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D. 3 Selection of indicators on best available renewable technologies

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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INDEX

Executive summary

The objective of the ARCAS project is to define the conditions to carry out construction or renovation operations with high environmental, energy and social performance objectives, while controlling the construction and renovation costs of social housing. This requires on the one hand to know and to make the best use of the free resources available, through a good design of the building envelope, and on the other hand to define and to implement the most efficient HVAC systems, giving priority to those which use renewable energies.

This report aims to identify the best available technologies for social renovation strategy of social collective housing in the ARCAS project climatic zone. It includes the definition of indicators and the production of guidelines for the selection and design of passive or active HVAC systems, focusing on those using renewable energy. The report is structured as follows:

- A first part (paragraphs 2 to 6) is devoted to the presentation of bioclimatic design and construction solutions, with the objective of minimising the heating needs of dwellings in the winter period, while obtaining satisfactory summer comfort conditions in order to avoid the use of active cooling systems. This includes first a review of the most widespread passive solutions used in the building sector in the context of energy efficiency and sustainability. Second, a proposal for retaining some indicators from a literature review in the context of the ARCAS project is done, to quantify the potential of environmental resources in covering energy needs of buildings and to evaluate the contribution of renewables. Then, application to an existing building as a case study, varying orientations and envelope performances allows to evaluate the coverage rate of heating need and a summer comfort analysis is achieved with shading and overnight ventilation strategies, in order to assess the validity of the proposals in the frame of the ARCAS project.
- In a second part a brief description of possible HVAC systems is done, considering their individual or collective aspects and renewable nature or not. A special focus is given to housing ventilation, which is an essential aspect of ensuring a healthy indoor environment, through a case study comparing different ventilation systems, both individual and collective.
- The third part focuses on defining a methodology for the integration of renewable energy in social collective housing. The methodologies for evaluating renewable energy use in buildings are described and some indicators are defined and tested. Differences between on-site and distant renewable production are highlighted. Among the indicators proposes, the self-consumption and self-sufficiency ratios and the grid-support coefficient are highlighted.
- The last part is devoted to the presentation of an analysis tool, which, based on the constraints and opportunities of an operation, enables the process of choosing the most appropriate HVAC systems for the operation under consideration. This multi-criteria framework highlights the importance of not only accounting for energy efficiency, but also for cost and technical aspects.

Glossary

The following acronyms are used within this report:

Latin letters

A	Living area
ACH	Air Change rate
BBio	Bioclimatic needs
C	Compactness
Cep	Primary energy consumption
$C_{exp,p}$	Average daily exposure concentration to pollutant p
C_p	Specific heat or pollutant concentration
DHW	Domestic hot water
D_{surf}	Urban built density
DSO	distribution system operator (electricity grid)
D_{vol}	Cubic density
E	Energy
ERI	Environmental Resources Indicators
EPB	Energy Performance of Buildings
HLC	Heat Losses coefficient
GSC	grid support coefficient
HVAC	Heating, Ventilation and Air Conditioning
IAQGs	Indoor Air Quality Guide values
$IAQG_{ST,p}$	IAQGs for Long and Short terms exposures
$I_{ULR-QAI,p}$	Proposed Indoor Air Quality index for pollutant p
NZEB	Nearly Zero Energy Buildings
ODH	Overheating in degree.hours
P	Power
PER	Primary energy renewable
Pt, Q	Potential
PV	Photovoltaic
Q_{inf}	Air infiltration flow
Q_{vent}	Air ventilation flow
Q_{4Pa}	Air leakage of the envelope under inside-outside 4 Pa differential pressure
RH	Relative Humidity
S	Surface
SC	Shape Coefficient
SHGC	Solar Heat Gain Coefficient
T	Temperature
Tic	Conventional indoor temperature
TSO	Transmission system operator (electricity grid)
U	Thermal Transmittance

V	Volume

Greek letters

ε	Emissivity
ρ	Density
v_p	Deposition rate of pollutant p
$\emptyset$	Solar potential
Φ_p	Emission rate of pollutant p
$\Psi_{p,i}$	Emission rate of pollutant p for activity *i*
σ	Boltzmann constant
τ_w	Solar transmission coefficient
τ_c	Curtain coefficient
τ_{exp}	Exploitation rate
τ_{cov}	Coverage rate
τ_{SHE}	Sheltering rate
τ_{gen}	Generated needs
τ_{vent}	Air change coefficient/ventilation
α_s	Solar absorption coefficient

Indices

abs	Absolute
cv	Convection
eav	Outdoor average
Env	Environmental
exp	Exported
ext, e	External, outside
Iav	Indoor average
in, i	Indoor, inside
max	Maximum
min	Minimum
rw	Roof and window
op	Operative
surf	Surface
vol	Volume
tot	Total
w	Wall/window

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 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 3. -Selection of indicators on best available renewable technologies

The objective of WP3 is to identify the best available technologies for social renovation strategy of social collective housing in the ARCAS project climatic zone. It includes the definition of indicators and production of guidelines for the selection and design of passive or active HVAC systems, focusing on those which use renewable energy. Two main steps can be identified:

1. Establish a catalogue of usual bioclimatic design solutions and the best passive heating, ventilation and cooling solutions adapted to the climates of the ARCAS-SUDOE zone
2. Propose indicators for energy efficiency, technical and economic aspects, health quality for active systems with a focus on those which use renewable energy.

2. Bioclimatic approach and related indicators

2.1 Generalities

The bioclimatic approach allows during the design phase of a project to optimize the potential for the use of free inputs (solar in particular), in order to reduce heating needs, while ensuring good comfort conditions in all seasons, with particular attention to mid-season periods, which are conducive to the risk of overheating, and to a lesser extent the summer period.
It is not a question here of a comprehensive bioclimatic design guide, many already exist, but of recalling some basic principles and focusing on common elements of the design of a building, by reviewing the elements/arrangements that seem most relevant in the context of a collective social housing operation, which is often financially constrained. Thus, effective solutions that are judged *a priori* out of the financial reach of a social housing landlord will not be included in this inventory.

This approach can be applied at the level of the plot or neighbourhood as well as one or more buildings in the same operation.

At the scale of the neighbourhood or plot, this approach results in the use of the opportunities of the site, for example for protection against prevailing winds in winter with the presence of reliefs, trees or hedges, which may also provide protection or mitigation of noise. If these elements do not exist, they can be carried out during the development work. The diagram of road networks and green spaces is an essential element of a good design that will structure the plot and allow the definition of a mass plan of buildings allowing access to the solar resource, the protection of views between dwellings [1], the protection from noise nuisance in relation to vehicle traffic… This is obviously simpler for a new development project than for existing built plots.
It is also at this scale that the realization of a green frame with green patches, paths or networks between vegetated basins, pools or ponds are all elements that will allow to mitigate the effects of urban heat patches [2] and to promote the reception and circulation of ordinary biodiversity.

At the building scale, we can distinguish different items, which are declined in the following chapters: aspects related to the orientation and morphology of the building, the quality of the envelope, which will allow to minimize the losses/ thermal loads by making the best use of the free resources (solar in particular) while guaranteeing a good comfort of use in all seasons.

2.2 Building orientation

Building orientation and layout are considered as one of the most effective strategies used in passive heating [3]. An appropriate orientation is a low-cost option to optimize the solar heat gains on a façade and to prevent from strengthening of thermal losses from wind. It consequently decreases energy bills [4], [5]. Therefore, in the Northern hemisphere, the best orientation for a rectangular building is to have its long side facing south in order to benefit from direct solar radiation during winter (North facing in the Southern hemisphere).

Of course, orientation of existing buildings cannot be changed, but this highlights the importance to well design the mass plan and the road networks for a new development project.

2.3 Morphological considerations and related indicators

The morphology indicators are related to the built density, the compactness of the buildings and directly impact heat losses and gains of a building [1].

2.3.1 Urban built density

The urban built density indicator, Dsurf, consists in the ratio between the ground occupation surface and the total area of the project. The more important D_{surf} is, the more natural soil is neutralized (with a significant reduction in water infiltration for example). The cubic density, D_{vol}, defined as the ratio between the built volume and the area of the urban territory represents the average height of the buildings, expressed in meters.
The importance of these two indicators relies in the fact that they define surface optimization related to the profitability of public services and equipment and the relative importance of mineralized or vegetated areas. They are also related to economic aspects in terms of consumption of the costly urban space as well as the complexity of the urban distribution networks. These indicators can also be involved in social aspects regarding the concentration of the residents for example.

2.3.2 Compactness

The **compactness indicator, C**, estimates the ratio between the exchange areas of the envelope and the floor area; the building envelope includes walls, ground and roof. The lower C value is, the more compact the building is. This indicator can be used to compare different configurations and then gives an idea about the differences in the outdoor envelope surfaces. A more accurate approach is to split C into two parts: C_1 for the exchange areas of ground and roof, C_2 for the walls only. This results in $C = C_1 + C_2$ (*Figure 1*). C_1 decreases with the number of floors and C_2 reflects the building morphology [1].

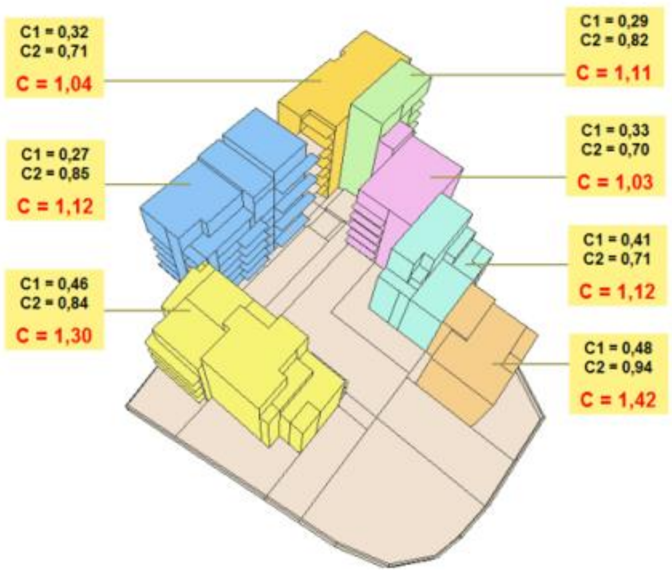


Figure 1: Examples of various compactness configurations [1]

Building compactness is also linked to its shape coefficient (SC) calculated through the ratio between the external surfaces area of the building and its inner volume. It highly impacts the heat losses, as for a given volume, a higher shape coefficient entails lower building compactness and therefore higher heat losses through the building envelope (*Figure 2*). It then should be minimized to passively reduce heat losses, and it also has an influence on the construction costs and maintenance expenses (for a given volume, the more compact the building, the less the area of the envelope).

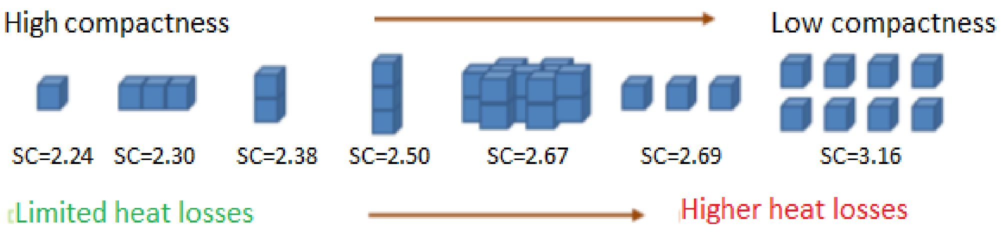


Figure 2: Influence of the compactness and shape coefficient on buildings heat losses

2.4 Building envelope properties

The building envelope needs to have high performances, both in terms of insulation properties of opaque and glazed surfaces and for air tightness, in order to decrease the heat losses, to optimize the free gains and to ensure a sufficient air change rate for healthy indoor conditions.

2.4.1 Thermal insulation of opaque walls

The choice of an insulation material for opaque walls is influenced by its physical properties, mainly thermal conductivity, density and effusivity, and also by its cost. Bio-based materials are generally more expensive than “conventional” ones and presents higher thermal conductivity, but also higher density which is an advantage for the dynamic thermal behaviour of a building, particularly when associated with inner insulation. The bio sourced nature of a material can also be a choice criterion for the decision-maker through sustainability or LCA considerations.

The U-values of the different walls of a building must comply with the regulations of each country, both for new buildings as well as for the renovation of old buildings, when present.

Some examples:

- **In France,** the RT2012 regulation [6] imposes different levels for renovation operations following the impacted net floor area of the project. For an area below 1000 m², performance conditions are imposed element by element:

Table 1: Minimum performances of some walls for the H2 climatic zone of the French thermal regulation for an element by element renovation project **[6]**

Wall type or glazed element	Outside vertical wall	Roof terrace	Roof, other cases	Floor, general	Windows and glazed doors
R_{min} (m².K/W)	2.9	3.3	4.8	2.7	1.9

For renovation areas higher than 1000 m² and buildings older than 1948, element by element performances approach also applies. For more recent buildings, the requirements apply on the overall envelope performance (RT2012 requirements for new buildings [6]) if the renovation cost of the project is lower than 25% of the actual value of the building, or element by element otherwise.

- **In Portugal**, only new buildings and existing buildings with major renovations must comply with the regulation requirements. Major renovations are defined according to EPBD [7]. The minimum reference values per element vary depending on the three climate zones defined in national regulations according to *Table 2*.

Table 2: Reference U values for Continental Portugal (W/(m^2.K)) **[7]**

	Climate Zone

Building envelope zone		I1	I2	I3
in contact with exterior environment	Vertical opaque elements	0.50	0.40	0.35
	Horizontal opaque elements	0.40	0.35	0.30
in contact with other buildings	Vertical opaque elements	0.80	0.70	0.60
	Horizontal opaque elements	0.60	0.60	0.50
Windows and glazed doors		2.80	2.40	2.20
In contact with soil		0.50		

Moreover, from January 2021, both new buildings and major renovations must comply with the nZEB standard as it was defined for the Portuguese context [8]:

1. The heating energy needs should be lower or equal to 75% of the maximum value defined in regulation;
2. The primary energy needs should be lower or equal to 50% of the maximum value defined in regulation;
3. Renewable energy should supply at least 50% of the primary energy needs.

In existing buildings, verification of the relation between energy needs and the maximum value is subjected to distinctive coefficients depending on the age of the building (1-Previous to 1960, 2- Between 1960 and 1990 and 3- Between 1990 and 2012, 4- After 2012).

- **In Spain**, in the case of small renovations (<25% of the envelope) limitation applies only to the elements modified in the renovation according to the limit values of *Table 3* and *Table* **4**, while larger renovations must comply with the whole CTE DB-HE 2019 Spanish regulation [9].

Table 3: Transmittance limit values (U_{lim}) for small renovations (< 25% of the envelope) for the C and D winter climatic zones in the Spanish thermal regulation

U_{lim} element ($W/(m^2.K)$)	Winter climatic zone	
	C	D
Wall and floor in contact with outside air	0.49	0.41
Roofs in contact with outside air	0.40	0.35
Walls, floors and roofs in contact with non-habitable spaces or with the ground Partition walls	0.70	0.65
Openings (set of frame, glass and, where and, if applicable, shutter box)	2.1	1.8

Table 4: Air permeability limit value ($Q_{100,lim}$) of thermal envelope openings

	Winter climatic zone	
	C	D
$Q_{100, lim}$ (h^{-1})	≤ 9	≤ 9

- Recommendations for satisfying the Passivhauss objectives are respectively $U_w \leq 0.15$ W/(m^2.K) for the outside opaque walls and 0.8 W/(m^2.K) for the glazed walls, whatever new or renovated building.

Although, high insulation levels should be coupled with suitable ventilation techniques to ensure the preservation of the heritage and prevent mould, and in a general way to ensure satisfactory healthy conditions for the occupants.

2.4.2 Thermal bridges

The treatment of the thermal bridges needs special attention. If they can be easily dealt with a new building, they constitute a critical point for renovation of existing buildings. Outside insulation presents a decisive advantage compared to inner one for the intermediate floors thermal bridges, whilst windows frames are a more difficult point to deal with. Balconies and outdoor terraces cause significant thermal bridges and are always a tricky point to consider in a renovation project.

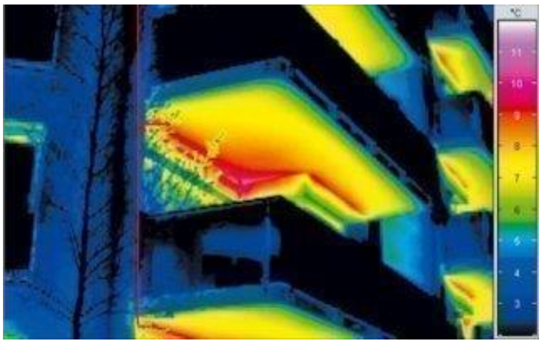


Figure 3: Example of a thermal bridge on a balcony

2.4.3 Glazed walls

Glazed surfaces and frames must be performant in terms of heat losses (U_W), solar gains (Solar heat gain coefficient SHGC), and light transmission (T_L factor of the glasses). They must also present good characteristics for the wind and rain permeability, as well as for acoustics.
Depending on the country or region, minimum performances may be required for glazed walls to obtain financial aid for the thermal renovation of housings (this is generally true also for the opaque walls performances).

2.4.4 Airtightness of the envelope

Particular attention should be paid to the air permeability of the envelope in order to control as well as possible the air change of dwellings to ensure good indoor air quality and to limit the thermal losses related to infiltrations. Energy retrofit projects provide opportunities to improve the air permeability of old buildings, which is often very important in particular because of the leaky frames, and to implement an efficient ventilation system with controlled air intakes.

Airtightness must be consistent with the thermal performances of opaque and glazed walls. The more efficient they are, the less air permeability must be. As an example the n_{50} coefficient required for Passivhauss label must be less than 0.6 h^{-1} for new or renovated buildings.

The overall performance of a building envelope with respect to the total thermal losses (transmission and total air change) can be evaluated through the Heat Loss Coefficient HLC [$W.degree^{-1}$].

2.5 Access to the solar resource

The potential of solar radiation and the possibility to benefit from natural light for a given dwelling in its environment is related to the area of sky that is visible from any point. This area depends highly on the building morphology itself, but also on the nearby environment: masks due to other buildings, trees, etc that can reduce drastically the access to the solar resource.

Figure 4: Illustration of the availability of natural light on a terrace (left) and to buildings with concave angles (right) [1]

2.5.1 Daylight Factor

For inner environment, the subjective daylight quality is usually calculated through the Daylight Factor, DF, which is the ratio of inside illuminance, E_{in}, over outside illuminance, E_{ext}, at a fixed point under an overcast sky:

$$DF = 100 * E_{in} / E_{ext} \quad [\%]$$

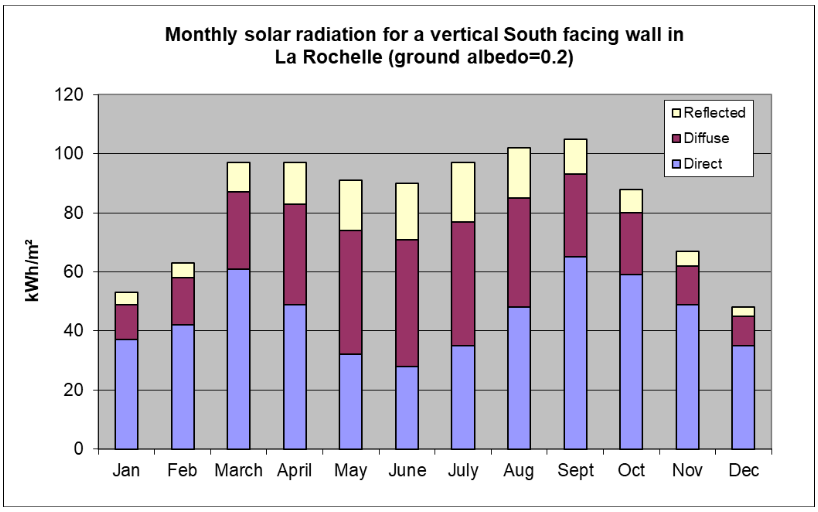
The higher the Daylight Factor is, the more natural light is available in the room and the less artificial lighting is required:

- Rooms with DF < 2% look gloomy and artificial lighting is needed most of the time,
- 2% to 5% DF rooms are considered well daylit with a good balance between natural lighting potential and artificial lighting needs,
- DF > 5% rooms are strongly daylit and can present risks of overheating in summer and important heat losses in winter.

2.5.2 Solar gains through glazed surfaces

For medium latitude zones, such as the SUDOE zone, East and West facing vertical glazed surfaces are critical during the mid and hot seasons and may lead to overheating and discomfort.

On the other hand, South orientation receives the highest amount of energy during the heating season and the glazed surfaces on these facades are quite easy to protect in summer from direct solar radiation with balcony, roof overhang, etc. Nevertheless, one must have in mind that diffuse and reflected radiations are also crucial to deal with, because they constitute an important part of the total solar radiation received on a vertical façade.



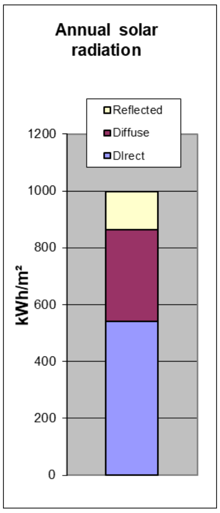


Figure 5: Decomposition of the solar radiation received by a vertical South facing wall in La Rochelle

Similarly, attention must also be paid to incline glazed surfaces, such as canopies or roof windows, which are interesting for natural lighting but often bring much energy.

Different indicators can be proposed for these surfaces and the related solar gains, such as:

- The ***ratio of glazed surface***, defined as an example for the French regulation as the ***ratio between the total glazed surface and the living area*** of a dwelling, whatever the orientation and inclination of the surfaces [-],
- The daily, monthly or annual solar ***energy entering a room by glazed surfaces***, relatively to the living area of the dwelling [Wh/m².time unit]

2.6 Reducing the thermal summer discomfort

As said before, solar gains can cause overheating and discomfort situation in mid and summer periods due to high and uncontrolled solar gains.

A few points of attention make it possible to reduce these situations passively and to avoid the use of active air-conditioning systems, or at least to reduce their power. They also can avoid the installation of air conditioners once the building is delivered for handling discomfort problems poorly treated at the design stage.

2.6.1 Shading systems

The main purpose of shading systems is to reduce heat gains and indoor temperature increase due to surrounding factors caused mainly by solar radiations [10]. The application of shading techniques is much various through different ways, using static or semi-mobile components: building orientation and shape, overhangs, eaves, rolling shades and self-shading. Passive shading is categorized as fixed shading devices and adjustable shading devices [11].

- Fixed shading devices can be horizontal, vertical, or a combination of both. Horizontal shading devices are effective on the equatorial facing facades where the sun altitude is high, which makes them suitable for the summer months. Vertical shading devices are recommended in the East and West directions, characterized by low solar altitude where the entire window faces the sun. They perform better when placed on the polar side, perpendicular to the windows. Beyond the fixed techniques, the most common are overhangs, horizontal louvres, light shelf and blind systems.
- Adjustable (movable) devices can be operated by the user or sensor automated. Internal or external protection techniques exist, but external shading systems stop the sun rays before entering the room and prevent most of the solar energy from reaching

the indoor ambiance. Their performances are generally higher than internal shading devices ones and must be preferred.

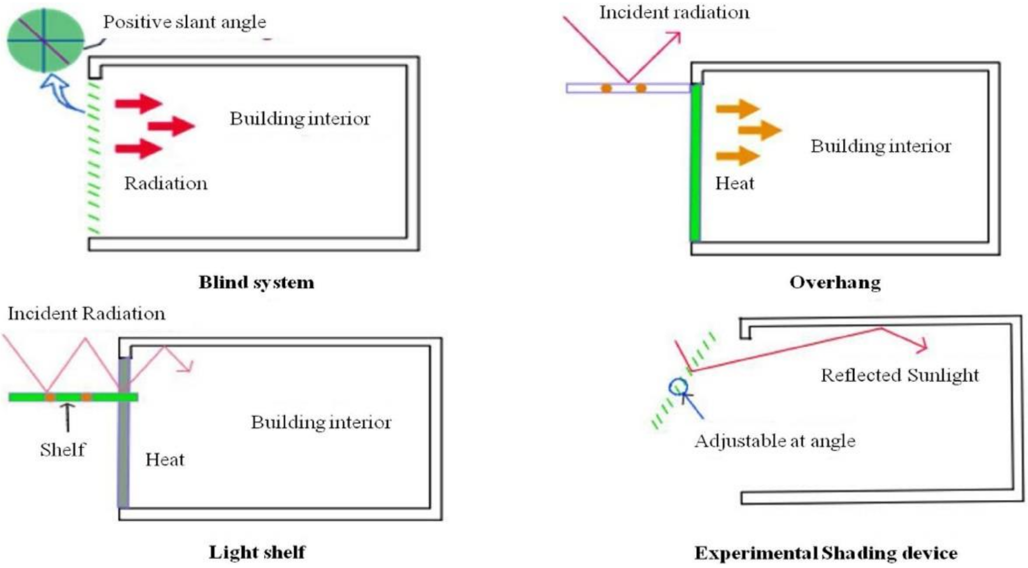


Figure 6: Overview of fixed shading types [11]

Intelligent or self-adaptive facades are special cases of mobile shading systems that involve components attached to the building envelope or openings able to adjust their performance according to surrounding changes in the environment. Different types of intelligent facades exist [12], such as ***kinetic facades***, able to adjust their shape, form, orientation or openings to face dynamically environmental conditions such as temperature, relative humidity or wind velocity [11].

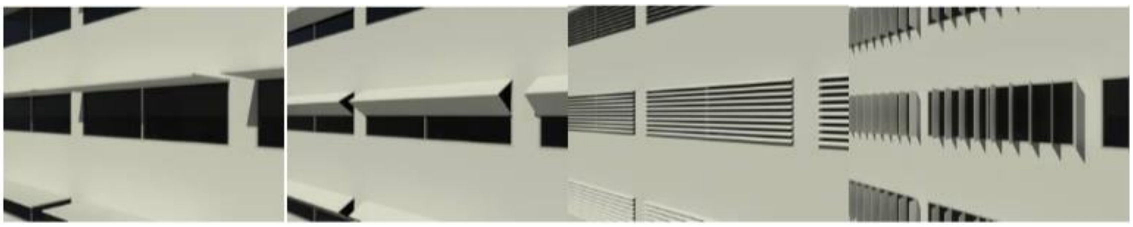


Figure 7: Schematic of kinetic facades [13]

However, they are very expensive and are more suitable for tertiary buildings than for social buildings.

On the contrary, interest in more traditional shading systems in the residential sector is high because of their affordability, low maintenance requirements and relatively easy implementation, both for new construction and for the renovation of existing buildings.

2.6.2 Double skin and solar facades

Other complex types of facades can also be mentioned, which allow the management of light and solar energy:

Open joint ventilated facades

They generally use external metallic frame holding opaque coatings like metal or ceramic. The geometrical assembly of the facade involves an air gap between the building envelope and the coating, enhancing the ventilation [14].

Double-skin facades

Double skin facade consists in two skins (building envelope covered over by a glazed skin) placed in such a way that it let air to flow in the intermediate cavity and thus provide ambient room temperature. The skins can be ventilated or air tightened. In this type of facades, the air cavity situated in between the skins is naturally or mechanically ventilated.

Double-glazed facades

They refer in general to the use of double-glazed windows consisting of two layers of glass separated by an air cavity.

Solar facades

Solar facades are based on the integration of photovoltaic cells in the building facades.

These technologies are however more affordable for office buildings than for residential buildings.

2.6.3 Vegetated facades

A more and more used passive outdoor sun protection consists in vegetating the facades with deciduous plants, which allows to pass the light in winter and to more or less obscure the facade in summer. This also contributes to reduce the urban heat island locally through evapotranspiration phenomena and to purify the outside air.

Figure 8: Example of vegetated facades

2.6.4 Roof treatments

2.6.4.1 Green roofs

The same idea of using vegetation to reduce solar gain also applies to roofs, which can be treated in different ways:

- with a consequent thickness of substrate, which makes it possible to plant shrubs and plants,
- with a low substrate thickness, vegetated with plants that require little water and maintenance such as sedans.

In both cases, the insulation and inertia of the roof are increased and these devices contribute to reduce the urban heat island [15]. They also regulate rainwater supplies in drainage systems.

Figure 9: Example of vegetated roofs (left: https://ideat.thegoodhub.com/2017/09/14/architecture-huit-projets-inspirants-de-toits-vegetalises/; right: -http://flickr.com)

2.6.4.2 Cool roofs

Metal and flat roofs (mainly) may be subject to selective coating treatments. These radiation-based passive techniques allow a significant proportion of solar radiation to be re-emitted compared to conventional coatings [16], [17]. The cool coating solution mitigates roof surface temperatures, temperature gradients in the roof, and thus thermal loads in the building [15].

