as buildings that are near traffic and parking areas. In such buildings, the sensors should be

spread out through many areas of the building to ensure that air is distributed evenly. The limit guidelines and the proper time-intervals for the measurements of CO concentrations are shown in Table 17.

Time Averaging	Limit Values
15 minutes	100 $\mu g/m^3$
1 hour	35 $\mu g/m^3$
8 hours	10 $\mu g/m^3$
24 hours	7 $\mu g/m^3$

Table 17. Limit values guidelines for indoor CO concentrations.

The *long-term* IAQ evaluation of CO concentrations KPI for a monitored space i for a time-period T, is defined as an *efficiency index*, expressing the absence of concentrations exceeding the limit values over time.

More formally, let's define as T_{occ}^{i} the total amount of time that space i was occupied and $t \in \{1,2,3,\dots,N_t\}$ a time-index of the occupied period. This index can divide the occupied time-period in 15 minutes, 1 hour, 8 hours or 24 hours intervals, leading to different *long-term* evaluation metrics. Now, let's we define a weight w_t^i as:

- $w_t^i = |CO_t^i - CO_t^{lv}|$, i.e. the distance between the CO measurements at time-index t and the limit value for CO concentrations, *if the CO measurements are higher than the limit*;
- And set $w_t^i = 0$, *if the CO measurements* at time-index t *are lower or equal to the limit*.

Then, we can define the *long-term evaluation efficiency index* for space i as follows:

$$LT\_KPI_{CO}^{i} = \frac{\sum_t w_t^i}{(N_w \times N_t)}.$$

Here, N_w is a normalization factor to be defined (e.g. could be set to two times the value of the upper limit). Values close to zero for the efficiency index indicate that the monitored space did not exhibit high CO concentrations over time.

Finally, this efficiency index can be calculated for all time-averaging options shown in Table 17, using of course the respective limit values in all cases.

8.1.3 Particulate Matter

Particulates are defined as suspended mixtures of solid of liquid particles. They include asbestos, silica dust, coal dust, bioaerosols, smoke, and fumes. The toxicity of particles is related to the size and nature of the particle. Smaller

particles are deposited further into the lungs and the removal processes at this location are slow. Particles less than 3 μm (microns) are of concern.

Concerning the current practice in measuring particulate matter, according to (TSI, 2003 [44]), first, it is important to minimize airborne particles as much as possible using more routine means such as good housekeeping practices, upgrading filters, maintaining a positive pressure relative to the outdoors and having proper exhaust design. Even with these practices in place, airborne particles may enter workspaces.

When it does become necessary to measure airborne particles, two basic methods typically are used: air sampling over time and measurements employing real-time instruments. With air sampling over time, materials are most often collected on a filter medium and subsequently analysed in an environmental laboratory located away from the sampling location. With real-time instruments, measurements are made and results obtained on-site (TSI, 2003 [44]).

Three types of instruments (photometer, optical particle counters and condensation particle counters) normally are used for real-time measurements. Performance features and applications for the three are compared in the following charts. The specific instrument of choice depends on the application and the desired results. For a detailed review on the available measuring instruments, please see (Amaral et al., 2015 [45]).

The limit guidelines and the proper time-intervals for the measurements of PM are shown in Table 18.

Particulate Matter	Time Averaging	Limit Values
PM_{10}	Annual	20 $\mu g/m^3$
	24 hours	50 $\mu g/m^3$
$PM_{2.5}$	Annual	10 $\mu g/m^3$
	24 hours	25 $\mu g/m^3$

Table 18. Limit values guidelines for indoor PM concentrations.

The *long-term* IAQ evaluation of PM concentrations KPI for a monitored space i for a time-period T is defined in the same way as the *long-term evaluation efficiency index* is defined for the CO concentrations.

8.1.4 Volatile Organic Compounds

A number of diverse definitions of the term Volatile Organic Compound exist. According to the European Decopaint Directive (2004/42/EC): "VOC is any organic chemical with boiling point below 250 °C at a standard atmospheric pressure of 101.3 kPa. To be given as grams VOC per litre product".

VOCs may have effects ranging from odour perception and irritation of the mucous membranes of the eyes, nose and throat to acute and/or systemic effects and

long-term effects. This also includes effects on the nervous system, allergenic or allergy-promoting and, in particular, carcinogenic, mutagenic or reprotoxic properties (AgBB, 2015 [46]).

Commercial, educational and government buildings contain VOCs, such as:

- Organic odors, aerosols, disinfectants, cleansers (washrooms, kitchens)
- Paints, waxes, cleaning supplies, pesticides (janitorial closets)
- Copiers, printers, correction fluids, adhesives, permanent markers, photographic solutions (copier/printing rooms)
- Fuel cans, solvents, preservatives, automotive and vehicle products (warehouses, shipping areas)
- Formaldehyde carpets (offices and office areas)

Many international and national standardization efforts are undergoing, aiming at identifying VOCs and providing proper limit values as guidelines. For example, ASHRAE standards provide a short list of concentrations of interest for selected VOCs (ASHRAE, 2010 [40]) while the German Committee for Health-related Evaluation of Building Products has identified more than 150 VOCs, providing concentrations of interest for each one (AgBB, 2015 [46]).

Photo-ionization and flame-ionization detectors can be used to identify many VOCs that can impact IAQ. In most cases, it is difficult to get an accurate picture of the extent of chemical contaminants in the air using real-time data collection. It is more often a complex mix rather than individual compounds that pose the difficult challenge. Consequently, sampling is an accepted practice generally conducted using techniques such as filtration, absorption in another media, or impaction (TSI, 2003 [44]).

For VOC concentrations, we are interested not only on their absolute values, but also for their increase/decrease compared to the previous values. So, we use a *visual long-term evaluation metric here*, where the Facility Management team of the building is provided with a plot illustrating the trend of VOC concentrations over time.

8.2 Monitoring techniques

As mentioned in previous section, different techniques can be used to measure the different variables needed for the assessment of the defined IAQ KPIs.

Table 19 summarizes the required equipment for the monitoring of the variables needed for the assessment of the IAQ indicators.

Monitoring of concentrations of CO_2 and CO can be easily done by CO_2 and CO concentration meters.

For real-time measurements of airborne particles, three types of instruments are usually used: photometer, optical particle counters and condensation particle

counters. And two types of equipment can be used to identify VOCs: Photo-ionization and flame-ionization detectors.

Variable	Monitoring technique
CO_2 concentration	CO_2 concentration meters
CO concentration	CO concentration meters
Airborne particles	Photometer
	Optical particle counters
	Condensation particle counters
VOCs	Photo-ionization detectors
	Flame-ionization detectors

Table 19. Monitoring techniques for IAQ variables.

8.3 Time and space granularity

Regarding the time granularity for the evaluation of IAQ, two categories of KPIs have been defined: the first category addresses the short- and medium-term evaluation (e.g. hourly or daily statistics) and the second addresses the long-term evaluation of IAQ. The latter category can be seen as a proper "averaging" for long-term values.

The ability to measure all the selected pollutants depends on the available sensing infrastructure. In any case, recording values at 15 minute intervals, even if the available sensors allow for finer time granularity, is enough for the IAQ indicators. The logged values are then retrieved to calculate the defined (short- and/or long-term) IAQ KPIs in intervals spanning from 1 hour (for CO_2 and CO), to daily, weekly, monthly and yearly reports for each selected pollutant.

