Ref. Ares(2022)3653023 - 13/05/2022

SATO

Self Assessment Towards Optimization of Building Energy

Deliverable 1.2

Requirements of the Self-Assessment Framework

Deliverable Lead: AAU

Deliverable due date: 30/04/2021

Actual submission date: 30/04/2021

Version: 2.0

This project receives funding in the European Commission's Horizon 2020 Research Programme under Grant Agreement Number 957128.

Document Control Page	
Title	Requirements of the Self-Assessment Framework
Editor	Aalborg University
Description	
Contributors	Polimi, FC.ID, XTEL, VL, EDP CNET, SONAE, SAGOE
Creation date	17/02/2021
Type	Report
Language	English
Audience	☐ public ☒ confidential
Review status	☐ Draft ☐ WP leader accepted ☒ Coordinator accepted
Action requested	☐ to be revised by Partners ☐ for approval by the WP leader ☐ for approval by the Project Coordinator ☐ for acknowledgement by Partners

Table of Contents

List of Figures

List of Tables

DISCLAIMER

EXECUTIVE SUMMARY

This deliverable includes the definition of the requirements for the user-centered self-assessment framework and services to ensure the interoperability of the developed systems, services and interfaces.

It defines which systems, energy components, and appliances to include in the assessment framework with a focus on those implemented in the SATO use cases and pilots, to ensure available data in the development phase as well as relevant use cases and conditions for test and demonstration of the developed platform, framework, and services.

It defines precisely the key variables that will be the object of the assessments and covers the scales and granularities supporting them, data and privacy requirements, models for equipment and building energy performance, and algorithms for automatic model parameter assessment. Key variables and performance indicators are defined in SATO to measure the performance of buildings and provide easily accessible and useful information about the performance of their systems, components, and appliances. The variables and indicators will present to the different actors easy to read and meaningful information that points toward weaknesses or strength points of the operation and control strategy. The outcome of this work is collected and organized in the "SATO Key Performance Indicator Tool" (separate Excel file).

A key part of the self-assessment framework of components and systems is the identification of benchmarks that can be used to determine whether the status of the measured performance of systems and components is better than expected, is acceptable or needs to be improved. This deliverable firstly presents the EPBD approach to characterizing and benchmarking building performance and secondly discusses the required approach and characteristics of the SATO project.

A key feature to support the implementation of building-level SATO services is the communication between SATO Self-assessment framework and end-users. Different types of communication based on passive and active feedback, respectively, are presented.

Finally, privacy and data protection issues when connecting buildings to cloud-based platforms and services to users are discussed.

1. Introduction

In this Task, the requirements for the user-centered self-assessment framework and services will be specified and refined. All specifications and requirements will be thoroughly defined to ensure the interoperability of the developed systems, services and interfaces. The Task is designed as a continuous process that will accompany the entire life cycle of the project and provide the inputs for all 3 phases of the project. This will establish a continuous feedback and validation framework to track the development process based on pre-defined KPIs and provide flexibility to readjust system requirements.

It includes defining precisely the key variables that will be the object of the assessments (e.g energy performance metrics and grid interaction metrics as defined in EN-ISO 52000 and short- and long-term comfort metrics as defined in EN 16798) and covers the scales and granularities supporting them, data and privacy requirements, models for equipment and building energy performance, and algorithms for automatic model parameter tuning. The state-of-the-art regarding data quality procedures, system identification, and models for energy performance will be pursued.

The task will focus on assessment of systems and services relevant for the three different building typologies included in the SATO project: Residential, Office and Retail and the starting point for developing the assessment framework will be the systems and components implemented in the different SATO use cases.

The results of this task (D1.2) will be used to identify requirements needed for parts of the SATO platform and for the development of the Self-assessment framework in WP3.

2. Definition of systems, energy components and appliances

To define the requirements for the implementation of an Energy Performance Self-Assessment Framework it is necessary to define which systems, energy components and appliances to include in the assessment framework. The starting point for this is to develop solutions for the systems, energy components and appliances implemented in the SATO use cases and pilots. This will ensure available data in the development phase as well as relevant use cases and conditions for test and demonstration of the developed platform, framework, and services.

Figure 1 shows the terminology and categorization used in the SATO project for the energy systems and components. We distinguish between the following categories:

- **Energy Grid (sources and sinks),** includes the electricity, gas, district heating and cooling grids. There will be an exchange of energy between the building and different grids that needs to be controlled to ensure that building demands are met, while minimizing the stress on the grids and ensure optimal use of renewable energy sources.
- **Environmental Energy (sources and sinks),** includes environmental sources and sinks of heat like solar radiation, outdoor air, ground water. There will be an exchange of energy between the building and the environment through the building envelope. Heat gains and heat losses need to be controlled to minimize the building energy demand. There will also be exchange of energy between different building systems and the environment exploiting environmental sources and sinks to reduce the need for delivered energy.
- **Energy Conversion**, includes building systems converting energy from grids and environmental sources to meet building thermal and electric energy demands, like boilers, heat pumps, solar

thermal systems or PV. Systems need to be controlled to ensure optimum efficiency while reducing losses and fulfilling building energy needs

- **Energy Distribution**, includes building systems distributing heat, water and fresh air within the building to different spaces according to their specific needs as well as exchanging energy with integrated energy storages as required for system optimization.
- **Energy Storage**, includes thermal and electric storages integrated in building as well as in electric vehicles. Needs to be controlled to ensure that building demands are met, while minimizing the stress on the grids and ensure optimal use of renewable energy sources. It can be also used to provide flexibility services to the electrical as well as the district heating and cooling grids.
- **Energy Use**, includes building terminals delivering heat, water, light and fresh air to users in different spaces to ensure optimum indoor environmental quality.
- **Appliances**, includes different types of energy using service equipment to provide comfort and convenience.
- **Building Envelope**, includes building systems that control the exchange of heat gain and losses with the environment like solar shading, shutters, windows and façade vents.

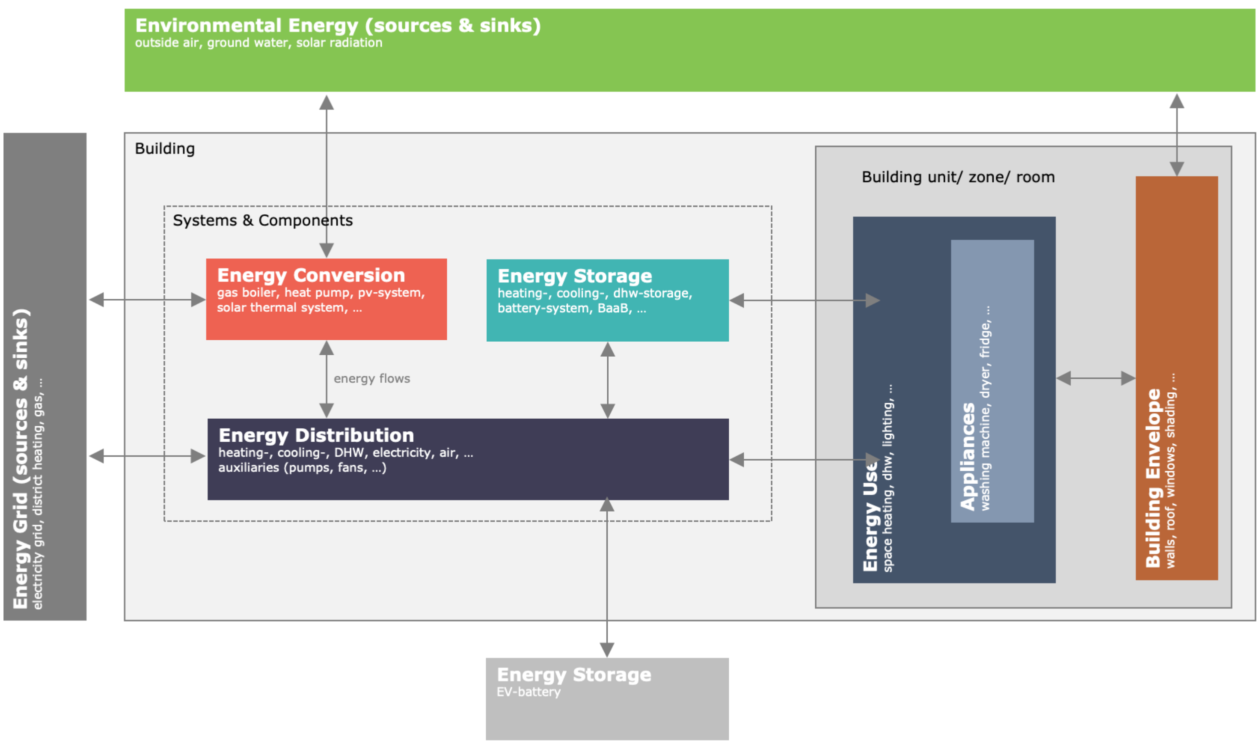


Figure 1. Energy system terminology and interrelations used in SATO.

A questionnaire was distributed among use case responsible as well as project partners to identify the building systems, energy components and appliances to be included in the SATO assessment framework and to define which performance indicators should be possible to assess. The outcome of this survey is summarized in Table 1 in accordance with the categorization previously defined and presented in Figure 1.

Table 1 List of building systems, energy components and appliances to include in the SATO Self-Assessment Framework including the key performance characteristics the platform should be able to assess.

System			**Energy components**	**Key assessment topics**
Type		**Description**	**What key energy components are included in the system?**	**What performance parameters/indicators should it be possible to assess?**
Energy Conversion	PV-System	PV-System for electricity generation	PV modules, inverter	**Metadata:** No. of PV modules, module power, total power, area per module, total area, inverter power Age of equipment, next maintenance date **Indicators:** Inverter power, inverter efficiency Electricity generation, average and time profile Electricity use, time profile, self-consumption
	Natural gas boiler	System to heat water by burning natural gas	Exhaust fan, circulation pump, burner	**Metadata:** Age of equipment, next maintenance date **Indicators:** Gas consumption, heating power, electricity consumption, delivered energy, boiler efficiency,
	Solar thermal collectors	System to heat water by absorbing sunlight	Solar thermal collector, circulation pump, hot water tank, heat exchanger	**Metadata:** No. of thermal collectors, module power, total power, area per collector, total area Age of equipment, next maintenance date **Indicators:** Heating power, heating energy production, time profile, flow, freezing Water storage efficiency, heat exchanger efficiency, efficiency of circulation pump, electricity use, system efficiency,
	Heat pump	Heat pump for space heating (SH), domestic hot water (DHW) heating or process heating (PH). Energy source from outside air, ground water, geothermal heat, waste heat	Energy source heat exchanger (evaporator), hot water heat exchanger (condenser), compressor, circulation pumps, fans (outside air source)	**Metadata:** Heat source characteristics Age of equipment, next maintenance date **Indicators:** Heating degree days, Source energy demand, heating energy generation, electricity use, SCOP, EER Source power, heating power, electrical power, COP, load profile Operating hours, operation state, supply and flow temperatures for source and sink, SH, DHW, PH Supply flow temperature of the heating system related to the outside air temperature Supply to return flow temperature difference of the heating system related to the outside air temperature Power of the heating system related to the outside air temperature
	Immersion Heater	Immersion heater integrated in hot water tank for heating.	Immersion heater, hot water tank	**Metadata:** Storage volume, **Indicators:**

				Electricity use, heating power, storage temperature, operation hours, operation state, storage efficiency
	Free cooling	Direct space cooling (SC) or process cooling (PC) with environmental energy. Energy sink to outside air, ground water, geothermal	Heat exchanger, pumps, fans (outside air source)	**Metadata:** Heat sink characteristics **Indicators:** Free cooling energy, electricity use, SEER Free cooling power, electrical power, EER Operating hours, operation state, supply and flow temperatures for sink, SC, PC Heat exchanger efficiency, pump/fan efficiency
	Chiller unit	Chiller for space cooling (SC) or process cooling (PC). Energy sink to outside air, ground water, geothermal	Energy source heat exchanger (evaporator), heat exchanger (condenser) circulation pumps, fans (outside air sink)	**Metadata:** Heat sink characteristics Age of equipment, next maintenance date **Indicators:** Cooling degree days Source energy demand, cooling energy generation, electricity use, SEER Source power, cooling power, electrical power, EER Operating hours, operation state, supply and flow temperatures for source and sink, SC, PC Supply flow temperature of the cooling system related to the outside air temperature Supply to return flow temperature difference of the cooling system related to the outside air temperature Power of the cooling system related to the outside air temperature