3. Passive systems for heating and cooling

After having seen how to design the envelope of a building so that it presents the best performance in terms of insulation and summer comfort, we will now focus on HVAC systems to achieve comfortable living conditions for the occupants.
Active systems will be considered next, and initially we will look at some passive or near-passive systems, i.e. those that use little or no electrical or mechanical energy. These systems are an integral part of the bioclimatic approach, complementing the envelope design.

3.1 Trombe wall and solar chimneys

Basically, a Trombe wall is a solar collector consisting of a high inertia wall placed behind a glass surface and connected to the room to be treated by air inlets in the lower and upper parts of the wall (*Figure 10)*. The role of the wall is to absorb and store heat in its thermal mass. In heating mode, cold air from the room enters through the bottom opening in the space between the wall and the glass, heats up along the wall and enters the room through the top inlet. In order to prevent from overheating in summer periods, the exterior glass can be obscured and/or the internal face of the wall can be insulated.

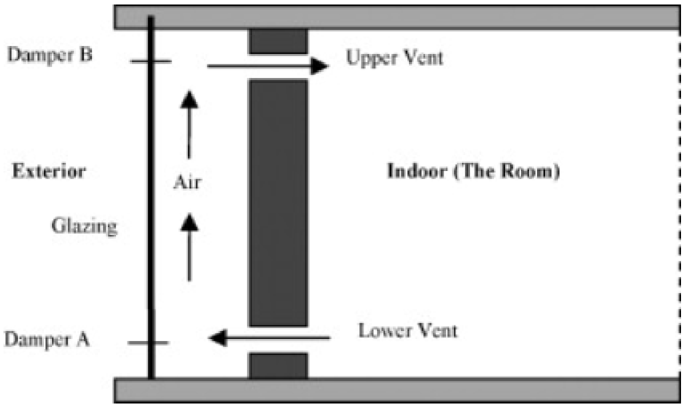


Figure 10: Trombe wall scheme

Trombe wall allows to reduce heating energy consumption by 20 to 40 % in cold climatic conditions [18]. Its impact on cooling energy needs varies between 30 % and 50 % in hot and dry or hot and humid climates [11] and could reach 60 % in Mediterranean climates [19]. They are however rather encountered in individual houses and reserved to strong thermal inertia and moderate insulated constructions in order to avoid too abrupt temperature variations and risk of overheating.

Many variations of the basic principle of the Trombe wall exist. One of them is to create a solar chimney by adding openings on the glass part (*Figure 10, Figure 11*).

Closing the damper A and the upper vent, the solar heated air between the wall and the glazing generates buoyancy forces that draw the room air from the lower vent letting the heated air to flow out via open damper B in a natural ventilation mode. It can also operate as an insulation layer to reduce heat gains of the room.

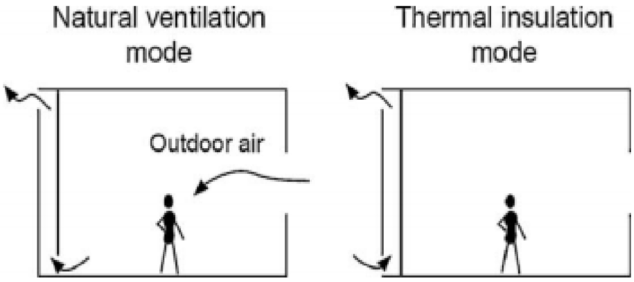


Figure 11: Solar chimney used for cooling mode **[20]**

3.2 Geothermal air pre-heating or cooling

Geothermal energy is the part of earth's heat that can be exploited. Dedicated applications use the earth temperature near the surface (shallow geothermal) or through deep boreholes (deep geothermal) [21]. The ground acts as a heat source in the heating season and as a heat sink when cooling is needed.

The potential of the ground can be used with semi-passive ventilation systems or by active systems, either by directly using the heat of the ground at medium or low temperature (water direct geothermal heating), or by the use of heat pumps for heating and/or cooling but also for Domestic Hot Water (DHW) production.

Pre-heating or cooling the supply air entering a building can be achieved by the use of so-called earth pipes, which are pipes buried at shallow depth (typically between 1 and 2 m).

The air can then be blown directly in the rooms (single flow ventilation systems, *Figure 12Figure 1*) or coupled to a heat recovery exchanger (dual flow ventilation systems, *Figure **13*****¡Error! No se encuentra el origen de la referencia.**).

These systems are more efficient in the climates with strong temperature differences between day and night, or contrasting climates [22].

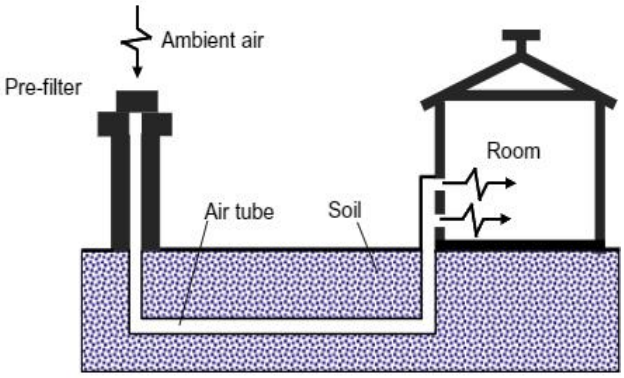


Figure 12: Schematic of an earth-pipe system for air pre-heating and cooling

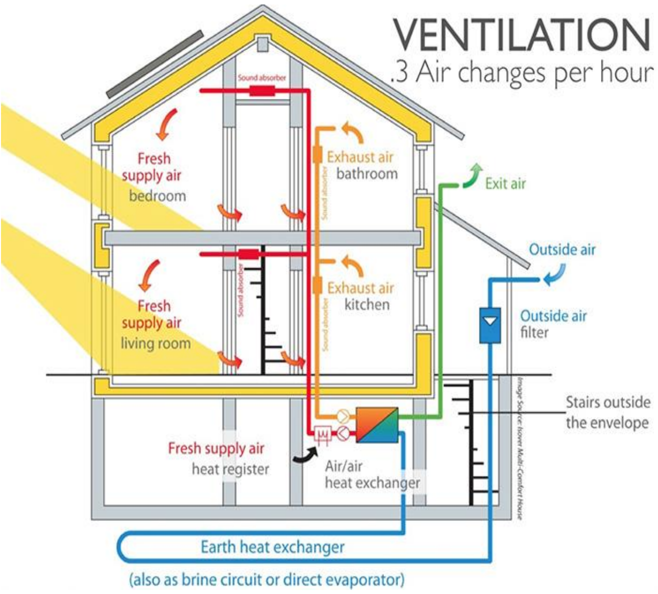


Figure 13: Ground heat-exchanger coupled to a dual flow ventilation system

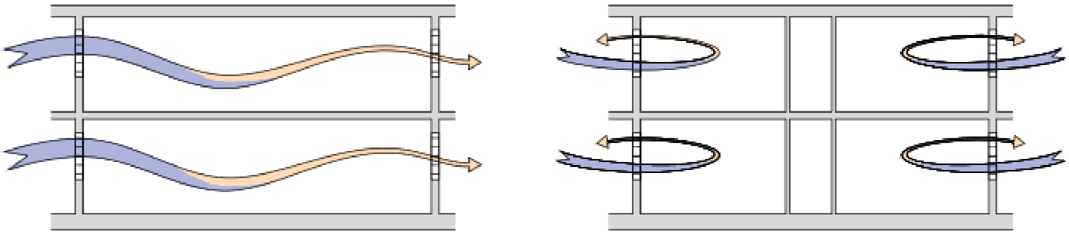
3.3 Free cooling and night-time over-ventilation

Free cooling is encountered in tertiary buildings equipped with air handling units and consists in switching to full fresh air ventilation mode when the outside air is colder than the inside air, without changing the flow rate.

Over-ventilation techniques consist in increasing the supply air flow rate by a significant amount (of the order of 3 ACH, instead of typically 0.5 ACH for basic ventilation). They are mainly used during night-time when the outside air allows to release the heat absorbed by the building thermal mass and to cool it, thus delaying the need for active cooling in day time [23].

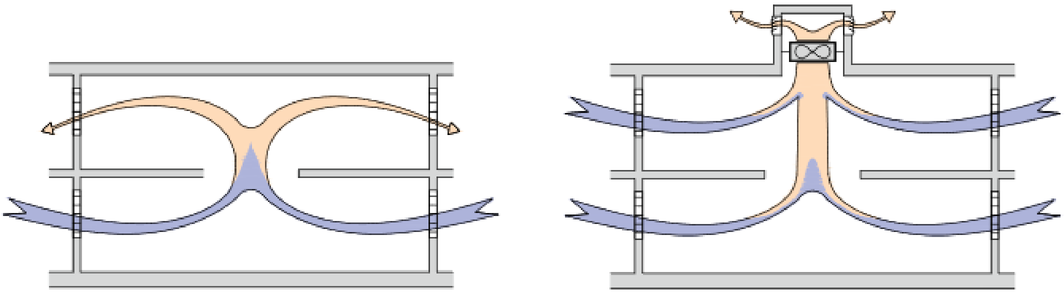
Over-ventilation can be used under almost every climate condition. However, its effectiveness is not guaranteed when the outdoor temperature is exceedingly high, or when the daily temperature amplitude is insufficient [24]. In fact, climates with high diurnal ranges are the most suitable to benefit from, while in contrast, hot-humid climates with warmer nights are generally less appropriate. Furthermore, as other natural ventilation techniques, it can be combined with solar chimneys and/or wind towers to be improved [25].

For residential buildings, over-ventilation can be achieved by natural ventilation or mechanical systems, through either individual or collective installations. Principles of natural or mechanically-assisted ventilation are presented in *Figure 14* [26].



14.a: Natural cross ventilation

14.b: Natural single-side ventilation



14.c: Natural ventilation by stack effect

14.d: Mechanically-assisted natural ventilation (hybrid ventilation)

Figure 14: Principles of natural or mechanically-assisted ventilation in dwellings **[26]**

Floor-through housing (*Figure **14**: Principles of natural or mechanically-assisted ventilation in dwellings Figure 14.a*) is favourable to cross ventilation. Stack effect ventilation (*14.c*) is favoured for flats located on several levels and hybrid ventilation (*14.d*) requires the presence of shunt ducts in the flats. Single-sided dwellings are not very conducive to natural over-ventilation.

Finally, floors can be used as thermal storage reservoirs through hollow core slabs associated to night-time over-ventilation systems or active air-cooling systems [27].

4. Definition of some bioclimatic indicators

From the previous elements, we can now consider defining bioclimatic performance indices of a building, with two approaches:

- one that focuses on defining the intrinsic performance of the building envelope to reduce energy needs and ensure summer comfort situations,
- the other that considers the ability of the envelope to recover and use free inputs from different sources such as the sun, the outside air, the sky vault...

4.1 Example of a bioclimatic indicator: the Bbio indicator of the French thermal regulation

An example of a bioclimatic indicator related to the quality of buildings with regard to their design and their ability to use the free resources of the environment is obtained from the French thermal regulation [28].

This regulation includes three performance requirements for new buildings:

- bioclimatic needs of the building (Bbio);
- primary energy consumption (C_{ep});
- conventional indoor temperature (T_{ic}), related to summertime thermal comfort;

which must respect maximum conventional values.

The Bbio indicator permits to characterize the impact of the building design on its energy demand for heating, cooling (if needed) and lighting, independently of the systems subsequently implemented. It is defined as:

$$Bbio = 2 \times \text{Heating need} + 2 \times \text{Cooling need} + 5 \times \text{Artificial lighting need}$$

This value must be less than a $Bbio_{max}$ level depending on the dwelling characteristics (individual, collective …) and climatic situation.

To achieve this bioclimatic requirement, the building design must promote several parameters: insulation and air tightness of the envelope, inertia of the structure, favourable exposure, compactness, and access to natural lighting and solar gains.

The very next 2022 regulation will retain the Bbio indicator, as well as the Cep, but abandons the Tic indicator in favour of an hourly indicator of discomfort.

4.2 Definition of some passive energy recovery performance indicators

This section focuses on the definition of some indicators of building performance in terms of coverage rate and recovery of free gains that could be interesting in the ARCAS context. It is mainly based on the work of Chesné et al. [29].

Starting from the nomenclature of EPB Annex under EN-ISO 52000-1:2017 [30], we define in a heating situation:

- The **raw need** of a building which correspond to the energy need for balancing the heat losses (transmission and ventilation losses),
- The **useful free gains** (solar, internal)
- The **energy need** or net energy need, which results from the raw need minus the useful free gains.

In a cooling situation, the energy need will be the sum of the raw need plus the free gains.

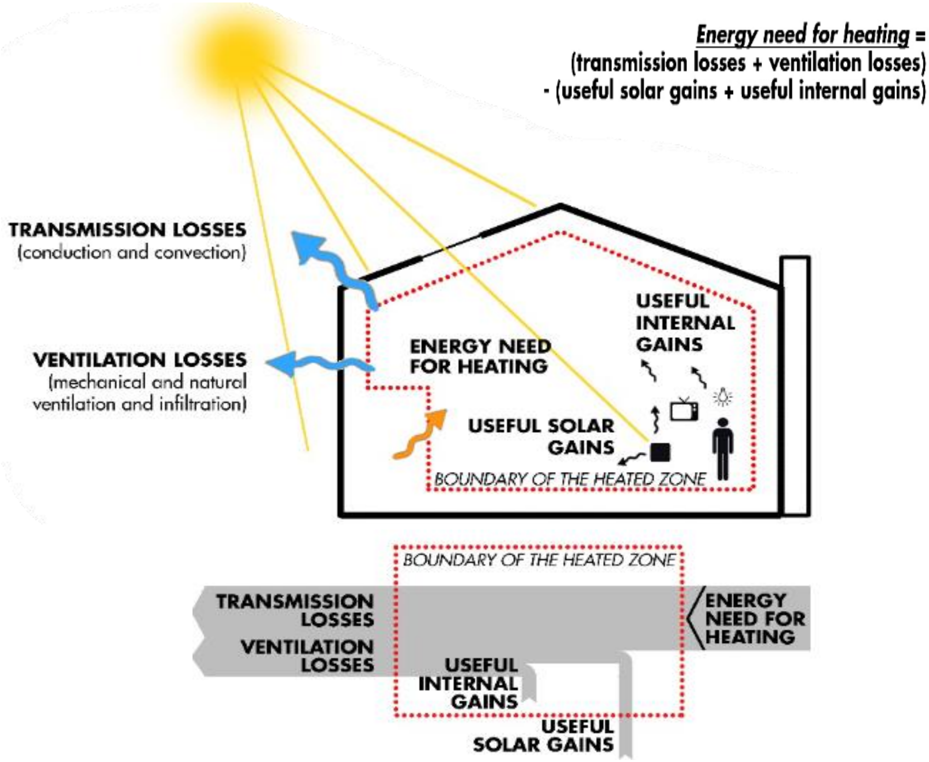


Figure 15: Schematic view of the energy need for heating **[30]**

Chesné et al., [29], [31] consider an external energy source as “useful” if it is effectively available in the environment when the building needs it. Thus, difference can be made between two types of needs in buildings: residual needs and real needs.

- Residual needs are those which correspond to the energy which can be delivered by energy simulation software or measured on-site in the presence of all the available sources and systems: in other terms, they correspond to the net building energy needs considering useful gains (energy need in *Figure **14**Figure 15*).
- Real needs represent the energy demand in the absence of the potential source studied (raw needs).

The difference between the raw energy and (net) energy needs results in the exploited potential, Pt^{exp}, of the source. Therefore, two sets of indicators are defined: potential indicators and performance indicators, in order to evaluate the natural resources potentials regarding building energy needs and on the other hand to assess the building capacity to take advantage of these resources (***Figure 16***).

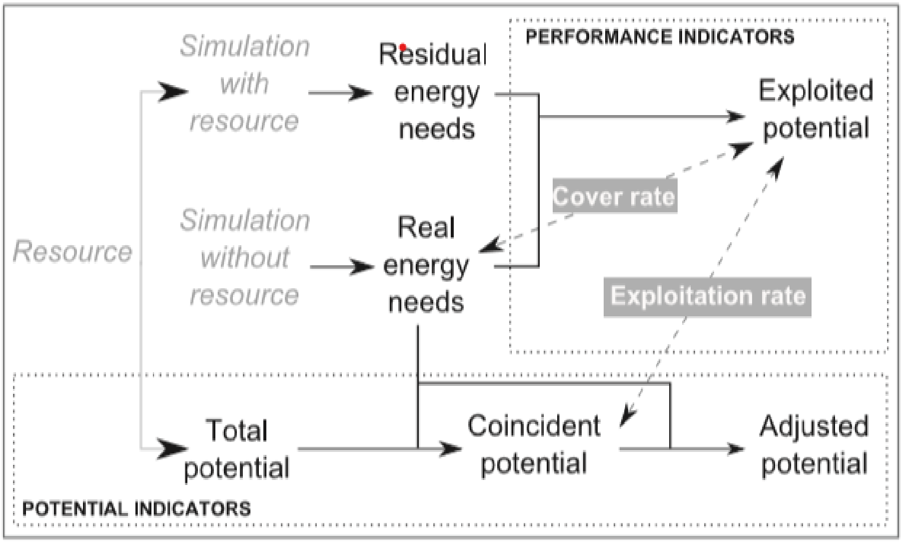


Figure 16: Bioclimatic indicators according to Chesné et al. **[29]**

4.2.1 Potential sources indicators

Two potentials are defined for each external energy source:

4.2.1.1 Total potential Pt^{tot}

$Pt^{tot}(t)$ represents the total energy potential provided by a source at each instant.
For the sun, the solar total potential includes both direct and diffuse incoming radiation on the building walls at each time step:

$$Pt_{sun}^{tot}(t) = \sum_{walls} (\emptyset_{dir} + \emptyset_{diff}) S_w$$

where $\emptyset$ is the heat flux and S_w the walls surface.

Such a potential can also be defined for the sky, which consists of the net heat flow exchanged between the sky vault and the building wall surfaces:

$$Pt_{sky}^{tot}(t) = \sum_{walls} F \varepsilon_w \sigma \left(T_{out}^4 - T_{sky}^4\right) S_w$$

where T_{out} is the average outside walls temperature considered equal to air external temperature, T_{sky} the sky vault temperature, S_w the walls surface, σ the Boltzmann constant, ε_w the walls emissivity and *F* the form factor between the wall and the sky.

The outside air potential is defined as the enthalpy flow exchanged between inside and outside air:

$$Pt_{air}^{tot}(t) = \dot{m} C_{pa} (T_{ac} - T_{out})$$

With T_{ac} is the inside air temperature equal to the cooling set-point temperature, if exists, C_{pa} the air specific heat and $\dot{m}$ the total air exchange mass flowrate.

The total potential of a source is obtained by integrating the instantaneous total potential over the desired period:

$$Pt_{source}^{tot} = \int_0^t Pt^{tot}(t) dt$$

4.2.1.2 Coincident potential Pt^{coinc}

$Pt^{coinc}(t)$ compares the instantaneous total potential of a source to the corresponding amount of delivered energy. So, it is set to zero when the energy demand is null and equal to the total potential when there is an energy demand.

$$Pt^{coinc}(t) = \begin{cases} Pt^{tot}(t) & if\ energy\ needs\ exist \\ 0 & if\ energy\ needs\ = 0 \end{cases} at\ instant\ t$$

In the same manner of the total potential *Pt^{tot}*, the coincident potential is calculated by the integration of the instantaneous coincident potential over the required time period (*Figure 17*).

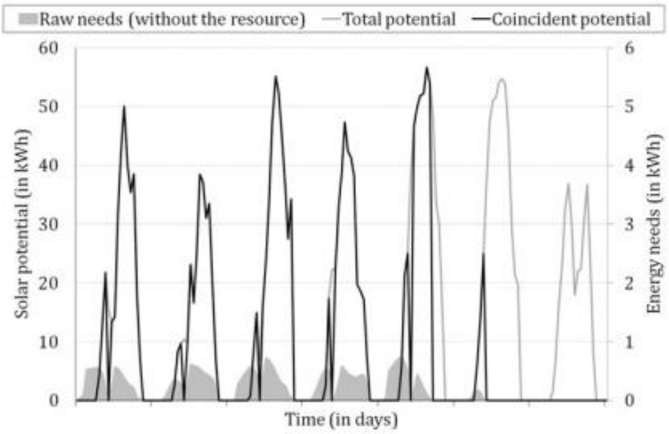


Figure 17: Principle of solar coincident potential **[29]**

4.2.2 *Performance indicators*

Two performance indicators are then defined according to the preceding definitions: the exploitation rate and the coverage rate.

4.2.2.1 The exploitation rate

The exploitation rate represents the ratio of the exploitation potential Pt^{exp} (defined as the difference between the raw energy need and the net energy need) and the coincident potential of the source Pt^{coinc}.

$$\tau_{exp} = \frac{Pt^{exp}}{Pt^{coinc}} = \frac{Raw\ energy - net\ energy\ needs}{Pt^{coinc}}$$

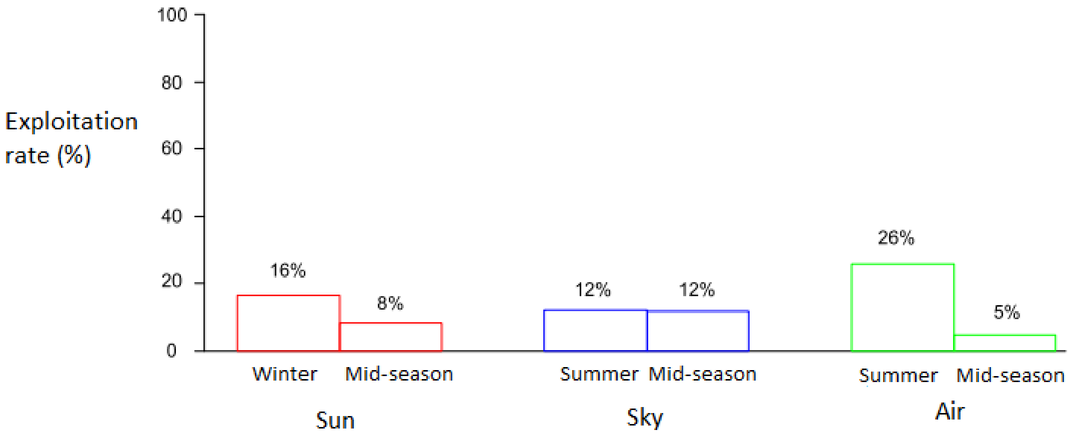


Figure 18: example of exploitation rate of sun, sky and outside air sources **[31]**

The exploitation rates of the sources are generally low as observed by Chesné et al. [29] which confirms the earlier results of the HABISOL-VALERIE project [32]. An exploitation rate of around 10% for all the available resources is found to be a valid approximation. Therefore, the actual building design restricts the exploitation ratio of environmental potentials. Consequently, the innovations to be introduced must primarily concern the improvement of the exploitation rates of the resources.

4.2.2.2 The coverage rate

The coverage rate is the part of the raw energy need covered by the energy source:

$$\tau_{cov} = \frac{Pt^{exp}}{Raw\ needs} = \frac{Raw\ needs - net\ energy\ needs}{Raw\ needs}$$

The situation where Pt^{exp} is negative means that the source generates another need to be fulfilled (for example, the sun is considered as heating source in the cold days, but generates cooling loads during the hot days).
This need is discretized as the ratio of absolute value of the coincident potential and the residual energy needs.

$$\tau_{gen} = \frac{|Pt^{exp}|}{Net\ energy\ needs} = \frac{|Raw\ neeeds - net\ energy\ needs|}{Net\ energy\ needs}$$

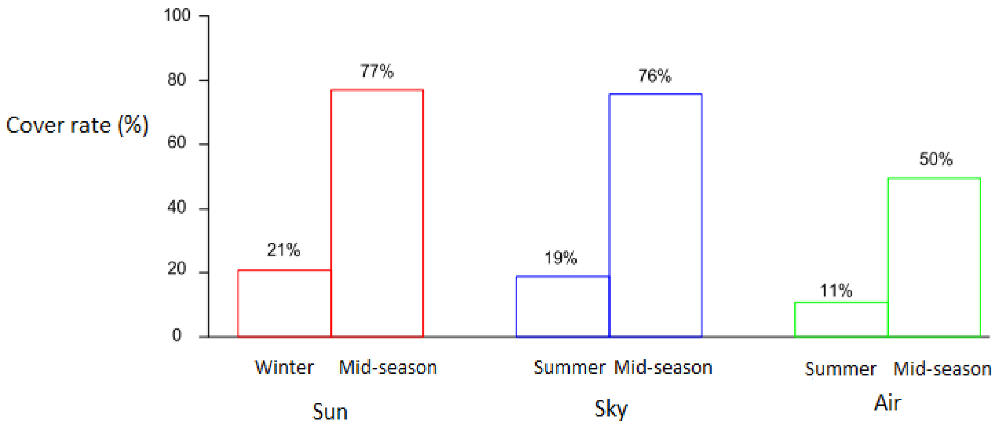


Figure 19: Examples of coverage rates (τ_{cov}) of sun, sky and outside air sources [31]

The sum of the coverage rates of two resources covering the same type of needs (such as sky and air for cooling needs) is not necessarily less than 100 % because the needs used for the

calculation are the real needs for each resource and the subtracted resources: the simulations being different, the needs are therefore different.
This approach allows to evaluate separately the bioclimatic potential of each environmental source with respect to the building energy needs.

5. Summary of possible bioclimatic indicators and adequacy of passive solutions and indicators in the ARCAS context

From the previous chapters, the following table summarises the bioclimatic indicators that can be considered, both at the urban scale and for single buildings.

Table 5: Summary of some bioclimatic indicators

<table>
<tr><th colspan="6">Simple bioclimatic indicators</th></tr>
<tr><th colspan="2">Urban indicators</th><th colspan="2">Envelope indicators</th><th colspan="2">Performance indicators</th></tr>
<tr><td colspan="2">Urban built density indicator D_{surf}</td><td colspan="2">Building airtightness</td><td colspan="2">Annual heating consumption/m^2</td></tr>
<tr><td colspan="2">Compactness C</td><td colspan="2">Heat Loss coefficient HLC</td><td colspan="2">RT2012 indicators (Bbio indicator)</td></tr>
<tr><td colspan="2">Facades exposure to sunrays</td><td colspan="2">Ratio of glazed surface</td><td colspan="2">Discomfort indicator</td></tr>
<tr><td colspan="2">Natural light Potential P_{light} or Daylight Factor DF</td><td colspan="2">Solar gains related to living area S_{floor}</td><td colspan="2"></td></tr>
<tr><th colspan="6">Energy related bioclimatic indicators</th></tr>
<tr><th colspan="3">Resources potential indicators</th><th colspan="3">Performance indicators</th></tr>
<tr><td colspan="3">Total Potential Pt^{tot}</td><td colspan="3">Exploitation rate τ_{exp}</td></tr>
<tr><td colspan="3">Coincident Potential Pt^{coinc}</td><td colspan="3">Coverage rate τ_{cov}</td></tr>
<tr><td colspan="3">Exploited Potential Pt^{exp}</td><td colspan="3">Generated need rate τ_{gen}</td></tr>
</table>

The objective of the ARCAS project is to be able to propose relevant indicators, which allow to evaluate the sensitivity of the envelope and system renovation choices to the performances both in terms of energy and comfort. The passive solutions to be considered must be reproducible (i.e. not specific to a case study), robust, reliable and technologically and financially accessible for social housing.

We therefore propose to test some solutions on an existing building model through building energy simulations:

- The building orientation (even though it can be restricted in real situation by the parcel geometry, the roads network …);
- The thermal insulation of opaque walls;
- The thermal characteristics and solar aperture of windows;
- The shading systems;
- The night-time over-ventilation.

Concerning the indicators, the following ones will be considered:

- Building characteristics indicators
    - Compactness
    - Heat loss coefficient
    - Glazed area related to floor area
    - Solar gains related to floor area
- Building performance indicators
    - Heating need / Overheating
    - Exploited Potential
    - Coverage/exploitation rate

6. A bioclimatic case study. Application to an existing building

6.1 Simulations description

With the objective of assessing the relevance of the proposed solutions to define a coherent set of bioclimatic indicators in the ARCAS context, parameter variation is applied to a real size building with the TRNSYS® Thermal Dynamic Simulation tool.

The selected building, referred as PN6, consists in a 50's social housing building that will be considered for a global renovation operation (*Figure 20*).