The spatial granularity of the IAQ KPIs differs for each selected pollutant. For the CO_2, measurements for each building space or virtual zone (as defined for the thermal and visual comfort KPIs) are required, while for the CO, measurements should be targeted in spaces that might have problems with high CO values, such as smoking areas or areas that are adjacent to parking spaces. PM and VOC measurements can be performed in larger virtual zones, like e.g. per building floor.

In any case, the spatial granularity of the IAQ KPIs calculation is a process that necessitates the availability of a BIM model for exploring and defining the IAQ virtual spaces, as well as feedback from the building owners to take into account any particular space-related IAQ problems.

9 Economic KPIs

9.1 Investment costs

The investment costs (retrofitting, initial investment for equipment) include the construction costs for all new building parts, components and materials brought to the building in the initial installation of equipment or in the course of energy retrofitting measures (investment costs for construction and installation process). The estimated costs should be based on the real price level from the respective European country.

The investment costs have to be adapted to the application of different business models for the retrofitting measures. Benefits from grants etc. have to be included in the calculation of the investment costs as negative costs and should lead to a reduction of the investment costs. Thus the benefits from the application of different business models are included in the Life cycle costs calculation.

The indicator investment costs shall be used to show the user of MOEEBIUS what share the investment costs have on the whole life cycle costs. Furthermore the investment costs indicator will be used for setting constraints in order to select possible retrofitting solutions for the buildings.

9.2 Savings in electricity and gas

The savings in running energy costs (electricity, gas, district heating...) are the difference between the running energy costs of the building after the deployment of energy measures in order to achieve energy savings (reporting period) and the running energy costs that the original building would have had.

9.2.1 Baseline comparison

The running energy costs that the original building would have had are considered in this proceeding to be similar to the running energy costs of the original building measured during a baseline period taking in to account an adjustment.

$$\text{Savings} = (\text{Baseline-Period Use or Demand - Reporting-Period Use or Demand}) \pm \text{Adjustments}$$

(Eq.1)

Care should be taken in selecting the period of time to be used as the baseline period and the reporting period. Strategies for each are discussed in IPMVP [1] as following:

Baseline Period

The baseline period should be established to:

- Represent all operating modes of the facility. This period should span a full operating cycle from maximum energy use to minimum. Whole-building

energy use can be significantly affected by weather conditions. Typically, a whole year of baseline data is needed to define a full operating cycle.

- Fairly represent all operating conditions of a normal operating cycle.
- Include only time periods for which all fixed and variable energy-governing facts are known about the facility. Extension of baseline periods backwards in time to include multiple cycles of operation requires equal knowledge of all energy-governing factors throughout the longer baseline period in order to properly derive routine and non-routine adjustments after ECM installation.
- Coincide with the period immediately before commitment to undertake the energy measure. Periods further back in time would not reflect the conditions existing before energy measure and may therefore not provide a proper baseline for measuring the effect of just the ECM.

ECM planning may require study of a longer time period than is chosen for the baseline period. Longer study periods assist the planner in understanding facility performance and determining what the normal cycle length actually is.

Reporting Period

The user of the savings reports should determine the length of the reporting period. The reporting period should encompass at least one normal operating cycle of the equipment or facility, in order to fully characterize the savings effectiveness in all normal operating modes.

The length of any reporting period should be determined with due consideration of the life of the ECM and the likelihood of degradation of originally achieved savings over time.

Basis for adjustments

As already seen in section 3.1, the “Adjustments” term shown in Equation 1 should be computed in order to compare in similar conditions if the initial conditions (governing the energy performance) have changed. Therefore an assessment of these already known two types of adjustments is needed:

- Routine Adjustments. Techniques may be as simple as a constant value (no adjustment) or as complex as a several multiple parameter non-linear equations each correlating energy with one or more independent variables. Valid mathematical techniques must be used to derive the adjustment method for each M&V Plan. Appendix B of IPMVP [1] offers some guidance on assessing the validity of mathematical methods.
- Non-Routine Adjustments. These static factors must be monitored for change throughout the reporting period.

Therefore Equation 1 can be expressed more fully as:

Savings = (Baseline Energy – Reporting-Period Energy) ± Routine Adjustments ± Non-Routine Adjustments

(Eq. 2)

The adjustments terms in Equation 2 are used to express both pieces of measured energy data under the same set of conditions. The mechanism of the adjustments depends upon whether savings are to be reported on the basis of the conditions of the reporting period, or normalized to some other fixed set of conditions.

Reporting-Period Basis or Avoided Energy Use

When savings are reported under the conditions of the reporting period, they can also be called avoided energy use of the reporting period. Avoided energy use quantifies savings in the reporting period relative to what energy use would have been without the ECM(s).

When reporting savings under reporting-period conditions, baseline-period energy needs to be adjusted to reporting-period conditions.

For this common style of savings reporting Equation 2 can be restated as:

Avoided Energy Use (or Savings) = (Baseline Energy ± Routine Adjustments to reporting-period conditions ± Non-Routine Adjustments to reporting-period conditions) - Reporting-Period Energy

This equation is often simplified to the following:

Avoided Energy Use (or Savings) = Adjusted-Baseline Energy – Reporting-Period Energy ± Non-Routine Adjustments of baseline energy to reporting-period conditions

(Eq. 3)

Where Adjusted-Baseline Energy is defined as the baseline energy plus any routine adjustments needed to adjust it to the conditions of the reporting period.

The adjusted-baseline energy is normally found by first developing a mathematical model which correlates actual baseline energy data with appropriate independent variables in the baseline period. Each reporting period’s independent variables are then inserted into this baseline mathematical model to produce the adjusted-baseline energy use.

Fixed Conditions Basis or Normalized Savings

Conditions other than those of the reporting period may be used as the basis for adjustment. The conditions may be those of the baseline period, some other arbitrary period, or a typical, average or ‘normal’ set of conditions.

Adjustment to a fixed set of conditions reports a style of savings which could be called “normalized savings” of the reporting period. In this method energy of the

reporting period and possibly of the baseline period are adjusted from their actual conditions to the common fixed (or 'normal') set of conditions selected.

Equation 4 restates the more general Equation 2 for such normalized savings reports:

$$\text{Normalized Savings} = (\text{ Baseline Energy} \pm \text{Routine Adjustments to fixed conditions} \pm \text{Non-Routine Adjustments to fixed conditions }) - (\text{ Reporting Period Energy} \pm \text{Routine Adjustments to fixed conditions} \pm \text{Non-Routine Adjustments to fixed conditions })$$

(Eq. 4)

The calculation of the reporting period routine-adjustments term usually involves the development of a mathematical model correlating reporting-period energy with the independent variables of the reporting period. This model is then used to adjust reporting-period energy to the chosen fixed conditions. Further, if the fixed set of conditions is not from the baseline period, a mathematical model of baseline energy is also used to adjust baseline energy to the chosen fixed conditions.

9.2.2 Calibrated Simulation

As seen in section "5.3.5.1 Retrofitting advisor and Investment Evaluation Module", calibrated simulation involves the use of computer simulation software to predict facility energy for one or both of the terms in Equation 1. A simulation model must be "calibrated" so that it predicts an energy pattern that approximately matches actual metered data.

Calibrated Simulation may be used to assess just the performance of individual systems within a facility. In this case, the system's energy use must be isolated from that of the rest of the facility by appropriate meters.

Calibrated Simulation is useful where:

- Baseline energy data do not exist or are unavailable.
- Reporting-period energy data are unavailable or obscured by factors that are difficult to quantify. Sometimes it is too difficult to predict how future facility changes might affect energy use.
- It is desired to determine the savings associated with individual ECMs.

