D2.1. Taxonomy of space cooling technologies and measures

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List of Acronyms

AB	Apartment blocks
AC	Air conditioning
BCR	Benefit-cost ratio
BMI	Body mass index
BMR	Basal metabolic rate
CAC	Centralized air conditioner
CAPEX	Capital expenditures
CBA	Cost-benefit analysis
CDD	Cooling degree days
COP	Coefficient of performance
CPI	Consumer price index
DSF	Double skin façade
EA	Exhaust air
EER	Energy efficiency ratio
ESEER	European seasonal energy efficiency ratio
GTB	Green tree barrier
HP	Heat pump
HVAC	Heating, ventilation, air conditioning
IAC	Indoor air curtain
MFH	Multi-family houses
NbS	Nature-based solutions
NPV	Net present value
OAC	Outdoor air curtain
OPEX	Operational expenditures
OVF	Opaque ventilation façade
PCM	Phase change materials
RAC	Room air conditioners
RPWGB	Roof ponds with wet gunny bags
SA	Supply air
SC	Space cooling
SEER	Seasonal energy efficiency ratio

SEERon	Seasonal energy efficiency ratio (operation in normative conditions according to EN14825[1]
SFH	Single family houses
S-RAM	Sanderson rocker arm mechanism
SVF	Sky view factor
TB	Thermal buffer
TDHP	Thermal driven heat pump
TRL	Technology readiness level
UHI	Urban heat island
UTCI	Universal Thermal Climate Index
VC	Vapor compression
VRF	Variable refrigerant flow

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Keywords list

- Space cooling
- Alternative cooling technologies
- Measures for space cooling mitigation
- Cost-benefit analysis

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Executive summary

Deliverable D2.1 “Taxonomy of space cooling technologies and measures” describes the currently available and future space cooling technologies and measures and identifies the most suitable ones to face the actual and expected increase in European space cooling needs.

In addition to conventional cold production technologies using vapour compression, 35 alternative technologies have been categorised according to 8 different criteria (physical energy form, basic working/operating principle, refrigerant or heat transfer medium, phase of the working fluid, specific physical process/device, type of space cooling technology, fuel type, and technology readiness level). The study reveals that several of these alternative technologies are promising in terms of energy efficiency, but that they are not yet competitive with conventional vapour compression systems in terms of cost-efficiency and scalability.

The measures identified to reduce space cooling demand in buildings have been grouped into three categories: passive, active, and lifestyle measures and user behaviours. A total of 28 passive, 13 active and 15 comfort lifestyle and user behaviours measures were listed. A description of their operating system and an assessment of their effectiveness and associated costs provide an indication of the potential relevance of each of them.

Once all these technologies and measures has been identified, they were subjected to a selection process based on six criteria: environmental factors, economic/financial feasibility, technical factors, legal/regulatory factors, socio-economic factors, and health factors. The selection process among the identified technologies and measures has led to a more focused set of solutions better suited to meet European space cooling needs. In the end, a total of 4 types of technologies and 4 types of measures have been selected. Each of them is characterized by a sufficiently high readiness level to consider its widespread adoption at the European scale in the short or medium term.

In order to ensure the relevance of the selection made, a cost-benefit analysis of the chosen technologies and measures was conducted. Utilizing appropriate literature, experts’ knowledge and data gathered in the scouting phases of this deliverable, as well as specific detailed assumptions, typical urban districts were modeled in order to quantify various impacts of the implementation of every selected technology and measure. The simulation-derived data provided values of internal and external costs characterizing the performances of the selected technologies and measures on thermal comfort, indoor and outdoor acoustic level and environment. By internalizing several of their externalities, these results were then compared based on the cost-benefit ratio and net present value, allowing to propose a ranking of the selected technologies and measures according to the urban context and the climate. Sensitivity analyses were also conducted for these comparisons in order to take into consideration variations in the occupant’s sensitivity to thermal and noise discomfort, as well as final energy prices. One may note that if prospective climate conditions at 2030 horizon have been considered to process the study, the heatwave situations have not been specifically focused on.

In “normal” summer conditions, fans appear overall to be a notable measure, benefiting from low cost and good efficiency outside extreme temperatures. Measures like shading devices or white roofs show a more limited global impact at the district level: for the first one; a limited percentage of occupants really use shading devices for mitigate solar irradiations in normal summer conditions (outside heatwaves),

while roofs surfaces are quite limited in dense city centers, relatively to the floor area and the associated potential cooling demand (as for large buildings).

Within the selected technologies portfolio, the portable air conditioning systems have the lower valuation in the current study since they cannot compete with the other technologies in term of actual efficiency. To a lesser extent, their valuation is also penalized by the indoor noise disturbances. Split systems, VRF, and district cooling network have comparable effects on thermal comfort but strongly differ greatly in term of investment costs. Despite of their higher cost, VRF may appear as an alternative to split system in dense urban areas as they limit the nuisance to close neighbours (noise and heat emissions).