The building characteristics are given in the Annex 1 building description sheet, completed with the associated scenarios for occupation and internal gains (*Annex 2*). The four-storey building is 35.40 m long, 6.90 m wide and 15.25 m high and includes 8 one-bedroom and 8 four-bedrooms apartments, with a total living area of 960 m². Its main sides face East and West and some surfaces characteristic as well as the heated volume are given in

*Table **6**: PN6 main characteristics**Table 6***.

The mains characteristics of the envelope are (see the building description sheet for a more complete description):

- Rubble walls without insulation
- Plaster brick ceiling with 120 mm rock wool insulation
- Single or old generation double-glazed windows (see below)
- The n_{50} airtightness coefficient of the envelope is estimated to 0.34 h^{-1} for the one-bedroom flats and 0.48 h^{-1} for the four-bedroom ones.

Figure 20: PN6 Building East (left) and West (right) facades

Table 6: PN6 main characteristics

Facades walls area (m^2)	1 154
Envelope surface (m^2)	1 404
Living area (m^2)	960
Heated volume (m^3)	3 062
Shape Coefficient SC (m^{-1})	0.46
Windows area (m^2)	214

Windows area / living area (%)	23

In the initial state of the building, only natural ventilation is present. The East facade windows are of single glazing type (U = 5.69 W/m^2.K, SHGC = 0.823) and represent 58 % of the total glazing area. Double glazed windows (U = 1.69 W/m^2.K, SHGC = 0.66) are used on the West facade (34 % of the total glazing area).

To test renovation proposals, the following modifications are considered:

- Change the building orientation;
- Add 14 cm external insulation of expanded polystyrene on the walls;
- Implement a constant mechanical ventilation of 60 m^3/h for single-bedroom apartment and 120 m^3/h for four bedrooms apartments according to the French regulation for ventilation;
- Extend the double glazing to all the windows with U-value of 1.69 W/m^2.K and a solar factor g-value of 0.66
- Install triple glazing windows with a U-value of 0.73 W/m^2.K and a solar heat gain coefficient (SHGC) of 0.3.

The different test configurations of the building are summarised in *Table 7****¡Error! No se encuentra el origen de la referencia.****.*

Table 7: PN6 test cases description

Model	**Description**
Reference case	Initial building (main façade East)
Case_1	Initial building facing South-North instead of East-West (+90°)
Case_2	Initial building facing S-W/N-E instead of East-West (+135°)
Case_3	Initial building facing West-East instead of East-West (+180°)
Case_4	Initial building-oriented N-W/S-E instead of East-West (+225°)
Case_5	Initial building-oriented North-South instead of East-West (+270°)
Case_6	Initial orientation. **External** insulation and mechanical ventilation are added to the initial building
Case_7	Case_6 + double glazed windows on the East facade
Case_8	Case_6 + triple glazed windows on the East facade
Case_9	Initial orientation. **Internal** insulation + mechanical ventilation + triple glazed windows on the East facade

6.2 Main results

6.2.1 Simple bioclimatic indicators

The main simple bioclimatic indicators retained in section **¡Error! No se encuentra el origen de la referencia.** for testing in the ARCAS project are summarized in *Table 8***¡Error! No se encuentra el origen de la referencia.**.

Table 8: Main simple PN6 bioclimatic indicators

Compactness C				
$C_1 = 1.20$, $C_2 = 0.56$, $C = C_1 + C_2 = 1.76$				
Glazed area related to living area				
23 %				
Heat Loss Coefficient HLC (W/degree)				
Reference case	Case_1 to Case_5	Case_6	Case_7	Case_8 & Case_9
4237.8	4237.8	2483.3	2109.7	1941.3

With a compactness factor equal to 1.76 and a shape coefficient of 0.46 m^{-1}, the PN6 building can be considered as intermediate in terms of compactness.

The glazed area related to living floor area is about 23 %, which is higher than the minimal ratio (1/6) of the RT2012 French regulation.
The highest values of the HLC coefficient are encountered in the initial state of the building. HLC coefficient decreases when the envelope thermal resistance increases (Case_6) and continues to decrease with the use of double-glazed (Case_7) and triple-glazed windows (Case_8 or Case_9) on the East facade.

The following figures present the solar gains during the heating period (*Figure 21***¡Error! No se encuentra el origen de la referencia.**) and the heating demand (*Figure 22*) relative to the living area. The Bbio coefficient is presented in
Figure ***23*** and is evaluated only through the heating demand (net energy need) and an artificial lighting demand based on an observed average load of 2.8 kWh/m^2 (the cooling need is not considered by the RT2012 in that case).

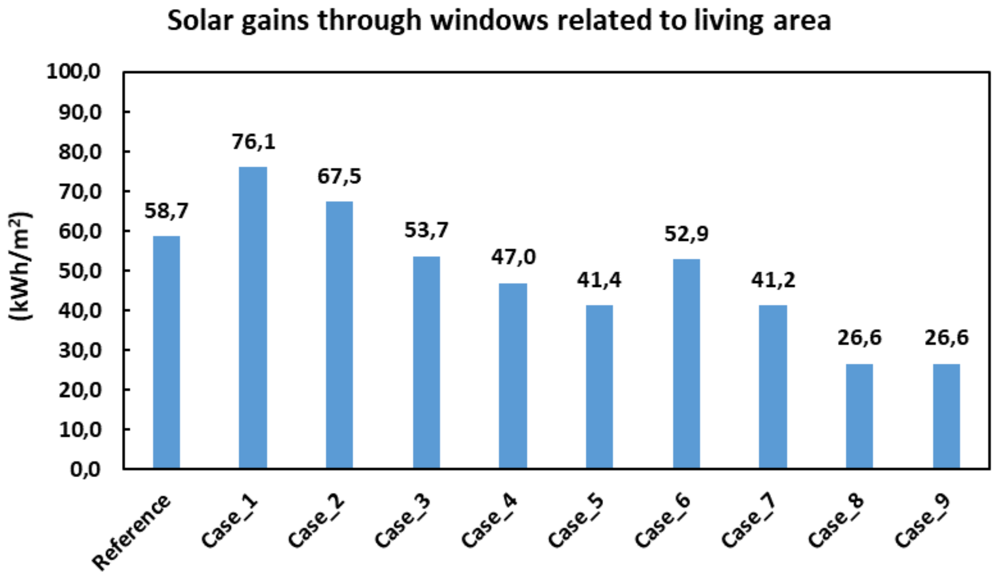


Figure 21: Variation of the solar gains via external windows related to living area during the heating period

For the building with its initial envelope, the orientation has obviously a strong influence on the solar gains during the heating season, and consequently on the heating need and the Bbio indicator, the best orientation being the North-South one.

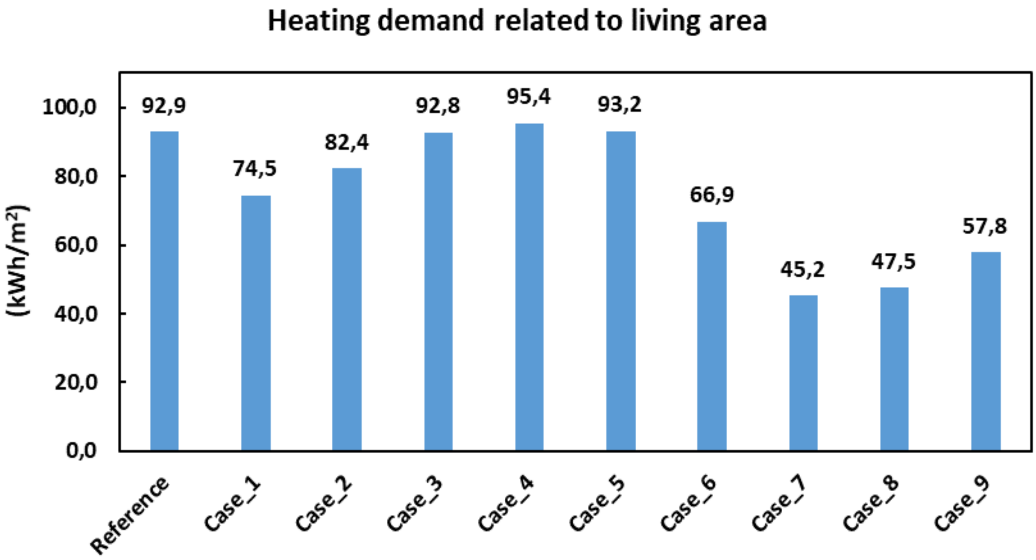


Figure 22: Variation of the heating demand related to living area (net energy need)

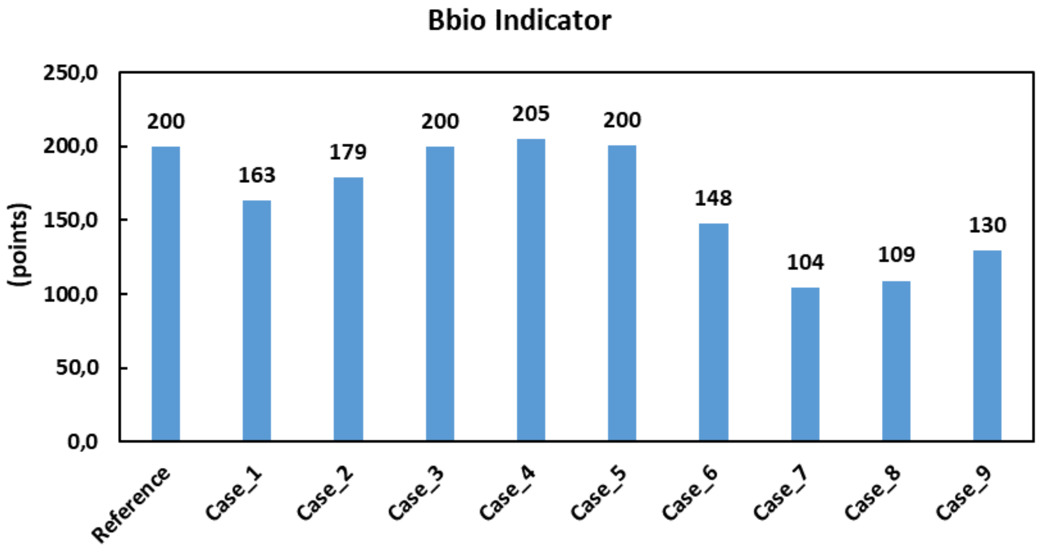


Figure 23: Variation of the Bbio indicator

When the performances of the envelope are improved, the evolutions are more complex, since the solar gains decrease with double and triple glazing on the East façade, but the heat losses also decrease, resulting in a global decrease of the total needs (case 6 to 9) compared to cases 1 to 5.

6.2.2 Energy performance indicators

Evaluation of the raw and net energy needs allows to calculate the exploited potential, Pt^{exp}, and the exploitation rate, τ_{exp}, of the solar resource by the building. The results are shown in *Figure 24* in addition to the coincident potential, Pt^{coinc}, for walls and windows in each configuration. The coincident potential for the different cases is higher for the initial envelope (non-insulated building and low windows U_w values but high SHGC), regardless of the orientation (reference case and Cases 1 to 5). The same observation applies on the exploited potential. Moreover, the exploitation rate is relatively low in all cases (lower than 15 %), which means that the source is not exploited much by the building, with higher values for the initial building than for the renovated one. The same results were obtained by Chesné et al. [29] with old buildings (before 1974) showing higher exploitation rates than newer low consumption buildings.

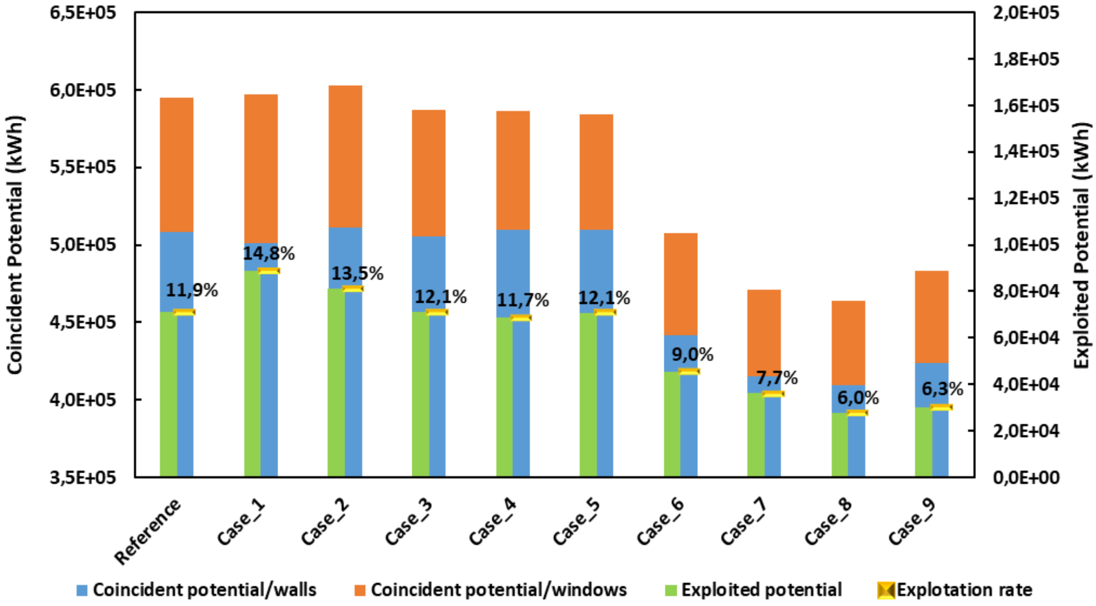


Figure 24: Variation of the solar coincident and exploited potentials and exploited rate

Figure 25 reports the variation of the coverage rate, which results in a balance between the raw needs, which depend on the HLC of the envelope, and on the solar gains which mainly depend on the solar factor of the windows. Double glazed windows decrease the solar gains compared to single glazing because of lower SHGC, but also decreases the raw needs because of lower U value. The combination of the relative influence of these two factors result in variations of the coverage rate which seem *a priori* surprising.

This is well illustrated between Case_7 and Cases_8 & 9 (double glazing versus triple glazing). The higher U value of the double glazing nevertheless improves the coverage rate (45.4 %) compared to triple glazed-windows (37.8 %) because in that case the useful gains are much lower due to a lower solar factor. Conclusions could probably be different for more rigorous winter climate conditions than La Rochelle conditions, where the decrease of the raw needs associated to triple glazing could be higher than the reduction of the solar gains, thus increasing the coverage rate.

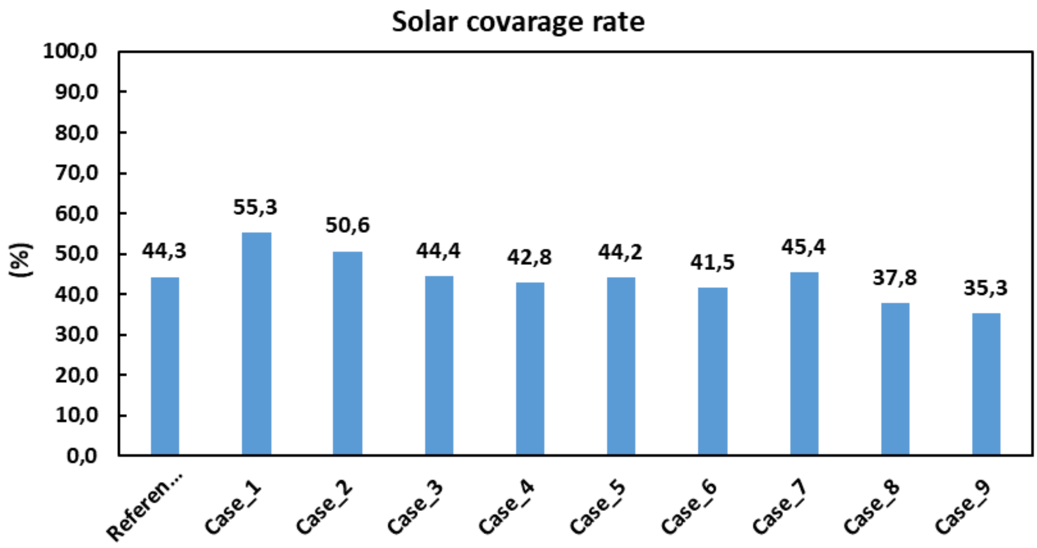


Figure 25: Variation of the solar coverage rate

6.2.3 Summer thermal comfort

As mentioned before, no cooling set point is applied for the building during summer and the indoor temperature then fluctuates freely (the cooling needs associated to a setup temperature is presented below).
The percentage of discomfort is evaluated by the number of hours of overheating, considering a maximum operative temperature of 27 °C according to Olesen et al. [33].

The number of overheating hours (when the operative temperature is higher than 27 °C) during the occupancy periods are calculated for each of the 16 apartments and for 2 cases (reference and Case 1). The results obtained for the most disadvantaged 4-room apartment are reported in *Table 9Table* ***9***, as well as the monthly distribution of overheated degree.hours (ODH), defined by:

$$ODH = \sum_{month} (T_{op,i} - 27) \times N_i$$

N_i is the number of hours where the operative temperature $T_{op,i} > 27$ °C is observed.

Table 9: Discomfort indicators for the reference case and case 1

	Reference Case	**Case 1**

<table>
<tr><td>Maximum temperature (°C)</td><td colspan="3">34.4</td><td colspan="2">33.8</td></tr>
<tr><td>Number of overheating hours (h)</td><td colspan="3">1813</td><td colspan="2">2022</td></tr>
<tr><td>Discomfort percentage</td><td colspan="3">27.4 %</td><td colspan="2">30.6 %</td></tr>
<tr><td colspan="6">Monthly ODH distribution for the reference case (°C.h)</td></tr>
<tr><td>January</td><td>February</td><td>March</td><td>April</td><td>May</td><td>June</td></tr>
<tr><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>4.9</td><td>897.8</td></tr>
<tr><td>July</td><td>August</td><td>September</td><td>October</td><td>November</td><td>December</td></tr>
<tr><td>2077.9</td><td>904.3</td><td>219.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="6">Total = 4103.9 °C.h</td></tr>
<tr><td colspan="6">Monthly ODH distribution for the Case 1 (°C.h)</td></tr>
<tr><td>January</td><td>February</td><td>March</td><td>April</td><td>May</td><td>June</td></tr>
<tr><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>2.2</td><td>327.0</td></tr>
<tr><td>July</td><td>August</td><td>September</td><td>October</td><td>November</td><td>December</td></tr>
<tr><td>1426.5</td><td>1287.9</td><td>1411.9</td><td>107.1</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="6">Total = 4562.6 °C.h</td></tr>
</table>

High discomfort percentages are detected in both cases since they are much higher than 5 %, defined as the acceptable summer discomfort level according to the European Standard EN 15251 [34].

We observe that even if the maximum temperature is lower in case 1 (North-South orientation of the building), the discomfort percentage and ODH are much higher than in the initial East-West orientation, which is accompanied by a temporal shift towards autumn. The south façade, with a 35 % window to wall ratio, is really critical for medium latitude zones such as La Rochelle city, especially if no solar protection is applied, which entails high discomfort levels.

Night-time over-ventilation and shading systems on the windows will be considered later as processes that can reduce these discomfort situations.

6.2.4 Cooling need

A cooling set-point temperature of 27 °C was applied on the different cases of *Table 7* in order to evaluate the net cooling needs and raw cooling needs (without the solar source). Omitting the sun results in a null raw cooling need for all the cases, which means that the cooling needs are only generated by the solar loads.

6.2.5 Impact of external shading systems and night-time over-ventilation on the summer thermal comfort and cooling need

Two passive cooling techniques are tested separately to evaluate their impact on the building thermal behaviour during summer season when no active cooling is present:

External shading systems

External shading devices are considered for all the windows. In a first approach, the solar protection is activated when simultaneously:

$T_{int} \geq 27$ °C and global vertical incident radiation flux density ≥ 650 W/m^2.

In a second approach the conditions are:

$T_{int} \geq 27$ °C and global vertical incident radiation flux density ≥ 300 W/m^2.

In both cases, the shading systems are activated at 80 % in order to benefit from the day luminosity.

Night-time over-ventilation

A night-time ventilation rate of 3 ACH is applied between 23h and 6h during the period June-September when $T_{int} \geq 23$ °C and exceeds by at least 2 °C the outdoor air temperature.

These strategies are applied for the reference case, Case_7 (double glazing) and for the Case_7 modified with a South-North orientation instead of East-West. The results are summarised in *Table 10.*

Table 10: Summer thermal behaviour for the 3 cases

Case	**Maximum Temperature (°C)**	**Overheating hours (h)**	**Discomfort percentage (%)**	**Annual ODH (°C.h)**
Reference	34.4	1813	27.4	4 103.9
Shading (650 W/m^2)	33.3	1722	26.0	3 288.7
Shading (300 W/m^2)	29.9	1135	17.2	1 009.9
Night-ventilation	32.1	837	12.7	1 136.9
Case_7	35.4	2081	31.4	5 665.6

Shading (650 W/m^2)	33.9	2013	30.4	4 509.7
Shading (300 W/m^2)	29.9	1190	18.0	957.4
Night-ventilation	32.5	726	11.0	935.6
Case_7 modified	34.5	2133	32.2	4 722.7
Shading (650 W/m^2)	33.9	1926	29.1	3 952.6
Shading (300 W/m^2)	29.1	812	12.3	467.3
Night-ventilation	31.7	623	9.4	744.3

As can be seen for the three cases, applying external shading systems when global solar flux density is higher than 650 W/m^2 results in a slight decrease in maximum temperature and overheating hours. The indoor thermal comfort is highly improved if shading systems are activated as soon as the solar flux density of 300 W/m^2 is reached. In addition, the use of night-time ventilation permits to decrease deeply the discomfort percentage in terms of overheating hours and annual ODH, especially when double glazing windows are present.
It should be noted that, according to the future French environmental regulation RE2020, the maximum threshold of ODH for social housing will be 2 100 °C.h for a living area higher than 60 m^2 and 2 600 °C.h for an area lower than 20 m^2. Therefore, in the PN6 case, the use of appropriate external shadings and/or application of night-time ventilation helps to fall within the future regulatory range of ODH.

The cooling needs evaluated with and without the use of shading systems or night-time ventilation are presented in *Figure 26* ***¡Error! No se encuentra el origen de la referencia.*** . We observe the potential of night-time ventilation, which exhibits performance equivalent to the one of external shading systems with a solar flux density of 300 W/m^2, in reducing the cooling needs.

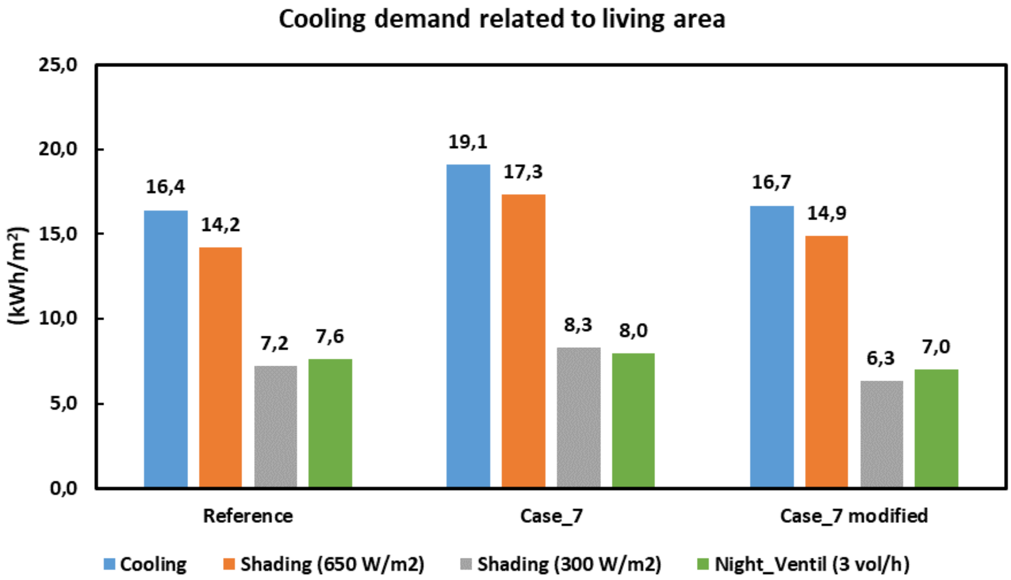


Figure 26: Variation of the net cooling needs with the use of passive cooling devices

6.3 Conclusions

This case study illustrates the concepts developed in the previous paragraphs on bioclimatic building design and the indicators that can be used. It highlights the role of orientation and envelope quality on heating needs and summer comfort criteria, and shows the potential of passive cooling techniques to improve summer comfort.

External air convection and sky vault potentials remain to be studied in the aim of analysing their contribution on cooling demand and summer indoor conditions, especially during heat waves periods.

7. Active HVAC systems

Active HVAC systems are considered in this section, and particular attention will be paid in a first part to ventilation systems, as they are often a focus in multi-family building renovation projects and are of primary importance to ensure healthy indoor conditions.

7.1 Ventilation

In a first part, comparison of the different national regulations for dwellings ventilation is performed. Then evaluation of the energy consumption and indoor air quality of various ventilation systems in collective building, from ventilated separated rooms to whole general and permanent ventilation and evolution from natural to mechanical/hybrid ventilation and pressure/humidity-controlled systems is achieved through a case study based on the French regulation.

7.1.1. Evolution of national regulations and ventilation systems in collective buildings

French situation

The French situation is a good example of the evolution of housing ventilation over the years, and thus of the evolution of ventilation systems. It will be used as a basis before extending to the evolutions of the Spanish and Portuguese regulations.

In France, buildings constructed between 1906 and 1937 were required to have a smoke flue in the kitchen and in each of the main rooms, for wood or coal heating. Air enters through leaks in the building envelope and openings in windows and leaves the building in the same room resulting in a **separated room ventilation**. In 1937, low and high air vents on facade with a minimum open cross-section of 100 cm^2 became mandatory in each utility room and main room with combustion device (*Figure **27***).

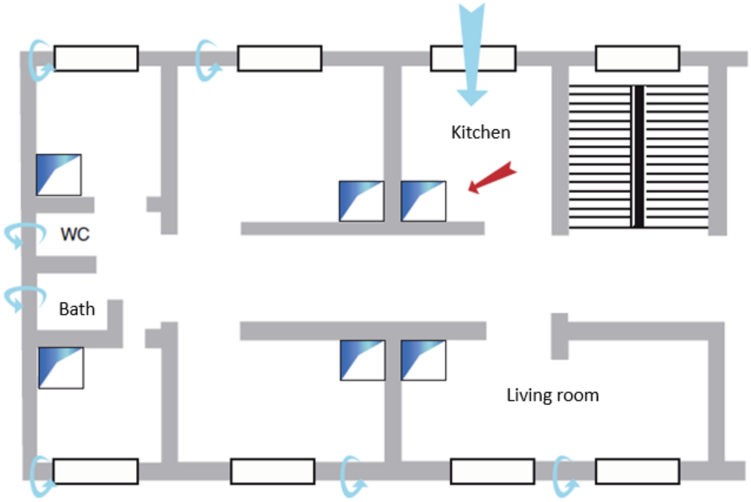


Figure 27: Separated rooms ventilation in buildings constructed between 1937 and 1958 [35]

Since 1958, rooms are no longer independently ventilated, except for bathrooms and toilets. The air is extracted through ducts located in the kitchen. These ducts can be of two types: individual or shunt (*Figure 28*). The individual ducts connect the bathroom, the sanitary facilities and the kitchen directly to the roof. Ducts corresponding to different rooms or dwellings do not communicate with each other. With the shunt system, bathrooms or kitchens, located one above the other, are connected to a vertical duct. The vertical duct and the individual connections of each dwelling make up the shunt duct. The air enters through leaks in the building envelope, and openings in each room are needed to satisfy good indoor air quality.

