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P. 2.1
Methodology for the measurement and evaluation of Energy Efficiency and Sustainability Indicators

Project: New Evaluation Method for Homes of Social, Sustainable and Energy Efficient Interest – Architecture for Climate- in the Sudoe Territory (ARCAS)

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Author(s)	Ivan Flores; Moisés Odriozola
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EXECUTIVE SUMMARY

This document describes the results obtained in the scope of the work package 2 (WP 2) of the ARCAS Project, concerning the identification of the most suitable energy efficiency and sustainability indicators and the definition and selection of the sensors needed to evaluate those indicators.

The structure of this report is as follows: Firstly, in section 1 a brief summary of the project as a whole is made, dedicating section 1.2 to the more detailed description of WP 2. Later, in section 2, a summary of the indicators chosen in this WP is exposed.

In section 3, an analysis of the variables to be measured for the determination of the indicators described in the previous section is made. It also describes the most common sensors available on the market to measure these variables.

Subsequently, section 4 describes different monitoring system configuration alternatives. In addition, aspects related to data acquisition and post-processing are detailed. After this general review, the main conclusions of this report are summarized in section 5. Finally, the references used are included in section 6.

The following acronyms and nomenclature are used within this evaluation report:

$\%H_{I\text{-}II}$	Percentage of hours in adequate comfort conditions (category I or II)
AMR	Automatic meter reading
Cp	Specific heat
C_v	Coefficient of heat losses due to total air change (ventilation + infiltration)
d	Diameter
DAS	Data Acquisition System
DHW	Domestic Hot Water
ΔT	Temperature difference
$\dot{E}_u$	Useful effect (heating, cooling, …)
$\dot{E}_{cons}$	Energy consumption
FE	Final energy consumption
GHG	Greenhouse gas
GWP	Global Warming Potential
h_c	Convective heat transfer coefficient
h_r	Radiative heat transfer coefficient
HLC	Heat Loss Coefficient of the building
IDAE	Instituto para la Diversificación y el Ahorro de Energía
$K_{electricity}$	Internal gains due to electricity consumption
$K_{ocuppancy}$	Internal gains due to occupants
LCA	Life Cycle Assessment
LP gas	Liquefied petroleum gas
m	mass
PE_C	Total primary energy consumption
PER_C	Renewable primary energy consumption
PER_P	Renewable primary energy production
Q	Total power input from space heating
Re	Reynolds number
RH	Relative Humidity
S_a	Solar aperture

SHGC Solar Heat Gain Coefficient

T_{GT} Temperature measured by the globe thermometer

T_{in} Indoor temperature

T_{out} Outdoor temperature

U Internal energy of a material

U_w Thermal transmittance of the wall/window

UA Global heat transfer coefficient of the envelope of the building

$\dot{V}$ Volumetric flow rate

V_{sol} Vertical south global solar radiation

v Velocity of the air

WP Work Package

α Primary energy factor

ρ Density

ε Emissivity

η_{equip} efficiency of the equipment

θ_a Temperature of the air

θ_{cl} Temperature of the clothing

θ_{de} External design temperature

θ_{di} Internal design temperature

θ_{imin} Lower comfort limit

θ_{imax} Upper comfort limit

θ_r Mean radiant temperature

θ_{rm} Outdoor running mean temperature

θ_{OCT} Optimal comfort temperature

σ Stefan-Boltzmann constant ($\sigma = 6.57 \cdot 10^{-8}$ $W/m^2 \cdot K^4$)

1 CONTEXT

1.1 The ARCAS Project

The objective of the ARCAS project is to develop an assessment and design methodology aimed at the renovation of buildings and groups of multifamily housing buildings of social interest, to address energy poverty and promote sustainable renovation, energy efficiency and healthy indoor environments in the SUDOE territory. The project is based on the integration of three research axes:

AXIS 1 - Energy autonomy - efficiency

AXIS 2 - Social quality - energy poverty

AXIS 3 - Air quality - health

As a result of this integration, the work in the project is developed to determine the optimal relationship between the three mentioned axes and obtain the best energy efficiency while maintaining the social quality and well-being of citizens.

ARCAS is based on the use of similar climatology in the South Atlantic region for the development of a tool that allows, through key indicators, the design of building architecture based on maximizing energy efficiency, air quality and thus promoting social welfare, making use of the best available techniques, including renewable energy sources.

This project combines efforts to develop strategies and measures that facilitate the development of policies, at national, regional and local governments scale, for the renovation of multifamily housing buildings with great autonomy and energy efficiency (axis 1), with healthy air quality for building occupants (axis 3) and reducing energy poverty, which is so important in many European countries (axis 2).

ARCAS results and outcomes will be applicable and reproducible in the public and private institutions participating in the project and will be especially useful for professional associations, manufacturers, builders and for national, regional and local public administrations.

The Action Plans that will be developed in an integrated manner on the three axes of the research project by ARCAS beneficiaries, in collaboration with ARCAS associated partners, constitute a key element that will ensure the transfer of knowledge to the entire SUDOE territory, as well as the future sustainability of the ARCAS methodology.

From a methodological point of view, the project is structured in different Work Packages (WP). In the first phase, the indicators that will be used in the ARCAS methodology are defined. These indicators are proposed within the first four Work Packages, as well as the specifications and protocols for their quantification. Those four Work Packages are specifically:

WP 1 - Climate indicators selection

WP 2 - Selection of energy efficiency indicators in residential buildings

WP 3 - Selection of indicators on best technologies available in renewables

WP 4 - Selection of social quality indicators

In WP 5, the ARCAS methodology will be developed and implemented in a computer tool. Therefore, it is essential that the indicators selected in the previous WPs can be measurable and evaluable, in addition to being compatible with their application to different types of residential buildings and in different countries.

The methodology will be validated in WP 6. For this, a set of demonstration buildings will be selected. As selection criteria, buildings that include a casuistic representative of the three axes considered and the three countries of the consortium will be sought.

WP 7, WP 8 and WP 9 encompass the part of the project that can be considered as the capitalization part. More specifically, in WP 7, the ARCAS certification procedure will be detailed, generating a series of guides for project owners, and other relevant actors that will audit ARCAS projects. This work will be carried out in coordination with the associated partners of the project. As for WP 8, this group of tasks has as its main objective the training of professionals, and to achieve it, a training program will be defined to train professionals in the application and certification of the ARCAS method, and a pilot program will be provided training in professional institutions that belong to the ARCAS project value chain. Finally, in WP 9, strategies will be developed to establish new sustainability, energy efficiency and social quality policies in the renovation of multifamily buildings of social interest. This includes, amongst others, proposals for renovation policies, financing models and criteria to prioritize interventions. For that, the indicators defined in WPs 1 to 4 will be used and will be carried out in coordination with the public administrations and private organizations associated with the ARCAS project.

1.2 WP 2 – Selection of energy efficiency indicators in residential buildings

The main objective of WP 2 is to identify and select appropriate energy indicators. These indicators will allow a holistic assessment of the energy efficiency aspects of residential buildings. For this purpose, two secondary objectives can be identified:

1. Selection of the indicators: European energy policies context is analysed to determine which indicators are mandatory at the European level, as well as the national and regional regulations. This analysis is completed considering the indicators that are the most widely used by the scientific community.

2. Definition of the minimum sensor specifications and measurement protocols: The minimum requirements of the measurement instrumentation are established based on the accuracy, reliability, connectivity, visual impact once placed in the dwelling, cost, etc.

In relation to the measurement methodologies and protocols, it is essential to notice that each partner is going to test some buildings in their own region, so these methodologies and protocols must be reliably applicable by all the partners. Furthermore, once the ARCAS project is completed, those methodologies and protocols are expected to be conducted by agents who have not participated in the development of the project, which reinforces this idea.

Therefore, this report contains the most relevant information regarding the second activity of the WP 2.

2 ENERGY EFFICIENCY AND SUSTAINABILITY INDICATORS

Within the second axis of the ARCAS project, called energy efficiency and sustainability, several indicators have been identified for the following 4 categories: energy consumption and production, thermal comfort, energy quality of the building and sustainability.

In the deliverable 2.1.1, a search was carried out for energy efficiency indicators commonly used, both at the regulatory level and in the field of research. After analysing their suitability to the objectives of the ARCAS project, the set of indicators shown in Table 1 were selected.