System			Energy components	Key assessment topics
Type		**Description**	**What key energy components are included in the system?**	**What performance parameters/indicators should it be possible to assess?**
Energy Distribution	Roof top unit	Combination of a heat pump with an air handling unit.	Same as Heat Pump and Air Handling Unit	**Metadata:** Same as Heat Pump and Air Handling Unit **Indicators:** Same as Heat Pump and Air Handling Unit
	Air-handling unit	Mechanical ventilation system for a building with heat recovery, air heater and cooler and bypass	Supply and exhaust fan counter flow, rotary or circuit system heat exchangers Heating and cooling coil	**Metadata:** System layout and characteristics Age of equipment, next maintenance date, optimized repairs/substitution timing. Maintenance and substitution needs. Life-time expectancy. Centralized live overview and management **Indicators:** Electricity use, thermal energy use for heating and cooling Heating, cooling and electrical power distribution Fan efficiency, SFP, heat and cooling recovery rate Supply, return, outside and exhaust air temperature and humidity Operation hours, operation state Optimized energy usage and GHG emissions info.
	Domestic Hot Water	Heating, storage and circulation of domestic hot water	Heat exchanger, pump, water tank, distribution and circulation network	**Metadata:** System layout and characteristics Age of equipment, next maintenance date, optimized repairs/substitution timing. Maintenance and substitution needs. Life-time expectancy. Volume water tank, **Indicators:** Domestic hot water use, use profile, peak usage. Power and peak loads, Energy use, energy profile, energy use and heat loss for hot water circulation
	Heating & Cooling Distribution	Monitoring/validation/assessment of heating/cooling distribution in separate zones/segments of an office-building using TABS (thermal active building parts).	Pumps, Valves	**Metadata:** System layout and characteristics **Indicators:** Energy use for cooling/heating per segment/zone/terminal device Use profile, seasonal, daily Pump electricity use, system efficiency, condensation, power profile, load profile Visualization e.g., using heatmaps to identify "hotspots" or KPI for proximity to hotspot.

	Natural ventilation	Natural system to provides fresh air and limited cooling.	Electrical window actuators	**Metadata:** System layout and characteristics **Indicators:** Operation hours, operation state Temperature difference (In/out) when active, motor operation, ventilation rate (amount of outdoor air introduced into a space per a unit of time), flow rate, airflow speed, air pressure (?)
	Air distribution network	Network of duct, valves and terminal devices	Duct, valve, air terminals	**Metadata:** System layout and characteristics **Indicators:** Pressure loss, air distribution, ….
	Mechanical ventilation	Balanced mechanical ventilation system with heat recovery, by-pass, fresh air supply and air exhaust	Supply and exhaust fan, counter flow heat exchanger. Air distribution network Air terminal devices	**Metadata:** System layout and characteristics Age of equipment, next maintenance date, optimized repairs/substitution timing. Maintenance and substitution needs. Life-time expectancy. **Indicators:** SFP, fan efficiency, fan energy use Heat recovery rate, defrosting how often and for how long time, periods with by-pass (when heat recovery is not needed), seasonal heat recovery/recovered energy

System			Energy components	Key assessment topics
Type		Description	What key energy components are included in the system?	What performance parameters/indicators should it be possible to assess?
Energy Storage	Storage Tank	Water storage tank for thermal energy	Tank	**Metadata:** Maintenance and substitution needs. Life-time expectancy. Storage volume **Indicators:** Storage temperature (possibly on different levels), min. and max temperature Energy storage capacity, state of charge, heat loss, storage efficiency Operating hours, operation state, supply and flow temperatures for charging and discharging
	Battery storage	Electrical battery storage.	Battery modules, inverter	**Metadata:** Maintenance and substitution needs. Life-time expectancy. **Indicators:** electricity use (charge), electricity generation (discharge) Electrical power, Battery state and efficiency
	EV battery storage	Electrical battery storage.	Battery modules,	**Metadata:** **Indicators:** electricity use (charge), electricity generation (discharge) Electrical power, Battery state and efficiency
	Building as a Battery	Building mass as thermal energy storage.	Building volume and construction	**Metadata:** Building volume, building mass, building mass surface, specific storage capacity **Indicators:** Room air temperature, building mass temperature Total energy capacity (per kelvin), storage efficiency

System			Energy components	Key assessment topics
Type		Description	What key energy components are included in the system?	What performance parameters/indicators should it be possible to assess?
EV Charging	EV Charging stations	Electrical supply to charge EV batteries.	AC/DC system	**Metadata:** **Indicators:** ON/OFF, energy flow, energy metering, state of charge, charging state (discharge), actual power, charging time

System			Energy components	Key assessment topics
Type		**Description**	**What key energy components are included in the system?**	**What performance parameters/indicators should it be possible to assess?**
Energy Use	Chilled/ Heated building construction (typically in the floor)	Hydraulic heated/chilled building structure used for space heating/cooling	Pipes embedded in the building construction for energy distribution. Water circulation pump.	**Metadata:** System layout and characteristics **Indicators:** Supply and return temperature, water flow Energy use for cooling/heating per segment/zone/terminal device Use profile, seasonal, daily Pump electricity use, system efficiency, condensation, Power profile, load profile Visualization e.g., using heatmaps to identify "hotspots" or KPI for proximity to hotspot. Response time of the floor temperature. Heat losses in the floor system.
	Exhaust fan	Removes air from building/room.	Fan	**Metadata:** **Indicators:** Pressure loss, fan efficiency, SFP, flow setting
	Fan Coil	Heats or cools the air in the single compartment or a part of a compartment.	Fan Heating and cooling coils	**Metadata:** Maintenance and substitution needs. Lifetime expectancy, optimized repairs/substitution timing. **Indicators:** Electricity use, thermal energy use for heating and cooling. Heating, cooling and electrical power distribution Fan efficiency, SFP, heat and cooling exchanger efficiency Supply, return, outside and exhaust air temperature and humidity. Operation hours, operation state Fluid temperature (heating/cooling), water temperature (in/out)
	Electric Heating		Heater terminal	**Metadata:** **Indicators:** Electricity use, heating power, peak power, power profile, operation hours, operation state
	Room	Comfort measures in the room	Room sensor	**Metadata:** **Indicators:** Room temperature, relative humidity, CO2, presence, brightness, illuminance, PMV, PPD, particle sensors (for CO, VOCs, Formaldehyde, Radon etc.)
	Lighting and plug loads			**Metadata:** Maintenance and substitution needs.

				Lifetime expectancy, optimized repairs/substitution timing. **Indicators:** Energy use, time of usage optimized energy usage and GHG emissions. Centralized live overview and management
	IT Hardware			**Metadata:** Maintenance and substitution needs. Lifetime expectancy, optimized repairs/substitution timing. **Indicators:** Energy use, time of usage optimized energy usage and GHG emissions. Centralized live overview and management
	Electrified furniture and store communic ation			**Metadata:** Maintenance and substitution needs. Lifetime expectancy, optimized repairs/substitution timing. **Indicators:** Energy use, time of usage optimized energy usage and GHG emissions. Centralized live overview and management
	Appliance stream	All major domestic appliances	dishwasher, washing machine, fridge, mobile phones, computers and small domestic appliances (e.g.: microwave oven)	**Metadata:** Maintenance and substitution needs. Lifetime expectancy, optimized repairs/substitution timing. **Indicators:** Energy use, time of usage optimized energy usage and GHG emissions. Centralized live overview and management.

System			**Energy components**	**Key assessment topics**
Type		**Description**	**What key energy components are included in the system?**	**What performance parameters/indicators should it be possible to assess?**
Building	Building envelope	Dynamic building envelope heat and mass transfer between the building and the environment	Solar shading, daylight shading, windows, skylights, insulated shutters	**Metadata:** Window to wall ratio, cardinal direction Maintenance and substitution needs. Lifetime expectancy, optimized repairs/substitution timing. **Indicators:** Heat loss, solar heat and light transmission, infiltration, air flow rate, surface temperature

System			Energy components	Key assessment topics
Type		Description	What key energy components are included in the system?	What performance parameters/indicators should it be possible to assess?
Environ ment	Environme nt	Outdoor environmental parameters that may influence the building energy use/production	Environmental sensors, commonly used in weather stations (e.g., thermocouple, anemometer, pyranometer, etc)	**Metadata:** **Indicators:** Outside air temperature, relative humidity, CO2, brightness, solar radiation, rain/snow, wind. Absolute humidity

3. Definition of key variables and indicators

Key variables and performance indicators provide means for the monitoring and management of the building and systems towards the operational goals and create the basis for further improvement and optimization. Key variables and performance indicators are defined in SATO to measure the performance of buildings and provide easily accessible and useful information about the performance of their systems, components and appliances. The variables and indicators will present to the different actors easy to read and meaningful information to the different actors that will point toward weaknesses or strength points of the operation and control strategy.

One of the key points of the work is the selection of the most useful variables and performance indicators to be used in the SATO platform. The selection involved several experts, who have scientific and/or technical background. The scope has been to avoid the selection of useless or too complex indicators and focus on those that are considered by the experts the most useful and meaningful.

The characterization and assessment of systems, components and appliances will be based on a number of key variables and performance indicators. In the SATO project these variables and indicators have been divided in the following categories:

- Building Performance
    - Building fabric, specific heat loss, thermal mass, airtightness
    - Building use, occupancy, loads
    - Weather characteristics, HDD, CDD, solar load, wind speeds, seasonal outdoor temperature profile, heat/cold waves,
- Energy Performance
    - Whole building (EPC, …)
    - Systems energy use (heating, cooling, ventilation)
    - standard values (full load, steady state), seasonal values, yearly average values, frequency distributions, dependencies on climate, load, ….
- System and Component Performance
    - SFP, COP, SCOP, ….)
    - standard values (full load, steady state), seasonal values, yearly average values, frequency distributions, dependencies on climate, load, ….

- Building2Grid (B2G)
  - Electricity, heat, demand response, self-consumption of renewables
- Environmental Impact
  - CO_2 emissions, ….
- Smart Readiness Indicators, SRI
- Cost Performance
  - Cost and Income (energy production/use, replacement, optimization, demand flexibility, ..)
- Indoor Environmental Quality
  - Thermal comfort, noise, light and daylight, air quality, (short and long term values)

The definition of variables and performance indicators has to a large extent been based on the relevant standards in the field.

The outcome of this work is collected and organized in the “SATO Key Performance Indicator Tool”. The following provides a short description of the tool and how it is organized.

3.1. Description of the SATO KPI Tool

The SATO KPI Tool is an Excel (.xlsm) based tool. It consists of the main menu tab, parameter selection tab, KPI Tool tab, and additional tabs.

The main menu tab describes the content, scope and aims to provide a KPI Tool user guide.

The parameter selection tab can be used separately from the KPI Tool tab to sort and filter KPIs based on systems, categories, necessary measured variables, and data acquisition methodologies. A snip of the parameter selection tab can be seen in Figure 2 below.