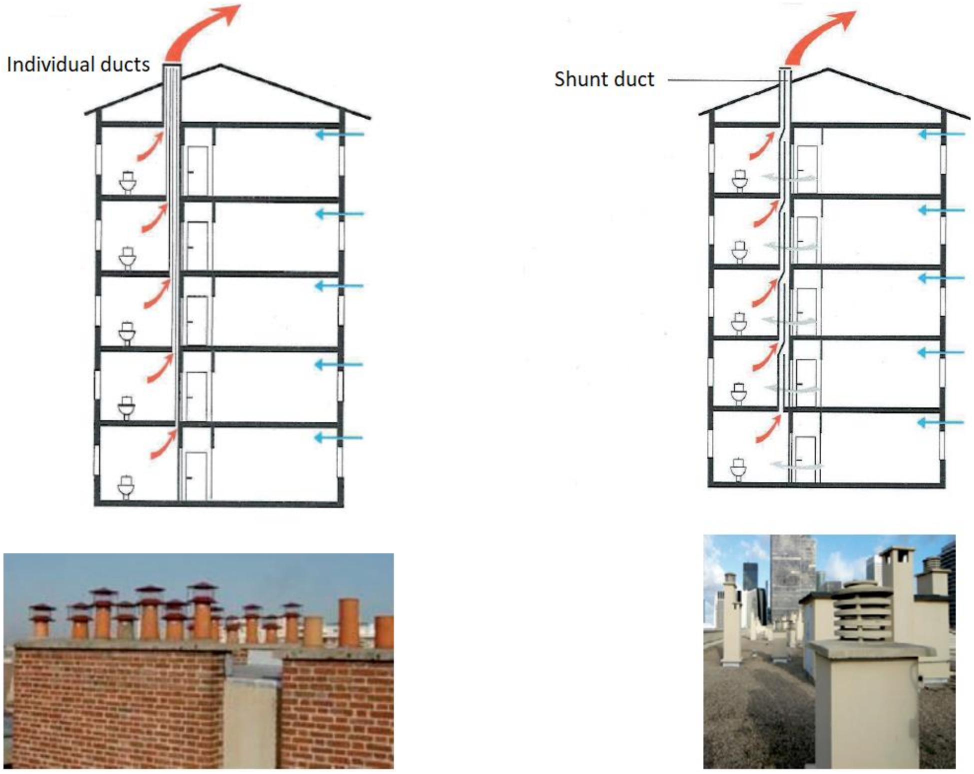


Figure 28: Individual and shunt ducts [36]

In buildings constructed from 1969, ventilation must be general, i.e. every rooms needs to be continuously ventilated, with fresh air intake in the main room and exhaust air in the utility rooms such as kitchens, bathrooms and toilets (*Figure 29)*. To perform this **whole-building ventilation**, air circulation between the different rooms must be ensured and is achieved through the door undercuts.

In order to better satisfy the legal requirements of the 1969 regulation, mechanical ventilation have been widely installed in dwellings and became until now much more common than natural ventilation in new buildings. Despite the electric consumption of fans, mechanical ventilation allows a ventilation flow rate that is better controlled and less sensitive to wind and inside-outside temperature difference. To assist natural ventilation when flow rates are not sufficient to allow an acceptable air change, a fan can be installed on individual or shunt ducts chimneys to enforce a minimum air extraction. This system called hybrid ventilation is frequently used in collective social housings to improve natural ventilation as it is convenient and cheap to install. When it is possible, installation of a controlled mechanical ventilation might be a better solution if it is well designed and well-maintained, to ensure constant air renewal throughout the year. These mechanical installations (including air inlets and extract units) can be pressure-controlled or humidity-controlled. In the last case, both the inlets and extract units (humidity-controlled ventilation system) or only the extract units (humidity-controlled MEV A system) react to humidity content of air influenced by human respiration or activity, and reduce the ventilation rate in the absence of occupant in the room. Thus, it allows energy saving when full regulatory flow rate is not needed.

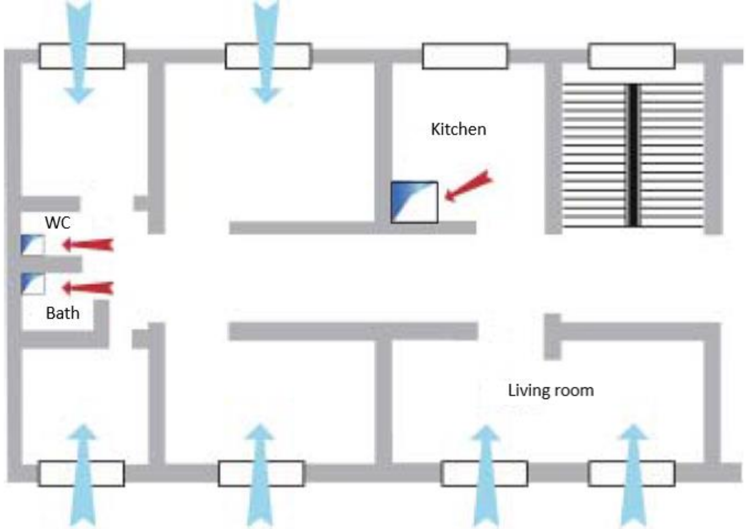


Figure 29: Whole building ventilation in buildings constructed since 1969 **[35]**

In collective social housing refurbishment operations, hybrid ventilation systems mounted on shunts are the most widely used at this time, with eventually humidity-controlled air inlets and extraction outlets in humid rooms.

Minimum air extraction rates are required from each room in the French sanitary regulation, depending on the number of main rooms of the dwelling. The ventilation system must be able to extract the sum of the minimal airflow rates of all the room (peak flow rate). However, the total instantaneous exhaust rate can be reduced to a minimum value if the ventilation system is capable of maintaining healthy indoor air quality with controlled pollutant concentration (humidity-controlled ventilation systems).

Table 11: Simultaneous extraction airflow rates required in each room of dwellings and minimum total values required by the French sanitary regulation

Number of main rooms (bedroom, living-room, dining-room…)		1	2	3	4	5	6	7
Minimal airflow rates (m^3/h)	Total	35	60	75	90	105	120	135
	Kitchen	20	30	45	45	45	45	45
	Bathroom	15	15	30	30	30	30	30
	Other wet room	15	15	15	15	15	15	15
	WC (unique)	15	15	15	30	30	30	30
	WC (multiple)	15	15	15	15	15	15	15

Boost airflow rates during cooking (m^3/h)	Kitchen	75	90	105	120	135	135	135

Spanish situation

In 1977, the Spanish Government approved a unified framework for building regulations that included Basic Building Standards (Normas Básicas de la Edificación, NBE, [37]) and Technological Building Standards (Normas Tecnológicas de la Edificación, NTE, [38]). The NBEs were mandatory and defined the minimum requirements to be met by a building. The "NBE CT-79 standard. Thermal conditions in buildings" directly or indirectly affect aspects related to thermal conditions inside the building, ventilation and indoor air quality [37]. This standard refers to ventilation, indicating that it is an adequate measure to avoid surface condensation, without making any other comments on aspects related to indoor air quality, which means that no type of ventilation system is considered. For this reason, air renewal in dwellings built under these standards is produced by air infiltration and by the opening of windows, which does not guarantee proper ventilation.

As for the NTE, these standards were not mandatory, but served as an operational development of the Basic Building Standards. Among these are the ISH and ISV (normas ISH Humos y Gases e ISV Ventilación) [38]. These describe the installations (openings, ducts, etc.) that are recommended to be included in order to comply with the requirements of the Basic Standards. Generally speaking, shunts connected to a vertical duct were included in toilet and bathroom, while in the case of the kitchens, in addition to a shunt, there was included an air intake in order to remove the flues of fuel-burning appliances and provide the air needed by the boilers. The range hood was also included since the 80s, in such a way that in some cases the hood came into operation automatically every time the boiler was turned on.

On May 6, 2000, Law 38/1999 of November 5 on Building Management (Ley de Ordenación de la Edificación, LOE) entered into force [39].The purpose of this law is to regulate essential aspects of the construction process. Basically, it establishes the conditions necessary for the correct development of the building construction process and guarantees the quality of the building by complying with basic requirements. In the second final provision, the LOE authorizes the Government to approve a Technical Building Code (Código Técnico de la Edificación, CTE) [40]. This document must establish the requirements that buildings must meet in terms of safety and habitability.

The Regulation on Thermal Installations in Buildings (Reglamento de Instalaciones Térmicas de los Edificios, RITE) establishes the conditions to be met by thermal installations in buildings [41], which aim to maintain the thermal comfort and hygiene demanded by means of sustainable energy use, considering both economic and environmental aspects.

Within this regulatory framework, the CTE is the keystone of any building project to meet the basic requirements of building established by the LOE and to ensure the safety and welfare of people and protect the environment.

One of the great novelties of the CTE is presented in the Basic Document HS 3 (DB HS 3), and it deals with the requirement of minimum ventilation flows in each room according to its occupation and use (*Table 12)*.

Table 12: Minimum airflow rates required in each room of the dwelling in l/s from CTE 2019 version

	Habitable rooms			Service rooms	
Type of dwelling	Main bedroom	Rest of the bedrooms	Living-room	Minimum total	Minimum per room
0 or 1 bedrooms	8	-	6	12	6
2 bedrooms	8	4	8	24	7
3 or more bedrooms	8	4	10	33	8

In addition to reducing the minimum required flows, the possibility of installing variable flow ventilation systems was incorporated. To validate the permission to install those ventilation systems it is mandatory to check that the following conditions are met in each room:

- average concentration lower than 900 ppm for the whole year, and
- yearly accumulated value of the CO_2 concentration above 1,600 ppm should be below 500,000 ppm·h.

The verification is performed by simulation, for which purpose the occupation of the dwelling, the hours of stay in each room and the emission of the pollutants (carbon dioxide and water vapour) are established. Ventilation systems are available that have been approved by the competent authority [42], so there is no need for additional verification.

In any case, in the kitchen, it is necessary to install an extraction system to eliminate the fumes, with a minimum extraction rate of 50 l/s.

Portuguese situation

Ventilation principles In Portugal are similar to those in France i.e. fresh air should be supplied in the main rooms (bedrooms and living rooms), and exhaustion occurring in the utility rooms (kitchen, toilets and bathrooms). Air circulation between the different rooms must be provided and is achieved through the door undercuts.

In Portugal, most buildings are ventilated naturally, with whole-building ventilation. Fresh air enters the main rooms through leaks in the building envelope and openings in windows and is extracted in the utility rooms.

In the kitchen, it is mandatory to install an extraction system to eliminate the fumes and water vapour. In the bathrooms and toilets that do not have windows, it is also necessary to install ventilation ducts, which can be assisted with a mechanical exhaust system. The mechanical exhaust system in the bathrooms, toilets and kitchen can work continuously or be switched on when the room is occupied (individual switch or connected to the light electrical switch) or during cooking.

The most relevant legislation and recommendations on ventilation in Portugal are the Regulamento Geral das Edificações Urbanas (RGEU, General Regulation of Urban Buildings, Decreto-Lei 38382/1951), the Energy Certification System for Buildings (Decreto-Lei 101/2020), NP 1037-1 (Ventilation and Evacuation of Combustion Products from locals with Gas Appliances, Part 1: Residential Buildings, Natural Ventilation) and NP 1037-2 (Ventilation and Evacuation of Combustion Products from locals with Gas Appliances, Part 1: Residential Buildings, Centralized Mechanical Ventilation).

The General Regulation of Fire Safety in Buildings (SCIE: Decreto-Lei 220/2008 and Decreto-Lei 224/2015) is also relevant to the analysis of ventilation of the buildings [43].

The RGEU (Decreto-Lei 38382/1951) has been constantly updated (the latest update being from 2001) and defines some important guidelines regarding the need for ventilation and indoor air quality of rooms in dwellings:

- the layout of the buildings must favour natural ventilation, through their orientation to the dominant sun and winds, taking advantage, as much as possible, from natural conditions;
- cross ventilation of the dwelling must be favoured;

The Portuguese standard NP 1037-1:2002 - Ventilation and exhaustion of products of combustion from spaces with gas appliances – natural ventilation – refers a set of requirements to be adopted to ensure the ventilation conditions:

- self-regulating air intake devices on the facades of buildings, in all main rooms (bedrooms, living-rooms, etc.), depending on the wind exposure of the facades;
- doors separating indoors from outdoors or from storage areas or similar must be sealed around their perimeter;

The ventilation requirements for residential buildings are presented in *Table 13, Table* ***14*** and *Table* ***15***.

Table 13: Ventilation requirements in buildings required by the Portuguese legislation **[44]**

Zone	Fresh air ($m^3/(hour.person)$)
Bedroom Sleeping (0.8 met)	$16^{(1)}$
Living rooms Resting (1.0 met)	$20^{(1)}$

Dining room Sedentary (1.2 met)	24⁽¹⁾
Building corridors and staircases	Corridors: windows with a minimum of 1.5 m^2 that ventilate the whole area; air intake with 0.10 m^2 openings near the ceiling, and exhaustion of smoke with 0.20 m^2 for each 15 m^2 of the corridor. Stairs: with windows: 0.25 m^2 per floor; without windows: openings with 1 m^2 at the top and 0.50 m^2 at the bottom of the staircase.
Garage	Openings with an area of not less than 0.06 m^2/vehicle or mechanical ventilation⁽²⁾

(1) Airflow per occupant (Portaria n.º 353-A/2013). The number of reference persons should correspond to the maximum occupancy normally provided for the building, complying with the maximum and minimum limits of 0.02 persons/m^2 in small spaces with low levels of occupancy and the minimum limit of 1.2 persons/m^2 in areas with a high concentration of people, respectively.

(2) In accordance with the Fire Safety Regulations for Covered Parking Areas (Decreto-Lei n.º 66/95).

The standard airflow rates to be extracted from the rooms in a residential building with natural ventilation as a function of their volume, defined in NP 1037-1:2002, are presented in *Table 14*. *Table* ***15*** shows the airflow rates to be respected for the main rooms, according to their total volume. When ventilation is combined for the whole dwelling, the total volume of the main rooms is considered.

Table 14: Airflow rates in the utility rooms (NP 1037-1:2002) **[45]**

Room		Volume				
		≤ 8 m^3	> 8 m^3 ≤ 11 m^3	> 11 m^3 ≤ 15 m^3	> 15 m^3 ≤ 22 m^3	> 22 m^3 ≤ 30 m^3
Kitchen and other spaces for installation of gas appliances		(1)	17 l/s (60 m^3/h)		25 l/s (90 m^3/h)	33 l/s (120 m^3/h)
Toilets	With bath or shower	13 l/s (45 m^3/h)	17 l/s (60 m^3/h)		25 l/s (90 m^3/h)	(2)
	Without bath or shower	8 l/s (30 m^3/h)	13 l/s (45 m^3/h)	17 l/s (60 m^3/h)	(2)	(2)
Laundry		8 l/s (30 m^3/h)	13 l/s (45 m^3/h)	17 l/s (60 m^3/h)	(2)	(2)

(1) Volumes for which the installation of gas appliances type A and B is not permitted. Type A appliances are designed not to be connected to ducts or devices for evacuating combustion products to the exterior of the installation site. Type B appliances are designed to be connected to ducts or devices for evacuating combustion products to the exterior, with combustion air captured directly at the installation site.

(2) Unusual volumes in this type of rooms, for which case-by-case design is recommended, taking into account the requirements of the space.

Table 15: Airflow rates to be admitted in the main rooms (NP 1037-1:2002) **[45]**

Volume (m^3)	≤ 30 m^3	> 30 ≤ 60 m^3	> 60 ≤ 90 m^3	> 90 ≤ 120 m^3	> 120 ≤ 150 m^3	> 150 ≤ 180 m^3	> 180 ≤ 210 m^3	> 210 ≤ 240 m^3

Airflow (l/s) (m^3/h)	8 (30)	17 (60)	25 (90)	33 (120)	42 (150)	50 (180)	58 (210)	67 (240)

In addition, NP 1037-2:2009 presents ventilation requirements through the definition of maximum airflow and base airflow rates (*Table 16* and *Table **17**: Minimum base airflow rates in utility rooms (bathrooms and kitchens) Table 17*).

Base airflow rates are established taking into account the indoor air quality criteria when the utility rooms are not being used, the gas appliances are not working and the main rooms have a normal occupancy (with the limitation of CO_2 concentration, resulting from human metabolism, at 800 ppm above the outdoor concentration and the relative humidity of the indoor air being less than or equal to 70%, at an indoor temperature of 18 °C) (NP 1037-2:2009).

Table 16: Minimum base airflow rates in main rooms (NP 1037-2:2009) **[46]**

Materials **non**-classified as with low emission of pollutants into indoor air	Materials classified as with low emission of pollutants into indoor air
$Q_{bedroom}(l/s) = Max.(\frac{Vol}{3.6}; 5xn_{ocup})$	$Q_{bedroom}(l/s) = Max.(0{,}5x\frac{Vol}{3.6}; 5xn_{ocup})$
$Q_{living\ room}(l/s) = Max.(\frac{Vol}{3.6}; 6xn_{ocup})$	$Q_{sliving\ room}(l/s) = Max.(0{,}5x\frac{Vol}{3.6}; 6xn_{ocup})$

Vol – Volume of the room (m^3)

n_{ocup} - Number of occupants in each room. For calculation purposes, the occupancy rate corresponds to two occupants in the main bedroom, and one occupant in the additional bedrooms and the occupancy rate of the living room corresponds to the sum of the occupants of each bedroom.

Table 17: Minimum base airflow rates in utility rooms (bathrooms and kitchens) **[46]**

Toilets and bathrooms with constant air flow rates	Kitchen
$Q_{toilets\ and\ bathrooms}\left(\frac{l}{s}\right) = Max.\left(4x\frac{Vol}{3.6}; 12.5\right)$ It may be limited to 25 l/s	$Q_{kitchen}(l/s) = 2x\frac{Vol}{3.6}$

Vol – Volume of the room (m^3)

In toilets and bathrooms with constant extracted airflow, the minimum airflow is of 4 air changes per hour (ACH) or 12.5 l/s, and may be limited to 25 l/s in the case of large size toilets or bathrooms. In kitchens, the minimum airflow 2 air changes per hour, to ensure a 60% reduction in the concentration of pollutants after 30 minutes.

If the total airflow rates in the utility rooms are different from the total airflow rates necessary in the main rooms (in the dwelling or each ventilation sector of the dwelling), the lower of these values shall be corrected by increasing the airflow intake in the main rooms or the exhaustion in the utility rooms.

If the ventilation system allows regulating the air flow rate depending on the occupancy of the rooms, during non-occupancy periods, the ventilation rate might be reduced to a minimum of 0.2 ACH. In this case, after the occupancy period of the spaces, the ventilation system must continue to operate with the airflow rates previously defined during the 24 hour period to ensure a minimum dilution of any pollutants accumulated during the occupancy of the rooms.

The maximum airflow rates are established, considering indoor air quality criteria when the utility rooms are in use, also considering the airflow rates necessary for the proper functioning of the combustion equipment.

The maximum airflow requirements for ventilation of the main rooms are those indicated for the base airflow (*Table 16*).

In the kitchen, the maximum airflow rate to be extracted should be the maximum value corresponding to the proper evacuation of the food cooking products and the operation of the gas appliances. The airflow rate to be extracted in the kitchen should not be less than the higher of the two values obtained considering an extraction of 50 l/s or 60 l/s.

Where gas appliances of Type B_{11} (except boilers) are installed, the airflow rate for these appliances ($Q_{gas\ appliances}$) shall not be less than $1.2xQ_n$ (l/s). Where boilers are installed, the airflow rate to be considered for this appliance shall not be less than $1.4xQ_n$ (l/s). Q_n is the nominal useful power of the gas appliance (kW) and L_{stove} the stove length (m). The airflow rate to be extracted in the kitchen is calculated according to the equations in *Table 18*.

Table 18: Minimum airflow in the kitchen (NP 1037-2:2009) [46]

Without B_{11} gas appliances	With B_{11} gas appliances
$Q_{kitchen}(l/s) = Max.(2x\frac{Vol}{3.6}; 50; 60xL_{stove})$	$Q_{kitchen}(l/s) = Max.(2x\frac{Vol}{3.6}; 50 + Q_{gas\ appliance}; 60 + Q_{gas\ appliance})$

These ventilation airflow values correspond to the typical flow required to ensure the proper operation of the stove (type A gas appliance) and domestic hot water production (type B_{11} gas appliance). If other gas appliances require air from the ventilation system, its specific air flow rate must be added to the above values, assuming that the devices can be operating simultaneously.

When a variable airflow extraction is adopted in the wet rooms, it is recommended that the airflow, calculated according to the equations in *Table 19*, be ensured for 20 minutes. The airflow may be limited to 50 l/s in the case of large toilets or bathrooms.

Table 19: Minimum airflow rates in toilets and bathrooms (NP 1037-2:2009) [46]

$$Q_{toilets\ and\ bathrooms}(l/s) = Max.(4x\frac{Vol}{3.6}; 8.3)$$

Whenever the maximum airflow rate in the kitchen exceeds its base airflow, it is assumed that this airflow difference can be compensated for by specific air intake openings in the kitchen.

The National Laboratory of Civil Engineering (LNEC) has developed an Excel based tool for assessing the performance of ventilation systems in the context of the thermal and energy performance of buildings regulations and verifying the minimum ventilation requirements.

Conclusion

The ventilation systems in collective buildings show a similar evolution in the three countries in terms of principle (from separated rooms to whole general and permanent ventilation) and evolution (from natural to mechanical/hybrid ventilation and pressure/humidity-controlled systems). The two following figures report minimum and maximum air change rates (*Figure 30*) and distribution of air intake and exhaust (***¡Error! No se encuentra el origen de la referencia.***) in the case study of a typical two bedrooms dwelling in France, Spain and Portugal. The surface of the dwelling (***¡Error! No se encuentra el origen de la referencia.***) is 54.5 m^2, its volume 136.5 m^3 with 2 adults and 1 child. Based on each country regulations values, we observe that in this example minimum country regulations values lead to slight differences in terms of total air renewal, with French and Spanish daily-averaged values of 0,7 h^{-1} and Portuguese one about 0,9 h^{-1}. On the other hand, maximal values are different between Spain/Portugal that account for the presence of kitchen hood and France that accounts for a lower increase of the global ventilation system itself. Finally, Portugal regulation considers differently the two bedrooms with a lower air intake for the additional one and presents the lowest air exhaust for the kitchen when no cooking occurs.

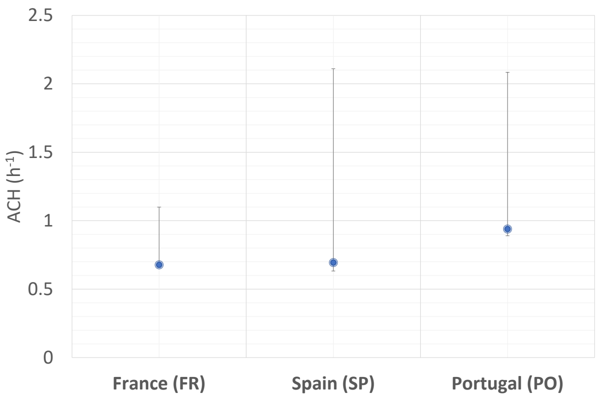


Figure 30: Minimum and maximum air change rates according to country regulations – case of a two-bedroom apartment

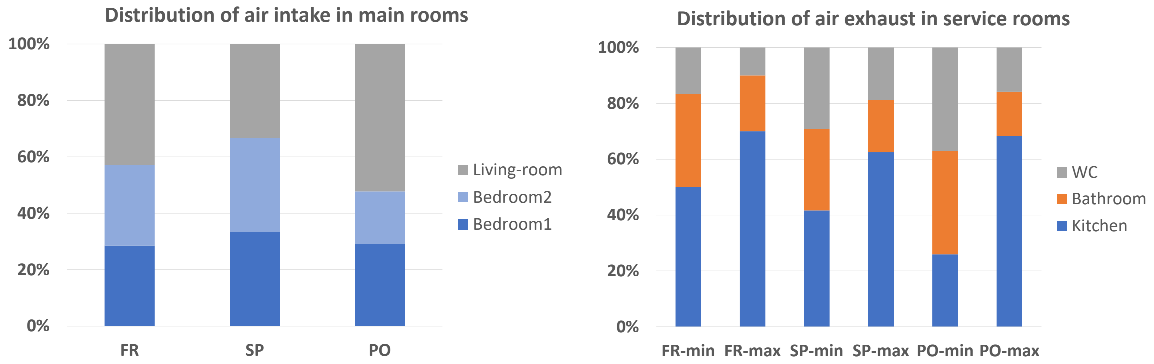


Figure 31: Distribution of air intake (left) and exhaust (right) according to country regulations – case of a two-bedroom apartment

7.1.2 Evaluation of energy and health efficiency of ventilation systems. A case study

In this chapter, the efficiency of different ventilation systems is investigated from the French regulation point of view, in order to define the ones that should be preferred for renovation projects of collective social housings.

Methodology

A modelling of occupant exposure to indoor air pollutants has been developed for a typical dwelling of collective French social housing. This modelling is based on a nodal approach with one node per room. The ventilation and infiltration rates of the dwelling are calculated following the French 3CL-DPE method [47], which also calculates the heating demand attributed to air change. This 3CL-DPE method is the official French method for determining the energy and greenhouse gas emissions certificates of dwellings. The flow values depend on the ventilation system, air permeability of the envelope and outdoor mean temperature. The inflow and outflow rates for each room are determined with an assumed flow path through the dwelling and the considered air inlets. Pollutant emission and interactions with surfaces scenarios of the considered pollutants are defined in each room, as well as the time spent by an occupant in each room in order to assess his exposure to the pollutants. Finally, the health risk associated with this exposure is assessed using the ULR-QAI air quality index [48].

Case study description

The case study has been chosen to be representative of social housing. It consists in a 54.5 m² two-bedroom (Type 3) apartment, which is the typology representing 33% of the French collective housing stock ahead of types 2 (26%) or 4 (20%). The internal spatial distribution of the rooms is shown in *Figure 32*. A variant of this layout where the kitchen is completely open to the living room was also studied.

The bedrooms, the living room and the kitchen have a wall in contact with the outside allowing infiltrations and the presence, as the case may be, of air inlets for ventilation. Three natural ventilation systems and four mechanical ventilation systems were studied. These systems are presented in Table 1. They can be grouped according to the ventilation strategy to which they respond, i.e. whether each room is ventilated separately or whether the ventilation is said to be a whole-apartment ventilation, i.e. the air enters through the living rooms (bedrooms and living room) and is extracted through the service rooms (kitchen, bathroom and toilets). These two strategies are also illustrated in *Figure 32*.

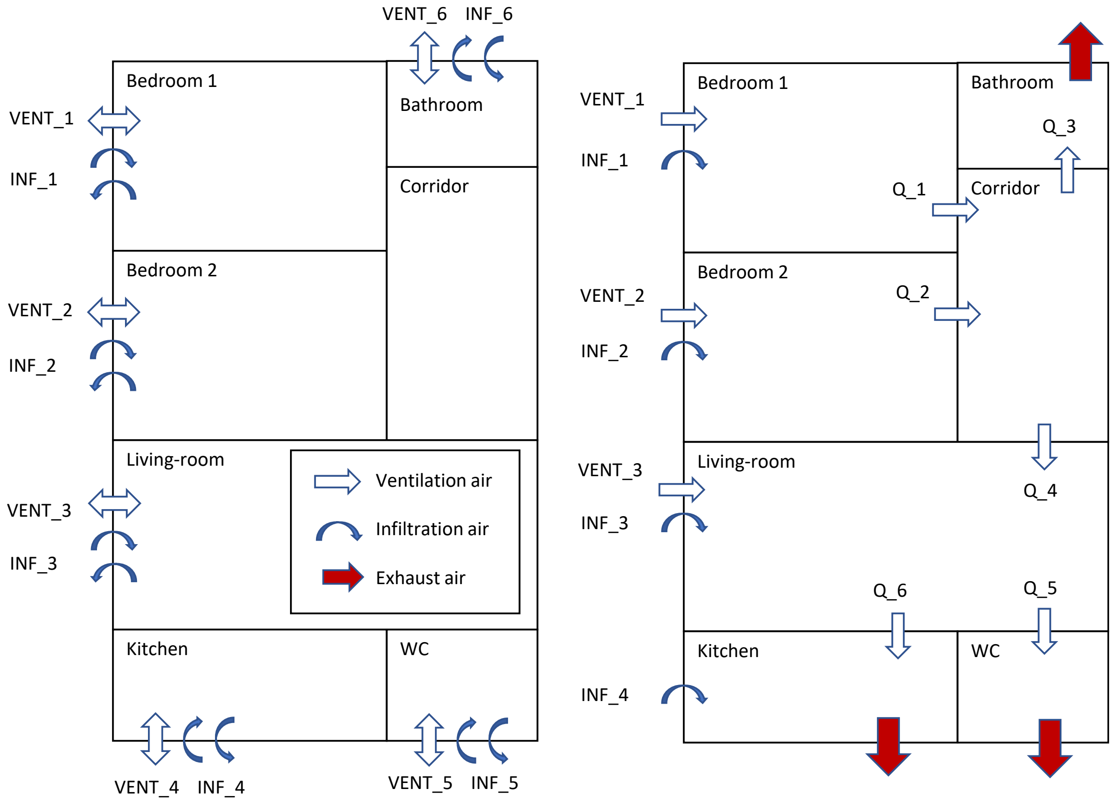


Figure 32: Schematic representation of the different airflows in the separated rooms ventilation case (left) and in the whole-apartment ventilation case (right)

Infiltration and ventilation airflow rates

For the simulation purposes, 7 different ventilation systems presented in *Table 20* are considered and compared: 3 natural ventilation systems and 4 mechanical ventilation systems.