In MOEEBIUS framework simulations are going to be used in order to predict the performance of the system and optimize the operation at building and district levels. Therefore, an evaluation of the energy savings achieved can be calculated since the simulation energy results for the original performance of the building, without any actuation related to the optimization introduced in the MOEEBIUS framework.

If the reporting-period energy is predicted by the simulation software, the determined savings persist only if the simulated operating methods continue.

Periodic inspections will identify changes from baseline conditions and modelled equipment performance. Simulation runs should be adjusted accordingly.

Calibrated Simulation is the primary M&V approach for assessing energy efficiency inclusions in new facility designs. The IPMVP Volume III Part I, titled "Concepts and Options for Determining Savings In New Construction", provides guidance on a variety of M&V techniques applicable to new buildings.

Accurate computer modelling and calibration to measured energy data are the major challenges associated with Calibrated Simulation.

Calculations

Savings can be determined using calibrated simulation results representing the baseline energy and/or the reporting-period energy. For projects with a physical baseline, the two calibrated models include one with the ECMs and one without them. For projects with a hypothetical baseline, calibrated models may include the hypothetical baseline and the as-built (reporting period) conditions, but measured data will only be available for calibration under as-built conditions. In either case, both models and measured energy data must be under the same set of operating conditions.

Savings can be estimated using two forms of Equation 1: Equations 5 and 6. Both forms presume that the calibration 'error' equally affects both baseline and reporting period models. The same savings will be determined from the two equations for any given set of data and simulations.

Savings = Baseline energy from the calibrated model [hypothetical or without ECMs] – Reporting-period energy from the calibrated model [with ECMs]

(Eq. 5)

One of the model-derived energy terms in Equation 5 may be replaced by the actual measured energy. However, you must adjust your calculations for the calibration error for each month in the calibration period, using Equation 6:

Savings = Baseline energy from the calibrated model [hypothetical or without ECMs] - Actual calibration-period energy ± Calibration error in the corresponding calibration reading

(Eq. 6)

9.3 Electricity energy costs

The electricity energy costs include the running costs in delivered electricity for the final energy demand consisting of space heating, water heating, auxiliary energy, lightning and HVAC. This comprise the total amount of costs, including the variable costs for electricity used and the fixed costs for electricity services (as the term for power capacity). The estimated costs should be based on the real price level from the respective European country.

The sub-indicator running costs energy shall be used to show the user of MOEEBIUS what share of the running costs energy have on the whole life cycle costs. Furthermore the running costs energy indicator will be used for setting constraints in order to select possible retrofitting solutions for the buildings.

The detailed description of calculating the running costs energy is already available under 3.1.1 Life cycle costs.

9.4 Gas energy costs

The gas energy costs include the running costs in delivered gas energy for the final energy demand consisting of space heating, water heating, and others. This comprise the total amount of costs, including the variable costs for gas consumed and the fixed costs for gas services. The estimated costs should be based on the real price level from the respective European country.

9.5 District heating costs

The district heating costs include the running costs in delivered district heating for the final energy demand consisting of space heating, water heating, and others. This comprise the total amount of costs, including the variable costs for heating consumed and the fixed costs for district heating services. The estimated costs should be based on the real price level from the respective European country.

9.6 Maintenance costs

The maintenance costs include the costs for repair, maintenance and replacement of faulty components and materials of the equipment (costs for acquisition and installation process). The estimated costs should be based on the real price level from the respective European country.

The indicator maintenance costs shall be used to show the user of MOEEBIUS what share of the running maintenance costs have on the whole life cycle costs.

9.7 Pay-Back Time

This KPI, as the following Return on Investment and Life Cycle Costs KPIs, are specific KPIs that will define the business framework for retrofitting activities, comparing the investment costs with the economic savings achieved due to the energy conservation measures introduced in the retrofitting.

Pay-back Time refers to the period of time (in years) required to recover the funds expended in an investment.

The payback period is considered a method of analysis with limitations for its use, because it does not account for the time value of money, but it is easy of use.

It is calculated according to the equation:

$$Payback\ Time = \frac{C_{INV}}{S}$$

Where:

C_{INV}: Investment costs

S: Yearly savings in running costs energy

9.8 Return on investment

Energy measures for buildings (retrofitting, maintenance) are economic efficient if the energy savings caused by these measures over the whole life cycle exceed the total investment costs for the measures. The Return on Investment is a very important issue for decision-makers to evaluate the economic efficiency of energy measures.

This KPI assesses the Return on Investment (ROI) of energy measures for the whole building by using the overall investment costs and the saving in running costs energy. The indicator only relies on the costs and savings from measures that are directly affecting the energy demand in the use stage over a defined period of consideration.

The calculation of Return on Investment (%) is calculated as follows:

$$ROI = \frac{S * \sum_{j=0}^{t}(1+Z)^t}{C_{INV} * (1+i)^t} * 100$$

Where:

S: yearly savings in running costs energy [€].

$$S = Energy\ running\ costs_{original} - Energy\ running\ costs_{after\_measure}$$

C_{INV}: The total investment costs for the energy measures [€]

i: discount rate

z: energy price changing rate

t: period considered

9.9 Life Cycle Costs (LCC)

Life Cycle Costs, as said before, is also a specific KPI that defines the business framework for retrofitting activities, but in a more complex form than the Pay-Back time. Thus, this KPI compares the investment costs with the economic savings achieved due to the energy conservation measures introduced in the retrofitting.

Life Cycle Cost analysis considers all cash inflows and outflows over the useful life of the project, reducing each flow to its present value.

Life Cycle Costs approach is an economic method to assist in the decision making process and to identify cost effectiveness of different design options and sensitivity of the cost resulting of the prices evolutions for products, services, energy and human operation. When two or more mutually exclusive alternatives are being evaluated, the one with the lowest life-cycle cost should be selected. That alternative will represent the lowest cost when expressed in present value terms. Net Present Value (NPV) is a form of LCC analysis.

This indicator supports the European Commission objective to increase the consideration for life-time costs of buildings rather than just the initial costs, including construction and demolition waste.

The calculation of Life Cycle Costs (LCC) are presented in different standards:

- EN ISO 15686- 5 introduces main principles and list of costs/benefits related to the buildings.
- EN 15459 describes more precisely the Global costing for the construction and operation stages. This standard provides a calculation method for the economics of heating systems and other systems that are involved in the energy use of the building (building envelope, ventilation, etc.). This standard applies to all types of buildings.
- EN 15643-3 presents the framework for development of LCC methodology applicable to buildings

Assessment shall be carried out at any time of the building life cycle (form inception to end of life).

Calculation and Rating

The life cycle costs indicators are based on the modular approach from inception to the demolition of the building/end of life of equipment.

The calculation of the Life cycle costs has to take into account the following Life Cycle Stages according to EN 15978:

- Construction Process Stage. The definition and quantification of the products used for the building construction and retrofitting are aligned with these defined for the calculation of the environmental indicators as presented in the European standards developed by CEN TC 350 ("EN 15978:2012; Sustainability in construction works - Environmental performance of buildings. Calculation method" and "EN 15643-4: 2011 Sustainability in construction works. Assessment of buildings. Part 4 Framework for the assessment of economic performance").

- Use Stage. For consistency with the Directive on Energy performance of buildings the incomes due to energy sales are introduced (as a negative cost). Costs for maintenance shall be aligned with the management system of the building.
- End of life Stage. The costs for disposal are introduced in the calculation as a percentage of the buildings products costs.