Table 1 – Selected indicators in WP2

Indicators	**Description**
Primary energy consumption	Total primary energy consumption, per m^2 of conditioned floor area. It will be measured disaggregated by use (heating, cooling, DHW, lighting and auxiliaries).
Energy needs	For heating or cooling. Heat to be delivered to or extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period of time.
Renewable energy self-sufficiency ratio	Ratio between the renewable energy consumption and total primary energy consumption (PER_C/PE_C).
Renewable energy self-consumption ratio	Ratio between the renewable energy consumption and renewable energy production (PER_C/PER_P)
$\%H_{I-II}$	Percentage of hours that the dwelling is in adequate comfort conditions (category I or II) according to standard EN 16798-1 [1]
HLC	Heat Loss Coefficient. It measures the total thermal losses of the building through the envelope (including thermal bridges and total air change) per unit of the temperature difference between indoor and outdoor temperatures.

Indicators	Description
GWP	Global Warming Potential. CO_2 emitted related with materials and equipment lifecycle, as well as the type of energy production during operational use of the building
Embodied energy	Direct and indirect energy consumption related with materials and equipment lifecycle

3 MEASUREMENT METHODOLOGY AND SENSORS

When the indicators of Table 1 were selected, a very important criterion for the development of the ARCAS project was taken into account. Proposed indicators must be able to be measured accurately and at low cost, using the simplest possible techniques. One of the objectives is that, once the project is finished, technicians who have not been part of it, will be able to apply the ARCAS methodology. Thus, measurement protocols must be as simple as possible.

Another consideration is that the sensors installed to carry out the measurements must make less visual impact as possible. The sensors and devices chosen, will stay installed for several months in the proposed dwellings, therefore, an extra effort must be made to install them in a less invasive way for the inhabitants.

Based on the above premises, the equipment necessary for the evaluation of the selected indicators is detailed in the following subsections.

3.1 Primary energy consumption

Definition: Total primary energy consumption, per m^2 of conditioned floor area. It will be measured disaggregated by use (heating, cooling, DHW, lighting and auxiliaries).

3.1.1 How to obtain the indicator value

To determine the primary energy consumption of the building or an apartment it is necessary to measure the final energy consumption of different types of energy: electricity, natural gas, biomass, renewable, …

Once the final energy consumption of the different types of energy is known, the primary energy factors of each type of energy are applied to determine the primary energy.

$$PE_{C,i} = FE_{C,i} \cdot \alpha_i$$

Where $PE_{C,i}$ is the primary energy consumption per square meter of conditioned area$\left[\frac{kWh_{PE}}{m^2}\right]$; $FE_{C,i}$ is the final energy consumption $\left[\frac{kWh_{FE}}{m^2}\right]$; α_i is the primary energy factor $\left[\frac{kWh_{PEC}}{kWh_{FE}}\right]$; and i is the energy source.

How final energy consumption is measured is described in the following subsection. Regarding the primary energy factors, they are shown in Table 2.

Table 2 - Primary energy factors for France, Portugal, and Spain (Source in each column).

Energy source	France	Portugal [2,3]	Spain [4]
LP gases	1	1	1.204
Biomass (pellets)	1	1.34	1.113
Natural Gas	1	1	1.195
Electricity	2.3	2.5	2.403

The following table shows the conversion factors for converting different units of measurement to kWh of primary energy, depending on the LHV of the fuel used.

Table 3 – Conversion factors from different units of measurement to primary energy [5].

Fuel	Conversion factor	Units
Butane	15.17	$\frac{kWh_{PE}}{kg}$
Propane	15.53	$\frac{kWh_{PE}}{kg}$
Biomass (in general)	4.36	$\frac{kWh_{PE}}{kg}$
Natural gas	13.87	$\frac{kWh_{PE}}{Nm^3}$

3.1.2 How to measure the needed variables

There are different energy sources, therefore, how to measure each one is different. We can classify them into two main groups: heat generation and electricity. The former includes heating and DHW, excluding those cases where electric radiators are used for heating or electric water heaters are used for DHW production. The latter includes the energy consumption related to cooling, lighting and auxiliaries.

3.1.2.1 Heat generation

For **heat generation** (non-electric), the final energy consumption can be determined in two ways:

Direct measurement. It would require the installation of a gas flow meter.

There are several types of gas meters, the most commonly installed ones are through diaphragm, rotatory and turbine gas meters [6].

The diaphragm meter is the most used type by distribution companies due to the simplicity and low cost, however wear problems, pressure losses and that they cannot indicate instantaneous flow rate value are the main disadvantages. However, due to the large number of traditional gas meters that are already installed, many manufacturers have developed an automatic meter reading (hereinafter AMR) solution. This AMR solution is used to upgrade the traditional gas flow meter to a smart flow meter.
In the case of high gas flow rates and when high-accuracy measurements are required, the rotatory meters suit well. Nevertheless, recently many static devices have been developed; one of those devices is the ultrasonic flow meter. This device shows high-accuracy and it is not intrusive, which make it very suitable for use in home monitoring.

The gas flow meters are widely available in the market. Its cost varies according to measuring technology, the compatibility with AMR solutions and the measuring range. In general, the static gas flow meters are more expensive than the dynamic meters.

Once the gas flow rate has been measured, the primary energy consumption can be determined from the values in Table 3.
One of the disadvantages of this method is that in the case of combi boilers, it does not allow differentiation between consumption due to heating and DHW production.

Indirect measurement. This method consists of obtaining the energy consumption from the measurement of the useful effect ($\dot{E}_u$), according to:

$$\dot{E}_{cons} = \frac{\dot{E}_u}{\eta_{equip}}$$

Where η is the efficiency of the equipment.

The useful effect is generally the heating of a water flow rate $\dot{Q}$, so it can be determined according to the following formula:

$$\dot{E_u} = \dot{Q} = \dot{V} * \rho * Cp * \Delta T$$

Where parameters are the following ones:

- $\dot{V}$: water flow rate [m^3/s]
- ρ: density [kg/m^3]
- Cp: specific heat [J/kg K]
- ΔT: temperature difference between supply and return [K]

There is a device called 'calorimeter' which directly provides the value of $\dot{Q}$, according to the above formula. It is composed of one flow meter and two temperature probes. Nowadays, calorimeters use an ultrasonic flow meter with no moving elements, which is able to measure water flow by measuring the time elapsed between the transmission and the reception of an ultrasonic signal. Thanks to this technology, aspects like accuracy and maintenance have improved significantly. Moreover, air bubbles that are responsible for several problems in traditional flow meters are not a problem. In the following images, the operation scheme (Figure 1) and one example of this kind of devices (Figure 2) are shown.

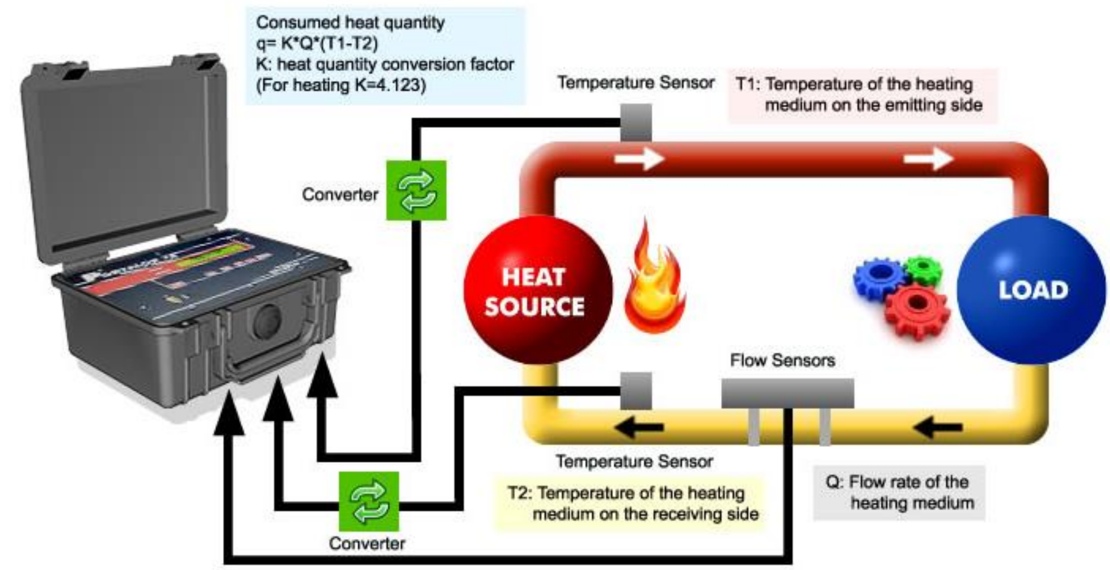

Figure 1 – Operation scheme of a calorimeter (Source: [7])