In a perspective of a mass distribution of space cooling technologies in a long term, cooling district is an advantageous technology whose externalities are limited and whose cost depends on the density of demand: obviously, only dense urban zones may find an interest to focus on this technology in a short term, even if the outskirts of cities can also be equipped with it if there would be a strong political support for making use of the network compulsory for instance. However, its main advantage lies in the system's lifespan, which assumes that the demand for space cooling will last for the next few decades.

The survey also highlights the impact of the climate on the technologies ranking: the hottest is the climate (the higher are the SC needs), the more higher CAPEX solutions can be amortized along their lifespan. Some measures can even be counterproductive in less warm climates.

Furthermore, occupants' sensitivity to thermal or acoustic discomfort is a key parameter in the analysis. Moreover, the present work cannot claim to propose a single and universal solution at the district or city level since the cost-benefit approach only consider average or global impacts of the space cooling technologies and measures.

While acknowledging the presence of uncertainties and limitations in the impact modelling and externalities valuation approaches, all these results helped identify the set of available technologies and measures and justify the selection of those that have been retained throughout the CoolLIFE project and for being further considered in the CoolLIFE Webtool.

1. Introduction

Buildings account for around 40 % of the primary energy consumption in Europe, and the overall electricity demand will be considerably impacted by the need for space cooling. Around 45% of the electricity used in residential and commercial buildings is estimated to be consumed by air conditioning systems [2,3]. Space cooling (SC) demand has been rising continuously for recent decades in Europe, and it is expected to continue growing in the next years. In 2016, SC accounted for 14% of peak demand globally [4], while reached 19% for Europe in 2022 [5].

There are different types of SC systems that we refer to as air-conditioning (AC) systems. The market for residential and commercial buildings is dominated by conventional Vapor Compression (VC) air-conditioning systems. These conventional VC technologies provide over 99 % of the total energy required for SC in the current European market (EU27 + UK) [6,7]. Thermally driven heat pumps, in addition to VC systems, have been commercially accessible in the market for many years due to the abundance of waste heat that can be used to power the systems, for example by generating power with a gas turbine. In recent years, thermal energy-driven cooling systems have become more integrated with renewable energy sources [8]. Thermally driven heat pumps and mainly sorption cooling technologies, supply the remaining 1% of the market [9]. VC systems have gained this dominant position as a result of their low initial cost, low running cost as well as high efficiency. Due to the contribution of the most widely used refrigerants in VC systems, halogenated alkanes, to green-house gases (GHG) emissions and climate change, it has become necessary to evaluate various alternative SC technologies.

Fischer et al. [10] investigated alternative cooling (space cooling and process cooling) systems, which would eliminate using chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. The industry's objective around 30 years ago was to use refrigerants with no Ozone Depletion Potential (ODP) [11]. The Ozone Regulation from 2009 in the EU imposes a number of requirements across the EU, aimed at minimizing the use and thus emissions of ozone-depleting substances. Ozone-depleting substances are generally banned, but there are some exemptions that allow and control the use of such substances in certain specific applications where there still are no feasible alternatives [12]. Recently, improving system efficiency and using refrigerants with low Global Warming Potential (GWP) became the main focus to reduce the impact of air-conditioning systems on climate change. Various SC technologies have been covered in previous research, a number of which have focused on the performance of VC systems [13–15]. Whereas a number of studies have focused on alternative thermally driven heat pumps [16–18].

Goetzler et al. [19] studied the alternatives in the heating, ventilation and air-conditioning (HVAC) sector in order to develop crucial recommendations to address the U.S. Department of Energy's (DOE) decision to decrease the support to VC systems. Moreover, Goetzler et al. [20] expanded the range of emerging technologies that could reduce commercial HVAC energy usage and imposed recommendations to the different stakeholders and DOE on prospective research. Recently, Goetzler et al. [21] evaluated the previous HVAC research studies to include recent and emerging technologies. Pezzutto et al. [11] indicated that between 2020 and 2030, there will be no cooling technologies that can compete with VC systems in the EU market. The study also provided a taxonomy for space and process cooling technologies and their main features.

Nevertheless, the AC penetration in residential buildings for SC is still low. While the average value is the EU is estimated to be around 19%, as seen above, this value differs highly between the member states. In 2010 the Entranze project anticipated AC penetration rates between 0.68% and 99% in the evaluated countries, with the highest penetration in Greece. [22] This range cannot be justified by the different climatic conditions alone. In many cases, avoiding air conditioning can be done by measures that maintain comfortable indoor thermal conditions by reducing the heat loads from the external, arising from the solar radiation, the temperature differences between the ambient and the indoor air, and the long-wave radiation of surfaces surrounding the building. These can be either passive, which require no energy input, for example, high reflectance surfaces, natural ventilation or window shades, or active, such as automized systems and mechanical ventilation. Further on, comfort, lifestyle and user behaviour actions can result in a shift in the space cooling demand, by adaptation to higher temperatures, or selecting locations that are less exposed to the outdoor environment. While policies focus on energy efficiency requirements for building design, HVAC and building services, the improvement of the technological aspects alone does not guarantee the low-energy buildings that are needed to achieve the current carbon goals of our society. As described by the IEA [23] occupant behaviour (OB) is one of the six influencing factors of the energy performance of a building. Thus, to decrease the need for further increase in the mechanical SC, these measures should be collected, understood, evaluated and implemented on a wider scale.