Table 20: Ventilation systems evaluated in the analysis

	Ventilation systems	Q_{4Pa_conv}	$Qvarep_{\_conv}$

	Natural (NV) or Mechanical (MV)	($m^{-3}.h^{-1}.m^{-2}$)	($m^{-3}.h^{-1}.m^{-2}$)
Separated rooms ventilation	Windows (NV-WINDOW)	2.0	1.2
	Inlets (NV-INLET)	2.0	2.145
Whole-apartment ventilation	Duct (NV-DUCT)	1.7	2.145
	Hybrid (MV-HYB)	1.7	2.0625
	Constant Air Volume (MV-CAV)	1.7	2.2425
	Pressure-controlled (MV-PRESS)	1.7	1.65
	Humidity-controlled (MV-HUM)	1.7	1.0725

Whole apartment infiltration and ventilation airflows. The total exhaust air flow rates (Q_{tot}) are the sum of the total infiltration (Q_{inf}) and ventilation (Q_{vent}) flow rates of the dwelling, which are calculated using the French conventional 3CL-DPE method (cf. *Annex 3*) that is based on NF EN 15242 *[49]*. According to this method that only accounts for stack effect, the air flow rate due to infiltration is evaluated by

$$Q_{inf} = 0{,}0146 \times Q_{4Pa\_conv} \times S_{env} \times (0{,}7 \times |19 - T_{out}|)^{0{,}667}$$

where Q_{inf} is the infiltration airflow rate ($m^3.h^{-1}$), Q_{4Pa_conv} is the conventional leakage airflow rate per envelope surface area for an indoor to outdoor pressure difference of 4 Pascals ($m^3.h^{-1}.m^{-2}$), S_{env} is the selected envelope surface area (28,8 m^2) and T_{out} is the conventional winter-averaged outdoor temperature for the French Aquitaine climatic zone (8,08 °C). The selected values for Q_{4Pa_conv} are presented in *Table 20* and correspond to airtight envelope for the newest ventilation systems using the whole-building ventilation principle.

The airflow rate extracted by the ventilation system is evaluated according to

$$Q_{vent} = Qvarep_{conv} \times S_{floor}$$

where Q_{vent} is the ventilation airflow rate ($m^3.h^{-1}$), $Qvarep_{conv}$ is the conventional ventilation airflow rate per floor area ($m^3.h^{-1}.m^{-2}$) et S_{floor} is the floor surface area (54,5 m^2). The 3CL-DPE method gives the $Qvarep_{conv}$ values presented in *Table 20*

Airflow rates between rooms. In the case of a separated room ventilation strategy, it is assumed that each room is ventilated independently of the others. Thus, the distribution of infiltration rates in each of the rooms is proportional to the surface area of the exterior walls and the ventilation rates are proportional to the floor area of these rooms.

In the case of whole-apartment ventilation, the distribution of infiltration rates is achieved in the same way but the calculation of the ventilation rate entering each room is done in accordance with the technical specifications of the ventilation system and the regulatory requirements, as detailed below.

For natural ventilation by ducts (NV-DUCT) and mechanical ventilation systems (MV-CAV, MV-PRESS and MV-HYB), the air inlets have been set to allow a nominal flow rate of 30 $m^3.h^{-1}$ in each bedroom and 50 $m^3.h^{-1}$ for the living room, i.e. 27.3% of the total ventilation flow rate entering through each bedroom and 45.4% through the living room. This distribution is then applied to the Q_{vent} flow rate previously calculated to determine the actual flow rate entering each room due to the ventilation system. In the same way, the minimum extract flow rates imposed by the French regulation for this type of housing (75 $m^3.h^{-1}$ in kitchen, 30 $m^3.h^{-1}$ in bathroom and 15 $m^3.h^{-1}$ in toilets) define the proportions of extract flow rates (62.5% in kitchen, 25% in bathroom and 12.5% in toilets) to calculate the actual extract flow rate in each room from the total flow rate of extract air (Q_{tot}).

Regarding the humidity sensitive ventilation (MV-HUM), since the air inlets are dependent on the presence of the occupant (through its influence on the relative humidity of the room), the ventilation flow rates can vary from 4 to 30 $m^3.h^{-1}$ in the bedrooms and the living room, and the extract flow rates from 10 to 50 $m^3.h^{-1}$ in the kitchen, from 5 to 45 $m^3.h^{-1}$ in the bathroom and from 5 to 30 $m^3.h^{-1}$ in the toilets. It is thus necessary to dissociate two scenarios: at night when the occupants are in their bedrooms, the airflow rates are at their maximum at the air inlets to the bedrooms and at the extraction in the bathroom (close to the bedrooms), and at their minimum at the air inlet to the living room and at the extraction from the toilets; and conversely during daytime when the occupants are in the living room.

In addition to this operation under normal conditions, there is a period of increased ventilation in the kitchen for half an hour during cooking activity for all mechanical systems (except for constant flow ventilation). During this period the Q_{vent} and Q_{tot} flow rates are not used to calculate the actual ventilation and extraction flow rates in each room, which are directly equal to their nominal values, and the kitchen extraction flow rate is increased to 105 $m^3.h^{-1}$.

In order to satisfy the equality of the flow rates into and out of the dwelling, the infiltration rate Q_{inf} must be adjusted. This is achieved by the relation linking the infiltration flow rates to the pressure difference on either side of the envelope:

$$Q_{inf}(\Delta p) = Q_{inf}(\Delta p = 1) \times \Delta p^{0,67}$$

where $Q_{inf}(\Delta p = 1)$ is the infiltration airflow rate for 1 Pa pressure difference ($m^3.h^{-1}.Pa^{-0,67}$). A value of 5.37 $m^3.h^{-1}.Pa^{-0,67}$ is set for a T3 apartment by the French regulation.

Once these flows exchanged between the exterior and interior of the dwelling are evaluated, we can then, in the case of whole-apartment ventilation system, determine by differentiation the interzone flows exchanged between each room, knowing the direction of airflow through the dwelling (*Figure 32*).

Pollutant exposure data

The calculation of the average pollutant concentrations is carried out in each room by considering a perfect homogeneity of the concentrations (one calculation node per room). The resolution of the equations of conservation of the mass of each pollutant is carried out in steady-state with however a new resolution each time the ventilation flow rates are modified (when the flow rate increases during cooking or by humidity-controlled system when an occupant is present in the room...) or that a new emitting activity of one of the studied pollutants is in progress. The balance considers the transport by air of the pollutants from one room to another or from outside, the emission of pollutants by building materials and occupants' activities and the deposition or sorption of these pollutants by reaction on the surface of the walls.

The pollutants considered in this study are fine particles (PM2.5), nitrogen dioxide (NO2) and formaldehyde because these pollutants are known to have a significant impact on the air quality of homes [50]. Formaldehyde is a well-known tracer of indoor air quality because it is ubiquitous in the indoor environment, emitted by furniture and building materials. Sources of particulate matter and NO2 can be outdoor sources, mainly from road traffic, or indoor sources from human activities such as cooking or incense burning. The outdoor concentrations used in these simulations are annual average outdoor concentrations measured by regional air monitoring agencies in the cities of La Rochelle, Poitiers, Bordeaux and Angoulême. They are 11.9 and 27.3 $\mu g.m^{-3}$ for PM2.5 and NO2 respectively and the outdoor concentration of formaldehyde is considered to be zero. Two types of indoor sources were considered here: formaldehyde emissions from building materials, and PM2.5 and NO2 emissions from human activities. Formaldehyde emission rates from materials were set at the limit value between categories A+ and A of the French labelling system for building and decorative materials for their emissions of gaseous pollutants [51] , i.e. 12.5 $\mu g.m^{-2}.h^{-1}$ for the floor and ceiling and 5 $\mu g.m^{-2}.h^{-1}$ for the walls. The activities defined in this case study are the use of a vacuum cleaner and cooking. The PM2.5 emission rate is 0.07 $mg.min^{-1}$ for 10 minutes per week for vacuuming and 1.6 $mg.min^{-1}$ for 30 minutes per day for cooking [52]. Cooking activity also emits 3.1 $mg.min^{-1}$ of NO2 [53]. Deposition (or removal by reaction) rates on walls, floor and ceiling are based on the values proposed by [53], namely 1.8 × 10-4 $m.s^{-1}$ for PM2.5 and 1.2 × 10-4 $m.s^{-1}$ for NO2.

Risk assessment

The health risk due to exposure to substances present in the air is assessed using the ULR-IAQ index developed by [50]. This index ranges from 0 for a very good IAQ to 10 for a very bad IAQ and relates the concentrations of pollutants in the air to the Indoor Air Guide Values (IAGV) promulgated by the National Agency for Food, Environmental and Occupational Health Safety (ANSES):

$$I_{ULR-IAQ,p} = 10 \times \frac{C_p^{expo} - IAGV_{LT,p}}{IAGV_{ST,p} - IAGV_{LT,p}}$$

where $IAGV_{LT,p}$ et $IAGV_{ST,p}$ are the IAGV for long and short-term exposure, respectively. The average daily exposure concentration C_p^{expo} of an occupant to a pollutant (p) is the average of the concentrations calculated during the presence of the occupant, weighted by the corresponding occupation durations. In the case studied here, the occupant is assumed to spend 9 hours in bedroom 1, 3 hours in the living room and 0.5 hours in the kitchen. To calculate the 24-hour exposure, it is also assumed that during the 11.5 hours spent outside the dwelling, the person is exposed to a concentration equal to that in bedroom 1 (which is similar to an office-type pollution). The $IAGV_{LT,p}$ et $IAGV_{ST,p}$ are respectively 10 and 25 µg/m³ for PM2.5, 40 and 200 µg/m³ for NO2 and 10 and 100 µg/m³ for formaldehyde.

ULR-IAQ sub-indices are calculated for the three selected pollutants and then, the multi-pollutant ULR-IAQ index is defined as the maximal value of those three sub-indices [48].

Results

For each studied ventilation system, the simulations were carried out considering on the one hand the case where the kitchen is separated from the living room (with the communicating door always closed) and on the other hand the case where it is completely open to the living room. The results expressed by the attribution of a ULR-IAQ score for each ventilation system in each of the two configurations are presented in *Figure 33*. In both cases and for all systems, the index is always highest for PM2.5 exposure and therefore corresponds to the multi-pollutant ULR-QAI index. The numerical work of [50] showed that this index was due to PM2.5 for 65% of the 2334 cases treated and formaldehyde for the other cases (NO2 had not been simulated). The main difference lies in the single and low source of formaldehyde in our study, based on the emission of the main walls according to an A+/A label. Those simulations also considered the emission from furniture and other occupant activities with emissions up to 4 times higher.

In the configuration where the kitchen and living room are separated, there is a cleavage between natural ventilation solutions, which all show an index of 10 (NV-WINDOW) or almost 10 (9.2 for NV-INLET and 9.6 for NV-DUCT), and controlled mechanical systems with about 3 points less (7.1 for MV-HYB, 7 for MV-HUM and 6.7 for MV-PRESS). Whilst the absence of ventilation rate modulation for the MV-CAV system generates a higher daily ventilation volume than other mechanical systems, this system (and also the natural ventilation ones) suffers from a higher ULR-IAQ index due to the impossibility of activating the increased ventilation mode in the kitchen during cooking activity.

In the case where the kitchen is completely open to the living room, the results are more differentiated and the levels are lower (in particular due to the dilution of the kitchen emissions in a larger volume). Separated rooms NV-WINDOW is still unable to ensure good air quality. On the other hand, natural inlet and duct ventilation in this configuration is much more efficient than when the kitchen and living room are separated, with an ULR-IAQ rating of 5.4 (compared to 9.6 in the previous case), however still less efficient than mechanical systems. Within the latter, the MV-CAV system has an efficiency closer to the other systems than in the previous configuration, this time equivalent to the MV-HUM system (ULR-IAQ = 4.4 and 4.5 respectively), the best solution being the MV-PRESS system with an index of 3.8.

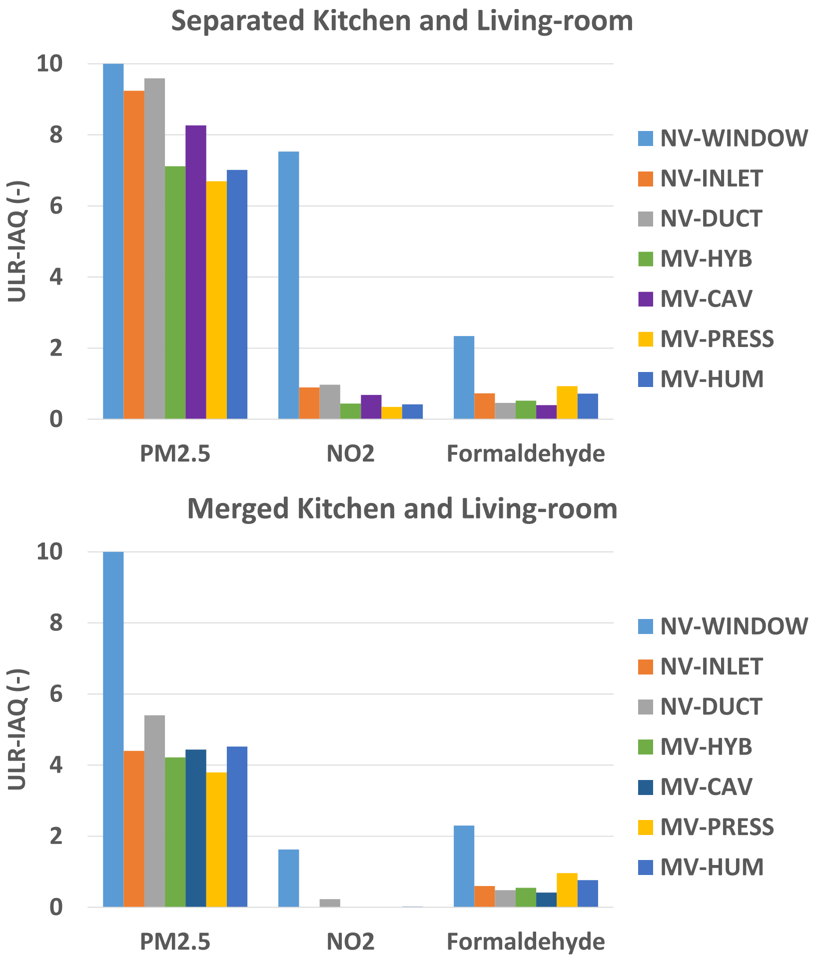


Figure 33: Comparison of the ULR-IAQ indexes of each pollutant for the studied ventilation systems and the cases where the kitchen is separated from the living room (upper graph) or not (lower graph)

Lastly *Figure 34* presents the results as a function of the share of heat losses due to air renewal compared to the total heating needs. We observe that mechanical systems minimize the heating needs while providing comparable IAQ. Humidity-controlled ventilation gives the lowest heating needs of all ventilation systems.

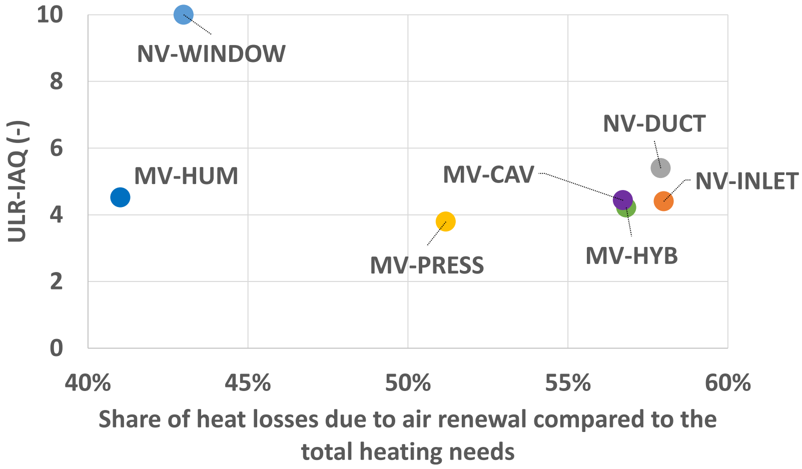


Figure 34: Comparison of ventilation systems according to the energy needs related to air renewal

Conclusion

First, we must notice that, in all the cases considered in the previous simulations, the ventilation flow rates respect the French regulation. The comparison thus allows comparing the different ventilation systems in terms of indoor air quality regarding typical indoor pollutants production.

We can conclude that, in the case where the kitchen is separated from the living-room, mechanical whole-building ventilation systems are to be preferred. In the case of merged kitchen and living room, natural ducted and assisted ventilation systems offer an air quality relatively close to what could be achieved with mechanical systems but lead to a higher power consumption than controlled mechanical ventilation. **Humidity-controlled system may be considered as a good compromise since it the best option for energy savings and very good one for indoor air quality.**

The merged kitchen and living-room configuration is always the most suitable in terms of pollutant concentrations, regardless the ventilation system. This is particularly noticeable for $PM_{2.5}$ and NO_2 with natural ventilation systems with separate rooms. This comes from the fact that cooking emission is then diluted in higher volume (living-room + kitchen). It should also be noticed that this analysis does not account for the presence of a hood in the kitchen, as it is not strictly speaking a ventilation system. The systematic use of such an additional system is however a key element to reduce exposure from cooking products.

This study, based on the French conventional rules for estimating the ventilation and infiltration flow rates of a dwelling for a wide variety of ventilation systems could be extended to others national situations if the necessary input data are available. But we guess that the conclusions of this study can serve to draw general figures for the ARCAS buildings renovation strategy of ventilation systems for combining indoor air quality and energy conservation.

7.2 Others systems

For other active heating, cooling and hot water production systems, we will not list all possible systems, which would necessarily be incomplete, but rather present the possible energy sources and the different applications they allow, according to the type of installation (individual or collective) and the sources used (renewable or not).

A multi-criteria decision support tool will be presented in chap. 0, to guide the project owners or engineering offices in the choice of the systems during the design of a rehabilitation or new construction project.

In the following, collective systems can be at the building scale or at the urban/plot scale through thermal energy networks.

The presentation follows the following logic:
Energy source or energy vector
Renewable or non-renewable character
Uses: systems description and individual/collective character

Fossils fuels
Non renewable
Heating, DHW: individual or collective boilers
Cooling: absorption (individual or collective) and desiccant systems (collective)

Electricity
Non-renewable (fossil fuels and nuclear power plants)
Renewable (photovoltaic, biomass, solar, hydraulic, high temperature groundwater or wind power plants)
Heating, DHW: individual or collective systems
Cooling: compression heat pump systems (individual or collective)

Biomass
Renewable
Heating, DHW: individual or collective boilers
Cooling: absorption and desiccant systems (collective)

Thermal solar
Renewable
Heating, DHW: individual or collective systems
Cooling: absorption and desiccant systems (collective)

Ground
Renewable
Heating, DHW: water direct geothermal heating, groundwater or ground source compression heat pump systems (individual or collective)
Cooling: groundwater or ground source compression heat pump systems (individual or collective)
Pre-heating and pre-cooling: earth pipes (individual or collective)

Water
As already mentioned, groundwater can be used directly for preheating or heating purposes, and for electricity generation if available at a sufficiently high temperature level. Water also serves as a thermal source for thermodynamic systems such as heat pumps.
Lastly it can be used for direct or indirect adiabatic cooling process in air handling units, which nevertheless are in the domain of tertiary buildings rather than residential buildings.

8. Renewable energy production and indicators

We now focus on the evaluation of the potential integration of renewable energy and advice on energy system selection. The use of renewable energy by buildings will thus be quantified and a framework for selecting the best available technologies will be proposed.

8.1 Renewable energy use in buildings

The International Energy Agency (IEA) defines renewable energy resources as those "derived from natural processes" and "replenished at a faster rate than they are consumed". Different sources of energy can be classified as renewable energy. They are split into two main categories (data in 2019 for EU-27 [54], [55]):

- Heat generation from renewables and waste *(101 Mtoe)*
    - **Primary solid biofuels** ***(81.5 Mtoe – 81%)***
    - **Heat pumps** ***(12.0 Mtoe – 12%)***
    - **Biogases** ***(3.6 Mtoe – 4%)***
    - **Solar thermal** ***(2.6 Mtoe – 3%)***
    - **Geothermal** ***(0.9 Mtoe – 1%)***
    - **Liquid biofuels** ***(0.6 Mtoe – 1%)***

- Renewable electricity generation *(83.2 Mtoe)*
    - **Wind** ***(30.0 Mtoe - 36%)***
    - Hydro *(29.6 Mtoe - 36%)*
    - **Solar PV** ***(10.1 Mtoe - 12%)***

- Primary solid biofuels *(8.2 Mtoe - 10%)*
- Biogases *(4.8 Mtoe - 6%)*
- Solar thermal *(0.5 Mtoe - 1%)*

First, we will focus on the main indicators to evaluate the renewable energy use and production on a yearly basis. Second, additional indicators evaluating the potential of renewable energies will be presented to obtain more details on the hourly and seasonal pattern of energy production and consumption. Finally, a case study will be developed.

8.1.1 Evaluation of renewable energy use in buildings on a yearly basis

At the building level, the energy use from renewable sources should be evaluated during the design phase (EN ISO 52000-1:2017 [30]). An indicator quantifies on an annual basis the energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases. The share of renewable energy for all types of energy used in buildings should thus be defined at the national level, such as the one proposed in France (*Table **21***, [56]).

Table 21: Conversion coefficient from final to primary energy, future French building regulation (RE2020)

Type of energy	Primary energy factor	Non-renewable	Renewable	%renewable
Natural gas	1	1	0	0
Oil	1	1	0	0
Wood	1	0	1	100
Electricity	2.3	2.3	0	0
District heating	1	1-ratioENR	ratioENR	ratioENR

The coefficients defined in Spain and in Portugal are shown in *Table **22*** and *Table **23***. The split between renewable and non-renewable has not yet been defined in Portugal.

Table 22: Conversion coefficient from final to primary energy in Spain.

Type of energy	Primary energy factor	Non-renewable	Renewable	%renewable
Natural gas	1.195	1.190	0.005	0,4%
LGP	1.204	1.201	0.003	0,2%
Oil	1.182	1.179	0.003	0,3%
Wood (non-densified)	1.037	0.034	1.003	97%
Wood (pellets)	1.113	0.085	1.028	92%
Electricity (nat.)	2.403	2.007	0.396	16%

Table 23: Conversion coefficient from final to primary energy in Portugal.

Type of energy	Primary energy factor	Non-renewable	Renewable	$\%_{renewable}$
Gas	1			
Oil	1			
Wood	1.34			
Electricity	2.5			

However, it should be highlighted that these various sources of renewable energy can be produced at different locations and not always close to the consumption point. Therefore, a distinction should be performed according to the distance from the building (*Figure 35*):

- building-level,
- on-site,
- nearby,
- distant.

The scope of the ARCAS project is limited to the renovation of buildings and groups of multifamily housing buildings. Therefore, the boundaries selected to evaluate technologies will focus on the area of influence of the building, i.e. building-level, on-site and nearby renewable energy sources. Indeed, no state-wide energy transition plan will be discussed in the frame of the ARCAS project. This definition is in line with the one defined for characterising nearly Zero Energy Building (*EPBD 2018, Art 2*).

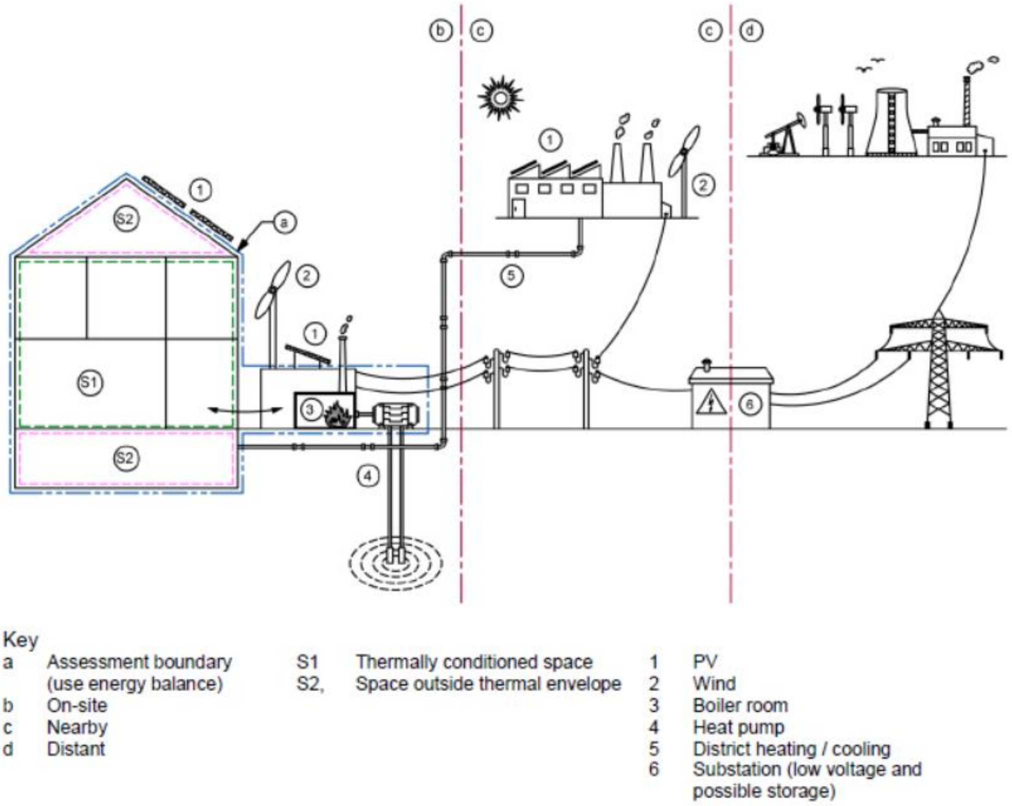


Figure 35: Building assessment boundary and energy balance locations [30]

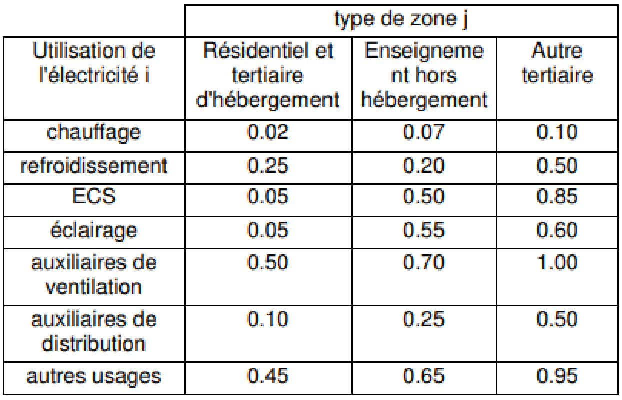
Moreover, the production technologies evaluated in the ARCAS project will be mainly related to on-site technologies, such as PV panels producing electricity or solar panels producing heat. The case of local PV production will be especially detailed in this report as there is a strong development in this field and it could bring some challenges in terms of grid interaction.

8.1.2 Evaluation of the on-site consumed and exported energy from the buildings on a yearly basis

From the on-site energy production, the share of energy production used directly by the building must be evaluated during the design phase. Most of the building regulations define a fixed ratio of energy production that is directly used by the building.

At the French level, the self-consumption ratio is calculated based on both occupants' related load profile and PV production. It leads to the following self-production ratio for the different types of buildings (*Figure **36***). It can be observed that a PV production system can cover a maximum of 45% of the electricity usage of a residential building, whereas it can increase up to 95% for an office building due to different occupancy patterns.

In Spain, the on-site PV production is only accounted for in tertiary buildings, for which a minimum and maximum installed power is defined based on the roof surface. The self-consumption ratio is then calculated for each project.
Portuguese regulation regarding self-consumption does not limit the production of local PV production.



	type de zone j		
Utilisation de l'électricité i	Résidentiel et tertiaire d'hébergement	Enseignement hors hébergement	Autre tertiaire
chauffage	0.02	0.07	0.10
refroidissement	0.25	0.20	0.50
ECS	0.05	0.50	0.85
éclairage	0.05	0.55	0.60
auxiliaires de ventilation	0.50	0.70	1.00
auxiliaires de distribution	0.10	0.25	0.50
autres usages	0.45	0.65	0.95

Figure 36: Self-production coefficients for various usages and types of buildings (residential, teaching, offices) [4]

In the following paragraph, more advanced methodologies relying on hourly data will be presented to evaluate the share of energy production used at the building level.

As buildings can export energy to the grids (thermal, electrical) during parts of the year, this exported energy can be accounted for (or not) in the yearly energy balance. At the European level (ISO 52000), a framework has been defined, with a k_{exp} factor varying between 0 and 1. A full compensation (i.e. accounting for the total exported energy) leads to a value of k_{exp} = 1, whereas the absence of compensation leads to k_{exp} = 0.