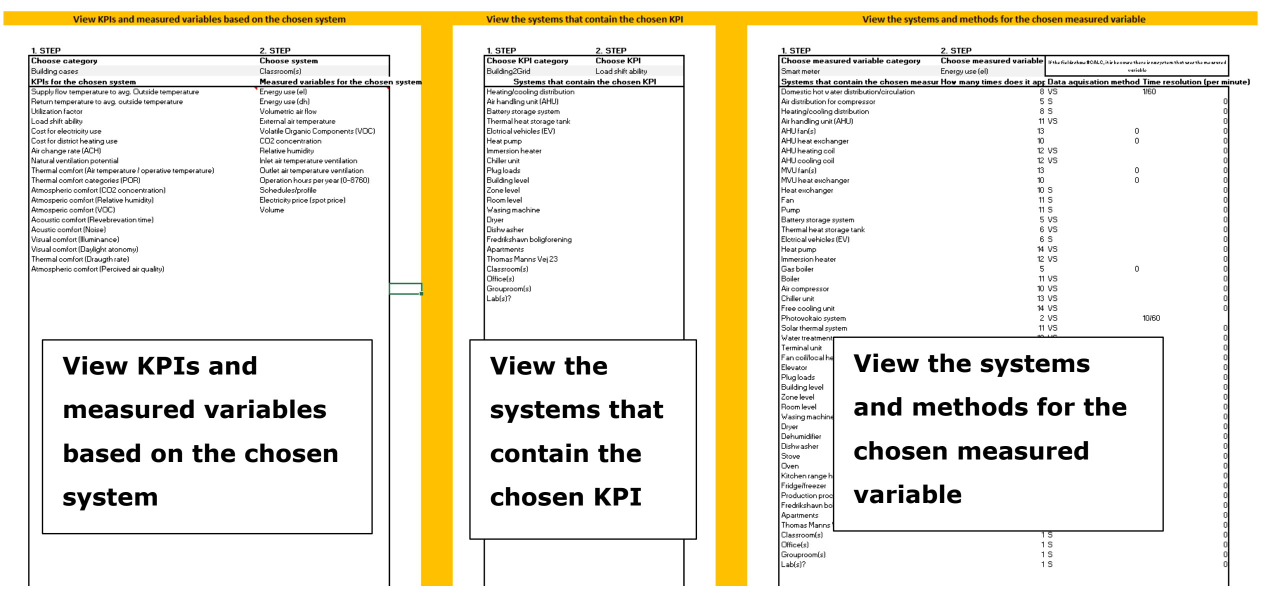


Figure 2: Parameter selection tab. Sort and filter KPIs based on systems, categories, necessary measured variables, and data acquisition method.

The additional tabs, such as Building Performance (PB), Energy Performance (EP), Systems & Components (SC), Building2Grid (B2G), Environmental Impact (EI), Smart Readiness Indicator (SRI), Cost Performance (CP), and Indoor Environment (IE) describe the various KPI categories, equations, units, meaning/definition, and references and aims to be used as a glossary.

The KPI Tool tab presents a KPI matrix that consists of 6 sections: Overview, Key Performance Indicators (KPIs), Calculation of KPIs, Necessary measured variables, Data acquisition methodologies, and Required time resolution. The location of the different sections in the KPI Tool tab can be seen in Figure 3 below.

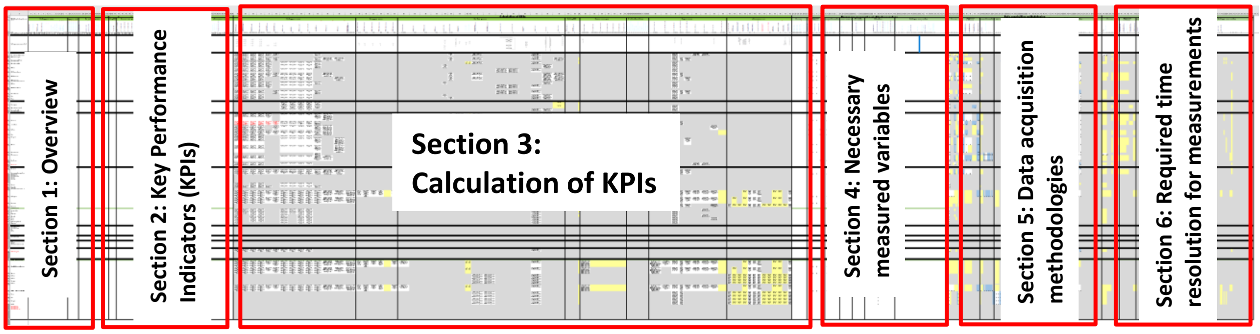


Figure 3: KPI Tool content, and where the various sections are located in the KPI Tool (snip from the .xlsm file).

3.1.1. Section 1: Overview

Section 1 consists of an overview of the different systems in the following categories: Energy distribution, Energy storage, Energy conversion, Energy use (+Appliances), Building envelope, EV charging station, Building control and monitoring system, Miscellaneous and Building use-cases.

3.1.2. Section 2: Key Performance Indicators (KPIs)

Section 2 consists of the defined key variables and indicators in 3.1 and is represented in the following categories: Building Performance (PB), Energy Performance (EP), Systems & Components (SC), Building2Grid (B2G), Environmental Impact (EI), Smart Readiness Indicator (SRI), Cost Performance (CP), and Indoor Environment (IE).

Within each KPI category, specific KPIs are defined, such as total specific annual energy use, primary delivered energy use, CO_2 equivalent emissions, and so on. These specific KPIs are defined in the third row of the Excel. Within Section 2, a cell marked with "x" indicates that the specific KPI will be calculated for the given system.

3.1.3. Section 3: Calculation of KPIs

Section 3 shows which measured variables are needed to calculate the KPI (section 2) for each system's overview (section 1). If an "x" is marked in a cell in section 2, the cell will appear white for the same combination of system and KPI in section 3. This indicates that the KPI will be calculated based on the following four identification model types:

Type 1: Based on measured time-series
Type 2: Based on filtered measured time-series
Type 3: Based on dynamic in-situ testing where building controls are modified to find the desired parameter
Type 4: Based on data-driven methods (grey box, ML, etc.)

An example of a measured variable and how the KPI will be calculated/measured/analyzed can be seen in Figure 4 below.

As one can see in the figure below, the unit "Fan coil/local heating and/or cooling unit in the terminal box" can be calculated with type 1: (energy use (el) OR energy use (DH) AND (DC)) AND surface and/or floor area. This means that the "Fan coil/local heating and/or cooling unit in the terminal box" can either be driven by electrical energy OR district heating/cooling. In addition, the surface and/or floor area is also needed to normalize the result.

	Total annual spesific energy use	Seasonal avg spesific energy use? (4 seasons, averaged over 3 months)
Unit	kWh/m2 per year	kWh/m2
Energy use		
Terminal unit		
Fan coil/local heating and/or cooling unit in terminal box	Type 1; (Energy use (el) OR (Energy use (dh) AND Energy use (dc))) AND Surface and/or floor area	Type 2; (Energy use (el) OR (Energy use (dh) AND Energy use (dc))) AND Surface and/or floor area

Figure 4: Snip from KPI Tool. Example on how to calculate the KPIs, in this example Fan coil for total annual specific energy use.

3.1.4. Section 4: Necessary measured variables

Section 4 consists of the following categories in row 2: Smart meter, Appliance temperatures, Outdoor weather condition, Room/zone measurements, System and component performance, Grid and utilities, and Building information/metadata.

The number in each cell beneath the variables indicates how many times it is sampled. An example of this can be seen in Figure 5 below for a selection of variables.

Smart meter											Appliance temperatures					Outdoor weather condition									
Power	Energy use (el)	Energy use (dh)	Energy use (dc)	Energy use (dhw)	Energy use (dcw)	Energy use (other)	Volumetric liquid flow	Volumetric air flow	Pressure difference		Temperature on the external side before	Temperature on the internal side after	Temperature on the internal side before	Temperature on the external side after	Additional temperature	External air temperature	Degreedays	External relative humidity	External CO2 concentration	Horizontal solar radiation	Solar azimuth	Solar altitude	Wind speed	Rain/snow?/cloud coverage	Wind direction
W	kWh	kWh	kWh	kWh	kWh	kWh	L/s	m3/h	Pa		°C	°C	°C	°C	°C	°C	°C days	%	ppm	W/m2	Deg	Deg	m/s		Deg
	11					1	6				6			5		1	1			1					
	10			1	1		1																		

Figure 5: Snip from Section 4. The numbers in the cells indicated how many KPI/system combinations it is sampled in total.

3.1.5. Section 5: Data acquisition methodologies

Section 5 is the Data acquisition methodologies and is based on/refers to section 4 (Necessary measured variables). However, here each cell is defined with the following letters and their description of the acquisition of the data:

S = sensor
VS = virtual sensor (same resolution as a sensor, but calculated from other measurements)
ES = external sensor (measured by a sensor not located in the unit/area)
M = metadata (acquired from producer/design team, etc.)
CAL = calculated (lower resolution than the sensor, but calculated from other measurements)

The color in this section is described as the following:
Grey = not required for analysis of KPI
Light yellow = required for analysis of KPI, but missing a value in the field
White = required for analysis of KPI, and filled in
Light blue = not required for analysis of the defined KPI, but the value is filled in (indicates sensors, which are expected to be used in the future)

Data acquisition methodology and color example can be seen in Figure 6 below.

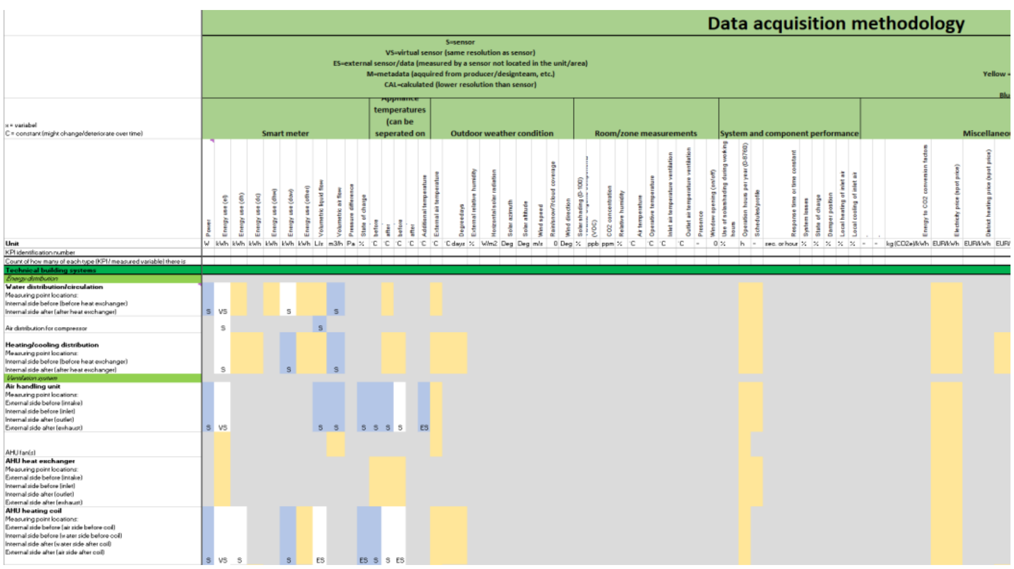


Figure 6: Section 5, snip from KPI Tool. Data acquisition methodology and color.

3.1.6. Section 6: Required time resolution for data

Lastly, section 6 is the Required time resolution for data, and this section also refers back to section 4 (Necessary measured variables). Here, each cell is filled with two values: An X and a Y, which is the preferred and acceptable time resolution based on what we want to measure. The format is written as X/Y and uses minutes as the unit for both.

The colors in this section are described below and can also be seen in Figure 7 below:
Grey = Not required for analysis of KPI
Light yellow = Required for analysis of KPI, but the missing value in the field
White = Required for analysis of KPI, and filled in

Figure 7: Section 6, snip from KPI Tool.

4. Identification of benchmarks

A key part of the self-assessment framework of components and systems is the identification of benchmarks that can be used to determine whether the status of the measured performance of systems and components is better than expected, is acceptable or needs to be improved.

Building performance design values and mechanical systems' technical specifications refer to conventional assumptions on operational scenarios that in general are different from the real ones. The section begins with a presentation of the EPBD approach to characterizing and benchmarking building performance, then it presents the energy labelling and ecodesign approaches to characterizing the energy efficiency of products and to setting minimum standards for the energy efficiency and environmental performance of products, and, finally discusses the required approach and characteristics of the SATO project.

4.1. EPBD approach and indicators

This section is an adaptation from [1] and provides an explanation of the indicators presented in the Annex I of the recent amendments to the Energy Performance of Buildings Directive (EPBD) [2].

The overarching standard EN ISO 52000-1 states: "the use of only one requirement, e.g., the numerical indicator of primary energy use, can be misleading. In ISO 52000-1 different requirements are combined to a coherent assessment of nearly Zero-Energy Building." To avoid this misleading interpretation of the energy performance of a building, the standard explains which indicators should be used:

1. **Energy needs for heating and cooling** (for quantifying energy losses through the envelope and via air infiltration and ventilation). An example may be seen in Figure 8 where, in winter, the heating energy needs depends on the balance of the transmission and ventilation energy losses with the energy gains from internal heat sources (appliances and people) and direct solar radiation (entering via the transparent elements).