This report aims at providing as complete as possible an in-depth review study that focuses on all existing and emerging SC technologies and measures (active measures such as active shading systems and mechanical ventilation, passive measures such as natural ventilation and window shades) as well as comfort, lifestyle, and user behaviour solutions (comfort-responsive control strategies) and their main features while taking into consideration the technical and environmental aspects of the technologies. The given report focuses on space cooling. However, there are a few parts of the text which refer to cooling (both space and process cooling). Space cooling (or air-conditioning) is defined as the process of cooling indoor air by removing heat from the air and providing buildings' occupants with thermal comfort [24]. SC lowers the temperature of the air. The European Standard EN 15251 recommends to design HVAC systems to be able to provide SC between 25 to 27°C both in residential and non-residential rooms.

Eventually, the WP2 aims at selecting the most relevant technologies and measures for SC that will be further considered for the CoolLIFE tool's calculation modules. To this end, a validation process has been implemented consisting of the assessment of the selected technologies and measures according environmental, socio-economic, technical, regulatory and health criteria. Then, the feasibility of implementing the solutions for different target groups (residential/non-residential sector) is assessed and, finally, recommendations are supported by a cost-benefit analysis of the detected solutions.

This report is structured into several parts. After an introduction, the scouting of technologies (Part 2) and measures (Part 3) will be presented. Then, the technology and measure selection process will be detailed (Part 4) followed by the cost-benefit analysis carried out on this selection (Part 5).

2. Technologies Scouting

2.1. Materials and Methods

A comprehensive review is conducted to assess various SC technologies that are already available on the market as well as emerging technologies. A critical analysis of the available literature is used to conduct this review through different databases such as scientific literature and grey literature sources (e.g. news, blogs, magazines) with the utmost caution. In addition to that, a patent search over the last ten years is carried out for the most promising cooling technologies, taking into account the International Patent Classification (IPC) code F25 (Refrigeration or cooling; combined heating and refrigeration systems; heat pump systems; manufacture or storage of ice; liquefaction or solidification of gases), and code F24F (Air-conditioning; Air-humidification; Ventilation; Use of air currents for screening) [25,26].

First, the conventional VC systems have been evaluated. A classification of the different systems (air-to-air or air-to-water) has been conducted while also the type of the system, room-air conditioner (RACs) and centralized air-conditioner (CACs) as shown in Figure 3. The analysis indicates four different types of RACs (Split systems, Multi-Split systems, packaged Units and Portable units). As well as three types of CACs (Chillers, Rooftop units and Variable Refrigerant Flow – VRF – systems). A previous study by Pezzutto et al. [27] analysed the different AC typologies based on the generation and distribution aspects of the technology ventilators and passive cooling technologies since the indoor temperature cannot be lowered below the ambient temperature by using ventilation systems alone. They also excluded thermally driven heat pumps as their market penetration rate is very low compared to electricity-driven AC systems.

Several studies are used as primary sources in this report to investigate the different SC technologies. Fischer et al. [10] discussed some technologies such as thermoelastic heat pumps, evaporative cooling, Stirling cycle refrigerator and Malone cycle refrigerator. Brown et al. [6] on the other hand, restricted further research on these technologies due to their low competitiveness in the market compared to VC systems. In this study by Brown et al. [6], six technologies were chosen including thermoelectric, sorption cooling, desiccant cooling, magnetic cooling, thermo-acoustic cooling and transcritical CO_2 cycle due to their high market existence and higher performance potentials. In addition to that, the study also evaluated different alternative SC technologies, stating that they would not be able to compete with VC technology for the foreseeable future.