In the new building regulation in France (RE 2020), the exported energy to the grid is not accounted for in the annual energy balance (thus k_{exp} = 0) but is accounted for in the LCA calculation [56].
In the building regulation for new construction in Spain, the exported energy to the grid is also not accounted for in the annual energy balance (thus k_{exp} = 0).

8.1.3 State of the art on indicators for self-consumption, self-production and grid interaction

The objective of this part is to provide indicators to evaluate the potential of various renewable energies to cover the need of the building and select the best available renewable technologies. These indicators are especially useful for electrical energy production, for which the mismatch between production and consumption can lead to losses and/or additional challenges on the national grid. Moreover, a lot of European countries are now promoting self-consumption (individual or collective) and not incentivizing export to the grid. For example, the feed-in tariff for excess electricity generated by a PV system is now lower than the market price for small installations in France [57]. The objective is to avoid incentives to use the energy grid as inter-seasonal energy storage, which would transfer cost from the building to the grid and could generate new environmental pressure (e.g for construction of large storage facilities) [58].

We will thus review indicators evaluating the hourly, daily and seasonal matching between on-site supply and demand. We can distinguish two types of indicators:

- Load matching metrics that quantify the overlap between the load and generation;
- Grid-interaction metrics that quantify the net power generation and demand, i.e. the non-overlapping parts.

Load matching is mainly important for determining the value of the on-site generation and could be used for this purpose by building designers and building owners, while grid interaction is mainly relevant for the capacity of the distribution grid or the operation of a building in response to time-of-use tariffs [59] . So far, this second type of indicators is mainly of interest for TSO, DSO or aggregators, even though there is a growing interest from the building perspective to sell additional services to the grid (e.g. smart-readiness or go-flex indicators).

Load-matching metrics

Among the load matching metrics, three indicators are often used in the literature to quantify and compare the local production to the consumption. For the sake of clarity, the definitions are illustrated with the case shown in *Figure **37***.

- The self-consumption corresponds to the self-consumed part relative to the total production:

$$self - consumption\ ratio = \frac{C}{B + C}$$

- The self-sufficiency corresponds to the self-consumed part relative to the total load:

$$self - sufficiency\ ratio = \frac{C}{A + C}$$

- The self-production corresponds to the total production relative to the total load. Thus, it does not give an indication on the load-matching, only in the total quantities.

$$self - production\ ratio = \frac{B+C}{A + C}$$

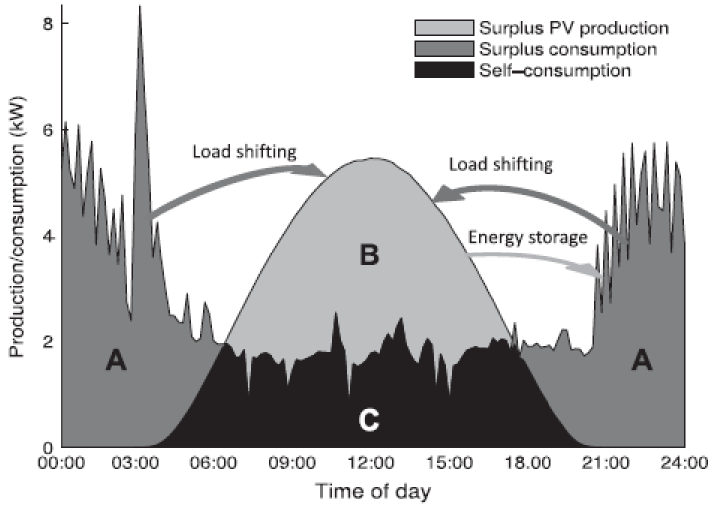


Figure 37: Daily profile of energy consumption of PV production (from **[60]***)*

Using only one of these indicators could lead to a biased interpretation of the technology under study. For example, a very small PV panel would have a self-consumption of 100% but would produce a negligible amount of energy compared to the total load (close to 0%). On the other hand, a very large PV system installed in an office building would have a self-sufficiency close to 100% if we make the hypothesis that most of the electrical need occurs during the daytime. However, it would hide the challenge of electricity export, which might be high during sunny days or weekends.

Therefore, Luthander et al. [60] proposed the "energy matching chart", which is a graphical visualization of self-consumption and self-sufficiency in buildings with local energy generation (*Figure* ***38***). This energy chart uses the two indicators presented above, namely self-sufficiency and self-consumption, to give an overview of the matching in time and size between production and consumption. From this graph, we can also observe the diversity of net-zero energy buildings (NZEB) that can be designed. NZEB can be assimilated to autonomous building in case 1, whereas NZEB can strongly rely on the grid to correct the mismatch between production and consumption (case 2). This graph also highlights buildings with a low production capacity despite a self-consumption ratio of 100% (case 3).

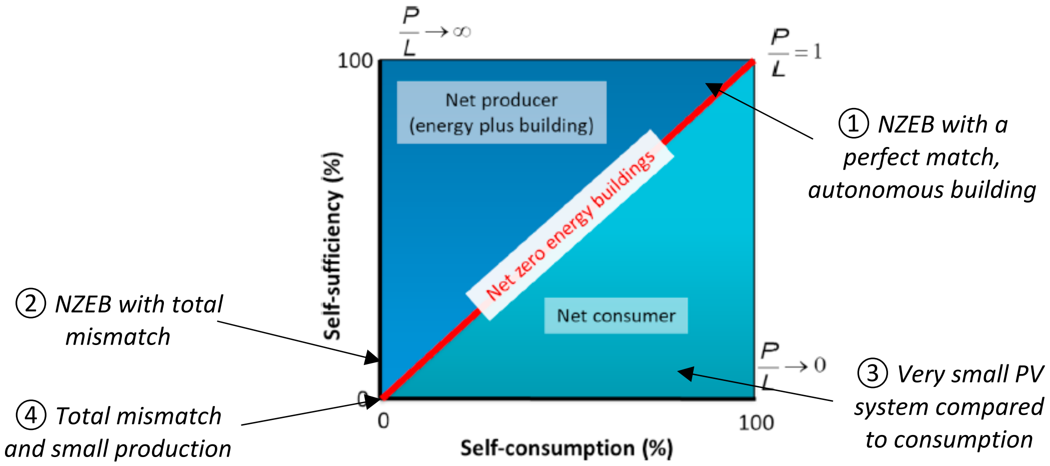


Figure 38: The principles of the "Energy matching chart", proposing a visualisation of the matching in time and size (from **[60]***).*

One important parameter that needs to be defined is the time-step of evaluation. In the literature, it ranges from 1 minute up to 1 hour in general. Jimenez-Castillo et al. [61] highlighted the combined influence of the PV sizing and household power consumption (*Figure 39Figure* ***39***) and advise a 10-minute recording interval to estimate performance metrics on an annual basis.

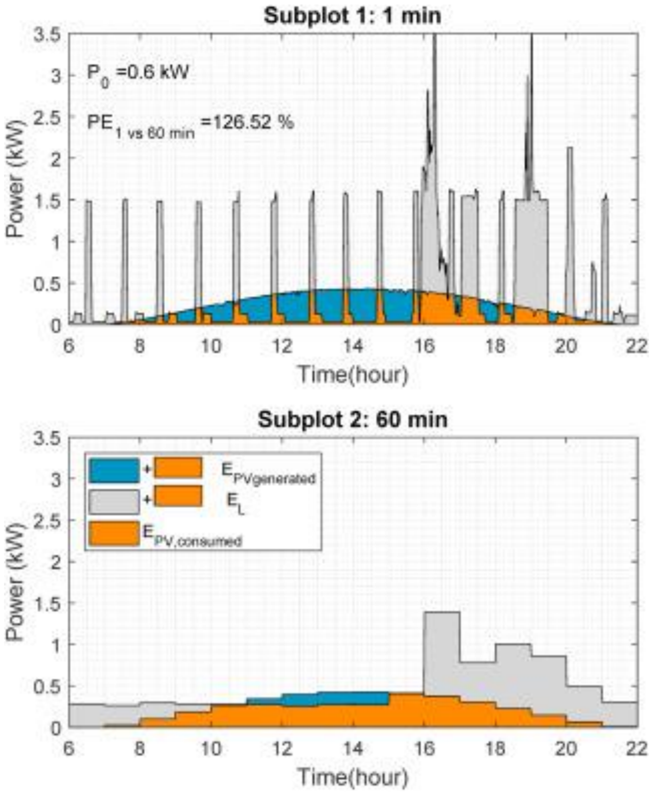


Figure 39: Daily generation, load power consumption and photovoltaic consumption profiles for different recording intervals (1 and 60 min) **[61]**

⇒ In the context of the ARCAS project, we will focus on the self-consumption and self-sufficiency ratio as it was defined in WP 2. The use of the "energy matching chart" can then help to get an overall picture of the renewable performance of the building.

Grid-interaction metrics

The objective of this second category of metrics is to evaluate the dynamic interaction between the building and the grid, and not only rely on annual metrics which often dampen the variations. There is a strong need to evaluate these interactions, as energy grids (and especially the electrical ones) cannot be assimilated to an infinite storage medium.

The challenge of these metrics is to link the global energy systems (national and international) to a local energy use (building scale). A direct scaling of the building energy use cannot be performed as it is only a small part of the global energy use. Indeed, other types of buildings (residential or offices) and other energy use (e.g. industry) drive the total consumption. Two indicators will be presented below:

- The grid support coefficient, that compares the building energy use to a grid-level indicator;

- The primary energy renewable factor, which builds up a theoretical energy mix to estimate the storage need at the grid level to cover the building energy use with 100% renewable energy.

Other indicators related to the dimensioning of the electrical infrastructure can be found in the literature, the reader can refer to reference [10] for further information. Additionally, some researchers model explicitly the coupling between buildings and energy production system (e.g. [62]). These models can estimate the influence of additional local energy production on the production fleet, but their level of complexity is high and their range of validity is limited.

The Grid Support Coefficient (GSC) has been introduced by Klein et al. [63]. It quantifies the coincidence of a load profile and the relative availability of electricity in the energy system. The GSC calculation by equation (1) requires the hourly energy consumption of the building W_{el}^{i} and the value of the grid-based reference quantity G^{i}:

$$GSC_{abs}(G) = \frac{\sum_{i=1}^{n} W_{el}^{i} \cdot G^{i}}{W_{el} \cdot \bar{G}} \; [-] \qquad (1)$$

where:

$$W_{el} = \sum_{i=1}^{n} W_{el}^{i} \; [kWh] \qquad (2)$$

$$\bar{G} = \frac{1}{n} \sum_{i=1}^{n} G^{i} \qquad (3)$$

The grid-based reference quantity should have an increasing trend in case of stress on the grid and a decreasing trend otherwise. The lower the grid support coefficient, the better for the energy grid.

An example of the calculation is given in *Figure 40* using the spot price (market) as an indicator of the grid stress. The grid-supportive building (green curve) is using energy during the lowest price period (GSC_{abs} = 0.8). The grid-adverse building (red curve) is using energy during the highest price period (GSC_{abs} = 1.14).

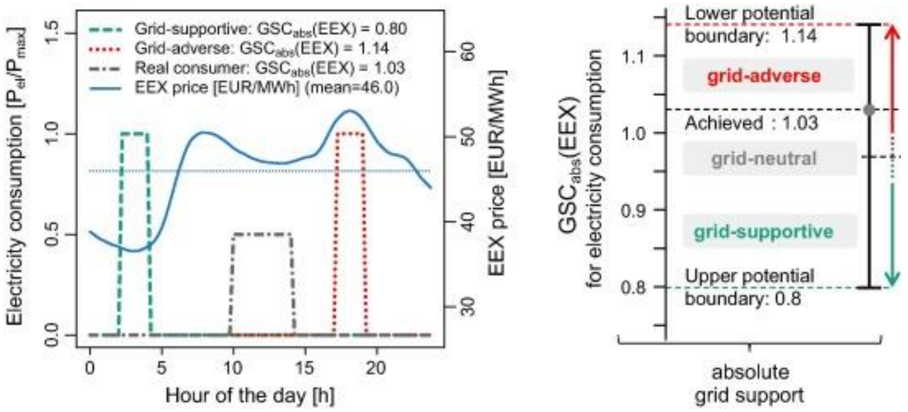


Figure 40: Example of calculation of the Grid Support Coefficients using the spot price as an example of the grid-based reference quantity (from **[63]***)*

The main advantage of this coefficient is that different grid-based reference quantities can be tested depending on the objective of the building (cost reduction, renewable integration, grid stability, etc). An example is given in *Figure 41*, where the control of a heat pump is set according to different signals: day-ahead spot-price (EEX), residual load (RES), (non-renewable) cumulative energy consumption (CEC), fraction of wind and PV in the electricity mix (WPV), etc.

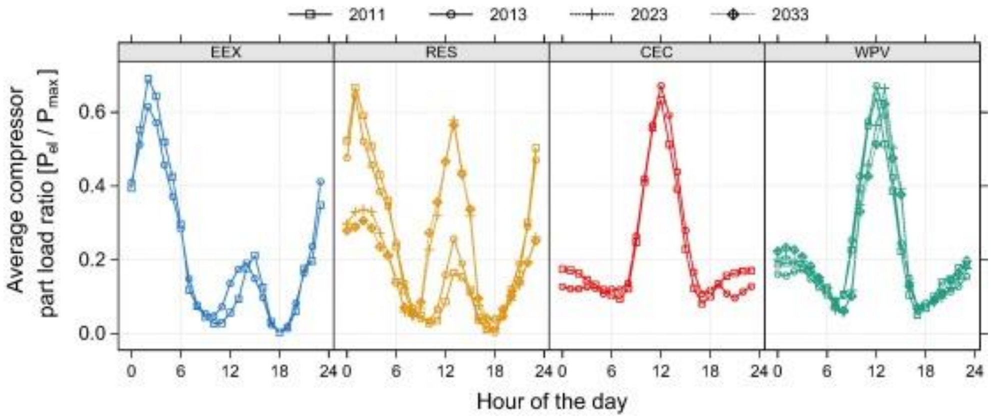


Figure 41: Different optimal consumption profiles depending on the grid-based reference quantity

The German Passive House Institute proposed a methodology to evaluate the Primary Energy Renewable (PER) need of a building [64]. The PER evaluation is based on a 100% renewable scenario (future projection) and assumes that the entire building energy consumption is covered by renewable sources (photovoltaic, wind energy and hydropower, biomass being treated differently). Therefore, a PER-factor of 1.5 means that a surplus of 50% renewable primary energy is needed to meet the final energy demand of the building. The methodology requires information on the load profile and on the local renewable energy generation (*Figure* ***42***):

- the load profile for each energy use (appliances, domestic hot water, space heating, space cooling, etc) should be defined on an hourly basis for a specific year;
- the local renewable energy production is also required on an hourly basis for the specific year.

These two loads curves are compared on a relative basis, assuming an annual consumption/production of 100 kWh/year.

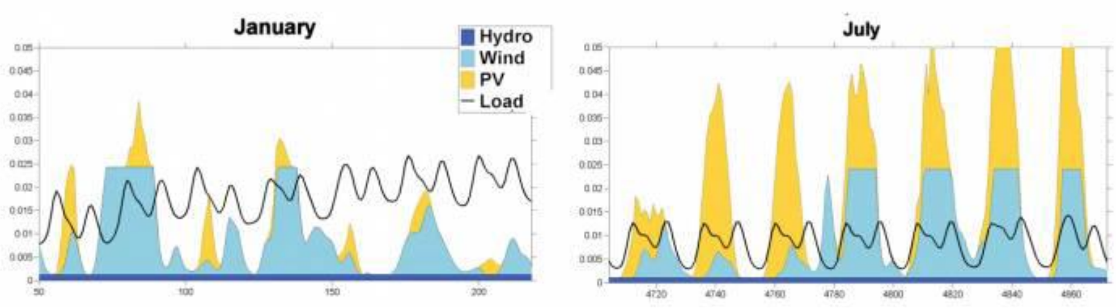


Figure 42: Example of load profile and renewable availability for January and July

The PER factor is then determined by the simultaneity of available energy resources and the energy demand. If the need can be covered by the actual renewable production, the ratio is one. Otherwise, storage options need to be considered, assuming the following:

- short-term storage (several hours/days) with an efficiency of approximately 80%;
- long-term storage (seasonal) with an efficiency of approximately 30%.

The PER factors for different locations and different usages are given in *Figure* ***43***. One can observe that this factor is usually higher for electric heating (> 1.8) due to the mismatch with renewable production (occurring during the summertime).

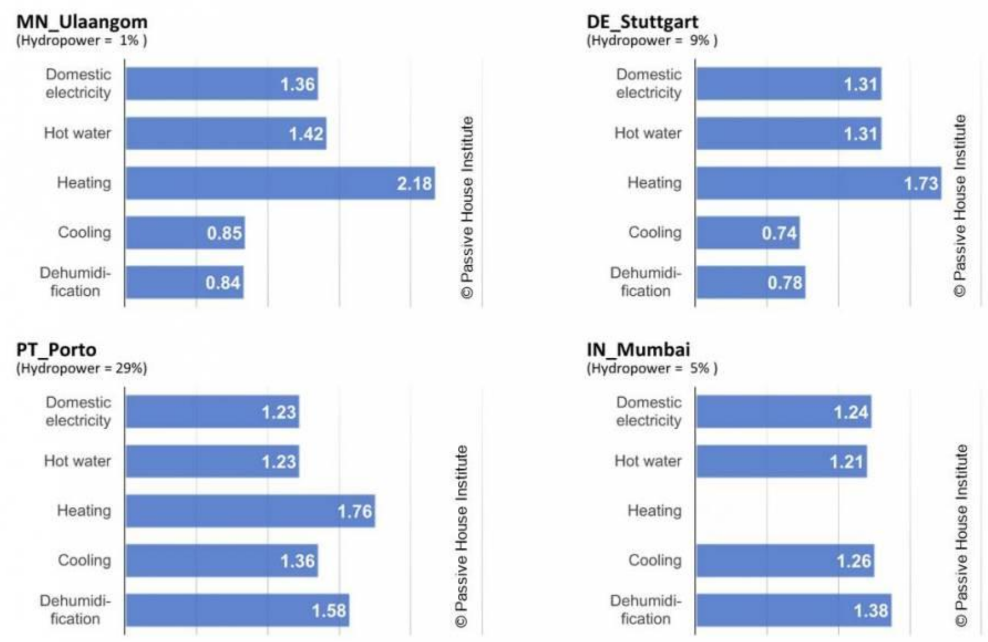


Figure 43: Examples of PER factors in different climatic zones (from [13]*)*

The limitations of this evaluation are the following:

- the energy mix does not correspond to the actual or near-future energy mix;
- an assumption of renewable energy mix and production should be performed (quite rough);
- the model does not consider consumption from other sectors (e.g. transportation, industry) and scaling is performed to compare production and consumption.

⇒ In the context of the ARCAS project, the grid-support coefficient can be selected to evaluate the coincidence of the load profile with the relative availability of electricity in the energy system. The availability of electricity in the energy system will be evaluated using the residual load, which is usually available from the national Transmission System Operator.

8.1.4 Case study: evaluation of self-consumption from PV panels

In this case study, we will evaluate the installation of PV panels on the roof of the multi-storey residential building PN6, already used in section 6. So, the case study corresponds to on-site renewable energy production. The tool used to evaluate the self-consumption from PV panels is AutoCalSol developed by the French Solar Institute [65]. The calculation time-step is set to one hour.

Presentation of the case study

The potential of installing PV panels on the East-side of the roof will be evaluated (*Figure 44*). The building is oriented toward the West-East directions and the roof is composed of tiles. The pitched roof (30°) and the presence of chimneys make the installation of PV panels more difficult. The main characteristics of the building and the PV system are presented in *Table* ***24***.

Figure 44: PN6 Building East façade and roof

Table 24: PN6 main characteristics

Building	Building orientation	East-West
	Building length (m)	35.4
	Building width (m)	6.9
	Number of dwellings	16
	Usable roof area (-)	70%
Energy use	Space heating / DHW electrical consumption?	No (≈12 000 kWh/dw.year of gas)
	Electrical energy use per dwelling	2 000 kWh/dw.year
	Electrical consumption profile	TSO data, single tariff
PV panels	Type of panels	Crystalline silicon
	Efficiency of the cells	0.150 kWp/m^2_{panels}
	Electrical losses of the system	85%
	Area	80 m^2
	Tilt	30°
	Azimuth	-90° (east)

Results

The monthly balance of energy consumption and production is given in *Figure* ***45*** for the year 2012. It can be observed that the maximum PV production occurs during the summer period, whereas the highest consumption occurs during the winter period. It should be noticed that the monthly production is always lower than the monthly consumption.

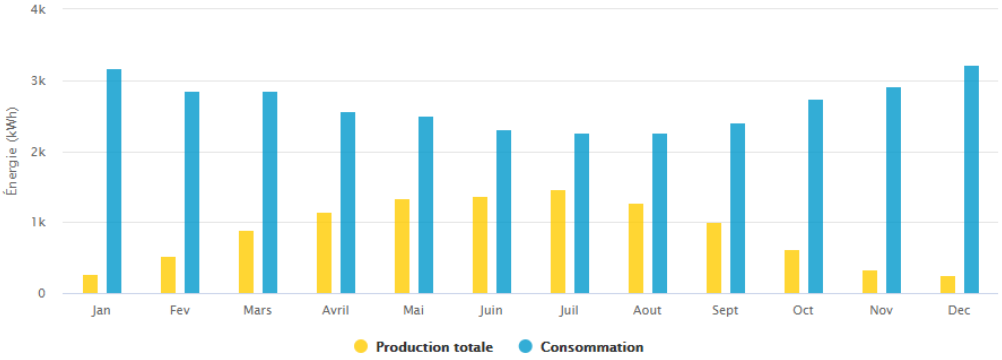


Figure 45: Monthly production and consumption for the simulated building

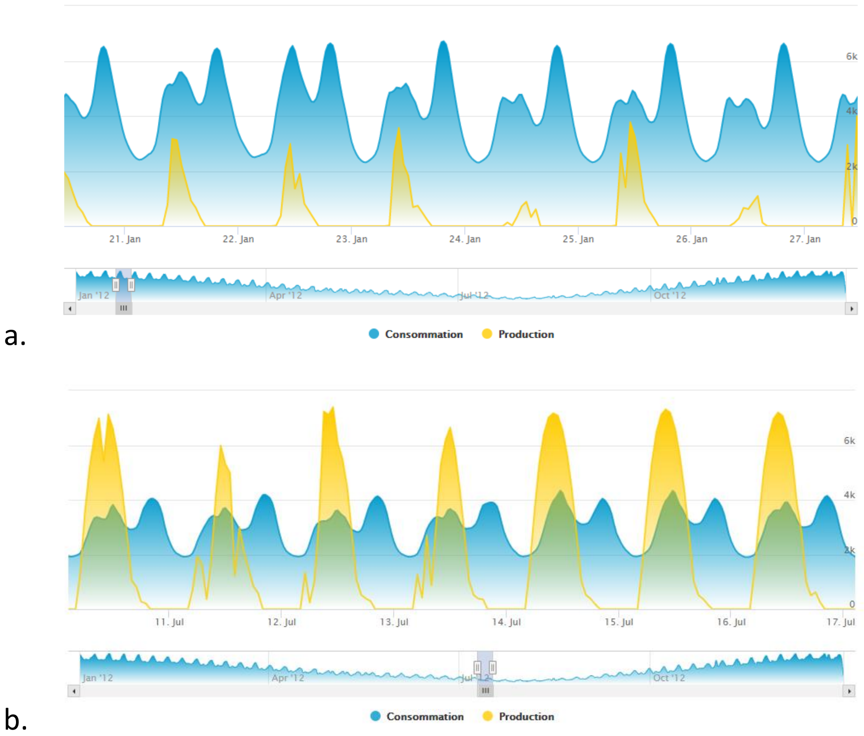


Figure 46: PV production and electrical consumption for a winter week (a) and a summer week (b)

To get a better insight into the mismatch between production and consumption, two typical winter and summer weeks are presented in *Figure 46*. First of all, it can be observed that the peak of production occurs in the morning as the PV panels are oriented towards the East. In the winter period, little energy is exported to the grid. During the summer period, the grid is used as a buffer to export the extra energy produced on-site.

With the PV installation under evaluation, the self-consumption of the building is 77% and the self-sufficiency is 27% (electricity only) and 4% (all energy, assuming a total building additional energy consumption for space heating and DHW of 190 000 kWh_{fe}/year). The performance of the PV installation compared to the building energy use can then be summarized in the "energy matching chart" (*Figure* ***47***). It can be observed that the multi-storey residential building is far from being a net zero energy building, but a large share of the energy locally produced can be directly used by the building.

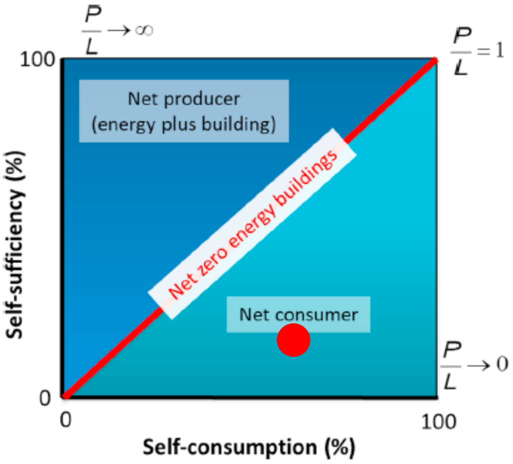


Figure 47: Energy matching chart for the building under evaluation (red dot)

It should be highlighted that these simulation tools assume a typical consumption profile, usually observed at the transformer level (i.e. aggregated level). As the building is composed of only 16 dwellings, the load diversity might not be as good as expected. Moreover, the installation of a battery or a different PV area will affect the performance of the local energy production.

The grid-support coefficients (GSC) with and without PV have been evaluated using the national residual load as indicator (*Figure* ***48***). The addition of PV panels allows a decrease in the need for electricity during the morning, which is usually a period of stress on the grid (indicated with a dimensionless residual consumption value over 1). Therefore, the GSC decreases by 0.3% with the PV installation (from 1.019 down to 1.016).

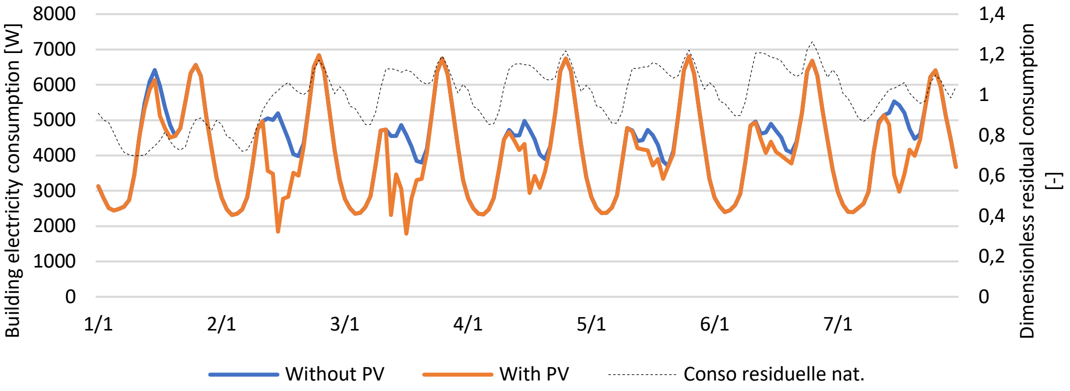


Figure 48: Evaluation of the GSC over the first week of January

Alternative design configurations are also tested, to observe their influence on the defined indicators (*Table* ***25***). These results are calculated assuming an annual electrical energy use of 32 000 kWh. With a smaller PV surface, the self-consumption ratio increases. With a change in PV orientation (East-West vs. North-South), one can observe both an increased self-consumed and exported chare of energy.

Table 25: Overview of the simulation results

	Base-case	**Case-study 1**	**Case-study 2**	**Case-study 1**
Description	Building orientation East-West	Building orientation East-West, 80 m²	Building orientation North-South, 80 m²	Building orientation East-West, 50 m²
Annual electrical energy use [kWh/year]	32 000	32 000	32 000	32 000
Annual PV production [kWh/year]	-	11 494	15 883	7 184
, self-consumed part	-	8 799	10 351	6 808
, exported part	-	2 694	5 532	375
Self-consumption [%]	-	77%	65%	95%
Self-sufficiency [%], electricity only	-	27%	32%	21%
Self-sufficiency [%], all energy use (final)	-	4%	5%	3%
GSC [-], first week winter	1.019	1.016		

A similar work can be performed for solar thermal production. The online tool SOLO can, as an example, be used for this purpose (http://solo2018.tecsol.fr/). In this case, we do not account for exported energy as there is usually no reinjection in a local district heating network. However, a thermal storage tank can be installed to improve the efficiency of the production. The only indicator evaluated is then the self-sufficiency ratio.