2. **Total primary energy use** (for quantifying the inefficiencies in the systems – e.g. avoid burning biomass in an inefficient burner)

3. **Non-renewable primary energy** use without compensation between energy carriers and without compensation for sales of renewable energy from the building to the grid. This indicator allows to quantify the non-renewable fraction within total primary energy use.

4. **Numerical indicator of non-renewable energy use with compensation**. Only at this stage can compensation between different energy carriers or times be taken into account (or not, depending on national choices). For example, cross-compensation between gas and on-site renewable generation or the accounting of exported energy at a certain time as a compensation of energy use at another time (on an hourly, monthly or yearly basis). This indicator has received a number of different interpretations. In particular there are critiques to its interpretation as Net energy balance over a year, since this brings to the likely overproduction (and export to the grid) of renewables on-site in summer and continued use non-renewables in winter.

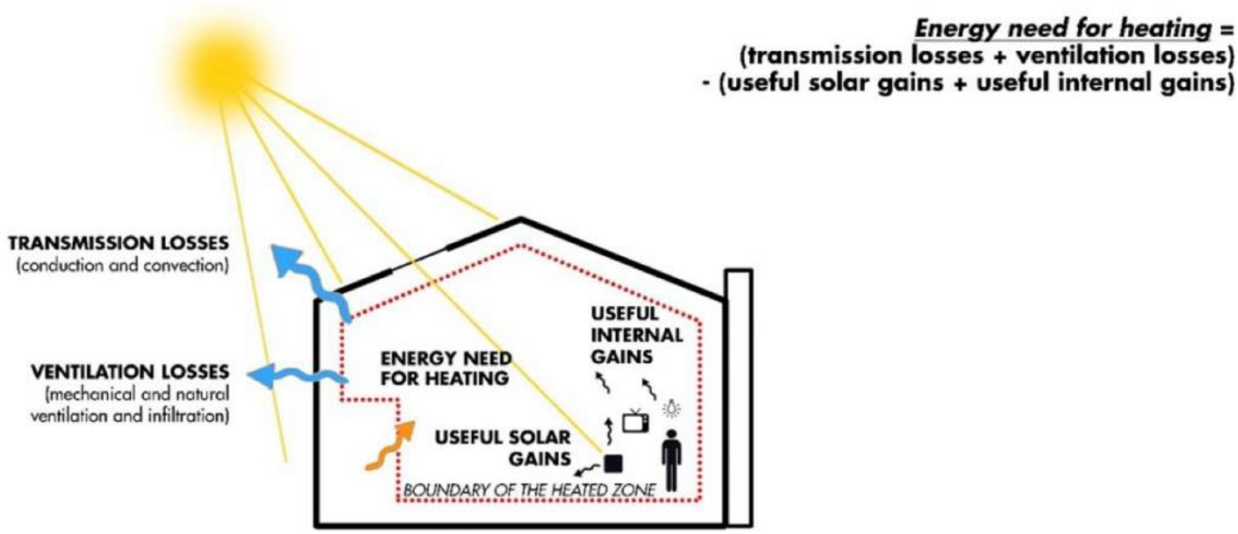


Figure 8: Description of the energy flows to take into account when calculating the energy needs for heating (Source: [1])

Energy needs indicator (in kWh/(m²·y)) gives information about the intrinsic efficiency of the building fabric (shape and orientation, form factor, insulation level, airtightness, solar protection, etc.). The calculation of this specific indicator should follow ISO 52016-1:2017 [3]. This specifies calculation methods for the assessment of energy need for heating and cooling, latent energy need for (de-) humidification, the internal temperature, etc. ISO 52018-1:2017 [4] could also help to report the choices made for the definition of this partial indicator. ISO 52018-1:2017 deals with the usage as requirement of partial energy performance of buildings (EPB) indicators related to the fabric and thermal balance of the building. Considering the thermal quality of the envelope (stationary and periodic thermal transmittance, solar protections and their controls, presence of summer night ventilation, typical operating temperatures, etc.), it is possible to calculate the energy need for heating and cooling of a defined building, expressed in kWh/(m²·y).

The use of an additional specific index, in terms of energy use per square meter for inbuilt lighting systems (typically not used for residential buildings), will define the performance of the lighting systems. This should take into account the quality of the lighting design and the daylighting contribution for the reduction of lighting consumption, typically dependent on the project (the methodology is defined in EN 15193-1:2017).

The second requirement, **total primary energy use**, includes technical building systems and considers the energy carriers that feed them, see Figure 9. This requirement is considered as the main indicator expressing the building energy performance in Annex I of the EPBD. It includes the energy used by each system (heating, cooling, ventilation) in order to cover the energy needs of the building in conjunction with a specified comfort category. The efficiency of the different technical systems is taken into account for calculating the amount of delivered energy flowing to the systems through the assessment boundary of the building from different sources (on-site, nearby and distant). The total primary energy is the sum of all flows of delivered energy (renewable and non-renewable), each being weighted with their respective f_{Ptot}.

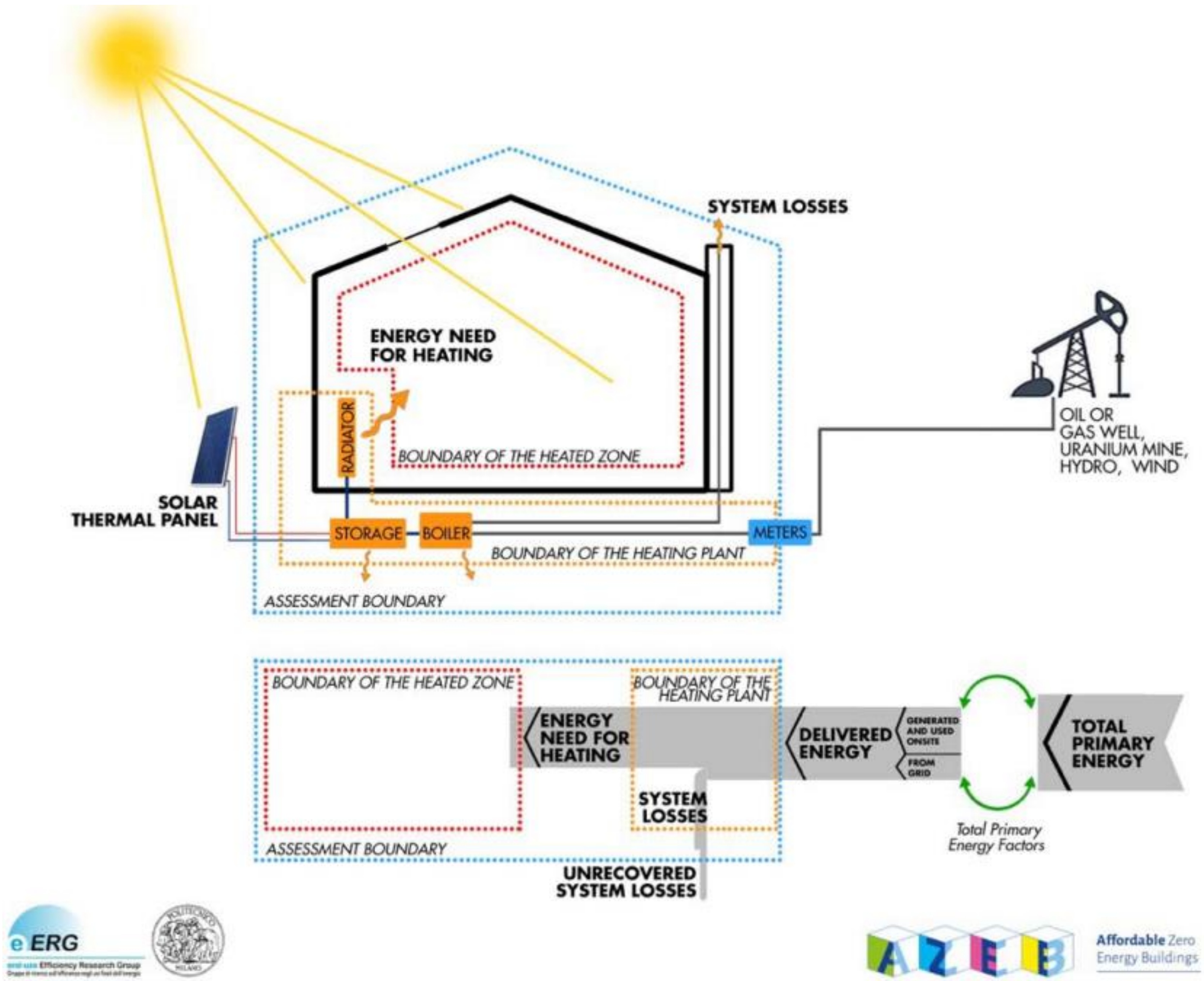


Figure 9: Schematic description of the relation between delivered energy (sometimes called final energy) and primary energy use (Source: [5])

In order to further clarify the role of Renewable Energy Sources (RES) another indicator is available and necessary, the non-renewable primary use.

The third requirement, **non-renewable primary energy**, is similar to the second (total primary energy or simply primary energy) but uses a different set of conversion factors for primary energy, since it uses the f_{Pnren} instead of the f_{Ptot} when weighting the various streams of delivered energy that cross the assessment boundary of the building.

In doing so, it attributes a weight of zero to the energy captured by natural energy flows (renewables). Clearly, this an approximation, since the use of renewables also has an environmental impact, though generally lower than that of non-renewable sources (e.g. use of biomass can be a net emitter of CO_2 if it is harvested faster than it is growing; biomass burning emits PM10 and PM 2.5 and has implications for land use; PV and wind turbines require mining of materials for the physical infrastructure, use of land, landscape impacts, etc.).

The efficiency of the different technical systems is taken into account, as well as the primary non-renewable energy factor (f_{Pnren}) for each energy carrier. The f_{Pnren} is used to transform the delivered energy – used by the technical building systems for covering the building's needs – into primary energy, and is defined at country/ regional level. Renewable energy generated on site and exported to the grid is not included in this calculation; only the self-consumed RES generation is counted, since it is this fraction which is delivered to the building.

The **non-renewable energy** indicator with compensation considers both the non-renewable primary energy used by the building and the exported renewable primary energy. At this stage compensation between different energy carriers may be taken into account, for example between gas and on-site RES production and the accounting of exported renewable energy as a compensation for energy use in another time period, on an hourly, monthly or yearly basis. In order to describe the extent to which Member States might choose to consider the accounting of exported energy as a compensation of energy use, the Standard EN ISO 52000-1 introduces a k_{exp} factor, variable between 0 and 1. A value $k_{exp} = 0$ describes the absence of compensation, whereas a value $k_{exp} = 1$ describes the situation where each unit of energy exported compensates for one unit of energy used. Intermediary situations are possible. One of the disadvantages of actually using compensation is that it makes likely a double-counting of renewable energy which is generated on site and exported. It would be counted as a direct improvement of the building performance and at the same time as an improvement of the f_{Pnren} of energy from the grid, which in turn intervenes in the calculation of the building performance. It also transfers costs for management of variable energy generation from the building to the grid, hence removing a price signal towards optimisation of demand loads.

In Italy, "DM 26 June 2015" defines how renewable energy generated on-site can be counted in the calculation of the yearly primary energy use:

- Only to contribute to the same energy carrier (e.g. electricity with electricity: no compensation between different energy carriers)
- Only as long as the monthly energy use of that carrier is covered. The excess RES production in one month (produced on site and exported, e.g. in July) cannot be used to compensate for energy use in another month (e.g. December) in excess of RES generation in that month. The choice of a month as minimum time interval is connected to the calculation procedure which is based on monthly average values of environmental variables

Since the calculation step is a month (and not e.g. an hour) there is no possibility to check if PV generated electricity in e.g. a certain hour is self-consumed in that hour or sold to the grid. Italian legislation assumes as self-consumed a part of PV energy generated in a month not higher than the energy use by the building, which is an overestimate [1]. The PV-generated energy in excess of use in that month is assumed as sold to the grid, but it cannot be used to offset primary energy use in another month. In the wording of EN-ISO the situation might be described by saying that the parameter k_{exp} is set zero in principle, but slightly higher than zero in practice due to the monthly calculation method.

The choice of calculating the non-renewable primary energy use essentially with no compensation (the excess production in one month - produced on site and exported - cannot be used to compensate for energy taken from the grid in another month for exported energy (a part from what is unavoidable due to the fact that a monthly calculation method is used) has the advantage of:

- focusing on the building and its success in fulfilling the definition of nZEB of EPBD art.2;
- avoiding incentives to use the energy grid as an inter-seasonal energy storage which would transfer cost from the building to the grid and generate new environmental pressure (e.g. for construction of large storage facilities).