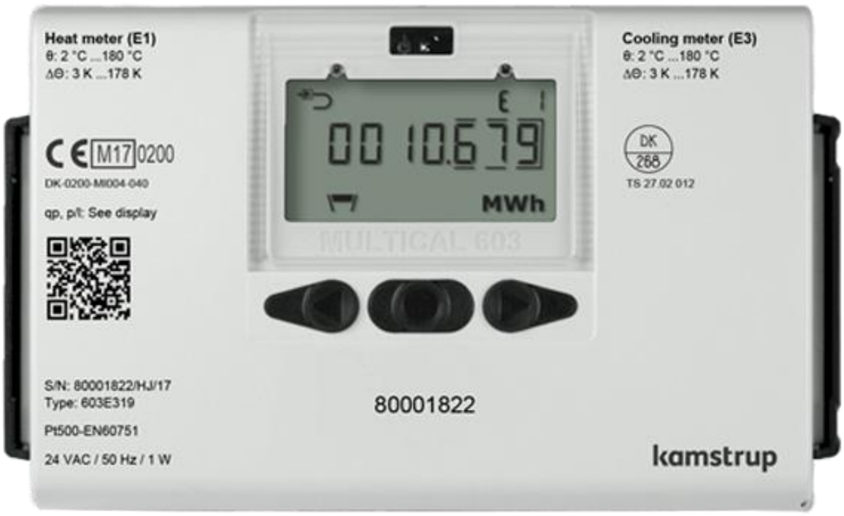

Figure 2 - Example of calorimeter (*Kamstrup Multical 603)* (Source: [8])

There are some specifications that have to be established before choosing a specific calorimeter. For example, nominal diameter, supply (electrical or battery), communication protocol, etc. are parameters that can be more or less suitable for the dwelling where they will be installed.

In Annex 1 there are some specifications about different calorimeters available in the market.

3.1.2.2 Power consumption

For the measurement of **power consumption**, there are a wide variety of sensors capable of measuring power consumption. In fact, when referring to "smart homes", they used to be houses equipped with this kind of sensors. If it is required to measure the final consumption of each use (lighting, auxiliaries, cooling, …), one device per each use is necessary. To obtain the total final electricity consumption, one energy module is enough.

Power meters. best known as energy modules, are used in the majority of research works related to monitoring. These energy modules can be divided into high-class modules, middle-class modules or low-class modules.

The classification depends on the capabilities of the module. In the study carried out by Dominguez et al. [9], they used high-class and middle-class modules to monitor the power consumption of several buildings. The high-class ones are capable of conducting a thorough analysis of electrical power. Taking into account the needs of the project and the difference in price, perhaps the option of a middle-class module is the most appropriate.

Traditionally, electromechanical meters have been the most widely installed in buildings. However, in recent years they have been replaced by electronic meters. The latter is more accurate and allows data to be stored and managed.
The accuracy of the electricity meters depends on the metering class, but the typical accuracy values are ranged between ±0,5% and ±2%.
In Annex 1 there are some specifications about different power meters available on the market.

3.2 Energy needs

Definition: For heating or cooling. Heat to be delivered to or extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period of time.

The energy class index is obtained from the energy class certificate, and it is defined based on total primary energy consumption and the CO_2 emissions. In order to get the energy class certificate, it is necessary to simulate the performance of the building. To do so, standardised operational characteristics of the buildings are defined to compare the results to the reference building.

The same procedure is mandatory in France, Portugal and Spain, although the simulation code and the operational characteristics of the building may differ. It seems logical to use the results of the certification process to define the energy needs of the buildings in ARCAS methodology.

3.3 Renewable energy self-sufficiency ratio

Definition: Ratio between the renewable energy consumption and total primary energy consumption (PER_C/PE_C).

How to measure the primary energy consumption has been defined in section 3.1, therefore, only how to measure the renewable energy production is needed.

As in the case of final energy, two are the main types of energy: electricity and heat. Electricity production can be measured with an energy module as it has been explained before (subsection 3.1).

When heat production is considered, the most common renewable production technologies are solar collector, geothermal energy and biomass. When solar collector and geothermal energy are considered, a working fluid is the energy carrier. Therefore, using a calorimeter that measures the flow rate and temperature difference of the working fluid is enough to determine the energy production of those technologies. For biomass, the consumed quantity has to be measured~~,~~ and then using the low heating value obtain the produced energy.

3.4 Renewable energy self-consumption ratio

Definition: Ratio between the renewable energy consumption and renewable energy production (PER_C/PER_P).

The energy production and consumption measurement procedures have been defined in sections 3.1 and 3.3. The same devices and protocols should be used.

3.5 $\%H_{I-II}$

Definition: Percentage of hours that the dwelling is in adequate comfort conditions (category I or II) according to standard EN 16798-1:2020 [1].

3.5.1 How to obtain the indicator value

The adaptive model defines the basis to define this indicator, which is used to analyse indoor environments where there is no mechanical heating or mechanical cooling system. According to this model, three comfort categories are defined, considering as the appropriate indoor conditions when the out running mean temperature is within the boundaries of the category II (see Figure 3).

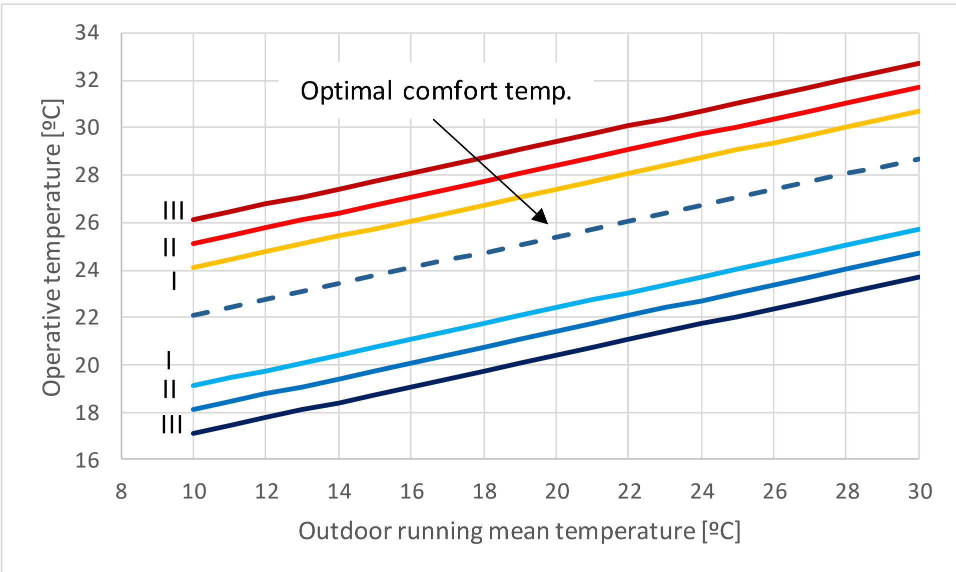

Figure 3- Outdoor running mean temperature according to EN 16798-1:2020.

Optimal comfort temperature: $\theta_{OCT} = 0.33 \cdot \theta_{rm} + 18.8$

Category I: Upper comfort limit → $\theta_{imax} = 0.33 \cdot \theta_{rm} + 18.8 + 2$

Lower comfort limit → $\theta_{imin} = 0.33 \cdot \theta_{rm} + 18.8 - 3$

Category II: Upper comfort limit → $\theta_{imax} = 0.33 \cdot \theta_{rm} + 18.8 + 3$

Lower comfort limit → $\theta_{imin} = 0.33 \cdot \theta_{rm} + 18.8 - 4$

Category III: Upper comfort limit → $\theta_{imax} = 0.33 \cdot \theta_{rm} + 18.8 + 4$

Lower comfort limit → $\theta_{imin} = 0.33 \cdot \theta_{rm} + 18.8 - 5$

The outdoor running mean temperature is calculated using the following expression:

$$\theta_{rm} = (1-\alpha) \cdot \{\theta_{ed-1} + \alpha \cdot \theta_{ed-2} + \alpha^2 \cdot \theta_{ed-3} \dots\}$$

Where θ_{ed-n} it is daily mean outdoor air temperature for n-days prior the day in question and α a coefficient which is considered to be equal to 0.8.

The temperature limits are based on studies in office buildings, but it is accepted that they can be applied in other types of buildings where the activity is sedentary, for example, in residential buildings.

Therefore, it is necessary to measure the outdoor air temperature and the operative temperature of the indoor environment.