For others renewable thermal sources such as biomass and groundwater the self-sufficiency ratio can be equal to 1, or less in the case of limited potential of the resource or for temperature-dependent operating restrictions (heat pumps for example). Exported energy may also be present if the local heat or cooling production is linked to a district network under a production contract for example (the same applies to electricity production, whatever renewable or not).

9. Best HVAC technologies choice guide

This last part is devoted to a multi-criteria methodology aiming to help the project owners or engineering offices during the design of a rehabilitation or new construction project, for the choice of the active HVAC systems.

9.1 Multi-criteria energy systems selection

The identification of the best strategy for the HVAC system replacement is generally tricky for many reasons. The first reason is the large variety of system types and technologies, and an even greater variety of offers on the market. Furthermore, several functionalities can be performed by a unique system. Another reason is that the selection of the system depends on many technical criteria, only known by designers. Most of these criteria are related to constraints from the existing building. Others depend on exogenous factors, such as the target for the energy performance or thermal comfort and can be clearly expressed only by experts. Finally, yet importantly, the cost of a solution is an important criteria.

Thus, the possible choices for the replacement of HVAC systems depend on both intrinsic and extrinsic parameters. Intrinsic parameters are those related to the existing building and its HVAC systems. Extrinsic parameters are those related to the building environment and the refurbishment operation itself. Identifying and formalizing these factors enables to clarify the design methodology for the HVAC systems replacement. The final objective is to supply to the building owner relevant information regarding the best-suited HVAC systems, considering the building integration easiness, the refurbishment operation objectives, the global energy efficiency, and the cost aspects.

This chapter is organized as follow:
In a first section, a non-exhaustive list of possible influencing factors is proposed, taking into account the existing building and systems as well as extrinsic parameters.
The second section proposes a set of HVAC systems for the replacement of the old ones. This document does not list exhaustively all the possible HVAC systems, but focuses on the most frequent and relevant ones, using or not renewable energy. For each system listed, a costing methodology is introduced in the third section. Finally, the last section exposes the global methodology for the ranking (and therefore for the choice) of the HVAC systems for the refurbished building. It is based on the combination of a set of expert rules – the input of which are the factors defined in the first section – and a multicriteria assessment tool.

9.1.1 Key factors for the HVAC system selection and pre-sizing

The intrinsic and extrinsic factors can be organized into three different groups: the constraints, the opportunities and the objectives. The constraints enable to remove some of the possible systems: the field of possibilities is therefore reduced, and the problem of HVAC systems selection simplified. The opportunities and the objectives guide the choices towards potentially suitable systems.

Table ***26*** to *Table* ***31*** aim at formalizing the description of the existing building HVAC systems on the one hand, and to give a methodology to describe their state on the other hand. The main objective is here to detect potential opportunities for refurbishment. Concerning the state of the system, a simple assessment rating is proposed to identify the possible improvements or replacements.

Table 26: Extrinsic factors influencing the refurbishment actions selection

1. Constraints

1.a. Constraints linked to the refurbishment operation specificities

Budget
Works on an occupied site
Limited work period

1.b. Constraints linked to the building envelope specifications

Urban rules: no modification allowed of the roof / façade appearance
No available roof / façade surface
No available land near the building
Shadings or masks from neighbouring buildings, relief or vegetation
Size of the housings
Limited possibilities of drilling the outdoor walls

1.c. Constraints linked to the building HVAC systems specifications

No available passage for ducts/pipes
No available / not enough space in common technical rooms
No available / not enough space in flat technical rooms

2. Opportunities

2.a. Opportunities linked to the refurbishment operation specificities

High energy consumption for heating/cooling / DHW
High energy needs for DHW
Poor winter/summer thermal comfort
Poor indoor air quality for some rooms/flats/common spaces

2.b. Opportunities linked to the building envelope specifications

Urban rules: modifications allowed of the roof/façade appearance
No shading/masks from neighbouring buildings, relief or vegetation
Size of the housings
Possibilities of drilling the outdoor walls

2.c. Opportunities linked to the building HVAC systems specifications

Cf. following tables

3. Objectives

Improve the aesthetical aspect of the building
Reduce the building energy needs
Reduce the building energy consumption
Reach certification or label requirements
Reduce the environmental footprint
Improve the thermal comfort of the occupants
Improve the HVAC systems-occupant interactions
Carry out the maintenance operation
Reduce the rental costs
Make the maintenance operation easier
Design a reproducible refurbishment strategy
Design a custom-made refurbishment strategy

Table 27: Description of the existing systems for heating only

Type of service		Type of generator	Type of emission	Type of supplemental	Generator state	Emission state	Distribution network state	State of supplemental
Heating only	Collective	1. Oil-fired boiler 2. Gas boiler 3. Wood boiler 4. Urban heating network	1. HT water radiator 2. LT water radiator 3. Hydraulic floor heating 4. Radiant ceiling	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good and lagged 3. Good but poorly lagged 4. Poor	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor
		1. Underfloor electric heating						
	Individual	1. Gas boiler	1. HT water radiator 2. LT water radiator 3. Hydraulic floor heating					
		1. Electric radiator		1. None 2. Bathroom heater				
		1. Underfloor electric heating		1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater				

Table 28: Description of the existing systems for domestic hot water generation only

Type of service	**Type of generator**	**Type of emission**	**Type of supplemental**	**Type of storage**	**Generator state**	**Emission state**	**Distribution network state**	**State of supplemental**	**Storage state**
DHW only Individual	Electric tank	n.a.	1. none	1. Stored	2. New or less than 5 years 3. Good 4. Good but no regulation 5. Poor	n.a.	1. New or less than 5 years 2. Good and lagged 3. Good but poorly lagged 4. Poor	n.a.	1. New or less than 5 years 2. Good, adequate volume and lagged 3. Good, insufficient volume and lagged 4. Good, insufficient volume and poorly lagged 5. Good, adequate volume and poorly lagged 6. Poor

Table 29: Description of the existing systems for heating & DHW, for the cooling only and for the heating and cooling

Type of service		Type of generator	Type of emission	Type of supplemental	Type of storage	Generator state	Emission state	Distribution network state	Storage state
Heating and DHW	Collective	1. Oil-fired boiler 2. Gas boiler 3. Wood boiler 4. Urban heating network	1. HT water radiator 2. LT water radiator 3. Hydraulic floor heating 4. Radiant ceiling	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater	1. Stored 2. Stored and looped 3. Instantaneous	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good and lagged 3. Good but poorly lagged 4. Poor	1. New or less than 5 years 2. Good, adequate volume and lagged 3. Good, insufficient volume and lagged 4. Good, insufficient volume and poorly lagged 5. Good, adequate volume and poorly lagged 6. Poor
	Individual	1. Gas boiler			1. Stored 2. Micro-Stored 3. Instantaneous				

Table 30 (Ctd)

Type of service		Type of generator	Type of emission	Type of supplemental	Type of storage	Generator state	Emission state	Distribution network state	Storage state
Cooling only	Collective	1. HP A/A 2. HP A/W 3. HP W/W	1. Fan 2. Hydraulic ceiling cooling	1. None	n.a.	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good and lagged 3. Good but poorly lagged 4. Poor	n.a.
	Individual	1. HP A/A							
Heating and cooling	Collective	1. HP A/A 2. HP A/W 3. HP W/W	1. Fan 2. Hydraulic ceiling cooling and floor heating 3. Hydraulic ceiling cooling and LT water radiator 4. Hydraulic ceiling cooling and radiant ceiling	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater	n.a.	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good and lagged 3. Good but poorly lagged 4. Poor	n.a.
	Individual	1. HP A/A							

Table 31: Description of the existing systems for ventilation only, for heating and ventilation and for heating, cooling and ventilation

Type of service		Type de ventilation	Vent extraction	Vent supply / Air inlet	Duct material	Type of emission	Type of generator	Generator state	Emission state	Distribution network state	Vent state
Ventilation only	Collective	1. Mechanical ventilation (extraction) 2. Mechanical ventilation (supply) 3. Mechanical ventilation (extraction+ supply) 4. Mechanical ventilation with HX	1. Constant air volume 2. Pressure-controlled 3. Humidity-controlled 4. Presence detector 5. Humidity-controlled and presence detector		1. Plastic 2. Aluminium 3. Steel 4. Cast-iron 5. Galvanized steel 6. Smooth concrete 7. Concrete 8. Brick 9. Fabric	n.a.	n.a.	n.a.	n.a.	1. New or less than 5 years 2. Good 3. Leaky 4. Poor	1. New or less than 5 years 2. Good 3. Clogged 4. Inadequate airflow rate 5. Poor
	Individual										
Heating and ventilation	Collective	1. Mechanical ventilation (supply) 2. Mechanical ventilation (extraction+ supply 3. Mechanical ventilation with HX				1. Fan	1. HP A/A 2. HP A/W 3. HP W/W	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor	1. New or less than 5 years 2. Good 3. Good but no regulation 4. Poor		
	Individual										
Heating, cooling and ventilation	Collective										
	Individual										

9.1.2 Renovation of HVAC system: detailed listing of the options

This section proposes a structured (but non exhaustive) list of potential systems for refurbishment. As previously, it is ordered according to the type of service supplied. Indeed, the diagnosis carried out previously highlights the systems and thus the services to be replaced. A combination of services can be selected, for instance, heating only and DHW only and ventilation only. For each service, the generation can be collective or individual. The latter can be combined with several possible emissions and eventually supplemental.

Table 32: Description of the renovation systems for heating only, DHW only, and heating and DHW

Type of service		Type of generator	Type of supplemental	Type of emission	Type of storage
Heating only	Collective	1. Gas boiler 2. Wood boiler 3. Urban heating network 4. HP Air/Water 5. HP Water/Water	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater 5. Individual HP A/A	1. LT water radiator 2. Hydraulic floor heating 3. Radiant ceiling 4. Fan	n.a.
	Individual	1. Gas boiler	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater	1. LT water radiator 2. Hydraulic floor heating	
		1. Radiant panels	1. None 2. Bathroom heater	n.a.	
DHW only	Collective	1. Thermodynamic water heater 2. Solar water heater	1. None 2. Bathroom heater 3. Gas boiler 4. Collective HP A/W	n.a.	1. Stored 2. Stored and looped
	Individual	1. Electric tank 2. Thermodynamic water heater	1. None 2. Electric		

Table 33 (Ctd)

Type of service		Type of generator	Type of supplemental	Type of emission	Type of storage
Heating and DHW	Collective	1. Gas boiler 2. Wood boiler 3. Urban heating network	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater 5. Individual HP A/A	1. LT water radiator 2. Hydraulic floor heating 3. Radiant ceiling	1. Stored 2. Stored and looped 3. Instantaneous
		1. HP Air/Water 2. HP Water/Water 3. Solar water heater 4. Hybrid PVT	1. None 2. Gas boiler 3. Bathroom heater 4. Electric radiator 5. Electric radiator and bathroom heater 6. Individual HP A/A		
	Individual	1. Gas boiler 2. HP Air/Water	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater		1. Stored 2. Micro-Stored 3. Instantaneous

Table 34: Description of the renovation systems for cooling only and for heating and cooling only

Type of service		Type of generator	Type of supplemental	Type of emission	Type of storage
Cooling only	Collective	1. PAC Air/Air 2. HP Air/Water 3. HP Water/Water 4. Absorption / Desiccant system	1. None	1. Fan 2. Hydraulic cooling ceiling	n.a.
	Individual	1. PAC Air/Air		1. Fan	
Heating and cooling	Collective	1. PAC Air/Air 2. HP Air/Water 3. HP Water/Water 4. Absorption	1. None 2. Gas boiler 3. Bathroom heater 4. Electric radiator 5. Electric radiator and bathroom heater 6. Individual HP A/A	1. Fan 2. Hydraulic cooling ceiling and heating floor 3. Hydraulic cooling ceiling and LT water radiator 4. Hydraulic cooling ceiling and et radiant ceiling	n.a.
	Individual	1. PAC Air/Air	1. None 2. Bathroom heater 3. Electric radiator 4. Electric radiator and bathroom heater	1. Fan	

Table 35: Description of the renewal systems for ventilation only, for heating and ventilation, and for heating, cooling and ventilation

Type of service		**Type de ventilation**	**Vent extraction**	**Vent supply / Air inlet**	**Duct material**	**Type of emission**	**Type of generator**
Ventilation only	Collective	1. Mechanical ventilation (extraction) 2. Mechanical ventilation (supply) 3. Mechanical ventilation (extraction+ supply) 4. Mechanical ventilation with HX	1. Constant air volume 2. Pressure-controlled 3. Humidity-controlled 4. Presence detector 5. Humidity-controlled and presence detector		1. Plastic 2. Aluminium 3. Steel 4. Cast-iron 5. Galvanized steel 6. Fabric	n.a.	n.a.
	Individual						
Heating and ventilation	Collective	1. Mechanical ventilation (supply) 2. Mechanical ventilation (extraction+ supply) 3. Mechanical ventilation with HX				1. Fan	1. HP A/A 2. HP A/W 3. HP W/W
	Individual						
Heating, cooling and ventilation	Collective						
	Individual						

Table 36: Description of the renovation systems for electricity generation, for electricity generation and heating, for electricity and DHW generation, and for electricity, heating and DHW generation

Type of service		Type of generator	Type of emission	Type of storage
Electricity generation	Collective	1. Solar photovoltaic	n.a.	n.a.
Electricity generation and heating		1. Gas boiler cogeneration	1. LT water radiator 2. Hydraulic floor heating 3. Radiant ceiling	n.a.
Electricity and DHW generation		1. Gas boiler cogeneration 2. Hybrid PVT	n.a.	1. Stored 2. Stored and looped 3. Instantaneous
Electricity, heating and DHW generation		1. Gas boiler cogeneration	1. LT water radiator 2. Hydraulic floor heating 3. Radiant ceiling	

9.1.3 Costing methodology for the HVAC systems

The following section introduces a proposition of methodology for the pricing of HVAC systems. Its principle is simply to give, for each of the possible systems listed above, a price range including the material and the installation, excluding taxes. The objective is here to obtain a rough estimation of the renovation strategy cost as one of the possible assessment indicators (energy performance, comfort, works easiness, etc.) and to give relevant information to compare several strategies. The objective is not to provide an accurate quotation.

The price is of course the results of, on the one hand, endogenous technical factors (size, performance, project specificities, etc.), and on the other hand of exogenous factors (location, conjuncture, manufacturer, installer, etc.).

The exogenous factors are, by definition, hardly predictable. That is why a statistical approach is preferred. Since this report aims at proposing a methodology and not to fully develop it, a first basic approach is given and could be achieved in the next work packages. For instance, instead of giving the minimum and maximum prices, it could be interesting to yield the median value and the variance that give more details about the cost breakdown.

Concerning the endogenous factors, a few of them enables to explain one system price. Typically, the price of a gas boiler is strongly dependent on its power. All the other factors can be treated as statistical variance around this estimation. Consequently, the following tables show for each system the factors that have been chosen to explain the minimum and maximum prices.

Most of the time, one factor has been retained, sometimes two. In the case of two factors, the cost has to be summed to get an estimation of the system. For example, the cost of the replacement of one low-temperature radiator is given by the sum of one term depending on its power (representing the material) and one term proportional to the number of radiators. The minimum price for a 1.5kW low-temperature radiator is then 100x1.5+200=350 € and the maximum 200x1.5+350=650 €. The total cost of the renovation is the sum of the different new systems. The parametric nature of these evaluations allows adapting them to each local situation, and missing information could be filled in future work packages.

Table 37: Description of the renovation systems for heating only, and DHW only

		Type of generator	**Unit**	**Unit price min [€]**	**Unit price max [€]**	**Details**
Heating only	Collective generation	1. Gas boiler	kW	90xP	350xP	power
		2. Wood boiler	?	?	?	
		3. Urban heating network	m	400xL	450xL	connection length
			kW	75xP	100xP	power
		4. HP Air/Water	kW	350xP	375xP	power
		5. HP Water/Water	kW	400xP	450xP	power
	Individual generation	1. Gas boiler	-	1725	4500	
		2. Radiant panels	kW	200xP	350xP	material
			kW	100xP	350xP	installation
	Supplemental	1. Bathroom heater	kW	450xP	1500xP	material
			-	100	250	installation
		2. Electric radiator	kW	200xP	350xP	material
			kW	100xP	350xP	installation
		3. Individual HP A/A	m^2	52,436xS + 295,05	93,657xS - 1097,7	dwelling area
	Emission	1. LT water radiator	-	200	350	installation
			kW	100xP	200xP	material
		2. Hydraulic floor heating	m2	44xS	55xS	heated area
		3. Radiant ceiling	?	?	?	
		4. Fan	?	?	?	
DHW only	Collective generation	1. Thermodynamic water heater	kW	1250xP	1500xP	power
			L	3xL	8xL	storage volume
		2. Solar water heater	m^2	850xS	1000xS	collector area
			kWh/an	800xE	950xE	solar energy produced yearly
	Individual generation	1. Electric tank	L	2xL	6xL	volume stockage
		2. Thermodynamic water heater	-	2500	5000	
	Supplemental	1. Gas boiler	kW	90xP	350xP	power
		2. Collective HP A/W	kW	350xP	375xP	power
	Storage	1. Tank	?	?	?	?

Table 38: Description of the renovation systems for heating and DHW, and cooling only

		Type of generator	Unit	Unit price min (€)	Unit price max [€]	Details
Heating and DHW	Collective generation	1. Gas boiler	kW	90xP	350xP	power
		2. Wood boiler	?	?	?	?
		3. Urban heating network	m	400xL	450xL	connection length
			kW	75xP	100xP	power
		4. HP A/W	kW	350xP	375xP	power
		5. HP W/W	kW	400xP	450xP	power
		6. Solar water heater	m^2	850xS	1000xS	collector area
			kWh/an	800xE	950xE	solar energy produced yearly
		7. Hybrid PVT	?	?	?	?
	Individual generation	1. Gas boiler	kW	90xP	350xP	power
		2. HP Air/Water	kW	350xP	375xP	power
	Supplemental	1. Bathroom heater	kW	450xP	1500xP	material
			-	100	250	installation
		2. Electric radiator	kW	200xP	350xP	material
			kW	100xP	350xP	installation
		3. Individual HP A/A	m^2	52,436xS + 295,05	93,657xS - 1097,7	housing area
		4. Gas boiler	kW	90xP	350xP	power
	Emission	1. LT water radiator	-	200	350	installation
			kW	100xP	200xP	material
		2. Hydraulic floor heating	m2	44xS	55xS	heated area
		3. Radiant ceiling	?	?	?	
	Storage	1. Tank	?	?	?	?
Cooling only	Collective generation	1. HP A/A	?	?	?	?
		2. HP A/W	kW	350xP	375xP	power

		3. HP W/W	kW	400xP	450xP	power
	Individual generation	1. HP A/A	m^2	52,436xS + 295,05	93,657xS - 1097,7	housing area
	Emission	1. Fan	?	?	?	?

Table 39: Description of the renovation systems for heating and cooling, ventilation, and heating and ventilation

		Type of generator	Unit	Unit price min [€]	Unit price max [€]	Details
Heating and cooling	Collective generation	1. HP A/A	?	?	?	?
		2. HP A/W	kW	350xP	375xP	power
		3. HP W/W	kW	400xP	450xP	power
	Individual generation	1. HP A/A	m^2	52,436xS + 295,05	93,657xS - 1097,7	housing area
	Supplemental	1. Gas boiler	kW	90xP	350xP	power
		2. Bathroom heater	kW	450xP	1500xP	material
			-	100	250	installation
		3. Electric radiator	kW	200xP	350xP	material
			kW	100xP	350xP	installation
		4. Individual HP A/A	m^2	52,436xS + 295,05	93,657xS - 1097,7	housing area
	Emission	1. LT water radiator	-	200	350	installation
			kW	100xP	200xP	material
		2. Hydraulic floor heating	m2	44xS	55xS	heated area
		3. Radiant ceiling	?	?	?	?
		4. Fan	?	?	?	?
		5. Hydraulic ceiling cooling	?	?	?	?
Ventilation only	Collective system	1. MV	-	200xNflat	400xNflat	fan and ducts
			-	200xNflat	250xNflat	vents
		3. MV with HX	-	1750xNflat	2250xNflat	fan and ducts
			-	200xNflat	210xNflat	vents
	Individual systems	1. MV	m2	$29{,}223xS-0{,}0661xS^2$	$44{,}011xS-0{,}102xS^2$	fan and ducts
			-	200xNflat	210xNflat	vents
		3. MV with HX	m2	$32{,}524xS-0{,}0882xS^2$	$48{,}963xS-0{,}1351xS^2$	fan and ducts
			-	200xNflat	210xNflat	vents

Heating and ventilation	Collective system	1. MV with HX - HP hot battery	?	?	?	?
		2. MV with HX - Gas hot battery	?	?	?	?
	Individual systems	1. MV with HX - HP hot battery	?	?	?	?
		2 MV with HX - Electric air heater	?	?	?	?

Table 40: Description of the renovation systems for heating, cooling and ventilation and electricity generation

		Type of generator	**Unit**	**Unit price min (€)**	**Unit price max [€]**	**Details**
Heating, cooling and ventilation	Collective system	1. Dual flow - HP hot battery	?	?	?	?
	Individual systems	1. Dual flow - HP hot battery	?	?	?	?
Electricity generation	Collective generation	1. Solar photovoltaic	kWp	2500	3175	power
Electricity generation and heating	Collective generation	1. Gas boiler cogeneration	kW	800	900	power
	Emission	1. LT water radiator	- kW	200 100xP	350 200xP	installation material
		2. Hydraulic floor heating	m2	44xS	55xS	heated area
		3. Radiant ceiling	?	?	?	?
Electricity and DHW generation	Collective generation	1. Gas boiler cogeneration	kW	800	900	power
		2. Hybrid PVT	m2	1100	1600	collector area
	Storage	1. Tank	?	?	?	?
Electricity, heating and DHW generation	Collective generation	1. Gas boiler cogeneration	kW	800	900	power
	Emission	1. LT water radiator	- kW	200 100xP	350 200xP	installation material
		2. Hydraulic floor heating	m2	44xS	55xS	heated area
		3. Radiant ceiling	?	?	?	?

Storage	1. Tank	?	?	?	?

9.2 A methodology for the identification of the potential HVAC systems replacement

This section briefly explains the methodology for the identification of the best solutions for the replacement of existing HVAC systems, based on the previous sections.

9.2.1 *Overview of the proposed methodology*

The variable domain is the concatenation of all the possible renovation choices for all the existing systems. This has been described in section 9.1.2. The set of constraints, considering the existing systems, the building envelope but also the renovation operation specificities has been introduced in section 9.1.1. A set of expert rules has to be built in order to automatically reduce the variable domain according to the set of constraints. Formalizing these expert rules can be made in future work packages, but examples are given in this section.

Then, a set of refurbishment alternatives can be built among the reduced variable domain (i.e. the allowed variable domain). These alternatives (or "strategies") have to be assessed according to criteria/indicators to be defined in the other work packages to form a decision matrix. Finally, a multicriteria analysis methodology enables to rank the different strategies, taking into account the building owner preferences.

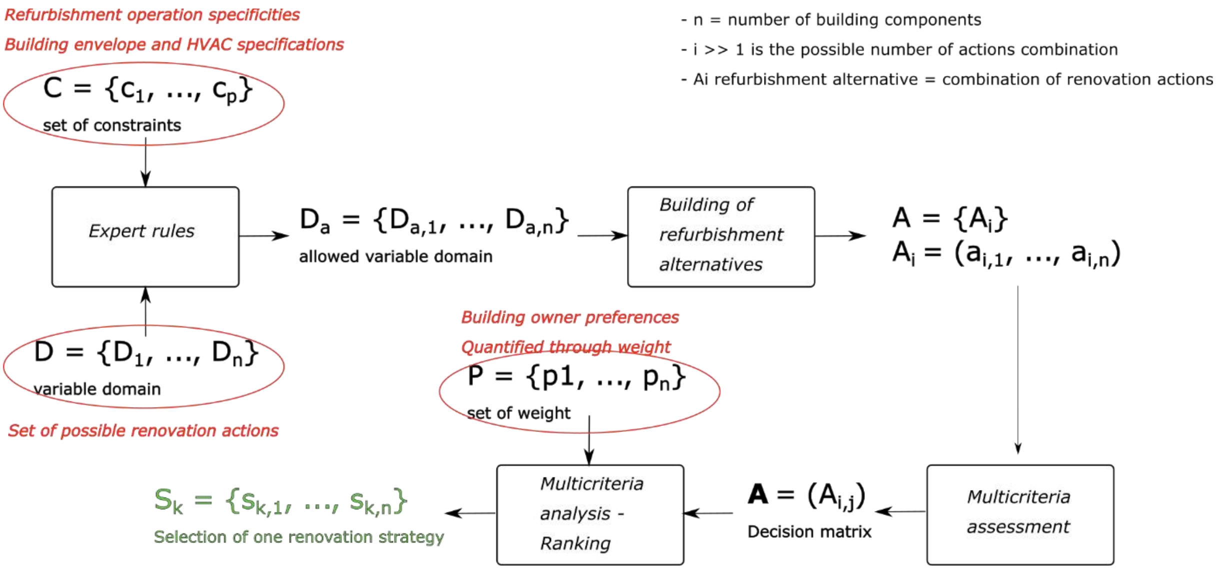


Figure 49: Overview of the muticriteria analysis methodology

9.2.2 *Premises of a set of expert rules*

One expert rule could be for instance:

IF *"Urban rules: modification of the roof is not allowed" OR "No available roof / façade surface"*
THEN *"Remove PV panels integration"*

Building other expert rules and organizing them in a decision tree formalism would allow the automatized construction of the authorized or preconized renovation actions.

9.2.3. *Multi-criteria analysis tools*

The multi-criteria analysis is a field of study, whose aim is to compare strategies in order to help in choosing, sorting and classifying the results (in accordance with the decision-making problem to be addressed).

Among all existing methods (such as Electre, MacBeth and Promethee), TOPSIS [66], [67], was chosen for being implemented in the current methodology. TOPSIS stands for "Technique for Order of Preference by Similarity to Ideal Solution". This method is intuitive and easy to implement and the calculation is fast. Moreover, it is suitable for comparing a very large number of alternatives. It easily supports the addition and deletion of alternatives in the decision matrix. It allows the classification of the strategies according to a restricted set of indicators. The user can rank these indicators according to his preferences (from the most important for planning to the least important). The TOPSIS algorithm then returns a ranking of the strategies according to these criteria, following the steps presented in *Figure* ***50***.

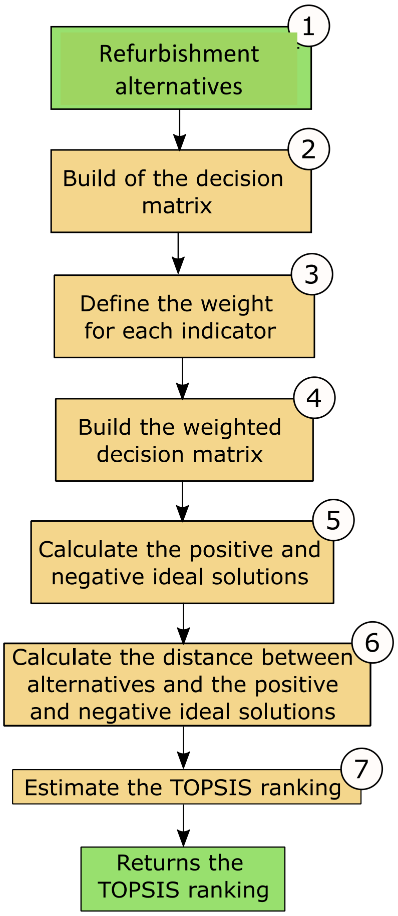


Figure 50 – Flowchart of the TOPSIS method

9.2.4 Illustration of the method

A simple illustration is given in the following: let us consider a renovation project for the heating/cooling and DHW production systems of a ten-flats building. The decision maker considers 5 possible alternatives (**step 1**):

- The first alternative is a full collective two-service solution based on a gas boiler.
- The second is similar but the low temperature radiators are replaced by a hydraulic heating floor.
- The third is equivalent to the second one, but a cooling production is added and supplied by an independent Air/Air heat pump.
- The fourth considers an individual two-service Air/Air heat pump for heating and cooling in addition to a collective single service solar water system for domestic hot water (DHW).

- The fifth is a fully individual system, which combines electric radiant panels and thermodynamic DHW production.