The opposite situation, where all energy exported over a year can be used to compensate (offset) energy taken from the grid over a year coincides with some of the definitions of Net Zero Energy Building (NZEB), where "net" is intended as difference between energy use and energy generation, or equivalently between delivered energy and exported energy, all quantities being considered over a year. In this case the parameter k_{exp} is set to 1. The idea that exactly the same amount of energy being gathered from renewable sources during summer can be used for heating during winter is obviously physically wrong due to the operating storage losses and the embedded energy in the storage systems [4].

4.2. Energy labelling and ecodesign approaches

The European Union (EU) introduced energy labelling and ecodesign legislation[1] with the aim of improving the energy efficiency of energy consuming devices and consumer awareness about device energy consumption.

Energy labels, first introduced in 1994, help consumers choosing products with higher energy efficiency and drive product manufacturers to develop products that achieve higher energy efficiency ratings. Besides the product's energy efficiency, energy labels also provide information about other important features related to the utilization of the products.

Building on the success of the energy labeling initiative, the EU ecodesign legislation sets mandatory minimum energy efficiency requirements for the products, preventing entry into market for products that do not reach ecodesign requirements. This not only helps improving the environmental performance of products, but also contributes to EU's energy and climate goals.

The labelling and ecodesign requirements for different product groups are set by the EU energy labelling framework regulation. There are currently 17 product groups required to provide an energy label:

- Lighting
- Heaters
- Refrigeration
- Vacuum cleaners
- Washing machines and driers
- Air conditioners and fans
- Electronic displays and TV boxes
- Kitchen appliances
- Pumps
- Transformers and converters
- Computers and servers
- Imaging equipment
- Game consoles
- Electric motors
- Tyres
- Products with off, standby and networked standby modes
- Welding equipment

[1] Rules and requirements for energy labelling and ecodesign https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/rules-and-requirements_en

Depending on the specific equipment, different requirements[2] are applicable. For most equipments, the labelling requirements that will be benchmarked by SATO, are related to:

- energy efficiency class
- energy consumption
- power consumption in 'off-mode'
- power consumption in 'left-on mode'

Regarding the ecodesign requirements that will be benchmarked by SATO, depending on the specific building equipment or appliances to consider, these might include:

- Maximum allowed power
- Minimum energy efficiency (EER, COP, SEER, SCOP)
- Seasonal space heating or cooling energy efficiency
- Seasonal energy performance ratio
- Energy efficiency index (EEI)
- Weighted condensation efficiency
- Specific energy consumption (SEC)

4.3. Thermal comfort

For long term evaluation of the general indoor thermal comfort conditions, the indicators described in Annex D of CEN/TR 16798-2 [5] can be adopted. To evaluate the comfort conditions over time (season, year) a summation of parameters can be made based on data measured in real buildings or dynamic computer simulations. Three methods which can be used for that purpose are listed below.

a) Method A – Percentage outside the range: Calculate the number or % of occupied hours (those during which the building is occupied) when the PMV or the operative temperature is outside a specified range.

b) Method B – Degree hours criteria: The time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted by a factor which is a function depending on by how many degrees, the range has been exceeded.

c) Method C – PPD weighted criteria: The time during which the actual PMV exceeds the comfort boundaries is weighted by a factor which is a function of the PPD.

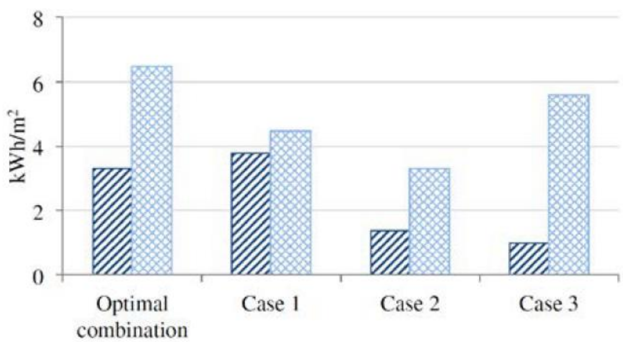
The recommended ranges of operative temperature (when using the adaptive model, which can be used in non-mechanically conditioned buildings and in mechanically conditioned buildings when the active systems are off – according e.g. to the recently revised ASHRAE 55, Chap. 5.4 [6]) are presented in standards. However, operative temperature and PMV are only a part of the variables involved in thermal comfort assessments, which imply assumptions often taken for granted, while on the contrary need to be subject to conscious analysis and decision by the users, designers and operators of buildings [7].

A tool for analyzing the influence of those parameters according to the EN and ASHRAE standards is available from Berkeley University [9][9].

The choice of the comfort scenario to be pursued strongly affects the energy use of the building, hence it should always be clearly and explicitly included in the assessment. E.g. in summer, comfort is highly dependent on insulation level of clothing + chair, air velocity, operative temperature and very little

[2] Requirements on energy efficient products: https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products_en

affected by relative humidity[3]. The same level of comfort can be achieved via various combinations of physical parameters (clothing level, metabolic equivalent, relative humidity and air velocity), each providing different levels of energy needs. With a correct choice of these parameters the user can therefore achieve the same or better comfort level with lower energy and power demand than with other combinations, resulting in energy savings and consequents costs reductions [11][12].



SIM.	T_{op}	R.U.	v	PMV	clo	met
	°C	%	m/s	-	-	-
Optimal combination	26	60	0.01	0.5	0.5	1.2
Case 1	25.7	70	0.01	0.5	0.5	1.2
Case 2	27.3	70	0.5	0.5	0.5	1.2
Case 3	27.6	60	0.5	0.5	0.5	1.2

Figure 10: Influence of comfort set point on sensible (dark blue) and latent (light blue) energy needs for cooling (source: [11])

The combinations of physical parameters leading to comfort are codified into Comfort standards as e.g. EN 16798 and ASHRAE 55. Sometimes in design and operation of heating and cooling systems designers and energy manager choose to aim at values of temperature and humidity within the stricter comfort category I (which is in fact proposed by the standards only for fragile persons in hospitals, care centres for elderly people, etc.) rather than the category II proposed for new buildings or category III proposed for existing buildings. Those choices are often then passed on to users habits. Moving from category I to II implies energy savings of 10 to 40% and moving from category I to III implies savings of 20 to 66%, according to Sfakianaki et al [13]. The authors also found similar savings are obtained by reducing ventilation rates from ventilation category I to II or III, keeping the same thermal comfort category.

Analysis is ongoing to ascertain whether people can actually distinguish among the proposed comfort categories. An analysis [14] of data from the ASHRAE, SCAT and Berkeley databases of field surveys concludes that category A (and possibly B) is too narrow to be discriminated by occupants of buildings. Regarding possible discrimination via measurement of physical parameters and the calculation of PMV [15], note that: 'the PMV range required by A-category can be practically equal to the error due to the measurements accuracy and/or the estimation of parameters affecting the index itself' [16]; as a matter of fact, the errors accepted by EN ISO 7726 [17] in terms of required accuracy give large errors in the PMV value.

Indeed ISO 7730-2005 acknowledges that: 'Owing to the accuracy of instrumentation for measuring the input parameters, it can be difficult to verify that the PMV conforms to the Class A category ($-0.2 < PMV < +0.2$). Instead, the verification may be based on the equivalent operative temperature range, as specified in A.2 and in Table A.5.' This is probably equivalent to setting to zero the uncertainties on all the other variables besides temperature [18] and hence makes little sense.

More fundamentally the question may be posed as to whether it is possible to discriminate a range of 0.2 * 2 = 0.4 points on the thermal sensation scale when the surveys and the judgements of people go in steps of 1.0 point on that scale. McIntyre [19] suggests that a seven-point (vs 3- or 25-point) scale is appropriate for psychological measurement. He observes that when people are presented with a set of stimuli that vary in one dimension only, the number of stimuli that can be unambiguously identified is relatively small. Subjects can identify about six different tones and five degrees of loudness without

3 E.g. EN ISO 7730 [10] states that "The influence of humidity on thermal sensation is small at moderate temperatures close to comfort and may usually be disregarded when determining the PMV value".

error. For several different types of stimuli, Miller [20] found that people cannot generally deal with more than about seven levels of sensation without confusion.

4.4. SATO approach

In SATO, measurements and analysis of continuous time series of data will provide the basis for defining more specific and relevant benchmarks for continuous evaluation of building operation (both in terms of energy and comfort). In case discrepancies are detected between expected and actual (measured) values, the benchmarking method must also allow for identifying the main reasons of this discrepancies.

This may imply (i) the adaption of existing or definition of new benchmarks – also for subsystems and components – (ii) possibility to develop new benchmarks related to building and system dynamics, (iii) new analysis methods to quantify benchmarks based on data time series.

The assessment should address both building fabric components (e.g. total solar transmittance of solar protections + glazing, accurateness of the controlling algorithm, …), and mechanical systems, both in steady state and dynamic conditions (how much time the system takes to respond to a control action, such as time needed to reach the set point once the system is turned on). Some parameters might be measured (e.g. pressure drop in ducts) others might be taken from the design documentation (e.g. solar protections existence and features). The output of this process should be not only in terms of operational improvements (suggested to the user or automatically performed by the BMS), but also in terms of structural improvements (e.g. to increase wall thermal insulation of walls, to install solar protections, …) suggested to the building owner/manager.

A database of building performances, based on many cases, with detailed and reliable monitored data, would be needed as a starting point for advanced benchmarking, via a clusterization of data based on building's features (e.g. type of building, S/V ratio, window-to wall ratio, year of construction, H_T, H_V, climate (HDD and CDD), …). A simplified version of this kind of assessment is performed in North America with the 1 – 100 ENERGY STAR score method [24], in which the considered building is compared to other similar buildings across the country and receives a score based on how it performs, compared to the national average. To this aim, the source of data is of utmost importance. That's why EPA (United States Environmental Protection Agency) uses rigorous statistical surveys as the foundation for the 1 – 100 ENERGY STAR score. These surveys are based on samples that represent the national building stock, consistently collecting the same data from all buildings, from information about their use and physical characteristics to energy data. All of the data is also verified, so it's the most accurate and complete picture available of the energy used by buildings. The detail provided by these surveys enables EPA to normalize for the unique building characteristics and provide a real-world comparison of the considered buildings to others like it across the nation.

Regarding energy label and ecodesign relevant requirements, SATO will:

- Integrate with the European Product Registry for Energy Labelling (EPREL)[4] to fetch the necessary energy label data, whenever the SATO platform assesses a building equipment/appliance that requires energy labelling.
- Incorporate into its databases, information extracted from the most up to date ecodesign regulations, thereby allowing assessment services to obtain the necessary limits on indicators used in the requirements.

[4] EPREL public website
https://eprel.ec.europa.eu/screen/home

5. Definition of performance thresholds

The identification of specific values related to performance threshold will be developed in the framework of WP3. Reference values will be obtained from literature, technical standard and regulations. Table 2 and Table 3 show an example of values for both low energy and passive house buildings, according to both prescriptive and performance approaches.

Table 2: Technical requirements – prescriptive method (indicative values) (Source: [25])

Parameter	Heating DD ≥	Cooling DD ≥	Low Energy building			Passive House building		
Peak heating load [W/m^2] ≤	-	-	-			10		
Air tightness n_{50} [ach] ≤	2000	-	1.0			0.6		
	1500	-	1.0			1.0		
U-values [W/m^{2}K] ≤			Wall, Roof	Floor	Window[a]	Wall, Roof	Floor	Window[a]
	3000	-	0.15 – 0.18	0.13	1.2	0.10 – 0.15	0.13	0.8
	1500	-	-	-	-	0.15 – 0.30	0.35	1.2 – 1.5
	500	-	-	-	-	0.25 – 0.40	0.5 – 1.7	1.5 – 2.0
Thermal bridges ψ [W/mK] ≤	500	-	≤ 0.03			≤ 0.01		
Windows shading effectiv. (S, E, W) ≥	-	500	70 %			70 %		
Opaque env. displacement (S,E,W, Hor.) [h] ≥	-	500	10			10		
Thermal admittance Y [W/m²K] ≤	-	500	0.1			0.1		
Heat recovery efficiency ≥	-	-	70 %			80 %		
Specific Fan Power SFP [kW/(m^3/s)] ≤	-	-	2.0			1.5		

[a] overall, including frame

Table 3: Energy requirements – performance method (indicative values) (Source: [25])

Energy	Heating DD ≥	Cooling DD ≤	Low Energy building [kWh/m^{2}a]	Passive House building [kWh/m^{2}a]
Energy need for heating ≤	4000	-	30 – 50 or EU labels A/B	20 – 30
	500	-	EU labels A/B	15
Energy need for cooling ≤	-	1000	15 or EU labels A/B	
Primary energy ≤	-	-	-	120

Regarding lighting, an example of reference values for installed power in new LED lighting systems is reported in Table 4.