The operative temperature of the indoor environment is defined as the uniform temperature of an imaginary environment by which the heat transfer between the human body and the environment by radiation and convection is the same as in the case of the actual environment [10]:

$$\theta_o = \frac{h_c \cdot \theta_a + h_r \cdot \bar{\theta}_r}{h_c + h_r}$$

Where, h_c is the convective heat transfer coefficient $\left[\frac{W}{m^2 \cdot ℃}\right]$; h_r is the radiative heat transfer coefficient $\left[\frac{W}{m^2 \cdot ℃}\right]$; θ_a is temperature of the air [℃]; and θ_r is mean radiant temperature [℃].

The following expressions show how to calculate the heat transfer coefficients:

In the case of natural convection: $h_c = 2.38 \cdot (\theta_{cl} - \theta_a)^{0.25}$

Where θ_{cl} is the temperature of the clothing [℃].

In the case of forced convection: $h_c = 12.1 \cdot \sqrt{v}$

Where v is the velocity of the air $\left[\frac{m}{s}\right]$.

The following expression is proposed by ASHRAE as an acceptable approximation for operative temperature [10]:

$$\theta_o = A \cdot \theta_a + (1 - A) \cdot \theta_r$$

Where the coefficient A is defined in
Table 4:

Table 4 - The values for coefficient A *in relation to the air speed.*

$v\left[\frac{m}{s}\right]$	< 0.2	0.2 < *v* < 0.6	0.6 < *v* < 1
A	0.5	0.6	0.7

According to [10], when the following 4 conditions are met, the operative temperature can be considered equal to air temperature:

1.- There is no radiant and/or radiant heating panel heating or radiant panel cooling system.
2.- The average U-factor of the outside window/wall is determined by the following equation:

$$U_W < \frac{50}{\theta_{d,i} - \theta_{d,e}}$$

$$U_W < \frac{15.8}{\theta_{d,i} - \theta_{d,e}}$$

Where U_W is the average U-factor of window/wall $\left[\frac{W}{m^2 \cdot °C}\right]$; $\theta_{d,i}$ is the internal design temperature [°C]; and $\theta_{d,e}$ is the external design temperature [°C].

3.- Window solar heat gain coefficients (SHGC) are less than 0.48, and
4.- There is no major heat generating equipment in the space.

The mean radiant temperature is calculated by measuring first the globe temperature, which is measured by the globe thermometer [11]. Once the globe temperature is known, the following expressions are used to determine the mean radiant temperature:

$$\bar{T}_r = \sqrt{{T_{GT}}^4 + \frac{h_c}{\sigma \cdot \varepsilon} \cdot (T_{GT} - T_a)}$$

$$\bar{T}_r = \sqrt{{T_{GT}}^4 + \frac{h_c}{\sigma \cdot \varepsilon} \cdot (T_{GT} - T_a)}$$

Where T_{GT} is the temperature measured by the globe thermometer $[K]$; h_c is the convective heat transfer coefficient for the globe thermometer $\left[\frac{W}{m^2 \cdot °C}\right]$; σ is the Stefan-Boltzmann constant $\left[\frac{W}{m^2 \cdot K^4}\right]$; and $\varepsilon \approx 0.95$ is the emissivity of the globe $[-]$.

The convective heat transfer coefficient of the globe is calculated as follows:

For natural convection: $h_c = 1.4 \cdot \sqrt{\frac{\Delta T}{d}}$ when $10^2 < Re < 10^5$

For forced convection: $h_c = 6.3 \cdot v^{0.6} \cdot d^{-0.4}$ when $Re < 10^2$

Where ΔT is the temperature difference between the globe and air $[K]$; d is the diameter of the globe $[m]$; Re is the Reynolds number $[-]$; and v is the air speed $\left[\frac{m}{s}\right]$.

3.5.2 How to measure the needed variables

Air temperature measurement devices can be classified into two groups: resistance thermometers and thermocouples.

The resistance thermometers use platinum as a resistor, which is a high-precision sensing resistor. The value of the resistance increases with temperature. The most common standard is Pt100. This device has 100 Ohms resistance at 0 ºC. The platinum is very stable and high measurement accuracy is obtained. Two, three and four wire options are available. When a 2-wire configuration is used, the connection cables between the thermometer and the instrumentation introduces an additional resistance and it could be considered as a higher temperature than the actual value. The diameter of the wires also affects to the precision. Therefore, a 2-wire configuration is only appropriate for short cable length situations. When there is no option than the 2-wire configuration, increasing the diameter of the cabling is recommended to minimize its resistance.

The 3-wire configuration allows compensating the resistance, but this compensation technique is based on the assumption of the three wires is the same and they are under the same environmental conditions.

The highest accuracy is obtained when a 4-wire configuration is selected.

The thermistors are also classified as resistance thermometers. They use a semiconductor, which resistance changes with the temperature (in this case, they typically have a negative thermal coefficient, that is, resistance decreases as temperature rises). It is cheaper than platinum resistance thermometer and it has a good accuracy. However, they show drift related problems, and an appropriate calibration is required.

In the case of the thermocouples, they are composed by 2-wires of different alloys. The “hot” junction is a short circuit while the “cold” junction is a reference junction. The electromotive force generated between both junctions due to the temperature gradient is measured (Seebeck effect). There are different types of thermocouples: J, K, T, N, …

If we compare the resistance thermometers and thermocouples, the formers are more accurate, stable and the resolution is better, but they are more expensive. The latter are cheaper, more rugged and sensitive, but they are less accurate and more prone to drift.

The outdoor air temperature can be obtained from a meteorological measurement station located near the building. Nevertheless, if the outdoor temperature value provided by the weather station is not representative of the building environment, it can be measured with one of the devices described in the previous paragraphs.

3.5.3 General advices and recommendations

For the measurement of outdoor temperature there are different alternatives. In works where the objective is to measure outside conditions, a weather station is often used. In these types of stations, in addition to the outside temperature, aspects such as relative humidity, wind velocity, etc. can be measured. For the proposed indicator, it is not necessary to measure so many parameters, although it can be interesting.

Besides, when measuring air temperature, the possible effect of radiation on the sensor reading should be taken into account. This can be critical when measuring the outdoor temperature at times of high solar radiation and low air velocities. To minimise the error that this situation can create in the signal reading, it is necessary to shield the sensor (see Figure 4) and use mechanical ventilation. In the case of indoor temperature measurements, the effect is generally minor except for sensors located near sources of radiation or exposed to solar radiation through windows.

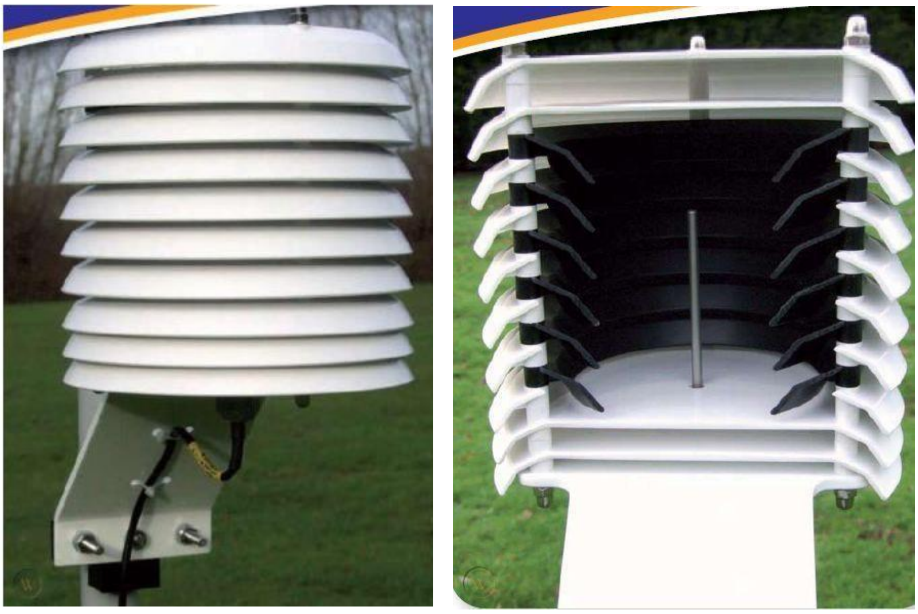

Figure 4 - Solar radiation shield for measurement of external air temperature. (Source [12])

In indoor environments, as we are considering residential buildings, the bedrooms and living rooms should be considered. At least the living-room should be monitored, but it is recommended to measure also at least the operative temperature at the main bedroom or the bedroom where more thermal comfort-related complaints arise.
In Annex 1 there are some specifications about different types of equipment for temperature measurements (comfort meters) available in the market.