Five criteria are consider for the decision:

- The first criterion is the final energy consumption;
- The second is the investment cost by dwelling, accounting for both material and installation;
- The third is the evaluation of the ease of use of the systems, based on a 5 levels grade (1 for the most easier to use, 5 for the worst).
- The fourth is the thermal comfort associated to each system, based on a 5 levels grade (1 for the strategies offering the best comfort);
- The last criterion is the CO2 emission, including only the annual emissions relative to the energy consumption.

Table ***41*** summarizes the situation as the decision matrix (**step 2**).

Table 41: Decision matrix - example for the replacement of the heating/cooling and DHW systems

	Alternatives				*Criteria*				
	Type of service		**Type of generator**	**Type of emission**	**Final energy consumption (kWh.m^{-2}.yr^{-1})**	**Investment cost (k€/dw)**	**Ease of use [-]**	**Thermal Comfort [-]**	**CO2 emission (kgCO2. m^{-2}.yr^{-1})**
1	*Heating and DHW*	*Collective*	*Gas boiler*	*LT water radiator*	85	10	2	4	17
2	*Heating and DHW*	*Collective*	*Gas boiler*	*Hydraulic heating floor*	80	15	3	3	16
3	*Heating and DHW*	*Collective*	*Gas boiler*	*Hydraulic heating floor*	105	18	4	1	23
	Cooling only	*Individual*	*HP A/A*	*Fan*					
4	*Heating and cooling*	*Individual*	*HP A/A*	*Fan*	50	20	3	2	16
	DHW only	*Collective*	*Solar water heater*	*Stored*					
5	*Heating only*	*Individual*	*Radiant panels*	*n.a.*	45	10	1	2	15

DHW only	*Individual*	*Thermodynamics water heater*	*Stored*	

Next, the decision-maker must set priorities by scoring each criterion (1 for the most important to 5 for the less important), as for an example this first set of priorities:

Table 42: Example of priorities of the different alternatives

	Final energy consumption (kWh.m^{-2}.yr^{-1})	**Investment cost (k€/dw)**	**Ease of use [-]**	**Thermal Comfort [-]**	**CO2 emission (kgCO2. m^{-2}.yr^{-1})**
Priority	4	1	2	3	5

TOPSIS method requires to affect different normalized weights (meaning that the sum of the weights is equal to 1) to each of the criteria, accounting for the priorities (**step 3**). Of the various possible methods to define theses weights, the present example uses the Rank Order Centroid (ROC), which is widely used, robust and easy to implement [68].

This results in a weighted MxN matrix (M=5 being the number of alternatives and N=5 the number of criteria) whose elements express as (**step 4**):

$$t_{ij} = \frac{x_{ij}}{\left[\sum_{i=1}^{M} x_{ij}^2\right]^{1/2}} . W_j \tag{4}$$

and $\sum_{k=1}^{N} W_k = 1.$

Elements x_{ij} are the values of the criterion C_j for the alternative *i* (cf. *Table 41*).

Best and Worst ideal solutions can then be obtained.

In the case under study, the criteria are better when their values are low. Therefore, the best ideal solution (t_j^+) is obtained when the criterion value is minimum and the worst solution (t_j^-) when the criterion value is maximum (**step 5**):

$$\begin{cases} t_j^+ = \min\limits_{i=1,M} t_{ij} \\ t_j^- = \max\limits_{i=1,M} t_{ij} \end{cases} \tag{5}$$

Furthermore, Euclidian distances (d_i^+ and d_i^-) are calculated between each alternative and respectively best and worst ideal solutions considering the *N* criteria (**step 6**).

A 2 dimensions illustration is given below for a problem with 11 alternatives and 2 criteria. The 11 resulting values are plotted in the following figure:

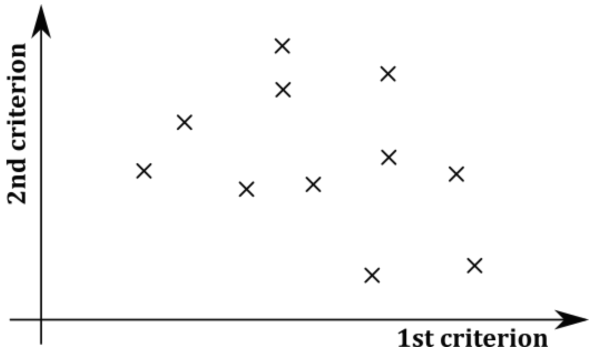
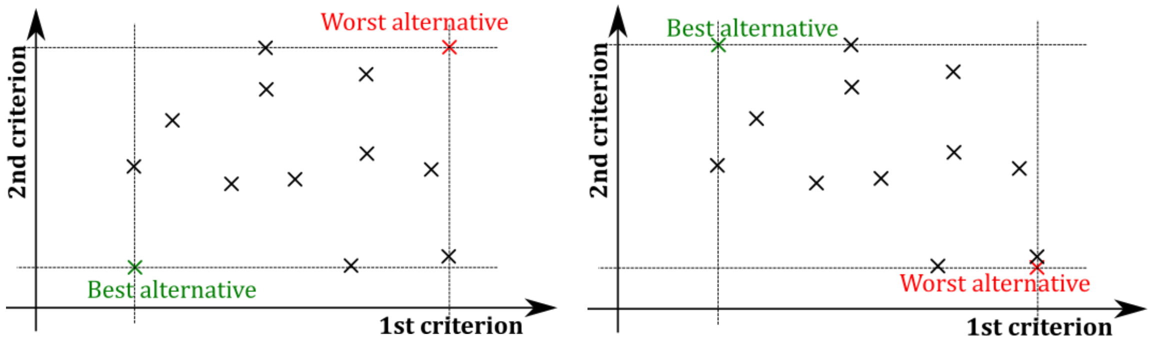


Figure 51: Diagram figuring 11 alternatives and 2 criteria

The first step of the methodology is to define the best and worst alternatives. The best alternative is defined as the combination of the best obtained values for each criterion:

- If both criteria have to be minimized, then the best alternative is the minimum observed values for both criteria (Figure 52-a);
- If the first criteria has to be minimized, and the second maximized, then the best alternative is the minimal value for the first criteria and the maximal one for the second criteria (*Figure* ***52****-b*);
- If both criteria have to be maximized, then the best alternative is the maximum observed values for both criteria (upper right corner of the scatter plot);



(a) (b)

Figure 52: Best and worst alternative (a) if both criteria have to be minimized and (b) if the first criteria has to be minimized and the second maximized

Then, for each alternative, it is possible to define the Euclidian distance to the best and the worst alternatives as illustrated on Figure 53, according to Figure 52-b configuration.

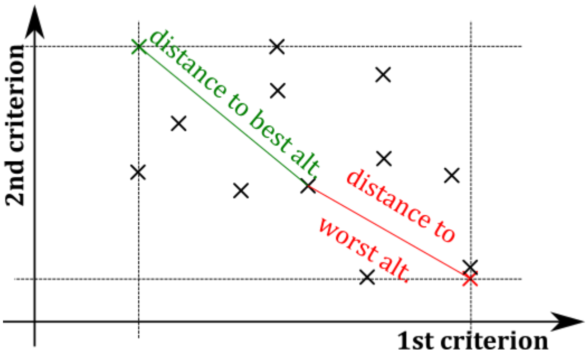


Figure 53 - Distance of a given alternative to the best and worst alternatives

In a general way, distances d_i^+ and d_i^- associated to each alternative *i* are measured by:

$$\begin{cases} d_i^+ = \left[\sum_{j=1}^{N} \left(t_{ij} - t_j^+\right)^2\right]^{1/2} \\ d_i^- = \left[\sum_{j=1}^{N} \left(t_{ij} - t_j^-\right)^2\right]^{1/2} \end{cases} \qquad (6)$$

Two rankings based on these distances, one according to the best and the other to the worst solutions, are finally yielded and result in the TOPSIS ranking (**step 7**).

Coming back to the present illustration (5 alternatives and 5 criteria), the following rankings (*Table 43)* are obtained and designates alternative 5 as the best choice, followed by alternative 1:

Table 43: Decision matrix – TOPSIS ranking

Alternatives					*TOPSIS ranking*	
	Type of service		**Type of generator**	**Type of emission**	**Rank to best solution**	**Rank to worst solution**
1	*Heating and DHW*	*Collective*	*Gas boiler*	*LT water radiator*	2	4
2	*Heating and DHW*	*Collective*	*Gas boiler*	*Hydraulic heating floor*	3	3
3	*Heating and DHW*	*Collective*	*Gas boiler*	*Hydraulic heating floor*	4	2

	Cooling only	*Individual*	*HP A/A*	*Fan*		
4	*Heating and cooling*	*Individual*	*HP A/A*	*Fan*	5	1
	DHW only	*Collective*	*Solar water heater*	*Stored*		
5	*Heating only*	*Individual*	*Radiant panels*	*n.a.*	1	5
	DHW only	*Individual*	*Thermodynamics water heater*	*Stored*		

As a conclusion, this trivial example shows the interest for this kind of method, which can be easily used in other contexts, with other criteria and possibly much more alternatives. However, some conditions have to be satisfied in order to ensure reliable results:

- First of all, the number of criteria should be limited to ten (or even five). Increasing the number of criteria does not allow a finer or more relevant analysis. In the previous example, the carbon emission with priority 5 has a relatively low impact on the alternative ranking. More specifically, the method aims at make choice, and adding criteria often make this choice more difficult.
- Furthermore, the criteria have to be independent, i.e. to not be correlated – or as little as possible – mathematically. In the above example, the carbon emission is of course correlated to the energy consumption, since the carbon emission is proportional to the energy consumption on the one hand, and to the energy vector on the other hand. This leads to more or less double-count the energy consumption (the first time in the energy criteria and the second in the carbon criterion).

General conclusions

This report is divided in 4 main parts, the main conclusions of which are given about systems and indicators that can be useful for the ARCAS project, based on energy efficiency, technical and economic aspects and healthy conditions for the occupants.

Bioclimatic approach and related indicators

In a first part some common passive principles and technologies for heating and cooling are reviewed, and few indicators are proposed to evaluate the bioclimatic potential of the surrounding building resources.

A study performed at the building scale for a building located in La Rochelle city is investigated via a Building Energy Simulation tool. Evaluation and evolution of the proposed indicators are derived through a parametric study concerning the orientation as well as the wall and windows performances of the building. Then summer discomfort is considered through the evaluation of an Overheating Degree Hours indicator.

The main conclusions are:

- The high impact of the building orientation on the heating needs and the useful heat gains as well as on the indoor summer comfort conditions.
- The insulation of the building associated to a regulatory mechanical ventilation allows to reduce considerably the heating demand and to maintain a high solar coverage rate.
- The use of double or triple glazing highlights the advantages of the double-glazed windows in terms of heating demands thanks to their higher solar factor, at least for climates similar to the climate of La Rochelle.
- The use of internal insulation instead of external one shows higher heating demand and lower solar coverage rate due to the different thermal bridges induced in existing buildings.

Although, in all tested configurations, the exploitation rate of the solar potential does not exceed 15 %, and decreases with the thermal performances of the envelope.

Finally, the influence of daytime shading and night-time over-ventilation scenarios were explored in a few cases, and shows the great potential of these passive cooling techniques to improve summer comfort by reducing the over-heating periods.

External air convection and sky vault potentials have not been studied but should be considered in a future study in the aim of analysing their potential in reducing the cooling demand and improve summer indoor conditions, especially during heat waves periods.

Ventilation

Among HVAC systems, a focus is made on ventilation systems as they are of primary importance to ensure healthy indoor conditions.

First, a review of the evolutions of the national regulations in France, Portugal and Spain, shows similar trends in terms of principle (from separated rooms to whole general and permanent ventilation) and evolution (from natural to mechanical/hybrid ventilation and pressure/humidity-controlled systems).
Then, a case study based on the French regulation allows to compare different ventilation systems in terms of indoor air quality regarding typical indoor pollutants production, and serves to draw general figures for the ARCAS buildings renovation strategy of ventilation systems for combining indoor air quality and energy conservation:

- In the case where the kitchen is separated from the living-room, mechanical whole-building ventilation systems are to be preferred.
- In the case of merged kitchen and living room, natural ducted and assisted ventilation systems offer an air quality relatively close to what could be achieved with mechanical systems but lead to a higher power consumption than controlled mechanical ventilation.
- Humidity-controlled system may be considered as a good compromise since it is the best option for energy savings and a very good one for indoor air quality.

The merged kitchen and living-room configuration is always the most suitable in terms of pollutant concentrations, regardless the ventilation system. This is particularly noticeable for $PM_{2.5}$ and NO_2 with natural ventilation systems with separate rooms. This comes from the fact that cooking emission is then diluted in higher volume (living-room + kitchen). It should also be noticed that this analysis does not account for the presence of a hood in the kitchen, as it is not strictly speaking a ventilation system. The systematic use of such an additional system is however a key element to reduce exposure from cooking products.

Renewable energy production and indicators

Indicators and methodologies to select active systems based on energy efficiency, technical and economic aspects and health quality have been developed.

The methodologies for evaluating renewable energy use in buildings are described and some indicators are defined and tested. Regarding the load matching metrics that quantify the overlap between the load and generation, we advise the use of the “energy matching chart” that help to get an overall picture of the renewable performance at the building level. Both self-consumption and self-sufficiency ratios should then be calculated. Regarding the grid-interaction metrics, the grid-support coefficient can be selected to evaluate the coincidence of the load profile with the relative availability of electricity in the energy system.

Best HVAC technologies

In the last part of the report, a methodology is developed to identify the most suitable strategy for the refurbishment of HVAC systems. A framework is proposed to identify the intrinsic and extrinsic parameters. Indeed, the selection of the renovation strategies does not only depend on the systems performances but also on the other parameters such as the constraints/opportunities from the existing building. The most frequent HVAC systems are listed (not exhaustively) and a costing methodology is introduced. Finally, a global methodology for the ranking of the HVAC systems for the refurbished building is proposed to assist decision makers and an example illustrates the methodology.

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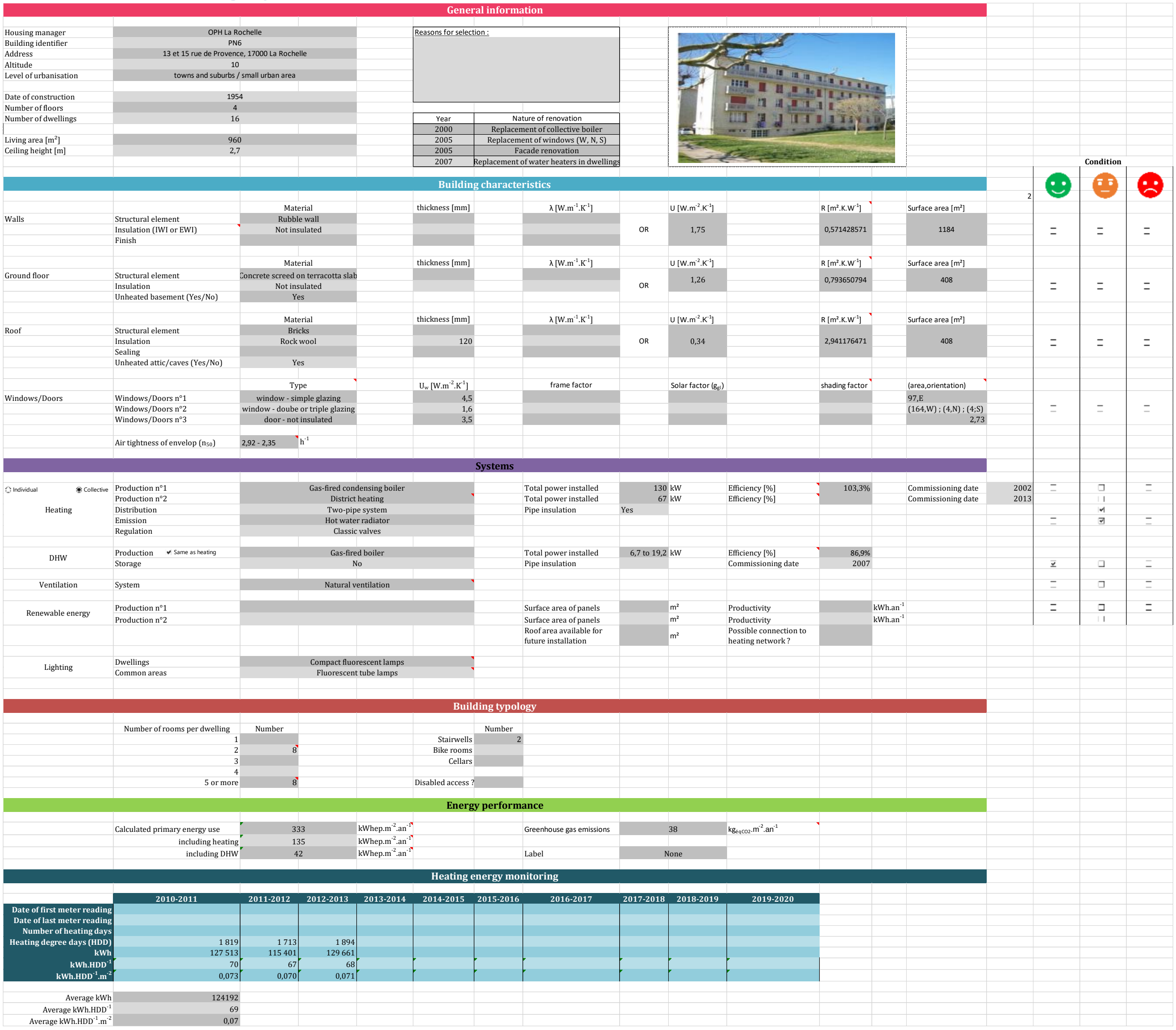
ANNEXES

A.1 PN6 building spreadsheet



General information

Housing manager	OPH La Rochelle
Building identifier	PN6
Address	13 et 15 rue de Provence, 17000 La Rochelle
Altitude	10
Level of urbanisation	towns and suburbs / small urban area
Date of construction	1954
Number of floors	4
Number of dwellings	16
Living area [m²]	960
Ceiling height [m]	2,7

Reasons for selection :

Year	Nature of renovation
2000	Replacement of collective boiler
2005	Replacement of windows (W, N, S)
2005	Facade renovation
2007	Replacement of water heaters in dwellings

Building characteristics

Condition

2

		Material	thickness [mm]	λ [W.m^{-1}.K^{-1}]		U [W.m^{-2}.K^{-1}]	R [m².K.W^{-1}]	Surface area [m²]	🙂	😐	☹
Walls	Structural element	Rubble wall			OR	1,75	0,571428571	1184	☐	☐	☐
	Insulation (IWI or EWI)	Not insulated									
	Finish										
Ground floor	Structural element	Concrete screed on terracotta slab			OR	1,26	0,793650794	408	☐	☐	☐
	Insulation	Not insulated									
	Unheated basement (Yes/No)	Yes									
Roof	Structural element	Bricks			OR	0,34	2,941176471	408	☐	☐	☐
	Insulation	Rock wool	120								
	Sealing										
	Unheated attic/caves (Yes/No)	Yes									

		Type	U$_w$ [W.m^{-2}.K^{-1}]	frame factor	Solar factor (g_{gl})	shading factor	(area,orientation)	🙂	😐	☹
Windows/Doors	Windows/Doors n°1	window - simple glazing	4,5				97,E	☐	☐	☐
	Windows/Doors n°2	window - doube or triple glazing	1,6				(164,W) ; (4,N) ; (4;S)			
	Windows/Doors n°3	door - not insulated	3,5				2,73			

Air tightness of envelop (n_{50}) 2,92 - 2,35 h^{-1}

Systems

									🙂	😐	☹
○ Individual ● Collective Heating	Production n°1	Gas-fired condensing boiler	Total power installed	130 kW	Efficiency [%]	103,3%	Commissioning date	2002	☐	☐	☐
	Production n°2	District heating	Total power installed	67 kW	Efficiency [%]		Commissioning date	2013			
	Distribution	Two-pipe system	Pipe insulation	Yes						✓	
	Emission	Hot water radiator							☐	☑	☐
	Regulation	Classic valves									
DHW	Production ✓ Same as heating	Gas-fired boiler	Total power installed	6,7 to 19,2 kW	Efficiency [%]	86,9%					
	Storage	No	Pipe insulation		Commissioning date	2007			☑	☐	☐
Ventilation	System	Natural ventilation							☐	☐	☐
Renewable energy	Production n°1		Surface area of panels	m²	Productivity	kWh.an^{-1}			☐	☐	☐
	Production n°2		Surface area of panels	m²	Productivity	kWh.an^{-1}					
			Roof area available for future installation	m²	Possible connection to heating network ?						
Lighting	Dwellings	Compact fluorescent lamps									
	Common areas	Fluorescent tube lamps									

Building typology

Number of rooms per dwelling	Number		Number
1		Stairwells	2
2	8	Bike rooms	
3		Cellars	
4			
5 or more	8	Disabled access ?	

Energy performance

Calculated primary energy use	333	kWhep.m^{-2}.an^{-1}	Greenhouse gas emissions	38	kg$_{éqCO2}$.m^{-2}.an^{-1}
including heating	135	kWhep.m^{-2}.an^{-1}			
including DHW	42	kWhep.m^{-2}.an^{-1}	Label	None	

Heating energy monitoring

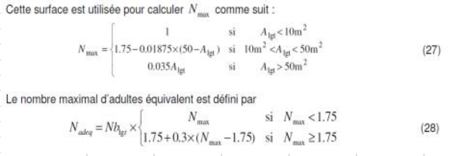
	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020
Date of first meter reading										
Date of last meter reading										
Number of heating days										
Heating degree days (HDD)	1 819	1 713	1 894							
kWh	127 513	115 401	129 661							
kWh.HDD^{-1}	70	67	68							
kWh.HDD^{-1}.m^{-2}	0,073	0,070	0,071							

Average kWh	124192
Average kWh.HDD^{-1}	69
Average kWh.HDD^{-1}.m^{-2}	0,07

A.2 PN6 scenarios for simulation

Additional information (simulation)

		Simulation	Reference values
Heating system	HLC (W/K)		
	Volumetric HLC (W/m³.K)		2,3 W/m³.K for non-insulated to 0,5 for actual building regulation
	Max. heating power (W/m²)	Not assigned	100 W/m² for non-insulated down to 30 W/m² for actual building regulation
	Set-point, occupied period (°C)	19°C	19°C
	Set-point, unoccupied period (°C)	16°C	16°C
	Set-point schedule	set-back from 11am until 6pm, no setback week-end and Wednesda	set-back from 11am until 6pm, no setback week-end and Wednesday afternoon
People thermal load	Thermal load one occupant (W)	90	80 W average / 90 W awake & 63 W sleeping
	Nbr. max occupant	2 for small appartments, 5 for big apparments	
	Schedule	Conventional RT2012 schedule	
	Yearly thermal load (kWh/yr)		9-10 kWh/m².yr
	Average termal load (W/m²)		0,7 - 1,2 W/m²
Equipment load (excluding ligh	Thermal load, occupied period (W/r	5,7	5,7 W/m²
	Thermal load, unoccupied period (W/m²)		1,1 W/m²
	Schedule	Conventional RT2012 schedule	
	Yearly thermal load (kWh/yr)		20-26 kWh/m².yr
	Average termal load (W/m²)		2-3 W/m²
	Ratio electrical/thermal load (%)		85%
Lighting load	Thermal load, lighting period (W/m	1,4	1,4 W/m²
	Schedule	Conventional RT2012 schedule	
	Yearly thermal load (kWh/yr)		2-3 kWh/m².yr
	Average termal load (W/m²)		0,2-0,4 W/m²

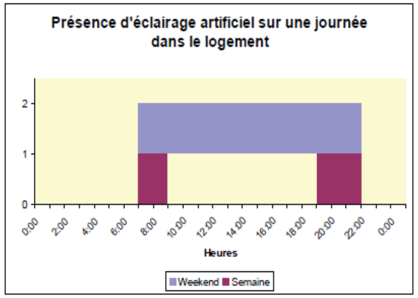


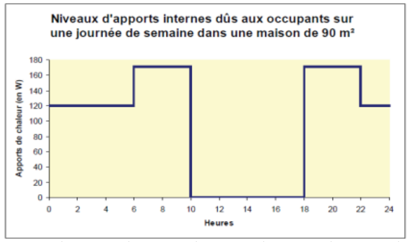
Cette surface est utilisée pour calculer N_{max} comme suit :

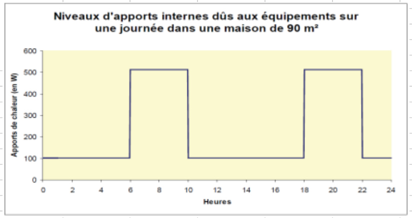
$$N_{max} = \begin{cases} 1 & \text{si} \quad A_{lgt} < 10\text{m}^2 \\ 1.75 - 0.01875 \times (50 - A_{lgt}) & \text{si} \quad 10\text{m}^2 < A_{lgt} < 50\text{m}^2 \\ 0.035 A_{lgt} & \text{si} \quad A_{lgt} > 50\text{m}^2 \end{cases} \tag{27}$$

Le nombre maximal d'adultes équivalent est défini par

$$N_{adeq} = Nb_{lgt} \times \begin{cases} N_{max} & \text{si} \quad N_{max} < 1.75 \\ 1.75 + 0.3 \times (N_{max} - 1.75) & \text{si} \quad N_{max} \geq 1.75 \end{cases} \tag{28}$$



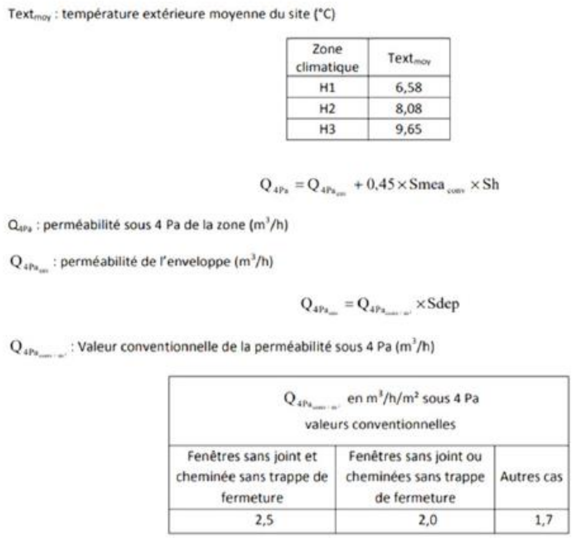




A.3 Flow infiltration and ventilation rates form the French 3CL-DPE method [47]

$$Qv_{inf} = 0{,}0146 \times Q_{4Pa} \times \left(0{,}7 \times \left|19 - Text_{moy}\right|\right)^{0{,}667}$$

$$Qv_{vent} = Qvarep_{conv} \times S_h$$



$Text_{moy}$: température extérieure moyenne du site (°C)

Zone climatique	$Text_{moy}$
H1	6,58
H2	8,08
H3	9,65

$$Q_{4Pa} = Q_{4Pa_{env}} + 0{,}45 \times Smea_{conv} \times Sh$$

Q_{4Pa} : perméabilité sous 4 Pa de la zone (m³/h)

$Q_{4Pa_{env}}$: perméabilité de l'enveloppe (m³/h)

$$Q_{4Pa_{env}} = Q_{4Pa_{conv}/m^2} \times Sdep$$

Q_{4Pa_{conv}/m^2} : Valeur conventionnelle de la perméabilité sous 4 Pa (m³/h)

Q_{4Pa_{conv}/m^2} en m³/h/m² sous 4 Pa valeurs conventionnelles		
Fenêtres sans joint et cheminée sans trappe de fermeture	Fenêtres sans joint ou cheminées sans trappe de fermeture	Autres cas
2,5	2,0	1,7

Type de ventilation	$Smea_{conv}$	$Qvarep_{conv}$
Ventilation par ouverture des fenêtres	0	1,2
Système de ventilation par entrées d'air hautes et basses	4	2,145
Ventilation mécanique auto réglable « avant 1982 »	2	1,8975
Ventilation mécanique auto réglable « après 1982 »	2	1,65
Ventilation mécanique à extraction hygroréglable	2	1,2375
Ventilation mécanique gaz hygroréglable	2	1,4025
Ventilation mécanique à extraction et entrées d'air hygroréglables	1,5	1,0725
Ventilation mécanique double flux avec échangeur	0	1,65
Ventilation mécanique double flux sans échangeur	0	1,65
Ventilation naturelle par conduit	4	2,145
Ventilation hybride	3	2,0625
Extracteur mécanique sur conduit non modifié de ventilation naturelle existante	4	2,2425
Ventilation naturelle par conduit avec entrées d'air hygroréglables	3	2,145
Ventilation hybride avec entrées d'air hygroréglables	2	2,0625
Puits climatique (canadien ou provençal)	0	1,65