The observation period (estimated life cycle of a building) will cover 50 years.

Considered costs in the Life cycle costs calculation

Determination of investment costs for retrofitting measures

The investment costs are to be considered as described in the specific section for this KPI: 9.1 Investment costs.

Determination of running energy costs

The running energy costs should include all costs arising from the use of energy sources (oil, gas, solid fuels, district heating, electricity) in the building. The determination of the running costs energy should be based on the results of the calculations for the final energy demand consisting of space heating, water heating, auxiliary energy, lightning and HVAC. The calculations of the running energy costs are to be considered as described in the specific sections for these KPIs: 9.3 Electricity energy costs, 9.4 Gas energy costs and 9.5 District heating costs.

Determination of running costs in maintenance and disposal

The calculations of the running costs in maintenance and disposal should include all Costs for deconstruction and disposal of eliminated building parts, components and materials. Furthermore costs for repair, maintenance and replacement of the building parts, components and materials remaining in the building, calculated as described in section 9.6 Maintenance costs, have also to be included.

Data collection and quantification

For existing buildings the costs arising from the point of time when the assessment is performed shall be consistent with the management of the building for maintenance and repair.

The costs arising shall include:

- Costs for deconstruction and disposal of eliminated building parts, components and materials
- Repair, maintenance and replacement costs for the building parts, components and materials remaining in the building
- Construction costs for all new building parts, components and materials brought to the building in the course of the energy retrofitting measures

(investment costs for construction and installation process), in case retrofitting measures are made.

The investment costs for the construction and installation process shall be set to zero if no retrofitting measures are executed.

Principles of economic calculation using net present value factors

The net present value factor is used to adapt the future costs to the moment when the economic assessment is performed.

The NPV sums the discounted cash flows. It integrates and converts at the same time amounts of money (incomes, expenses, etc.) of various time periods. The formula that is used for the determination of the NPV is:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{F_t}{(1+p)^t}$$

Where:

t: is the time period, usually a year

F_t the net cash flow for year *t*:

$$F_t = B_t - C_t$$

B_t: the benefit (inflows) for year t

C_t the cost (outflows) for year *t*

C_0 reflects the initial investment

p the cost of capital

n: is the number of years of the investment's lifetime or, differently, the number of years for which the economic evaluation is requested.

It is assumed that the various net cash flows are collected at the end of the time periods, i.e. at the end of years. An investment should be realised only if *NPV > 0*, while in case alternative investments are compared, the best of them would be the one with the higher *NPV*. Finally, it is worth mentioning that there is an inverse relation between the cost of capital *p* and *NPV*: the increase of *p* results in a decrease of *NPV*, when all other parameters remain constant.

Presentation of results

Results can be presented in two formats:

- Value of the Life Cycle Costs for the period of calculation [€]

- Value per year and per unit related to the functional equivalent of the building [€/annum·m²]

The second option for the presentation of results illustrates the average yearly effort for construction, operation and demolition of the building.

For respect of confidential information the values could be harmonized using value of 100 for the initial investment costs.

9.10 Building level and district level

The above presented economic KPIs are to be considered concurrently at both building and district level. At a building level, costs and savings will be considered until the building boundary, while at district level they will be considered as an aggregation of the individual building costs and savings.

10 Predictive Maintenance KPIs

Apart from the energetic, economic, and comfort KPIs mentioned above, MOEEBIUS will define business model specific KPIs. One of the defined business scenarios for MOEEBIUS is "BSC-03: Optimized **Predictive maintenance** diagnostics and decision making tool to ensure high levels of business performance".

The predictive maintenance module should provide fault detection and diagnostic functionalities for the main subsystems/equipment of the HVAC system of complex buildings, in order to enable early detection of faults and suboptimal operational conditions.

The module should take advantage of the information provided by the sensor networks existing or deployed on the main subsystem/equipment of the HVAC system, and additionally use the output provided by the existing building level simulation model.

This module should provide 2 different levels of information/diagnostics/alarms:

- High level alarms based on the detection of changes in the behaviour of complete systems. The module should be able to detect changes in the total consumption disaggregated by functional systems (heating, cooling, etc.) that are not consistent with the observed external climatic conditions or usage intensity (user behaviour). Additionally, if the detail level of the available building model allows, model outputs could be used as additional information to detect inconsistencies between the monitored consumption, climatic conditions and user behaviour and indicate equipment performance deterioration, errors in the control logic or abnormal usage patterns.

  This functionality is relevant to all type of buildings.

- Low level alarms and diagnostics focused at equipment level including the identification of the possible causes of the problems, using the information provided by the sensor networks and automation devices. This functionality requires a more complex sensor network to monitor the necessary operational variables of the subsystem/equipment included in the scope of the low level predictive maintenance program.

  The collected data will be used by the fault detection and diagnostic engine and will enable the early detection of symptoms known to lead to operational faults and sub-optimal equipment performance.

  As in the previous case, if a detailed EnergyPlus building model is available the model outputs will provide additional information relevant for the application of monitoring rules, detecting deviations from the generally expected system behaviour.

The predictive maintenance functionality will be primarily focused on those HVAC subsystems/equipment that have the highest impact on the building energy consumption, which will enable to maximize the value of existing sensor networks.

The deployment of the predictive maintenance module (at least regarding the availability of low level alarm and diagnostic capabilities) will only be relevant to buildings with centralized systems with a complexity level consistent with these functionalities.

In principle, in this type of buildings, the availability of a relatively rich sensor network can be expected before the deployment of the MOEEBIUS system. This will increase the feasibility of the implementation of the advanced (low level) predictive maintenance functionalities as the cost of the necessary additional sensors will be reduced.

The complexity level of the existing HVAC system in any specific building, considered in the frame of the MOEEBIUS project will be affected by the following factors:

- Type of building: Residential/non-residential
- Type of HVAC system: Individual/centralized

Before the final selection of the subsystems/equipment to be included in the scope of the predictive maintenance module, the typologies of the HVAC systems and their relative impact on buildings' performance will be further analysed.

10.1 HVAC Equipment Performance

Various HVAC performance metrics have been successfully used in the practice for multiple types of HVAC equipment. But the system-level performance is usually assessed by continuous monitoring of deviations between the predicted and actual energy consumption. Following paragraphs summarize the most frequently used performance indicators for selected types of HVAC equipment.

Coefficient of Performance (COP)

The Coefficient of Performance (COP) of a heating pump (or cooling unit) is the ratio of the generated heating power [kW] to input electrical power [kW], being a unit-less coefficient.

$$COP = \frac{\dot{Q}_{heat}}{\dot{W}_{elect}}$$

It provides the performance of the unit for given operating conditions. Therefore, the input electrical power and the heating power are required for its calculation. These indicators are obtained as indicated in 5.3.6:

- Electrical consumption. In order to monitor the electrical consumption of a technical subsystem, electronic meters measure the diverse components of

AC power (total, true and reactive power). For this purpose, variables such as voltage, current, frequency and phase angle are internally measured by the meters.

- Thermal flows for cooling equipment. The thermal outputs of heating and cooling equipment can be calculated through the following equation:

$$\dot{Q} = \dot{m} C_p \Delta T$$

Where:

$\dot{Q}$ is the thermal energy flow (kW)

$\dot{m}$ is the mass flow (kg/s)

C_p is the specific heat of the thermal fluid at a constant pressure (kJ/kg K)

ΔT is the difference between inlet and outlet fluid temperature (K)

Therefore, the mass flow needs to be metered through a liquid flowmeter and its temperatures on the impulsion and return sides through resistance temperature detectors (RTDs).