Another study by Goetzler et al. [28] identified the electrocaloric, critical-flow refrigeration, and Bernoulli heat pump technologies as being in the early stages of research and development and provided a detailed review of each technology. In addition to that, magnetocaloric, thermoacoustic, thermoelastic, thermoelectric, thermotunneling, Vuilleumier heat pumps, sorption heat pumps, Brayton heat pumps, ejector heat pumps, duplex Stirling cycle, desiccant cooling systems and membrane heat pump were considered the final viable technology options. This study only focused on SC applications and did not include vortex-tube and pulse-tube cooling systems which are more suitable for process cooling applications [29]. In 2017, Goetzler et al. [20] carried out another study that led to updates of alternative cooling technologies that were taken into consideration in the study from 2014 [28]. Four groups of eighteen technologies were analysed in the study, the first group is “Technology Enhancements for Current Systems”. The second group is called “Alternative Gas-Fired Heat Pumps Technologies”, this group primarily makes use of natural gas and thermally driven heat pumps to more effectively deliver heating and cooling. While the third group, with electricity as the main energy source, seeks to deliver more effective heating and cooling using VC and non-VC systems and it is named “Alternative Electrically Driven Heat Pump Technologies”. The fourth group is called “Alternative System Architecture” which aims to decrease the running costs of HVAC systems by enhancing comfort in buildings and it includes robotic devices, dynamic cooling clothing technologies and wearable devices for personal comfort.

Another study by VHK et al. [30] investigated different cooling technologies that are still in development by defining their working principle and Technology Readiness Level (TRL) to define their potential in the market. The study marked different technologies as promising non-available cooling technologies such as Lorenz–Meutzner cycle refrigeration, ejector cycle, Stirling cycle refrigeration, thermoacoustic refrigeration, thermoelastic refrigeration, and magnetic refrigeration. In relation to non-VC systems, Goetzler et al. [21] noted that different studies predict energy savings of 20% compared to conventional VC systems, which may have a higher potential for applications in buildings.

An efficient methodology was established by starting with a thorough review of numerous sources in order to build a broad taxonomy of the present cooling technologies. For the technologies scouting phase, the studies mentioned above [6,10,20,21,27,28,30] were crucial sources to produce the cooling taxonomy of this report.

In the previous work of Brown et al. [6], the primary energy input was the main used parameter to classify the cooling technologies. In addition to that, other taxonomies might be created, by including different parameters like the operational temperature range (low, medium or high), and operational fluid phases (gas, liquid, solid or multiphase). The recent work by Pezzutto et al. [11] categorized each technology according to its physical form of energy input (electrical, mechanical, acoustic, magnetic, chemical, potential, thermal and natural) to create the cooling taxonomy. The study also included technology efficiency, sector applicability, integration with renewable energy, market share, costs and TRL.

In order to complete missing from the literature review, experts’ interviews have been carried out in order to fill the missing information and data. The experts group was made up of both internal and external members from the consortium: they also were representative from academia and research institutions (Armines, CNAM, CREM, Eurac Research, Mines Paris, TU Wien) and from the sector industry (AICARR, CARRIER, EDF;. EUROVENT). The expert interviews have been performed in full compliance with related legal issues treated in the GDPR (General Data Protection Regulation) as well as thoroughly respecting IPRs.

This report categorizes the SC technologies based on the physical form of energy, basic working principle, phase of the working fluid, refrigerant/heat transfer medium, specific physical process/device, cooling technology (active, passive or both), fuel (fuel type to drive the SC technology, the possibility to be driven by renewable energy source) and TRL (see Figure 1).

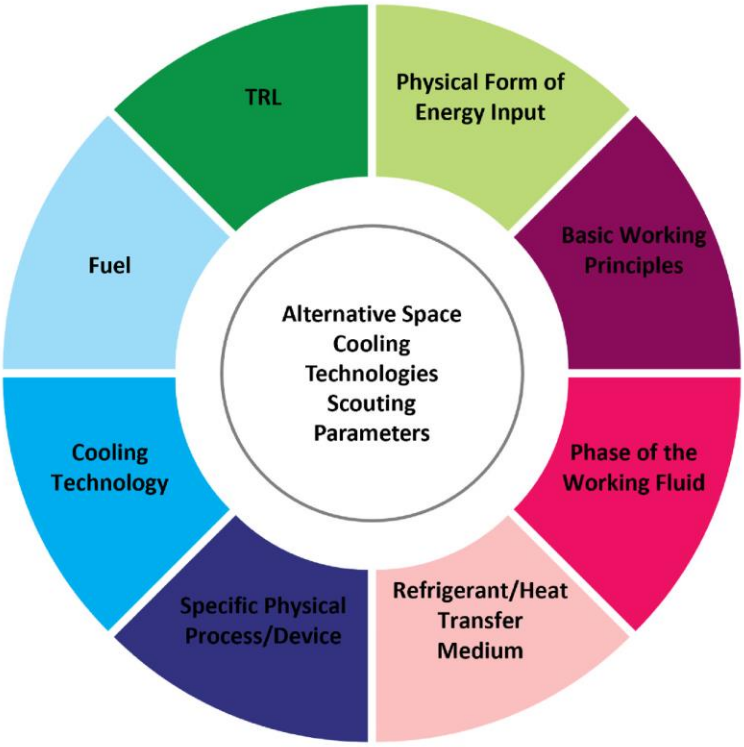


Figure 1. Space cooling technology scouting parameters [31]