3.6 Heat Loss Coefficient (HLC)

Definition: Heat Loss Coefficient. It measures the total thermal losses of the building through the envelope (including thermal bridges and total air change) per unit of the temperature difference between indoor and outdoor temperatures.

3.6.1 How to obtain the indicator value

According to the definition, the HLC can be compactly defined as:

$$HLC = UA + C_v$$

Where UA is the global heat transfer of the envelope of the building [kW/ºC] and C_v is the coefficient of heat losses due to total air change (hygienic ventilation and uncontrolled air infiltration) in [kW/ºC].

In an unoccupied building, the experimental determination of the HLC can be done by the Co-heating method. This method is widely documented in the literature. For reference, the following research works are recommended [13, 14, 15, 16].
On the other hand, in occupied buildings the determination of the UA of the building is not trivial. In fact, it is usual to experimentally determine the HLC and the coefficient C_v, and then deduce the value of UA.
In recent years, significant efforts have been made by researchers to reliably determine experimentally the HLC in occupied buildings. One of them is the one proposed by Erkoreka et al. [17]. This proposed average method has some similar characteristics regarding the mathematical estimation method used by the ISO 9869-1 method [18] for obtaining in-situ U-values of walls.

The method starts from the application of an energy balance on the dwelling. Considering the energy exchanges represented in Figure 5, the energy balance can be expressed as following equation. The complete process of obtaining this equation can be found in [19].

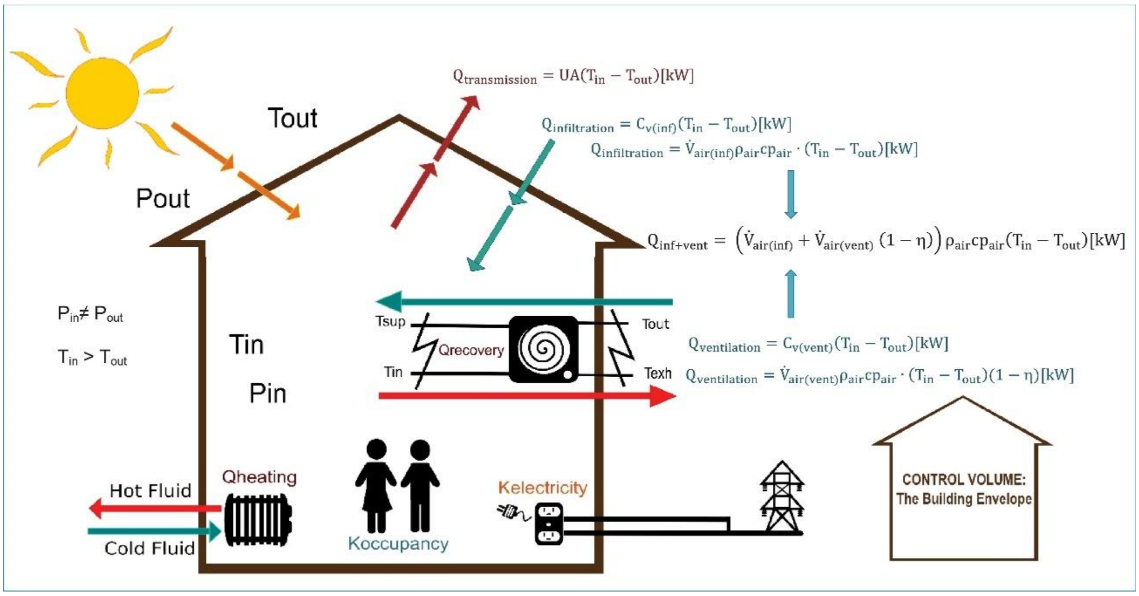

Figure 5 – Schematic of all energy and mass exchanges through the control volume defined by the building envelope. (Source [19])

$$\frac{dU(t)}{dt} = S_a\, V_{sol}(t) + Q(t) + K_{electricity}(t) + K_{occupancy}(t) - HLC\,(T_{in} - T_{out})(t)$$

Where:

- *dU(t)/dt* is the energy rate being stored in the house. The internal energy of a material i (U_i) can be calculated as the product of its mass (m_i), its specific heat (c_i) and its temperature (T_i).
- S_a·is the solar aperture. A characteristic of a building, measured in square-meters of south vertical perfectly transparent surface, which lets coming in the same solar radiative energy as the whole building.
- V_{sol} is the global south vertical solar radiation. Therefore, the product $S_a \cdot V_{sol}$ represents the heat gains due to the solar radiation.
- *Q* is the total measured power input from space heating.
- $K_{electricity}$ and $K_{occupancy}$ represent the internal gains due to electricity consumption and occupants respectively. They are usually considered in a single term, called *K(t)*.
- T_{in} - T_{out} is the indoor to outdoor temperature difference.

The determination of some of these variables by instantaneous measurements, especially the accumulated energy term and solar gains in occupied buildings is very difficult. Therefore, it is necessary to perform the integrated balance over a period of time (from t_1 to t_N). Taking into account that the monitoring system performs discrete measurements every Δt, the integrals are converted into summations from k=1 (t_1) to k=N (t_N), so that the above balance can be rewritten as:

$$HLC = \frac{\sum_{i=1}^{Z} m_i\, c_i \left(T_i(t_1) - T_i(t_N)\right) + \sum_{k=1}^{N} (Q_k + K_k + (S_a\, V_{sol})_k)\, \Delta t}{\sum_{k=1}^{N} \left(T_{in,k} - T_{out,k}\right) \Delta t}$$

Where z is the number of different materials (concrete, bricks, wood, ...) in the building under consideration.

If the monitoring period fulfils the same initial and final thermal level conditions, applying the method to periods of at least 72 h (three days), the accumulation term effect on the HLC will be negligible, and the previous equation can be simplified:

$$HLC = \frac{\sum_{k=1}^{N} (Q_k + K_k + (S_a\, V_{sol})_k)}{\sum_{k=1}^{N} \left(T_{in,k} - T_{out,k}\right)}$$

If the monitoring period, not only has the same initial and final temperature of the building, but also is cold and cloudy, the weight of the solar gains in the energy balance is small and allows making accurate estimates of the HLC, even though the solar gains are roughly calculated. In this sense, a period can be considered cold if the average indoor to outdoor temperature difference is 10 ºC or bigger.

Another advantage of considering cloudy periods is that in such situations, radiation can be considered purely diffuse. This circumstance allows any measure of global radiation, including global horizontal (H_{sol}), to be used as an estimation of V_{sol}.

In the particular case where, solar gains are considered to be zero, the value of HLC can be obtained in a simpler way according to the following equation:

$$HLC_{simple} = \frac{\sum_{k=1}^{N}(Q_k + K_k)}{\sum_{k=1}^{N}(T_{in,k} - T_{out,k})}$$

To differentiate it from HLC, it appears as HLC_{simple}.

3.6.2 How to measure the needed variables

According to the equation seen above, the experimental determination of the HLC requires the measurement of the following variables: T_{in} and T_{out}, Q, K, and solar radiation.
The following table (Table 5) summarizes the sensors required for the determination of the HLC, as well as the recommended uncertainties for each one.

Table 5 - List of input parameters for applying the average method (Source: [20])

Measured parameter	Description	Sensor	Accuracy
$T_{out,k}$ [ºC]	Outdoor temperature	Thermocouples / Pt100	± 0.5 ºC
$T_{in,k}$ [ºC]	Indoor temperature	Thermocouples / Pt100	± 0.5 ºC
Q_k [kWh]	Boiler heat output	Energy consumption device	± 2%
K_k [kWh]	Total electricity consumption	Energy consumption device	± 2%
V_{sol} [W/m^2]	Global south vertical solar radiation	Pyranometer	± 5%

3.6.3 General advices and recommendations

In addition to the comments already made about the need to protect temperature probes against radiation, there are several additional considerations to take into account.

Regarding the measurement of the indoor temperature, it should be measured in different rooms of the house. In order to achieve a unique temperature a non-weighted average temperature is estimated using the following formula:

$$T_{in,k} = \frac{\sum_{j=1}^{N} T_{in,j,k}}{N}$$

Where N is the total number of indoor temperature sensors installed in the house.

Regarding the measurement of solar radiation, it can be obtained from a nearby meteorological station. Besides, if the monitoring period allows it (cold and cloudy days), the global horizontal solar radiation can be used (H_{sol}).