Referencing to the European regulation on light sources [26], the best available technology on the market for light sources in terms of their efficacy based on useful luminous flux was identified as follows:

- Mains voltage non-directional light sources: 120-140 lm/W
- Mains voltage directional light sources: 90-100 lm/W
- Directional light sources not operating on the mains: 85- 95 lm/W
- Linear light sources (tubes): 140-160 lm/W

The best available technology on the market for separate control gears has an energy efficiency of 95%.

For standby load for smart products, it is recommended a value of 0.3 W.

Table 4: Maximum installed power in W/m² for new lighting systems (Source: [27])

Type of building and room		Maximum W/m²
Art	Theater room	5.8
	Hall	5.8
	Exhibition hall	5.8
Hospital	patient room	5.6
	Observation room	10.3
	Treatment room	10.3
Hotel	Guest room	6.4
	Lobby	5.5
Office	Single and Group room	10,3
	large room	8,1
	Meeting room	10.3
	Hall	5.9
Restaurant	Restaurant	4.9
	Cafeteria	2.9
	Kitchen in restaurant	15.5
	Kitchen in Cafeteria	12.1
Retail	Food sales	12.3
	Shop	12.3
	Furniture sales	9.9
School	Class room	9.1
	Teachers room	6.2
	Library	4.9
	Concert hall	8.1
	Laboratories	9.1
Sport	Gym	9.3
	Fitness room	5.3
	Swimming hall	6.0
Parking area, Park house and others	Traffic area	2.9
	Hospital traffic area	5.9
	Stairwell	5.9
	Outbuildings	2.5
	Kitchen, Tea room	4.2
	WC, Bath, Shower	5.0
	WC	8.2
	Wardrobe, shower	4.7
	Car park	1.2
	Wash and Dry room	7.0
	Cooling room	2.3
	Server room	2.8

6. Definition of Self-assessment framework and user communication.

The communication between SATO Self-assessment framework (SAF) and end-users is a key feature to support the implementation of building-level SATO services that provide energy or cost savings while maintaining user satisfaction. In this section, the different types of communication, between the SAF and end-users, considered in SATO SAF are detailed.

The communication between the SAF and end-users of the SATO system can be divided in two levels:

- Passive feedback – The results of the SAF are openly available to end-users who wish to have a better understanding of the energy performance and indoor comfort conditions of their buildings/appliances in the form of figures, graphs, diagrams, KPI, etc..
- Active feedback – The SAF directly communicates with end-users by sending notifications, emails, etc., to inform and increase end-user's awareness about the energy performance and indoor comfort conditions of their buildings/appliances and to provide user guidance to trigger behaviour changes.

6.1. Passive feedback

Passive feedback refers to a communication type between the SATO SAF and the end-user where no automated control requirements are necessary. Instead, passive feedback aims to relay relevant information to the end-user, from the SATO SAF, that increases user awareness and create an informed basis for creating new or changing existing user actions.

Passive feedback is mainly achieved in SATO using information and data visualization techniques, using a mobile or web application as the user interface to convey this information.

6.1.1. Information

Different information can be shared with building occupants with the goal of reducing energy consumption and/or costs. The elicitation of such information in SATO is driven by user preferences, ensuring a user-centric design with a high satisfaction level on the indoor environment conditions.

The following information will be conveyed to the users of SATO:

- Key variables and indicators;
- Performance benchmarking;
- Visual metrics.

The key variables and indicators (see section 2) enable end-users to know their real performance and evaluate it over a period of time. While key variables and indicators are suitable for evaluations over larger periods of time, they may be challenging for evaluation by non-experts due to their technicality.

As such, the use of performance benchmarking enables to have both the long-term comparison of performance but also the short-term by comparing individual user or individual equipment performance with similar ones, such as neighbors' houses or equipment, countries' average performance or manufactures' performance labels. To ensure the compliance with data protection, benchmarking will be anonymized.

Visual metrics is a type of information that intends to be more user-friendly than key indicators or benchmarking. By using appealing schemes and graphics, SATO aims to engage more easily with the end-users. The information provided in these visual metrics can represent both key indicators and/or benchmarking metrics.

All the described information metrics will be accessible to end-users through the existing interfaces of the EDP re:dy management system, the SIEMENS TWINS, in the case of residential or commercial buildings respectively or other third-party solutions. The data granularity and scale should allow for individual appliance performance or overall building energy performance within a small timeframe.

6.2. Active feedback

Active feedback refers to the communication that is bi-directionally exchanged between the SAF and end-users, which is divided in alerts, and recommendations, and between end-users and the SAF, referred as user feedback loop.

6.2.1. Alerts

The end-users of the SAF will be able to receive communications as alerts. The aim of the alerts is to inform of possible malfunction and unexpected building, room and appliance performances. In addition to the alerts, tips may be given to end-users on how to solve the warned situations. With this information, end-users can trigger short-term behavior changes that can result in fast and tangible energy performance improvements.

The alerts will be communicated according to defined metrics and thresholds. A set of pre-defined alerts will be available in the framework, which can then be modified at any time by the end-users to best fit their preferences. Thus, end-users will have the capability to adjust pre-defined thresholds/preferences and to define new preferences (e.g., equipment turned on at unusual hours) and thresholds (e.g., energy consumption 20% higher/lower than usual) which will trigger the alerts. Additionally, end-users will be able to choose the priority level of the different alerts and the fastest way to be communicated to them. The alerts will be communicated to users with pop-ups/notification/emails, and user will be able to define which ones best adjust to their needs.

6.2.2. Recommendations

The SAF will produce recommendations that will be sent directly to end-users with the objective of improving the energy performance and comfort implicitly. The resultant increased awareness intends to trigger behavioral changes of end-users, and, ultimately, will result in the reduction of energy consumption while maintaining or increasing indoor comfort conditions.

The recommendation will be based on suggestions that will educate end-users on an incremental way. Thus, suggestions will increase complexity as user behavior and building performance increases with time.

Initially, the provision of recommendations will be based on current best practices and generally proven methodologies to improve the energy performance and indoor comfort conditions of buildings (e.g., operate your radiator rather on a steady low temperature level continuously rather than ramping the radiator up and down whenever you are too hot or too cold). As these methods are already widely known, others may not, whilst with increased usage and time, the SATO SAF will be able to learn the user behavior and send user-specific recommendations tailored to the individual usage patterns of the end-user.

Moreover, the SAF will differentiate user-specific recommendations (e.g., consider using more natural lighting during working hours; consider using more natural ventilation to reduce energy consumption or increase thermal comfort) and building-specific recommendations (e.g., for offices, consider turning off lighting systems overnight; consider sending alerts when detecting occupancy overnight).

Contrary to alerts, recommendations do not intend to trigger an immediate change. Recommendations aim to educate users and increase, on a step-by-step basis, the energy performance of the building and appliances. This process assumes that energy performance and user behavior can constantly evolve over time.

6.2.3. User feedback loop

Besides purely communicating information from the SAF to the end-users, the SATO concept foresees to establish a bi-directional communication flow between the system and user.

Within this user feedback loop, the user will be encouraged to provide feedback to the SATO system in case of malfunctions (e.g., missing data points, bugs, incorrect information), but also regarding the received alerts, recommendations and user preferences. The actual design of the user interfaces, mobile and web-based applications as well as overall system as part of the user-centric design approach, in particular during the demonstration phase of the project.

The user may also indicate the usefulness of certain functionalities offered and information provided by SATO based on ad-hoc surveys (e.g., How often do you use functionality XYZ? Rate from 1 to 5; Did you find this information helpful? Rate from 1 to 5; with 1 – fully agree and 5 – totally disagree).

This feedback will guide the improvement of the user-centric design towards user needs, by incorporating this knowledge in the development of the SAF, SATO platform and services in WP2 to WP4. Moreover, the users' feedback will help to better understand the actual performance of the system and troubleshoot issues during operation of the SATO system.

As part of WP5 of the SATO project the aforementioned theoretical approaches will be specified and implemented into interactive applications that will allow users (i.) to receive feedback and be incentivized with advice about the impact of potential investments onto energy performance of their building, and (ii.) provide feedback in an easy way (e.g. too hot or too cold), about their thermal comfort and/or select the preferred level of interaction and degree of automation. This may vary from high interaction/low automation (e.g., daily setting of heating and cooling set-points, manually selecting the day period for laundry) to low interaction/high automation (monthly check performance report, act only on incentives/suggested actions).

Users can also provide information about their schedule, or absences, so the SATO system can optimize its behavior accordingly.

7. Identification of communication methodologies

The way alerts and recommendations are sent to users depends not only on the type of user they are intended for, but mainly on the type (or severity) of the alert/recommendation that is sent.

Therefore, the communication of alerts and recommendations must be as effective and efficient as possible to reach their recipients at the right time. This is even more important for alerts related to malfunctions or devices that need immediate maintenance. Thus, the user interface should distinguish different levels of alerts and recommendations and should let users configure their interface to present this information in the most appropriate way. One could also consider having high severity alerts, which cannot be deactivated by users, thus ensuring that information is always delivered to recipients in the most critical situations.

Another important aspect in the delivery of alerts is that they should not only warn users of what is happening, but also help them resolve the situations in question. To do this, the interface when presenting alerts should also provide information or shortcuts to take users to the site or part of the application that will help them solve the problem. For example, if the user receives an alert that a particular appliance is overheating, that alert should include a direct link to the part of the interface that allows the user to reduce power or even turn off the appliance. Or if the system alerts an occupant to their high consumption, encouraging them to subscribe to a more flexible energy service, then the alert, sent by email, or SMS, should contain a direct link to the suggested service, reducing the effort to make the change happen.

To collect feedback from users, one can use surveys included in the application itself, such as the mechanisms used in social networks (e.g., Like/dislike), or a comfort scale, or emotional feedback (e.g., positive, neutral, negative), etc. The goal will be to collect information from users that will allow the system to understand if the suggestions or adaptations it is making are meeting their expectations.

In summary, situations that require a prompt response from the user, such as the failure of equipment crucial to the building's operation, should be communicated using alerts in the application (and/or via SMS), while less urgent situations could be communicated via lower priority alerts or email. In both cases, users should have the flexibility to choose how they want to receive alerts, and alerts should include additional information to help users perform the action that the alert/recommendation requires.

8. Security and privacy requirements

Privacy and data protection are two important issues that need to be ensured when connecting buildings to cloud-based platforms and services to users. To tailor the SATO assessments to different end-users and users' lifestyle, besides building and equipment related data, the SATO platform may collect information about occupants, such as their location and daily routines (e.g., movement patterns, energy habits, usage of electrical appliances, opening windows), energy use, and bills, or even information about their personal health. Safeguarding the privacy and security of personal, building, and equipment data, and developing secure systems, especially for remote control of smart building services is one of the key challenges addressed in SATO. The SATO platform and the consortium will observe and pursue strict compliance with the European General Data Protection Regulation (GDPR) and national legislation and directives relevant to the country where the data collections and data storage are taking place.

Each data item that will be stored and/or processed in the SATO platform will require associated descriptive metadata to specify its requirements on confidentiality, privacy, and availability.

Data items include building occupants' and platform users' personal data, data items metadata, variable measurements or other information coming from buildings, and all the performance metrics, indicators, and assessments that may be computed within the self-assessment framework.

8.1. Informed consent

It is important that end-users are aware of the data protection plan and explained on how their data will be used and protected. Individual research participants will be recruited for the residential pilots and, eventually, for office building pilots when/if building zones with permanent single occupants or permanent small groups of potentially identifiable occupants are considered.