Technology Readiness Level is a system used to determine technology maturity, *"TRL is based on a scale from 1 to 9, with 9 being the most advanced technology"*, according to the U.S. Department of Energy's Technology Readiness Assessment Guide [32]. The TRL is defined according to the H2020 EU research program [151] resulting in the list below:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Furthermore, the report describes various characteristics of the SC technologies – among others: on-site and/or off-site, cold sources and reference sink temperatures, generation of waste heat or cold, variations of main system configurations depending on sectors of use, resource usage type, such as water consumption or refrigerant leaks, range of available size per type of subsystem, amount of units per type in various sectors and subsectors (per country), mean capacity installed, equivalent full load hours (per sector/subsector and country), efficiency level (seasonal energy efficiency ratio – SEER), lifetime, costs (investment, installation, maintenance, reparation, and dismantling costs, etc.), noise, specific environmental and health risks (e.g. legionella for open cooling towers), typical applications in terms of economic sectors and buildings and development trends.

2.2. Space Cooling Technologies Taxonomy

The SC taxonomy is presented in Figure 2, a comprehensive list of alternative SC technologies categorized by the physical form of energy input, basic working principle, phase of the working fluid, refrigerant/heat transfer medium, specific physical process/device, active/passive solution, fuel type to drive the technology and TRL.

In this taxonomy shown in Figure 2, the physical form of energy input contains seven forms of energy (electrical, mechanical, acoustic, magnetic, chemical, potential, thermal and natural). The phase of the working fluid indicates if the working fluid is in a single phase, two-phase, no phase change, subcritical or transcritical, for the caloric systems, the phase of the working fluid is not applicable because there is no working fluid in the vast majority of the caloric systems, the fluid is only a heat-carrier but does not undergo any phase change. The refrigerant/heat transfer medium describes the status of the medium (solid, gaseous and/or liquid). The cooling technology indicates the type of SC technology according to the area of intervention (active, passive or both). In addition to that, the fuel is used to describe the fuel type to drive the SC technology (in particular, renewable or not). The last parameter in the taxonomy is TRL, which is used to define the technologies' life stage in the market from the basic idea to the application.

The next two sections evaluate the different SC technologies in depth while taking into consideration the various characteristics of the SC technologies. Section 2.3 discusses the characteristics and configurations of conventional VC systems and their classification. Section 0 describes the alternative SC technologies shown in the taxonomy.