3.7 Global Warming Potential (GWP) and embodied energy

GWP definition: CO_2 emitted related with materials and equipment lifecycle, as well as type of energy production during operational use of the building.

Embodied energy definition: Direct and indirect energy consumption related with materials and equipment lifecycle.

As both parameters are indicators of sustainability and both require, as will be seen later, a life cycle analysis, it has been decided to address them together in one section.

3.7.1 How to obtain the indicators values

The GWP indicator basis is the GWP of the CO_2 emissions, therefore, as a reference gas, its GWP is 1. According to this, the GWP of the some of the greenhouse gases (GHG) is shown in *Table 6*. A complete data showing the 100-year time horizon global warming potential (GWP_{100}) is available in [21].

Table 6 - The GWP_{100} relative to CO_2 according to the Fifth Assessment Report (AR5).

Greenhouse gas	GWP100
Carbon dioxide	1
Methane	28
Nitrous oxide	265
CFC-11	4660
CFC-12	10200
CFC-13	13900
CFC-113	5820

In order to assess the GWP and embodied energy of the building, different contributions have to be considered:

- Raw materials
- Manufacturing
- Construction
- Operation and maintenance
- Demolition

All these contributions define the Life Cycle Inventory of the building. It is usually evaluated by using a Life Cycle Assessment methodology (LCA) tool. LCA is used to assess the environmental impact at all stages of the life cycle, from raw material extraction, manufacturing, distribution, and use, to recycling/reuse and final disposal at the end [22]

By using LCA, both the embodied energy and operating energy are taken into consideration. The embodied energy in buildings can be divided into the initial (IEE) and recurring embodied energy (REE) [23]. The IEE represents the non-renewable energy used for raw material extraction, processing, manufacturing, transportation and construction. It is composed of two components: direct energy, which is used for product transportation on-site and then building construction and indirect energy, used to acquire, process, and manufacture the building materials, and transportation needed for these activities. The REE can be described as the non-renewable energy used to maintain, repair, restore, refurbish, or replace materials, components, or systems over the lifecycle of the building.

The LCA methodology is based on EN ISO 14040 [24], which defines four phases:

- Goal and scope definition
- Life cycle inventory modelling
    - Material inputs
    - Operational energy inputs
- Impact assessment
- Interpretation of the results

Several studies [25, 26, 27] have demonstrated that in conventional buildings, most of the energy and GHG emissions production is related to the operational stage. Ramesh et al. [26] showed that operational energy has a major influence on a building's environmental impact, contributing to 80–90% of the total energy produced during the life cycle. The remaining 10%–20% of embodied energy is almost completely related to the product stage (the rest of the phases have a practically negligible share).
For energy-efficient buildings (low energy and nZEB), the embodied energy represents a higher share in the whole life cycle [27, 28] because of the lower energy needs.

The GHG emissions related to the operational stage depend directly on the specific energy mix of the country. Therefore, if renewable or low carbon fuels are considered, the total contribution of the construction materials to GHG emissions during a building's lifetime could rise to 80% [29].

3.7.2 LCA assessment tools

There are several LCA tools, which are more or less advanced. Some tools are generalist [30, 31], while others are specifically oriented towards the design or environmental certification of buildings. [32, 33].

The most appropriate option would be to integrate into the ARCAS methodological tool, a free and simple tool for the GWP and embodied energy assessment. This way, it is possible to avoid the technician having to use/learn another software.

It could also be interesting that, optionally, the technician could directly enter the values of the indicators obtained by applying his own LCA software.

4 MONITORING SYSTEM AND DATA TREATMENT

4.1 Monitoring scheme

In addition to the sensors to be used, in all monitoring, it is important to correctly define the architecture of the acquisition and control system. This architecture will depend on each specific case, and there is no single general solution for building monitoring. The possible solutions depend, among others, on the following factors:

- Number of sensors used
- Distance between sensors
- Duration of the monitoring period
- Sampling frequency
- Accessibility of the sensors
- Objective of monitoring

Based on these criteria, the following three possible schemes can be identified:

- Individualized system (on-site storage).
- Centralized system (on-site storage).
- Centralized system (remote storage)

Each of these is described in more detail below.

Individualized system (on-site storage): In this case, each sensor stores the data in its internal memory. The main characteristics of this scheme are:

- This is the monitoring system that requires the least amount of equipment (only the sensors). That means that it is generally the cheapest in terms of investment.
- It is a minimally invasive system since it does not require linking the sensor with the data acquisition system (DAS).
- It requires access to the home to download the data, which can be a critical drawback in a pandemic situation such as the current one.
- Risk of data loss. If the battery runs out or the device's memory fills up, the system stops storing data.

- The sampling frequency is conditioned by the capacity of the device's memory or by the frequency of manual data downloading.
- This is the scheme usually used when the number of dwellings to be monitored, and the number of sensors is small.

When only one dwelling is monitored, a scheme in which the sensors send the data to a DAS located in the housing is usually adopted. This structure can be considered as an intermediate solution between the scheme described above and the following one. For more than one house, the advantages usually do not outweigh the extra cost of duplicating the DAS or other equipment.

Centralized system (on-site storage): In this scheme, unlike the previous one, each sensor sends data to a central acquisition system usually located in the same building. The main features of this scheme are:

- To reduce the invasiveness and cost of wiring all the sensors to the DAS, it is common to use wireless sensors.
- Depending on the communication protocol used and the distances between the sensors and the DAS, it may require the installation of repeaters or amplifiers.
- It requires the placement of a cabinet or similar where the DAS, the computer if it exists, and the rest of the auxiliary equipment is located.
- Data collection is more straightforward than in the previous scheme since it does not involve coordinating with all the owners.
- The sampling frequency can be freely set.
- If the DAS has a sufficiently large storage memory, the visits can be reduced to two. The first to install the equipment and the second to pick it up.
- The previous advantage is counterbalanced due to the fact there is no direct control of the correct functioning of the sensors.
- There is a risk of data loss, generally dependent on the quality of the sensor signal. As before, a small number of visits to the building to check the system can result in a significant loss of data.

Centralized system (remote storage): This scheme attempts to solve some of the drawbacks of the previous one by providing daily or even real-time monitoring of the data acquisition system. To this end, the system can send a message every day at a specific time with the information collected in the last 24 hours, or just a message indicating if there is any problem. This scheme has the same advantages as the previous one, and some specific features, among which are:

- It requires an Internet connection.
- It also requires the installation of all equipment (DAS, computer, router, etc.). If possible, it is usually located inside a cabinet in the installation room.
- It allows data to be shared in the cloud, which becomes this scheme very suitable when several groups must have access to the data.

- Data losses and the effect of any system failure can be highly minimized if adequate control measures are put in place.
- Although it reduces the cost associated with visits to the building to download the data, it is usually the most expensive of the three monitoring varieties because it requires specific programming to send the data.

4.2 Monitoring period and sample rate

The correct assessment of the energy efficiency and sustainability indicators defined in this WP will require monitoring for **at least one full year**.

Such a long period allows the proper quantification of seasonal consumptions (heating and cooling) and year-round consumptions (DHW, ventilation, and lighting). It will also allow determining the differences in the production of renewable energy that arise throughout the year.

Regarding other indicators, yearly based indicators such as the percentage of hours in comfort conditions require such a monitoring period.

On the other hand, although such a long period is not necessary for determining the Heat Loss Coefficient, the availability of more data will allow a much more accurate determination of this indicator. The reason is that by having more data available, it will be possible to select a period where the influence of solar radiation is lower (cloudy days), thus reducing the uncertainty in the solar gains term and consequently in the HLC value.

Finally, it is worth mentioning that such a long period practically rules out the use of an individual monitoring scheme.

Regarding the sampling frequency, there is no consensus in the literature on the most appropriate sampling frequency. It is usually conditioned by the specific objective of the monitoring and the storage capacity of the sensors (if an individualised monitoring system is considered).

If a centralised system is used, the criterion when setting the sampling frequency is the balance between allowing detecting variations in the variables and managing a not excessive amount of data. In this sense, it is common practice to use a relatively high frequency (measurements every 1 minute) and then work with values averaged over a broader time base (e.g., 10 min., or 1 hour).

As an example, the sampling frequencies used in some research works are described below.

- In the work by Domínguez et al. [9], It was decided to set the frequency at **two minutes**. In this work, it is commented that the most used frequencies are those of one minute and two minutes. Also, mention is made of a problem that may arise if the sample rate is set too high.