Energy Efficiency Ratio (EER)

The Energy Efficiency Ratio (EER) of a cooling unit is the ratio of generated cooling energy [BTU] to input electrical energy [Wh] for a time period.

$$EER = \frac{Q_{cool}}{W_{elect}}$$

The EER uses mixed units, thus it is not unit-less as the COP. It can be also obtained by considering the COP in the cooling mode and multiplying the COP by the conversion factor from BTU/h to Watts:

$$\text{EER} = 3.41 \times \text{COP}$$

It provides the performance of the unit for given operating conditions. Therefore, the input electrical energy flow and the cooling energy flow are required for its calculation. This indicators are obtained again as indicated in 5.3.6 and for COP.

Seasonal Energy Efficiency Ratio (SEER)

The Seasonal Energy Efficiency Ratio (SEER) is also the COP (for heating) or EER (for cooling), but instead of being evaluated for a given operating condition, it represents the overall performance for a year. Therefore for its calculation are required the generated cooling/heating energy [kWh] and the consumed electrical energy [kWh] of a device over a year.

10.2 Boiler efficiency

As boilers are one of the major energy consumers in buildings, especially in Europe, their efficient operation is essential. Following KPIs related to boiler efficiency should be monitored.

Combustion Efficiency

This is an indication of the burner's ability to burn fuel. The amount of unburned fuel and excess air in the exhaust are used to assess a burner's combustion efficiency. Burners resulting in low levels of unburned fuel while operating at low excess air levels are considered efficient. The KPI is therefore based on expected number of excess air which is typically calculated as:

$$\%\, Excess\ air = \frac{\%\ of\ O_2\ measured}{20.9 - \ \%\ of\ O_2\ measured}$$

Where 20.9 represents oxygen combustion in the atmosphere.

Thermal Efficiency

This is a measure of the effectiveness of the heat exchanger of the boiler. It measures the ability of the exchanger to transfer heat from the combustion process to the water or steam in the boiler. KPIs suitable for heat exchangers like heat transfer coefficient apply here.

Overall boiler efficiency

This KPI accounts for effectiveness of heat exchanger as well as the radiation and convection heat losses. Suitable KPI is based on input-output efficiency measure that means a ratio of the boiler output divided by the boiler input.

10.3 Other Performance Metrics

Multiple equipment-specific metrics are used for various types of HVAC equipment. For the objectives of MOEEBIUS project, these metrics will be further reviewed and down-selected based on assessment of individual pilot sites. These metrics may include, among others:

- Heat transfer coefficient for heat exchangers (coils, condensers, evaporators, etc.)
- Number of Transferred Units (NTU) metrics for heat exchangers
- Pumps and fans efficiencies based of pumps/fans performance maps
- etc.

11 MOEEBIUS Simulation system Performance KPIs

Apart from the list of KPIs mentioned above, associated with the end to end functionalities of MOEEBIUS tool, we further define business specific KPIs. We highlighted above the list of specific to predictive maintenance engine KPIs and here we present the list of KPIs associated with the evaluation of the performance of the MOEEBIUS building performance simulation engine. The role of this engine is to reinforce the EnergyPlus building energy simulation engine so as to be able to accommodate and perform simulations on the basis of the enhanced, improved and more accurate MOEEBIUS models, profile and short-term weather forecasts, hence, allowing for more accurate predictions of building energy performance.

Towards this direction, a list of KPIs is defined to evaluate the gap between predicted values (as extracted from building performance simulation engine) and the actual conditions, addressing that way the evaluation of MOEEBIUS building performance simulation engine performance. As the role of this engine is to support multi-parameter analysis of heterogeneous data sets (energy consumption, emissions, energy performance, weather, occupancy, comfort, etc.), we are supporting the evaluation of this engine on the different metrics (energy demand, operative indoor temperature and illuminance conditions etc.…) addressed during the simulation process.

These performance indicators are significant since the MOEEBIUS tool aims to reduce this gap between simulation and actual conditions, by refining the different modules in order to get a closer prediction to real performance. We further present a short list of KPIs considered for the evaluation of MOEEBIUS building performance simulation process.

11.1 Energy demand

One of the main innovations of MOEEBIUS project is the definition of an analytics process both at building and district level, where the main objective is the identification of deviations between performance predictions and real-time measurements.

Therefore, MOEEBIUS considers the deviation of simulation from real time performance (per site / asset) [kW] that defines the deviation of real time building operation from building simulation. The analysis is performed for the different elements that examined in MOEEBIUS project, starting from the different device types integrated and moving to building and district level analysis. The same approach is followed for additional indicators calculated by taking into account energy consumption/generation data (CO_2 emissions, energy cost, etc.).

The time granularity for KPI calculation will be defined by the time interval of the prediction results of the simulation tool, supporting that way a dynamic framework

for the evaluation of MOEEBIUS building performance simulation platform (short term and long term building and district simulation).

11.2 Indoor Operative Temperature

A main innovation of MOEEBIUS project is the incorporation of building occupants' comfort profiles in decision support process. In terms of assessment, MOEEBIUS building performance simulation engine will integrate the local energy performance models and provide additional predictions upon indicators, especially reflecting behavioural aspects in the buildings.

Towards this direction, we introduce an indicator about the deviation of the simulated indoor temperature from actual conditions [K]. That defines the difference between the expected and actual indoor conditions, which will influence the user's behaviour and consequently the energy demand.

Therefore, the evaluation of MOEEBIUS building performance simulation engine is not performed addressing only energy consumption data but also contextual conditions in premises, as the objective of the project is to establish not only an energy efficient but also a sustainable environment that fully preserves end users preferences and needs.

This indicator will be assessed at room or monitoring zone, considering also the thermal zones defined in BIM models (and further incorporated in the MOEEBIUS building performance simulation framework). The time granularity for KPI calculation will be defined by the time interval of the prediction of the simulation tool, considering also the actual temperature conditions at the same time-period.

11.3 Indoor Operative Illuminance

The same approach is considered also for indoor luminance data. We are introducing the indicator about "Deviation of simulated indoor illuminance from actual performance [lux]". That defines the difference between the expected (as extracted from MOEEBIUS building performance simulation) and actual indoor illuminance, which will influence the user's behaviour and consequently the lighting energy demand.

Again, this indicator will be assessed per space or monitoring zone, considering also the visual zones defined in BIM models (and further incorporated in the MOEEBIUS building performance simulation framework). The time granularity for KPI calculation will be defined by the time interval of the prediction of the simulation tool, considering also the actual illuminance conditions at the same time-period.

The approach of calculating the deviation of simulated from actual conditions, is considered also for the rest of MOEEBIUS local energy performance models further incorporated in the MOEEBIUS Building energy performance simulation engine. Therefore, we are further defining additional indicators addressing business (LCA-

LCC concepts) and health (IAQ) aspects, as metric outcomes from building performance simulation process.

The aforementioned analysis and KPIs definition is provided to enable the evaluation of MOEEBIUS Building Performance Simulation Engine, as a standalone application of MOEEBIUS framework. The role of this engine is critical for the project as a main objective of the MOEEBIUS is to provide a framework that minimizes or even eliminates the gap between simulated and real time conditions.