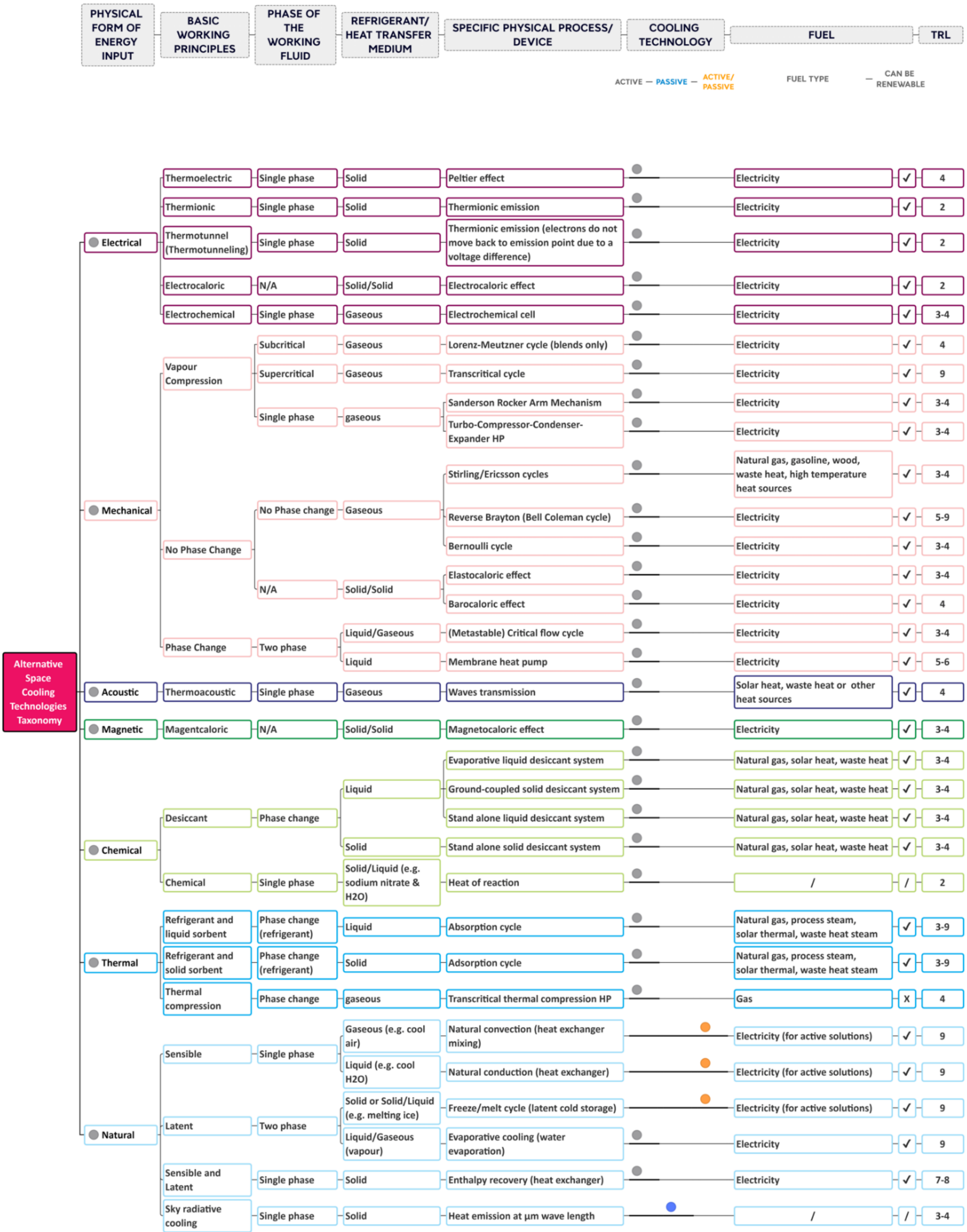


Figure 2. Taxonomy of space cooling technologies [31]

2.3. Conventional Vapor Compression Systems

Due to several factors, conventional VC systems are dominating the market among other SC technologies. The most significant factors are their scalability, low costs, use of non-toxic and non-flammable refrigerants, high efficiency, and relatively small size [33]. The majority (almost 99%) of Europe's SC needs are met by VC systems [6,7]. Vapour compression technologies are characterized by a TRL level of up to 9 since they are already actual systems in the different sectors of the market.

The VC air-conditioning systems are classified based on the generation of air-to-air systems and air-to-water systems and based on distribution to centralized[1] and decentralized systems as shown in Figure 3. RACs and CACs are the two main types of VC air-conditioning systems. The RACs are used to cool one or a number of rooms, while CACs are used to cool the whole building. There are four types of RACs (split systems, multi-split systems, single duct systems and packaged units) and three types of CACs (VRF systems, rooftop systems and chillers) as classified in Figure 3.

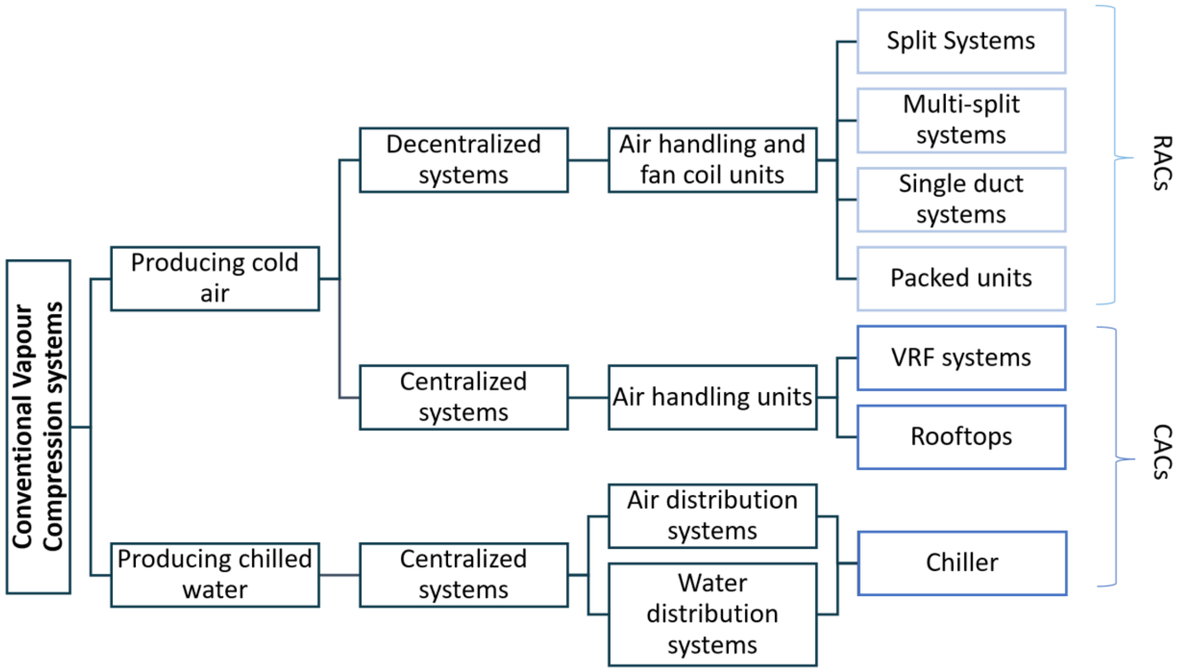


Figure 3. Classification of conventional vapour compression air-conditioning systems [31]

[1] Centralised systems refer to systems in which cold production is centralised in a single location and then distributed by a water or air network, whereas decentralised systems refer to systems in which cold production takes place directly in the room to be cooled.