Informed consent forms will be employed in the language of the potential participants and in terms easily understandable. An information sheet will accompany the consent form to convey relevant information on the project and on the participant involvement: aims, methodology, implications, and risks and benefits of the participation, including information on the data collected, its purpose, and the personal data protection mechanisms in place; and, inform on the right to refuse to participate and to withdraw the participation and all related data.

The informed consent procedure will guarantee some of the GDPR rights of the data subjects:

- Art. 12 GDPR – Transparent information, communication and modalities for the exercise of the rights of the data subject

- Art. 13 GDPR – Information to be provided where personal data are collected from the data subject
- Art. 14 GDPR – Information to be provided where personal data have not been obtained from the data subject
- Art. 15 GDPR – Right of access by the data subject
- Art. 21 GDPR – Right to object

8.2. Security

By observing the requirements on each data item, the SATO platform will guarantee its confidentiality, integrity, and availability. To guarantee these properties the platform will consider a Public Key Infrastructure (PKI) and appropriate functionalities in its design:

- Secure communications – all communication between platform components and between the platform and any external component, platform, application, or system operating on buildings or actor's devices, will be encrypted.
- Secure storage – stored data will be encrypted, including sensitive data temporarily stored on persistent storage of devices/equipment during operation.
- Authentication – Access to data items will be restricted to authenticated users or platform components. When required 2-way authentication will be used. When appropriate, Message Authentication Codes (MAC) will be used to guarantee integrity of messages.
- Authorization – the availability of data items will be governed using Access Control Lists (ACL). Thus, only authorized users and components will be granted access to specific data items. Each data item will have its own access control list.

8.3. Privacy

Each data item will have an associated privacy policy that specifies its privacy information, rules, and requirements. For personal data, this includes defining related GDPR roles such as the *data subject*, the *data controller*, the *data processors*, and de-identification and anonymization requirements. Additionally, and for all data items, it also specifies access controls.

The SATO platform architecture is being designed and built using techniques and methodologies to guarantee that all specified privacy requirements are observed and applied on the fly, to all data operations, in real-time. This will guarantee that all personal data (including data items generated by processing personal data, that are also considered personal), is constantly protected and that any change regarding the GDPR data subjects' rights is easily implemented:

- The right of access
- The right to rectification
- The right to erasure
- The right to restrict processing
- The right to data portability
- Rights in relation to automated decision making and profiling.

As appropriate, de-identification and/or anonymization techniques will be applied at different stages in the data flows of the SATO platform: when producing data in the building (e.g., when obtaining occupancy indicators from Wi-Fi/BlueTooth addresses), when storing data at the platform (e.g., when storing unidentifiable user IDs), or when communicating results to authorized users or stakeholders (e.g., anonymizing the information).

9. Definition of assessment and optimization methodology

When assessing the buildings energy performance, the current methodology usually consists of comparing the buildings real energy use to predicted theoretical values. This method is fairly easy to implement on a building level, but it does not necessarily provide a realistic measure of the building performance, as the foreseen condition and assumptions made in the predictions are rarely met during actual operation and the buildings therefore in practice usually cannot achieve the theoretical performance values.

The SATO project therefore focuses on using the building itself (or similar buildings) to provide more realistic measures of performance, and thereby providing more usable feedback for the building owners/operators in terms of how to best utilize the building.

To assess the performance of buildings, systems and individual components during real-life operation different methodologies can be applied. The definition of the type of models for assessing building, system and component performance, for identification of performance parameters and for automatic model parameter tuning can be categorized in different types.

The data timeseries used for performance assessment can be categorized in the following types:

Type 1: Parameter identification and performance assessment is based on measured data time-series. This could, for example, be a calculation based on the entire available empirical data. Either calculate a given parameter directly from the selected empirical data, e.g., calculate the energy use, indoor temperature, or outdoor weather conditions. This type can also include annual values, for example, energy use of the different systems, utilization of the individual systems, etc.

Type 2: Parameter identification and performance assessment is based on measured data time-series filtered according to specific periods (e.g., heating season, night), specific conditions (for example, weather, occupied/unoccupied), or specific characteristics (steady-state, dynamic). Parameters like heating profile, infiltration, the U-value, SFP, Heat Recovery Efficiency, COP, or other components can be calculated based on a subset of the available data. This subset is selected for specific periods when some disturbances are not present and allow direct estimation of a given parameter. E.g., domestic hot water is the only heating need from the district heating network during the summer period. Therefore, the summer period is better to estimate the DHW usage when only total heat demand from district heating is known [12, 13], or estimation of U-values are more suitable if using winter data during the night when the internal gain is stable, when the temperature is relatively stable, when there is usually no natural ventilation and when the temperature difference between the indoor and the outdoor is at maximum.

Type 3: Parameter identification and performance assessment is based on dynamic in-situ testing and data analysis carried out during specific limited periods and under specific conditions by modifying system control and operation. On-site investigation can consist of e.g., direct inspection of filters in ventilation systems, direct inspection by experts, direct inspection of the insulation layer, investigating U-value of a building wall, blower door test (leakage/infiltration), and verifying stability, accuracy etc.

Similar methods as used for fault detection and diagnosis can be used for building, system and components performance assessment. Fault detection and diagnosis methods cover a wide field, as they span from quantitative model-based to qualitative model-based to process history-based [26]. Faults are in this context seen as both mechanical failures, as well as poor performance or lack of optimization. These three main categories of methods cover several different sub-categories, as seen on Figure 11.

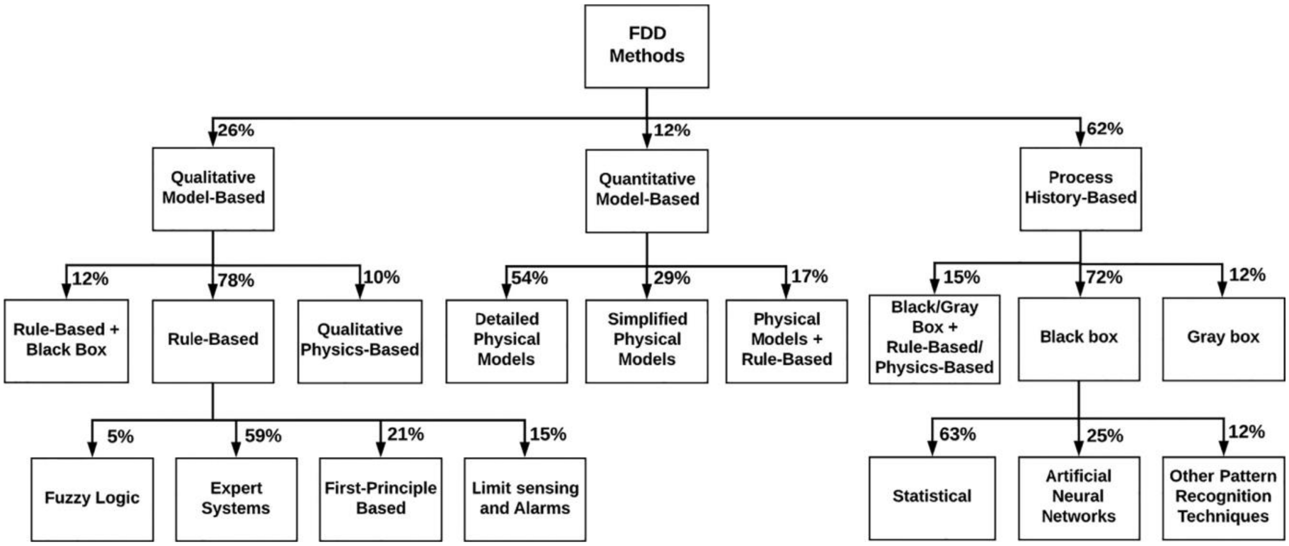


Figure 11: Classifications for fault detection and diagnosis along with share of publications containing them [27].

Over time these different categories have received different attention, as it was found in [19] that out of 197 reviewed publications 62% of those were about Process history-based approaches, while Qualitative and Quantitative model-based were only used in 26% and 12% respectively.

Development and implementation of data-driven methods for automated detection and diagnosing faults in buildings have significantly increased over the last decade. Parameter identification and performance assessment can consist of, for example; calibrating grey-box models from either empirical data from building management system (BMS), building operation, or by heating up an un-occupied building (from data recorded during unoccupied building with a heating system, and recorded both from accurate internal heat load and temperature response of the building to calibrate the grey-box model). From this calibrated grey-box model, characteristics of the building can be directly extracted [15]. This grey-box model can also be used for design optimization, model predictive control (MPC), or further developed for fault detection and diagnosis. Sun et al. [16] developed a simply device-level grey-box model for fault detection that can detect both device faults and propagate the effect of the faults across subsystems using statistical process control (SPC) and Kalman filter.

Virtual sensors have also shown potential to perform fault detection in an AHU, as done by Mattera et al. [17], the study investigated a combination of system knowledge and black-box models, where it was known which variables influenced the desired parameter. To calculate the output, a linear regression model was applied. The virtual sensor approach has also been applied in the study of Verbert et al. [18].

Many studies demonstrate successful automated fault diagnostic and fault detection methodologies (AFDD) using black-box models. Polynomial regression (PR), autoregressive (AR), principal component analysis (PCA), logistic regression (LR), and partial least squares (PLS) were the most used statistical techniques [19]. Serval other studies have successfully used artificial neural networks (ANN) as a fault detection method to a chiller [20 - 21], VAV-system [22], and the air condition system [23]. Also, the support vector machine (SVM) method has shown the potential to detect faults in chillers [20, 24] and the electrical system (electrical power for lighting and total active electrical power) [25].

In general, all the different methods have advantages and disadvantages, some of these can be seen in Table 5. In WP3 of the SATO project different methods will be developed and applied depending on the purpose and the complexity and collected in a common toolbox. Qualitative model-based methods will typically be used for assessment of individual component performance, quantitative model-based methods will typically be used for assessment of individual components and simpler systems performance while process history-based methods will be used for the more complex systems and whole building assessment. Guidance on the selection, application and realistic expectations of the different methods will be provided after test and evaluation in the use cases.

Table 5: Advantages and disadvantages on the different FDD categories [19]

Category	Advantages	Disadvantages
Qualitative model-based	- Simple to develop - Simple to implement - Does not necessarily require detailed knowledge about how the system is governed - Fastest type to deploy	- Very specific to the individual system/component - Can be difficult to expand the rules, without affecting other rules or losing the simplicity - Depends on the expertise of the person(s) implementing them
Quantitative model-based	- Based on sound physical/engineering - Can model both normal and faulty operations - Can capture transient behavior	- High complexity - Expensive to develop - Hard to generalize - Necessary data may not be available in the field
Process history-based	- Well suited for problems where precise models are lacking - Good for use with large datasets or areas where data is cheap to collect - Relatively easy to implement	- Is usually not valid beyond the range of the training data - Specific for the system - Require large amounts of data - Black box models consist of thousands of different variations, so it can be difficult to know which to use - Grey box models require a high level of user expertise to implement

After identification and assessment of the performance of individual components, systems and/or buildings, the performance should be compared to a relevant reference, see section 4, evaluated and a decision made of specific actions to carry out to improve it. Figure 12 below describes a generic methodology to perform fault detection and diagnosis/isolation process, together with fault evaluation and decisions for actions to improve operation of the desired system based on [14].

In WP4 of the SATO project different methods will be developed and applied for evaluation and decision support in order to deliver the required optimization services and control actions. The methodologies will be collected in a common toolbox and guidance on the selection, application and realistic expectations of the different methods will be provided after test and evaluation in the use cases.