12 Conclusions

In this Deliverable, the basis for the MOEEBIUS Measurement and Verification Protocol has been established (section 3) and the most important Key Performance Indicators to fully characterize the performance of the systems where MOEEBIUS is going to be deployed have been defined (sections 5 to 11). The definition of the measurement and verification protocol and the selected KPIs presented in this document corresponds to the methodology for the general MOEEBIUS framework. This general methodology must be used and adapted for the deployment of the MOEEBIUS at the pilot sites (Tasks T7.3, T7.4 and T7.5) or implementation area of MOEEBIUS. In fact, the monitoring diagrams employed and the metering grid complexity will be adaptable to the needs and requirements of each MOEEBIUS implementation scenario.

For the definition of the KPIs, the 5 business scenarios for MOEEBIUS defined on Deliverable 2.1 have been taken into account. Thus, the definition of KPIs addresses the necessary indicators for the characterization of the buildings (and districts) performance in order to enable the deployment and evaluation of these business scenarios.

Finally, the considered KPI categories comprise:

- Energetic issues
- Demand response issues
- Indoor environmental issues
- Indoor air quality issues
- Economic issues
- Predictive maintenance issues
- MOEEBIUS simulation system performance issues

Following are listed the finally selected KPIs at each category at both Building and District level:

KPIs List to be considered at Building level

	ENERGY
	Energy building needs/use
En.1	Energy need for heating
En.2	Energy need for cooling
En.3	Energy need for DHW
En.4	Energy need for other (humidification, dehumidification)
En.5	Energy use for ventilation
En.6	Energy use for internal lighting
En.7	Energy use for other (appliance, external lighting, etc.)

	Energy generation at building site
En.8	Thermal energy from RES
En.9	Electrical energy generated in the building and used onsite
En.10	Electrical energy generated in the building and exported to the market
	Energy consumption
En.11	Delivered electricity
En.12	Delivered fossil fuels
En.13	Other delivered energy (biomass, district heating/cooling, etc.)
	Final energy consumption/use
En.14	Referred to primary energy
En.15	Referred to CO2

	DEMAND RESPONSE
	Generic Bussiness KPIs
DR.1	Average aggregated capacity per customer
DR.2	Average aggregated capacity in operation
DR.3	Average revenue (per kW or kWh) managed for DR participation
	Technical KPIs
DR.4	Potential turndown
DR.5	Enrolled turndown
DR.6	Measured turndown
DR.7	Delivered capacity
DR.8	Turndown/Energy Consumption
DR.9	Delivered capacity

	OCCUPANTS COMFORT KEY PERFORMANCE
	Thermal Comfort
OC.1	Predicted Mean Vote
OC.2	Predicted Percentage Dissatisfied
OC.3	Operative Temperature
	Visual Comfort
OC.4	Illuminance
OC.5	Contrast Rendering Factor
OC.6	Luminance Ratio
	Extended MOEEBIUS Comfort
OC.7	Thermal Discomfort Factor
OC.8	Visual Discomfort Factor

	INDOOR AIR QUALITY
IAQ.1	Carbon Dioxid
IAQ.2	Carbon Monoxide
IAQ.3	Particulate Matter
IAQ.4	Volatile Organic Compounds

	ECONOMIC
Ec.1	Investment Costs
Ec.2	Savings in Electyricity and Gas
Ec.3	Electricity Energy Costs
Ec.4	Gas Energy Costs
Ec.5	District Heating Costs
Ec.6	Maintenance Costs
Ec.7	Pay-Back Time
Ec.8	Return on Investment
Ec.9	Life Cycle Costs

	PREDICTIVE MAINTENANCE
	HVAC Equipment Performance
PM.1	EER
PM.2	COP
PM.3	SEER
	Boiler Performance
PM.4	Combustion Efficiency
PM.5	Thermal Efficiency
PM.6	Overall Boiler Efficiency

	MOEEBIUS SYMULATION SISTEM PERFORMANCE
PT.1	Difference between predicted and actual Energy Demand
PT.2	Difference between predicted and actual Indoor Operative Temperature
PT.3	Difference between predicted and actual Indoor Operative Illuminance

KPIs List to be considered in MOEEBIUS at District level

	ENERGY
	Energy needs/use
En.1	Energy need for heating
En.2	Energy need for cooling
En.3	Energy need for DHW
En.4	Energy need for other (humidification, dehumidification)
En.5	Energy use for ventilation
En.6	Energy use for internal lighting
En.7	Energy use for other (appliance, external lighting, etc.)
	Energy generation at building site
En.8	Thermal energy from RES
En.9	Electrical energy generated in the buildings and used onsite
En.10	Electrical energy generated in the buildings and exported to the market
	Energy consumption
En.11	Delivered electricity
En.12	Delivered fossil fuels
En.13	Other delivered energy (biomass, district heating/cooling, etc.)
	Final energy consumption/use
En.14	Referred to primary energy
En.15	Referred to CO2
	Energy generation at district plants
En.16	Electrical energy generated in the district and used onsite
En.17	Electrical energy generated in the district and exported to the market
En.18	Thermal energy generated in the district and used onsite
En.19	Thermal energy generated in the district and exported to the market
	Energy consumption of the district plants
En.20	Delivered electricity
En.21	Delivered fossil fuels
	Distribution/Delivered fossil fuels
En.22	Energy losses from the plant to the building

	Final energy consumption/use at district plants	
En.23		Referred to primary energy
En.24		Referred to CO2
	Energy generation at the district	
En.25		Electrical energy generated in the district (buildings and plants) and used onsite
En.26		Electrical energy generated in the district (buildings and plants) and exported to the market
En.27		Thermal energy generated in the district (buildings and plants) and used onsite
En.28		Thermal energy generated in the district (buildings and plants) and exported to the market
	Energy consumption at the district	
En.29		Delivered electricity at buildings and plants
En.30		Delivered fossil fuels at buildings and plants
	Final energy consumption/use at the district	
En.31		Referred to primary energy
En.32		Referred to CO2

	DEMAND RESPONSE	
	Generic Bussiness KPIs	
DR.1		Average aggregated capacity per customer
DR.2		Average aggregated capacity in operation
DR.3		Average revenue (per kW or kWh) managed for DR participation
	Technical KPIs	
DR.4		Potential turndown
DR.5		Enrolled turndown
DR.6		Measured turndown
DR.7		Delivered capacity
DR.8		Turndown/Energy Consumption
DR.9		Delivered capacity

	ECONOMIC	
Ec.1		Investment Costs
Ec.2		Savings in Electyricity and Gas
Ec.3		Electricity Energy Costs
Ec.4		Gas Energy Costs
Ec.5		District Heating Costs

Ec.6	Maintenance Costs
Ec.7	Pay-Back Time
Ec.8	Return on Investment
Ec.9	Life Cycle Costs

PREDICTIVE MAINTENANCE

	HVAC Equipment Performance
PM.1	EER
PM.2	COP
PM.3	SEER
	Boiler Performance
PM.4	Combustion Efficiency
PM.5	Thermal Efficiency
PM.6	Overall Boiler Efficiency