Table 1. Main features of system configurations for the conventional VC systems

Fuel type	electricity
Cold source	air or water
Reference sink temperature	27–35 °C for air-to-air systems 35 °C for air-to-water systems 30 °C for water-to-water
Variations of main system configurations	room air-conditioners (RACs) centralized air-conditioners (CACs)
Resource usage	refrigerant
Range of capacity installed	3 to more than 150 kW [27]
Efficiency level	mean SEER of VC technologies is 2.7 [34], (typical range from 2 to 3)
Lifetime	10 – 20 years [35,36]
Specific environmental and health risks	legionella bacteria (wet surfaces of cooling towers [37])
Typical applications	dominant cooling technology for Nearly 99% of Europe's cooling demand is covered by VC technologies [19,27,35,38].
Development trends	R&D efforts in: energy efficiency increase deployment of environmentally friendly refrigerants miniaturized mechanical VC refrigeration systems small-scale cooling devices, etc. [19,27,34,35,38].
TRL	9

2.3.1. Split systems

A reversible air source heat pump that consists of an indoor unit and an outdoor unit is referred to as a split air-conditioning system. The condensing unit (outdoor unit), which includes a compressor and condenser coils, is located outside the building, while the indoor unit, which includes an evaporator coil and an air filter, is located inside the building.

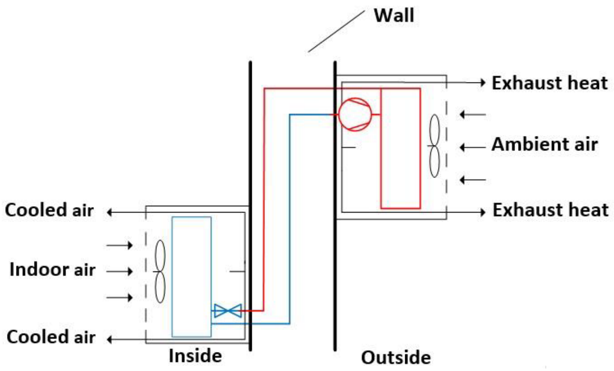


Figure 4. Split system configuration [24,34]

The configuration of the split system is shown above in Figure 4, the high-temperature level is shown in red while the low-temperature level is shown in blue.

2.3.2. Multi-split systems

An air conditioner with an outdoor unit and several indoor units is referred to as a multi-split system. The total number of indoor units determines the multi-split system's maximum cooling capability. The schematic of the multi-split system is shown in Figure 5.

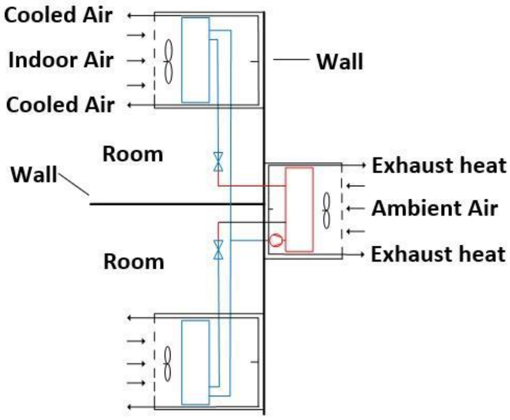


Figure 5. Multi-split system configuration [24,34]

2.3.3. Packaged units

A packaged air-conditioning unit is sometimes known as a unitary air-conditioning system. The typical packaged air conditioner consists of a compressor, a condenser, an expansion valve, an evaporator, and a working fluid all enclosed in a single casing. Due to their mounting type in residential buildings, packaged units are also known as "through-the-wall-air-conditioner" (see Figure 6) [34,39].

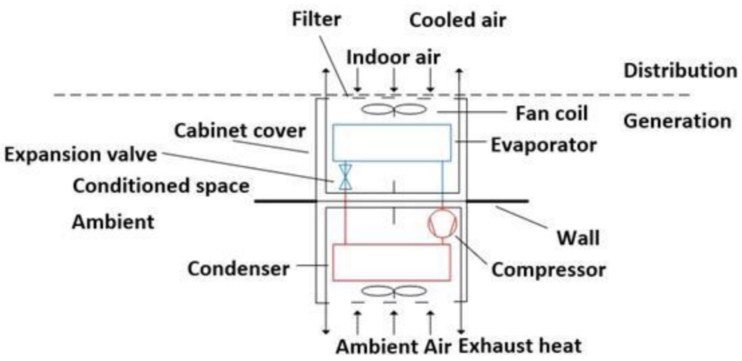


Figure 6. Packaged unit configuration [24,34]

2.3.4. Portable unit systems

Portable units are designed to be easily carried inside the building. Portable unit systems are also known as moveable unit systems where all the system's parts are contained in the same cabinet. The system requires very limited installation. The condenser, which circulates the refrigerant (the cooling medium), draws in the indoor air to be cooled; the refrigerant is then rejected outside by a duct. See Figure 7.