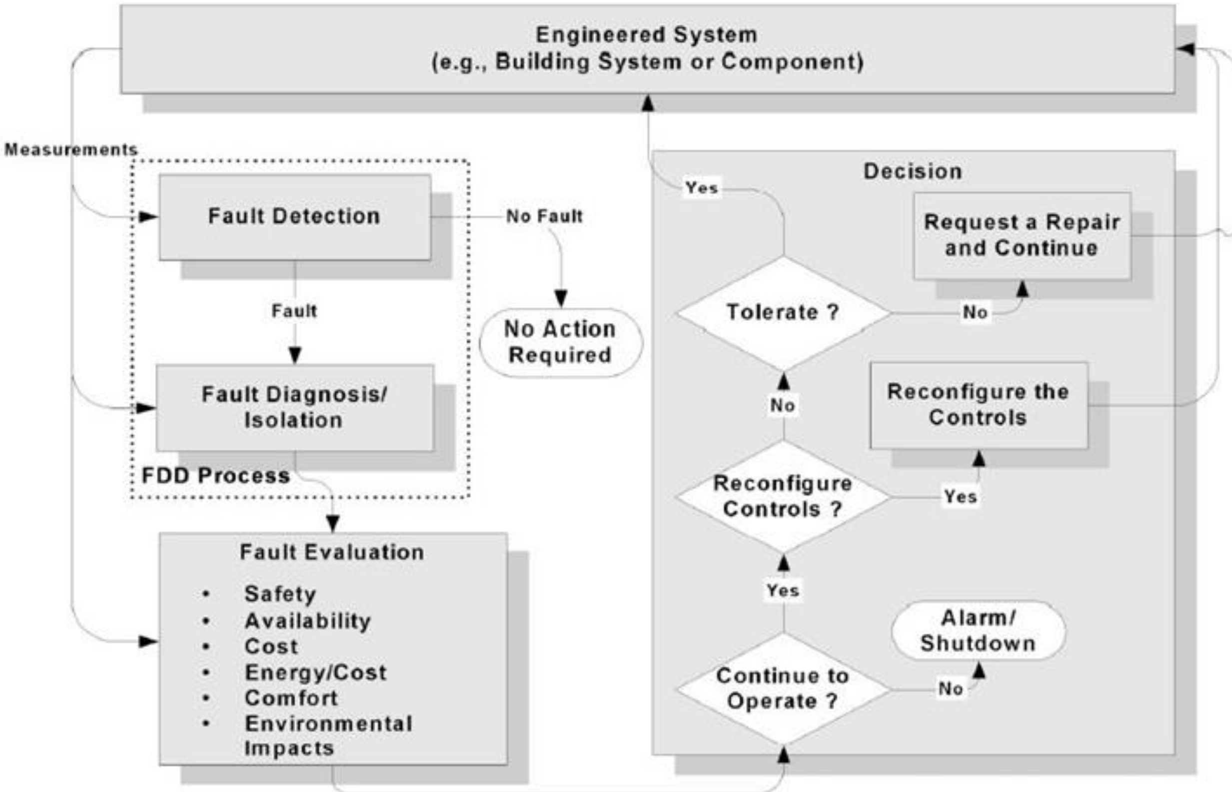


Figure 12: Generic methodology of fault detection and diagnostics for operation and maintenance of a desired system based on [14].

10. References

[1] Pagliano L, Roscetti A, A BPIE guide to implement the Energy Performance of Buildings Directive, Annex I – Calculating energy performance.

[2] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

[3] International Organization for Standardization, ISO 52016-1:2017 - Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures. 2017, p. 204.

[4] International Organization for Standardization, ISO 52018-1:2017 - Energy performance of buildings - Indicators for partial EPB requirements related to thermal energy balance and fabric features - Part 1: Overview of options. 2017, p. 43.

[5] Pagliano L, Erba S, Peuportier B. Definition of indicators and assessment methods - an AZEB projects Report [Internet]. 2019 Apr. Report No.: D.2.1. Available from: www.azeb.eu

[6] CEN/TR 16798-2:2019 - Energy performance of buildings - Ventilation for buildings. Part 2: Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for

design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Module M1-6)

[7] ANSI/ASHRAE Standard 55-2020 – Thermal Environmental Conditions for Human Occupancy

[8] Carlucci, S., Pagliano, L., & Sangalli, A. (2014). Statistical analysis of the ranking capability of long-term thermal discomfort indices and their adoption in optimization processes to support building design. Building and Environment, 75, 114–131. https://doi.org/10.1016/j.buildenv.2013.12.017

[9] https://comfort.cbe.berkeley.edu/

[10] Tartarini, F., Schiavon, S., Cheung, T., Hoyt, T., 2020. CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations. SoftwareX 12, 100563. https://doi.org/10.1016/j.softx.2020.100563

[11] EN ISO 7730 – Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 3rd version, International Standard Organization, Geneva (2005).

[12] Dama, E. De Lena, G. Masera, L. Pagliano, M. Ruta, P. Zangheri. 2014. Design and Passive Strategies Optimizazion towards Zero Energy Target: The Case Study of an Experimental Office Building in Milan. Building Simulation and Optimization Conference, At London

[13] Erba, S., & Pagliano, L. (2020). AZEB Best Practices Manual for Users. www.azeb.eu

[14] Sfakianaki, A., Santamouris, M., Hutchins, M., Nichol, F., Wilson, M., Pagliano, L., Pohl, W., Alexandre, J. L., & Freire, A. (2011). Energy Consumption Variation due to Different Thermal Comfort Categorization Introduced by European Standard EN 15251 for New Building Design and Major Rehabilitations. International Journal of Ventilation, 10(2), 195–204. https://doi.org/10.1080/14733315.2011.11683948

[15] Arens, E., Humphreys, M. A., de Dear, R., & Zhang, H. (2010). Are 'class A' temperature requirements realistic or desirable? Building and Environment, 45(1), 4–10. https://doi.org/10.1016/j.buildenv.2009.03.014

[16] d'Ambrosio, F. R., Palella, B. I. and Riccio, G. (2006) 'Thermal comfort design in indoor environments: A comparison between EU and USA approaches', in Proceedings of Healthy Buildings 2006, Lisbon, vol II, pp1–6

[17] Alfano, G., d'Ambrosio, F. R. and Riccio, G. (2001) 'Sensibility of the PMV index to variations of its independent variables', in Proceedings of Thermal Comfort Standards into the 21st Century, Windsor, April, 158–165

[18] EN ISO 7726:2001 Ergonomics of the thermal environment - Instruments for measuring physical quantities

[19] Pagliano, L., & Zangheri, P. (2010). Comfort models and cooling of buildings in the Mediterranean zone. Advances in Building Energy Research, 4(1), 167–200. https://doi.org/10.3763/aber.2009.0406

[20] McIntyre, D. A. (1980) 'Design requirements for a comfortable environment', in K. Cena and J. A. Clark (eds) Bioengineering: Thermal Physiology and Comfort, Elsevier, Amsterdam, pp157–168

[21] Miller, G. (1956) 'The magic number seven, plus or minus 2', Psychological Review, vol 67, pp81–97

[22] EN 16798-3:2017 - Energy performance of buildings. Ventilation for buildings. For non-residential buildings. Performance requirements for ventilation and room-conditioning systems.

[23] Hermelink A, Pagliano L, Voss K, Zangheri P, Schimschar S, Armani R, et al. Towards nearly zero-energy buildings - Definition of common principles under the EPBD - Final report [Internet]. 2013. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_full_report.pdf

[24] https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager/understand-metrics/how-1-100

[25] Sartori I, Candanedo J, Geier S, Lollini R, Athienitis A, Pagliano L, et al. Comfort and Energy Efficiency Recommendations for Net Zero Energy Buildings. In: Proceedings of the EuroSun 2010 Conference [Internet]. Graz, Austria: International Solar Energy Society; 2010. p. 1–8. Available from: http://proceedings.ises.org/citation?doi=eurosun.2010.06.20

[26] COMMISSION REGULATION (EU) 2019/2020 of 1 October 2019 - Laying down ecodesign requirements for light sources and separate control gears pursuant to Directive 2009/125/EC of the European Parliament and of the Council and repealing Commission Regulations (EC) No 244/2009, (EC) No 245/2009 and (EU) No 1194/2012.

[27] Premium Light PRO (H2020 EU project) guidelines on indoor LED lighting in service sector (update 2019). Available from: http://www.premiumlightpro.eu/indoor-lighting/guidelines-downloads/

[28] S. K. Lien, D. Ivanko & I. Sartori, "Domestic hot water decomposition from measured total heat load in Norwegian buildings," BuildSim Nordic 2020. SINTEF Proceedings 2020.

[29] A. Marszal-Pomianowska, C. Zhang, M. Pomianowski, P. Heiselberg, K. Gram-Hanssen, and A. R. Hansen, "Simple methodology to estimate the mean hourly and the daily profiles of domestic hot water demand from hourly total heating readings," *Energy Build.*, vol. 184, pp. 53–64, 2019, doi: 10.1016/j.enbuild.2018.11.035.

[30] S. Katipamula and M. R. Brambley, "Review Article: Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems—A Review, Part II," *HVAC R Res.*, vol. 11, no. 1, pp. 3–25, 2005, doi: 10.1080/10789669.2005.10391133.

[31] R. E. Hedegaard, M. H. Kristensen, and S. Petersen, "Experimental validation of a model-based method for separating the space heating and domestic hot water components from smart-meter consumption data," *E3S Web Conf.*, vol. 172, pp. 1–8, 2020, doi: 10.1051/e3sconf/202017212001.

[32] B. Sun, P. B. Luh, Q. S. Jia, Z. O'Neill, and F. Song, "Building energy doctors: An SPC and Kalman Filter-based method for system-level fault detection in HVAC systems," *IEEE Trans. Autom. Sci. Eng.*, vol. 11, no. 1, pp. 215–229, 2014, doi: 10.1109/TASE.2012.2226155.

[33] C. G. Mattera, J. Quevedo, T. Escobet, H. R. Shaker, and M. Jradi, "A Method for Fault Detection and Diagnostics in Ventilation Units Using Virtual Sensors †," pp. 1–21, 2018, doi: 10.3390/s18113931.

[34] K. Verbert, R. Babu, and B. De Schutter, "Engineering Applications of Arti fi cial Intelligence Combining knowledge and historical data for system-level fault diagnosis of HVAC systems," vol. 59, no. January, pp. 260–273, 2017, doi: 10.1016/j.engappai.2016.12.021.

[35] W. Kim and S. Katipamula, "A review of fault detection and diagnostics methods for building systems A review of fault detection and diagnostics methods for building systems," vol. 4731, 2018, doi: 10.1080/23744731.2017.1318008.

[36] H. Han, B. Gu, Y. Hong, and J. Kang, "Automated FDD of multiple-simultaneous faults (MSF) and the application to building chillers," *Energy Build.*, vol. 43, no. 9, pp. 2524–2532, 2011, doi: 10.1016/j.enbuild.2011.06.011.

[37] Q. Zhou, S. Wang, and F. Xiao, "A novel strategy for the fault detection and diagnosis of centrifugal chiller systems," *HVAC R Res.*, vol. 15, no. 1, pp. 57–75, 2009, doi: 10.1080/10789669.2009.10390825.

[38] O. Morisot and D. Marchio, "Fault Detection and Diagnosis on Hvac Variable Air Volume System Using Artificial Neural Networks," *Proc. IBPSA Build. Simul.*, vol. 105, p. 1087, 1999, [Online]. Available: http://www.ibpsa.org/proceedings/bs1999/bs99_pb-09.pdf.

[39] Z. Hou, Z. Lian, Y. Yao, and X. Yuan, "Data mining based sensor fault diagnosis and validation for building air conditioning system," *Energy Convers. Manag.*, vol. 47, no. 15–16, pp. 2479–2490, 2006, doi: 10.1016/j.enconman.2005.11.010.

[40] S. M. Namburu, M. S. Azam, J. Luo, K. Choi and K. R. Pattipati, "Data-Driven Modeling, Fault Diagnosis and Optimal Sensor Selection for HVAC Chillers," in IEEE Transactions on Automation Science and Engineering, vol. 4, no. 3, pp. 469-473, July 2007, doi: 10.1109/TASE.2006.888053.

[41] A. Capozzoli, F. Lauro, and I. Khan, "Fault detection analysis using data mining techniques for a cluster of smart office buildings," *Expert Syst. Appl.*, vol. 42, no. 9, pp. 4324–4338, 2015, doi: 10.1016/j.eswa.2015.01.010.

[42] S. Katipamula & M. Brambley, Methods for Fault Detection, Diagnostics and Prognostics for Building Systems - A Review Part I, HVAC&R Research Volume 11, number 1 (2005), DOI: 10.1080/10789669.2005.10391133

[43] M. Bang, S.S. Engelsgaard, E.K. Alexandersen, M.R. Skydt, H.R. Shaker & M. Jradi, Novel real-time model-based fault detection method for automatic identification of abnormal energy performance in building ventilation units, Energy and Buildings 183 (2019) 238-251, DOI: 10.1016/j.enbuild.2018.11.006