MOEEBIUS SYMULATION SYSTEM PERFORMANCE

PT.1	Difference between predicted and actual Energy Demand

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Annexes

ANNEX I: VOTE RESULTS FOR KPIS SELECTION

Results for KPIs at Building Level

		RATING 0-not significant / 5-very significant								
		TECNALIA	HONEYWELL	HYPERTECH	SOLINTEL	THN	KIWI	ISQ	BEOELEK	AVERAGE
Environmental										
Ev.1	Global Warming	1	0	5	0			2	3	1.83
Ev.2	Ozone depletion	1	0		1			1	3	1.20
Ev.3	Acidification	1	0		1			1	2	1.00
Ev.4	Land use	1	0		1			1	3	1.20
Ev.5	Water consumption	2	0	1	3	2		5	5	2.57
Energy										
	Energy building needs/use									
En.1	Energy need for heating	5	5	5	5	5	5	5	5	5.00
En.2	Energy need for cooling	5	5	5	5	5	2	5	5	4.63
En.3	Energy need for DHW	5	5	5	5	5	2	5	5	4.63
En.4	Energy need for other (humidification, dehumidification)	5	5	5	3	5	2	5	4	4.25
En.5	Energy use for ventilation	5	5	5	4	5	3	5	4	4.50
En.6	Energy use for internal lighting	5		5	5	5	4	5	5	4.86
En.7	Energy use for other (appliance, external lighting, etc.)	5	3	5	4	5	3	5	5	4.38
En.8	Difference between predicted and delivered energy (gap)	5	5	5	5	5	5	5	5	5.00
	Energy generation at building site									
En.9	Thermal energy from RES	5	5	5	5	5	4	5	4	4.75
En.10	Electrical energy generated in the building and used onsite	5	5	5	5	5	4	5	4	4.75
En.11	Electrical energy generated in the building and exported to the market	5	5	5	5	5	4	5	2	4.50
	Energy consumption									
En.12	Delivered electricity	5	5	5	5	5	4	5	5	4.88
En.13	Delivered fossil fuels	5	5	5	5	5	4	5	5	4.88
En.14	Other delivered energy (biomass, district heating/cooling, etc.)	5	5	5	5	5	4	5	5	4.88
	Final energy consumption/use									

En.15	Referred to primary energy	5	5	5	4	5	3	5	5	4.63
En.16	Referred to CO2	5	5	5	5	5	4	5	5	4.88
Demand response										
	Generic Business									
DR.1	Number of customers		5				2			3.50
DR.2	Number of sites in operation		5				2			3.50
DR.3	Total aggregated capacity in operation		5				5			5.00
DR.4	Average aggregated capacity per site		5				3			4.00
DR.5	Average aggregated capacity per customer		5				5			5.00
DR.6	Average revenue per MW managed per year		5				5			5.00
	Technical									
DR.7	Potential turndown		5	4			3			4.00
DR.8	Measured turndown		5	4			4			4.33
DR.9	Response time		5				5			5.00
DR.10	Dispatch time		5				5			5.00
DR.11	Recovery time		5				5			5.00
DR.12	Delivered capacity per asset		5	5			4			4.67
DR.13	Delivered capacity per contract		5	3			5			4.33
DR.14	Availability windows		5				3			4.00
Social										
	Thermal comfort									
S.1	Predicted mean vote		5	3	5	5			4	4.40
S.2	Predicted percentage dissatisfied		5	3	5	5			4	4.40
S.3	Operative temperature		5	5	4	5			5	4.80
S.4	Indoor temperature		5		5	3			5	4.50
S.5	Temperature difference between Indoor and designed Temperature		5		5	5			4	4.75
S.6	Humidity		5		4	5			4	4.50
	Visual Comfort		3							
S.7	Operative Illuminance			4	5	5			5	4.75
S.8	Contrast rendering factor			4	4				4	4.00
S.9	Luminance ratio			3	3				4	3.33
S.10	Noise level		3		2	4			5	3.50
	Indoor air quality		4							
S.11	Pollutants		3		3				3	3.00
S.12	Carbon dioxide		5	5	4				3	4.25
S.13	Safety and security				0				4	2.00
Economic										
Ec.1	Investment costs		3	4	2				5	3.50
Ec.2	Savings in electricity and gas		5	5	4				5	4.75
Ec.3	Electricity energy costs		5	5	5				5	5.00

Ec.4	Heat energy costs		5	5	5				5	5.00
Ec.5	Maintenance costs		3	4	5				5	4.25
Ec.6	Pay-Back Time		3	5	5				5	4.50
Ec.7	Return on investment		3	5	5				5	4.50
Ec.8	Life Cycle Costs			5	4				5	4.67
Ec.9	Change in values of property			1	1				5	2.33
SUGGESTIONS										
S.7a	Thermal discomfort factor			5						5.00
S.10a	Visual Discomfort Factor			5						5.00
S.11	Luminance difference between Indoor and designed luminance			x						
	Indoor air quality									
S.11	Effective Ventilation (Carbon Dioxide)					5				5.00
S.12	Combustion Infiltration (Carbon Monoxide)					3				3.00
S.13	Particulate Load (Particulate Matter)					3				3.00
S.14	Volatile Organic Compounds					3				3.00
HVAC SYSTEM PERFORMANCE										
	HVAC Control Performance									
	Average Absolute Error		x							
	Systematic Offset in Indoor Temperature		x							
	Control Oscillation Period		x							
	HVAC Equipment Performance									
	Energy Efficiency Ratio (EER)		x							
	Coefficient of Performance (COP)		x							
	Seasonal Energy Efficiency Ratio (SEER)		x							

Results for KPIs at District Level

RATING
0-not significant / 5-very significant

		TECNALIA	HONEYWELL	HYPERTECH	SOLINTEL	THN	KIWI	ISQ	BEOELEK	AVERAGE
Environmental										
Ev.1	Global Warming				0				3	1.50
Ev.2	Ozone depletion				1				3	2.00
Ev.3	Acidification				1				2	1.50
Ev.4	Land use				1				3	2.00
Ev.5	Water consumption				3				5	4.00
Energy										
	Energy building needs/use									
En.1	Energy need for heating				4		5		5	4.67
En.2	Energy need for cooling				4		2		5	3.67
En.3	Energy need for DHW				0		2		5	2.33
En.4	Energy need for other (humidification, dehumidification)				0		2		4	2.00
En.5	Energy use for ventilation				0		3		4	2.33
En.6	Energy use for internal lighting				0		4		5	3.00
En.7	Energy use for other (appliance, external lighting, etc.)				4		3		5	4.00
En.8	Difference between predicted and delivered energy (gap)				5		5		5	5.00
	Energy generation at building site									
En.9	Thermal energy from RES				4		4		4	4.00
En.10	Electrical energy generated in the building and used onsite				4		4		4	4.00
En.11	Electrical energy generated in the building and exported to the market				3		4		2	3.00
	Energy consumption									
En.12	Delivered electricity				5		4		5	4.67
En.13	Delivered fossil fuels				5		4		5	4.67
En.14	Other delivered energy (biomass, district heating/cooling, etc.)				5		4		5	4.67
	Final energy consumption/use									
En.15	Referred to primary energy				4		3		5	4.00
En.16	Referred to CO2				5		4		5	4.67
Demand response										
	Generic Business									#¡DIV/0!

DR.1	Number of customers						2			2.00
DR.2	Number of sites in operation						2			2.00
DR.3	Total aggregated capacity in operation						5			5.00
DR.4	Average aggregated capacity per site						3			3.00
DR.5	Average aggregated capacity per customer						5			5.00
DR.6	Average revenue per MW managed per year						5			5.00
	Technical									
DR.7	Potential turndown						3			3.00
DR.8	Measured turndown						4			4.00
DR.9	Response time						5			5.00
DR.10	Dispatch time						5			5.00
DR.11	Recovery time						5			5.00
DR.12	Delivered capacity per asset						4			4.00
DR.13	Delivered capacity per contract						5			5.00
DR.14	Availability windows						3			3.00
Social										
S.1	Noise level				2					2.00
S.2	Safety and security				1					1.00
Economic										
Ec.1	Investment costs				2				5	3.50
Ec.2	Savings in electricity and gas				4				5	4.50
Ec.3	Electricity energy costs				5				5	5.00
Ec.4	Heat energy costs				5				5	5.00
Ec.5	Maintenance costs				4				5	4.50
Ec.6	Pay-Back Time				5				5	5.00
Ec.7	Return on investment				5				5	5.00
Ec.8	Life Cycle Costs				5				5	5.00
Ec.9	Change in values of property				1				5	3.00
Other										

ANNEX II: EXAMPLES OF PREDICTIVE MAINTENANCE FUNCTIONALITIES AND REQUIRED MONITORING LEVEL

Below are some examples, of the possible predictive maintenance functionalities that could be included in the module and the monitoring requirements are displayed in a compact shape.