- In the work of Erkoreka et al. [17] about the rectorate building of the University of the Basque Country (UPV/EHU), it was used a **minute basis** sampling rate. Nevertheless, to carry out the analysis it was used the **hourly average** of the collected data.

- In the work carried out by Farmer et al. [34], whose objective was to analyse the thermal behaviour of a building in a steady-state, the calculation of heat flow was carried out on a **minute basis**. To reduce fluctuations and achieve a steady-state, it was decided to use the **daily mean** of the collected data.

- Marshall et al. [35], in order to analyze the behaviour of a building and compare it with a simulation in DesignBuilder, decided to take a sampling frequency of **10 minutes**. For the analysis, however, it was decided to take the **hourly average** of the collected data.

- Alzetto et al. [36] conducted a test to measure heat loss in different scenarios, using a **minute basis** sampling rate.

- Vanus et al. [37] carried out a research work in which indoor and outdoor temperatures, relative humidity and CO_2 concentration were monitored. The sampling frequency was defined on a **minute basis**. For the analysis, the **maximum and minimum method** was used.

- Sirombo et al. [38] used a sampling frequency of 15 minutes in a monitoring system installed in a large social housing intervention in Figino (near Milan) to verify the actual building consumption regard to the design (and expected) targets, to control and optimize the building system operation and to analyze the occupant behavior considering its strong influence on the energy consumption.

In the following table, a summary of the reviewed works is shown:

Table 7 - Summary of sampling rates

AUTHORS	SAMPLING RATE	DATA ANALYSIS
Dominguez et al. [9]	2 min	-
Erkoreka et al.[17]	1 min	Hourly average
Farmer et al. [34]	1 min	Daily average
Marshall et al. [35]	10 min	Hourly average
Alzetto et al. [36]	1 min	-
Vanus et al. [37]	1 min	Maximum and minimum method
Sirombo et al. [38]	15 min	-

As shown in *Table 7*, the sampling rate varies between 1 minute and 15 minutes, with the **one-minute frequency** being the most common. Since *a priori* there is no limitation to choose such a high frequency, it is proposed to use this frequency for evaluating the indicators of WP 2 of the ARCAS project.

5 CONCLUSIONS

Throughout the previous sections, a description of the sensors necessary for the measurement or evaluation of the WP 2 indicators has been carried out. For more information on other energy efficiency and sustainability indicators not contemplated in the project, please refer to deliverable D.2.1.1.

For the measurement of **primary energy consumption** and **renewable energy** production, the proposed devices to be used will be energy modules and calorimeters.

For the evaluation of the **number of hours in adequate comfort conditions**, the use of resistance thermometers (Pt100) is most appropriate. Considering possible needs in other WPs, it would be advisable to use devices that simultaneously measure temperature, relative humidity and CO_2 concentration.

For the evaluation of the **HLC**, it is proposed to use the averaging method, which with a suitable selection of the monitoring period requires only the determination of the indoor and outdoor temperatures, the global solar radiation, the internal gains due to electricity consumption and occupants, and the power input from space heating.

Finally, in relation to the **sustainability indicators** (GWP and embodied energy), the fact of considering them during the whole life cycle of the building implies the need to carry out a life cycle analysis. The difficulty of assessing it in a simple way has been highlighted. A deeper reflection is necessary to study how to integrate it in the developed ARCAS tool.

In addition to the indicators, the usual types of monitoring have been analysed, distinguishing between individual or centralized, and between on-site or remote storage. Considering the number of variables to be measured, it is proposed to use a centralized system with remote storage.

Finally, an analysis of the most appropriate **sampling frequency** has been carried out. In this sense, although there is no established criterion in the bibliography, it is proposed to use a frequency of 1 minute, which is the most common value.

6 REFERENCES

[1] CEN, EN 16798-1 Energy performance of buildings. Ventilation for buildings. Part 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, Brussels, 2020.

[2] Despacho 15793D/2013 – Ministério do Ambiente, Ordenamento do Território e Energia – Direção -Geral de Energia e Geologia.

[3] LCI Ecoinvent v2.2.

[4] IDAE, Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumida en el sector de edificios en España, Instituto para la Diversificación y Ahorro de la Energía, Ministerio de Industria, Energía y Turismo, Madrid, 2016.

[5] IDAE, Guía para cumplimentación de líneas de actuación en la plataforma MENAE, Instituto para la Diversificación y Ahorro de la Energía, Ministerio para la Transición Ecológica, Madrid, 2019.

[6] Ahmad, M.W.; Moursheda,M.; Mundow, D.; Sisinni, M.; Rezgui, Y. (2016). Building energy metering and environmental monitoring – A state-of-the-art review and directions for future research. *Energy and Buildings*, 120, pp. 85-102. https://doi.org/10.1016/j.enbuild.2016.03.059

[7] http://eesiflo.com/thermal-energy-flow-meter.html

[8] https://www.kamstrup.com/en-en/heat-solutions/heat-meters/multical-603

[9] Domínguez, M., Fuertes, J. J., Alonso, S., Prada, M. A., Morán, A., & Barrientos, P. (2013). Power monitoring system for university buildings: Architecture and advanced analysis tools. *Energy and Buildings*, *59*, 152–160. https://doi.org/10.1016/j.enbuild.2012.12.020

[10] ASHRAE, ANSI/ASHRAE Standard 55-2013, Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA, USA.

[11] CEN, EN ISO 7726:1998 Ergonomics of the thermal environment – instruments for measuring physical quantities. International Organization for Standardization Annex B: 14, Brussels, 1998.

[12] www.worthpoint.com/worthopedia/solar-radiation-shield-stevenson-1772537178 (accessed on 16 February 2021)

[13] Sonderegger, R. C., Condon, P. E. and Modera, M. P. (1980) In-situ measurements of residential energy performance using electric co-heating. ASHRAE Transactions, 86 (I), LBL-10117.

[14] G. Bauwens, S. Roels, (2014) Co-heating test: a state-of-the-art, *Energy and Buildings*, 82, pp. 163–172. https://doi.org/10.1016/j.enbuild.2014.04.039

[15] J. Chapman , R. Lowe , R. Everett , Pennyland project: executive summary, Final Rep. PB-86-151412/XAB (1985) ERG-054 .

[16] Farmer, D.; Johnston, D,; Miles-Shenton, D. (2016) Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating). *Energy and Buildings*, 117, pp. 1–10. https://doi.org/10.1016/j.enbuild.2016.02.013

[17] Erkoreka, A., Garcia, E., Martin, K., Teres-Zubiaga, J., & Del Portillo, L. (2016). In-use office building energy characterization through basic monitoring and modelling. *Energy and Buildings*, 119, pp. 256–266. https://doi.org/10.1016/j.enbuild.2016.03.030

[18] ISO, Thermal Insulation –Building Elements –In-Situ Measurement of Thermal Resistance and Thermal Transmittance – Part 1: Heat flow Meter method, AENOR, Genova, 2014 ISO Standard 9869-1.

[19] Uriarte, I.; Erkoreka, A.; Giraldo-Soto, C.; Martin, K.; Uriarte, A.; Eguia, P. (2019) Mathematical development of an average method for estimating the reduction of the Heat Loss Coefficient of an energetically retrofitted occupied office building. *Energy and Buildings*, 192, pp. 101–122. https://doi.org/10.1016/j.enbuild.2019.03.006

[20] Giraldo-Soto, C. (2021) Optimized monitoring techniques and data analysis development for in-situ characterization of the building envelope`s real energetic behaviour. PhD Thesis, University of the Basque Country.

[21] https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf (accessed on 28 January 2020).

[22] Ilgin, M.A.; Gupta, S.M. (2010) Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art. Journal of Environmental Management, 91 (3), pp. 563–591. https://doi.org/10.1016/j.jenvman.2009.09.037

[23] Dixit, M.K. (2019) Life cycle recurrent embodied energy calculation of buildings: A review. Journal of Cleaner Production, 209, pp. 731–754. https://doi.org/10.1016/j.jclepro.2018.10.230

[24] CEN, EN ISO 14040 Environmental management - Life cycle assessment - Principles and framework, Brussels, 2006.

[25] Azari, R. (2014) Integrated energy and environmental life cycle assessment of office building envelopes. *Energy and Buildings*. 82, pp. 156–162. https://doi.org/10.1016/j.enbuild.2014.06.041

[26] Ramesh, T.; Prakash, R.; Shukla, K.K. (2010) Life cycle energy analysis of buildings: An overview. *Energy and Buildings*. 42, pp. 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

[27] Saade, M.R.M.; Guest, G.; Amor, B. (2020) Comparative whole building LCAs: How far are our expectations from the documented evidence? *Building and Environment.* 167, 106449. https://doi.org/10.1016/j.buildenv.2019.106449

[28] Blengini, G.A.; Carlo, T.D. (2010) The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings*. 42, pp. 869–880. https://doi.org/10.1016/j.enbuild.2009.12.009

[29] Wallhagen, M.; Glaumann, M.; Malmqvist, T. (2011) Basic building life cycle calculations to decrease contribution to climate change—Case study on an office building in Sweden. Building and Environment. 46, pp. 1863–1871. https://doi.org/10.1016/j.buildenv.2011.02.003

[30] https://simapro.com/ (accessed on 23 January 2021)

[31] https://www.openlca.com/ (accessed on 23 January 2021)

[32] https://www.athenasmi.org/ (accessed on 23 January 2021)

[33] https://www.oneclicklca.com/ (accessed on 23 January 2021)

[34] Farmer, D., Gorse, C., Swan, W., Fitton, R., Brooke-Peat, M., Miles-Shenton, D., & Johnston, D. (2017). Measuring thermal performance in steady-state conditions at each stage of a full fabric retrofit to a solid wall dwelling. *Energy and Buildings*, *156*, 404–414. https://doi.org/10.1016/j.enbuild.2017.09.086

[35] Marshall, A., Fitton, R., Swan, W., Farmer, D., Johnston, D., Benjaber, M., & Ji, Y. (2017). Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance. *Energy and Buildings*, *150*, 307–317. https://doi.org/10.1016/j.enbuild.2017.06.028

[36] Alzetto, F., Farmer, D., Fitton, R., Hughes, T., & Swan, W. (2018). Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios. *Energy and Buildings*, *168*, 35–41. https://doi.org/10.1016/j.enbuild.2018.03.024

[37] Vanus, J., Belesova, J., Martinek, R., Nedoma, J., Fajkus, M., Bilik, P., & Zidek, J. (2017). Monitoring of the daily living activities in smart home care. *Human-Centric Computing and Information Sciences*, *7*(1). https://doi.org/10.1186/s13673-017-01

[38] Sirombo, E.; Filippi, M.; Catalano,A.; Sica, A. (2017). Building monitoring system in a large social housing intervention in Northern Italy. *Energy Procedia*. 140, pp. 386-397. https://doi.org/10.1016/j.egypro.2017.11.151

ANNEX 1

CONFORT METERS		SUPPLY	TEMPERATURE RANGE	ACCURACY	RH RANGE	ACC.	CO2 RANGE [ppm]	ACC. [ppm]	COMMUNICATION PROTOCOL
MET	t6540	9 - 30 VDC	-30 - 80 ºC	± 0.6 ºC	5 - 95%	± 2.5%	0 - 2000 ppm	±50	Modbus, XML, WWW, SNMPv1, SOAP
ARCUS	SK-08-CO2-TF	21 - 32 VDC	-10 - 55 ºC	± 0.5 ºC	10 - 90%	± 3%	0 - 5000 ppm	± 20	KNX bus
PressacSensing	60. CO2 SLR TMP HUM	3,6 V	0 - 51 ºC	± 0.5 ºC	0 - 100%	± 5%	0 - 2550 ppm	± 125	Enocean protocol
VAISALA	GMW95RD	18 - 35 VDC, 24 VAC	-5 - 55 ºC	± 0.5 ºC	0 - 95%	± 0.5%	0 - 5000 ppm	± 30	RS-485 (BACnet, Modbus)
Schneider Electric	SED-CO2-G-5054	3,6 V	0 - 50 ºC	± 0.3 ºC	0 - 100%	± 3%	0 - 5000 ppm	± 60	Zigbee
NibbleWave	Triple MODBUS CO2…	24 VDC (7-28 VDC)	-20 - 50 ºC	± 0.3 ºC	1 - 100%	± 3%	400 - 4000 ppm	± 20	ModBus RTU

CALORIMETERS		SUPPLY	COMMUNICATION PROTOCOL	TEMPERATURE RANGE	NOMINAL DIAMETER	DATA LOGGER	DOWNLOAD
B METERS	HYDROCAL-M3	Battery	M-Bus (integrated), wireless M-Bus	5 / 90 °C	DN15, DN20	-	In-situ
	HYDROSONIS-ULC	Battery	M-bus, wireless M-Bus	5 / 105 °C	DN15, DN20	24 m, every 15 days	In-situ
	HYDROSPLIT-M3	Battery /Power	M-Bus (integrated), wireless M-Bus	5 / 180 °C	> DN20	-	In-situ
ARMATEC	AT 7500 F	Battery, 230 VAC (opt.)	M-Bus, pulse output	1 / 180 °C	DN15, DN20,…,DN100	-	In-situ
	AT 7505	Battery, 230 VAC (opt.)	M-Bus, pulse output	- 20 / 130 °C	DN15, DN20,…,DN100	-	In-situ
KAMSTRUP	MULTICAL 302	Battery (3.6 VDC) - (230 VAC)	M-Bus (integrated), wireless M-Bus	2 / 150 °C	DN15, DN20	960h, 460d, 36m, 15y	In-situ
	MULTICAL 403	Battery (3.6 VDC) - (230 VAC)	M-bus, wireless M-Bus, RS232	2 / 180 °C	DN25, DN40, DN 50	1400h, 460d, 36m, 20y	In-situ
	MULTICAL 603	Battery (3,6 VDC) - (230 VAC)	M-Bus, wireless M-Bus	2 / 180 °C	-	-	In-situ
DIEHL	SHARKY 775	3.6 VDC, 24 VAC, 230 VAC	M-Bus, RS 232, RS 485, Modbus RTU RS485, pulse output	5 / 130 °C	DN15, DN20	Daily, monthly, yearly	Online
	SHARKY 774	3.6 VDC 2*AA Cell	M-Bus, wireless M-bus	5 / 105 °C	DN15, DN20	720d, 120m	Online/In-situ

POWER METERS		**SUPPLY**	**COMMMUNICATION PROTOCOL**
ABB	EM/S 3.16.1	21 - 30 V CC	KNX
Schneider Electric	Zelio Logic Serie Sr2/Sr3	12 - 24 V DC	Modbus, Ethernet
	iEM 3150	Auto	RS485
	PM 800 series		RS485
(Electro Industries/GaugeTech	Shark 100		RS485
Siemens	SENTRON 7KM PAC2200	Auto	M-bus

PYRANOMETERS		**SUPPLY**	**RADIATION RANGE**	**SPECTRAL RANGE**	**TEMPERATURE RANGE**	**COMMUNICATION PROTOCOL**
ARCUS	SK-08 GLBS-MES	21 - 32 VDC	0 - 1800 W/m^2	400 - 1100 nm	-40 - 65 ºC	KNX Bus
APOGEE	SP-420	5V	0 - 2000 W/m^2	360 - 1120 nm	-40 - 70 ºC	USB
	SP-421-SS	5,5 - 24 V DC	0 - 2000 W/m^2	360 - 1120 nm	-40 - 70 ºC	SDI-12
	SP-422-SS	5,5 - 24 V DC	0 - 2000 W/m^2	360 - 1120 nm	-40 - 70 ºC	Modbus
KIPP & ZONNEN	SP Lite 2	-	0 - 2000 W/m^2	400 - 1100 nm	-40 - 80 °C	-
	SMP3	5 - 30 V DC	0 - 2000 W/m^2	300 - 2800 nm	-40 - 80 °C	RS-485
	CMP3	-	0 - 2000 W/m^2	300 - 2800 nm	-40 - 80 °C	-
	SMP22	5 - 30 V DC	0 - 2000 W/m^2	200 - 3600 nm	-40 - 80 °C	RS-485
EKO	MS-80S	5 - 30 V DC	0 - 4000 W/m^2	285 - 3000 nm	-40 - 80 °C	Modbus 485 RTU, SDI-12, 4-20mA…
	MS-80M	12 - 24 V DC	0 - 4000 W/m^2	285 - 3000 nm	-40 - 80 °C	Modbus RTU
	MS-60S	5 - 30 V DC	0 - 2000 W/m^2	285 - 3000 nm	-40 - 80 °C	Modbus 485 RTU, SDI-12, 4-20mA…
	MS-60M	12 - 24 V DC	0 - 2000 W/m^2	285 - 3000 nm	-40 - 80 °C	Modbus RTU