HEATING/COOLING SUBSTATION		
Monitored components	**Faults and suboptimal operational status**	**Required monitoring input**
Heating Heat Exchanger	Lack of capacity of the connection to the thermal network	Outdoor temperature
DHW production HE	Overcapacity of the connection to the thermal network	Delivered heating/cooling energy
Cooling HE	Low capacity of the proportional valve to control the delivered supply water flow rate (unstable operation, etc.)	Heating/DHW production/cooling HE primary and secondary side circuit water flow rates
Heating/cooling primary side water flow rate control proportional valve	Excessive return temperature, leading to inefficient thermal network operation	Heating/DHW production/cooling HE primary and secondary side circuit supply/return water temperatures
If any, substation building side circuit distribution pumps	Substation primary side strainer clogging	Primary side pressure loss in the thermal substation
	HE fouling	Primary side supply flow rate control proportional valve position
	Heating/cooling HE primary side deficient supply/return water temperature difference	

AHU-s		
Monitored components	**Faults and suboptimal operational status**	**Required monitoring input**
Heating/cooling coils	Incorrect AHU supply air temperature	Supply air temperature
Hot/cool water mixing valves of the heating/cooling coils	Incorrect AHU supply air humidity	Return air temperature
Heat recovery heat exchanger	Incorrect supply air flow rate	Supply air flow rate
Supply/return fans	Incorrect outdoors air % in supply air flow rate	Return air flow CO2 concentration
Dampers (outside air/exhaust/recirculation/ Heat recovery HE bypass)	Incorrect heat recovery bypass damper operation	Outdoors air temperature
Filters	Incorrect outdoor air % during economizer operation	Damper position (outdoor air inlet, exhaust, recirculation, heat recovery bypass)
	Lack of coordination of	Heating/cooling coil mixing

	dampers	valve position
	Unstable operation of heating/cooling coil mixing valves	Heating/cooling coil inlet/outlet water temperature
	Poor efficiency of the heat recovery HE	Heating/cooling coil air inlet/outlet temperature
	Filter clogging	Heating/cooling coil water supply hydraulic circuit status (flow switches)
	Heating/cooling coil fouling	Air pressure drop in filters
	Antagonistic heating/cooling coil operation	Supply duct pressure
	Supply/exhaust fan failure	
	AHU operation out of the availability schedule	

HEATING/COOLING PLANTS		
Monitored components	**Faults and suboptimal operational status**	**Required monitoring input**
Heating generators (boilers, CHP, heat pumps etc.)	Incorrect water supply temperature	Heating/cooling plant generator status
Cooling generators (chillers, reversible heat pumps, etc.)	Incorrect supply water flow rate	Heating/cooling generator supply water temperature
If present energy delivery HE	Low supply/return water temperature difference	Heating/cooling generator return water temperature
	Incorrect heating/cooling generator operation sequence	Heating/cooling generator supply water flow rate
	Poor generator performance	Heating/cooling generator electricity/fuel consumption (gas, biomass, etc.)
	Heating/cooling generator operation without thermal load	Exhaust fume temperature and O2 concentration (boilers and CHP)
	Heating/cooling generator operation out of the availability schedule	Source side supply/return water temperature (water condensed chiller)
		Source side supply/return water temperature (Ground source heat pumps)
		HE primary side inlet/outlet temperature
		HE secondary side inlet/outlet temperature
		HE primary/secondary side water flow rates

HEATING/COOLING DISTRIBUTION SUBSYSTEM		
Monitored components	**Faults and suboptimal operational status**	**Required monitoring input**
Main heating/cooling hydraulic loop	Poor hydraulic circuit tightness	Outdoors air temperature
Heating cooling distribution pumping groups	Incorrect distribution circuit supply water temperature	Pump status
If present mixing valves/actuators	Distribution circuit Low supply/return water temperature difference	Main pumping group electric consumption
If present energy delivery HE	Distribution system incorrect supply water flow rate	Distribution circuit status (flow switches)
	Distribution circuit operation without thermal loads	HVAC system make up water consumption
	Excessive pressure drop on heating/cooling distribution circuits	Main heating/cooling distribution circuit pressure
	Deficient heating/cooling distribution circuit insulation/excessive temperature drop	Heating/cooling distribution circuit supply/return temperatures
	Excessive pump consumption	Heating/cooling main distribution circuit supply flow rate
	Hydraulic circuit pressure loss (hydraulic circuit breakage)	If any mixing/diverting valve position
	Pump failure (null water flow rate and circuit pressure loss)	HE primary side inlet/outlet temperature
	Low supply/return temperature difference on HE primary side	HE secondary side inlet/outlet temperature
	Incorrect water flow rate on HE primary side	HE primary/secondary side water flow rates
	Low supply/return temperature difference on HE secondary side	
	Incorrect water flow rate on HE secondary side	
	Poor Heat exchanger efficiency	

HEATING/COOLING STORAGE SUBSYSTEM		
Monitored components	**Faults and suboptimal operational status**	**Required monitoring input**
Hot water storage tanks	Incorrect storage temperature	Heating/cooling generator status/production
Cool water storage tanks	Excessive energy loss	Storage tank temperature (top and bottom temperature of the tanks)
If present energy delivery HE	Deficient stratification	Load side inlet/outlet temperature
	Low storage capacity	Source side inlet/outlet

	exploitation	temperature
	Poor hydraulic balance of source side and load side hydraulic circuits	Source/load side water flow rates
	Low supply/return temperature difference on HE primary side	HE primary side inlet/outlet temperature
	Incorrect water flow rate on HE primary side	HE secondary side inlet/outlet temperature
	Low supply/return temperature difference on HE secondary side	HE primary/secondary side water flow rates
	Incorrect water flow rate on HE secondary side	
	Poor Heat exchanger efficiency	

HEATING/COOLING EMISSION SUBSYSTEM		
Monitored components	**Faults and suboptimal operational status**	**Required monitoring input**
Heating terminal units	Inadequate terminal unit sizing (lack of capacity to provide required comfort)	Outdoors temperature
Cooling terminal units	Active terminal unit in unoccupied thermal zones (zones with not permanent occupancy)	Zone temperature
CAV boxes	Active ventilation in unoccupied thermal zones (zones with not permanent occupancy)	Zone occupancy status
VAV boxes	Excessive/deficient ventilation in zones with variable occupancy	Zone CO2 concentration
	Excessive/deficient zone comfort settings	Heating/cooling terminal unit status
	Poor coordination of heating and cooling terminal unit during the intermediate season	CAV/VAV box status
	Poor coordination of the settings of the ventilation and the heating/cooling terminal units (antagonistic operation during the intermediate season)	Zone heating/cooling terminal unit water supply circuit supply/return temperature
	Heating/cooling terminal unit failure	Zone heating/cooling terminal unit mixing valve position
	Excessive/low supply/return temperature difference	