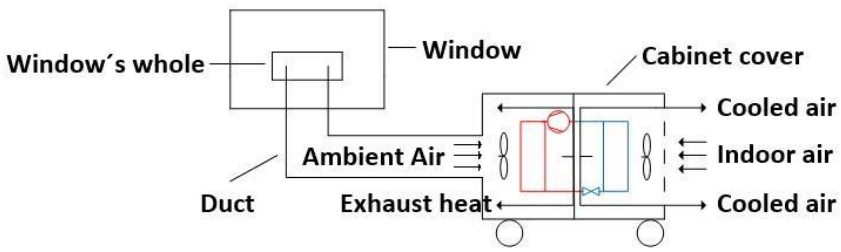


Figure 7. Portable unit system configuration [24,34]

2.3.5. Rooftop units

Rooftop units also known as outdoor packed units, use ducts to deliver cold air into the buildings and usually are available in large sizes mounted on the building's roof. Rooftop systems are available in different capacities to fit the needs of medium- to large-sized buildings. The schematic of rooftop units is shown in Figure 8.

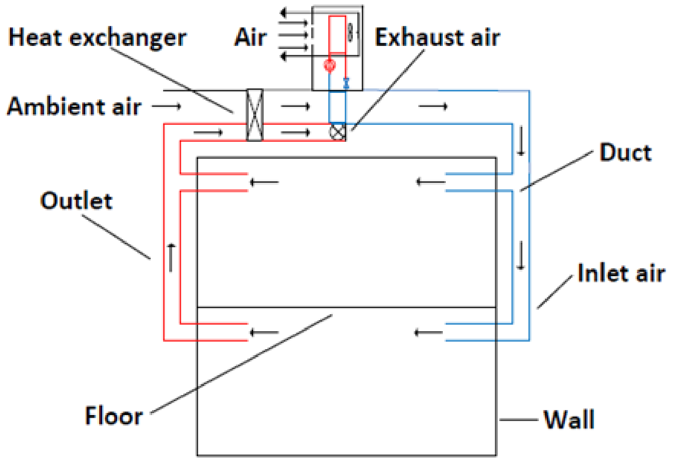


Figure 8. Rooftop system configuration [24,34]

2.3.6. Chillers

Chillers are large air-conditioning systems that produce chilled water and distribute it through a cooling network of pipes and heat exchangers to terminal units and cooling coils in air handling units that cool the indoor air. There are 3 types of chillers (air-cooled, water-cooled and evaporative-cooled). The schematic of the chiller where water is used as a source is shown in Figure 9.

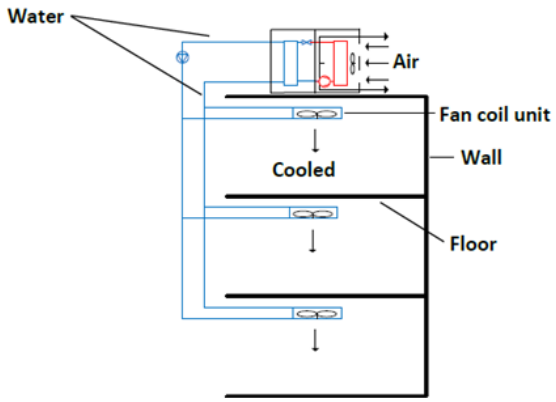


Figure 9. Chiller configuration (air-to-water system with fan coil terminal unit) [24,34]

2.3.7. Variable Refrigerant Flow (VRF) systems

VRF system, which is also known as a VRV (variable refrigerant volume) system, consists of one outdoor condensing unit that provides chilled water to numerous indoor units. VRF systems are generally characterized by a higher cooling capacity than traditional split systems. The schematic of VRF systems is shown in Figure 10.

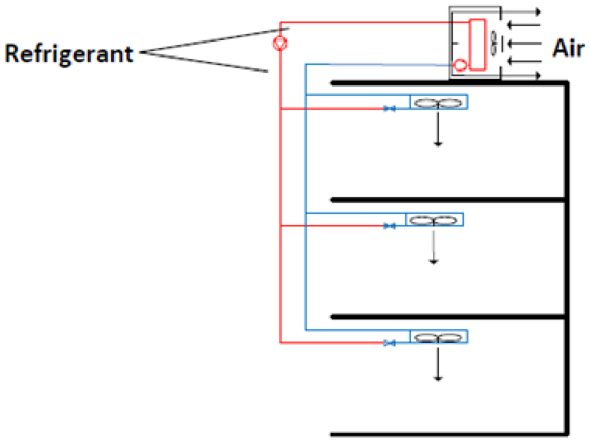


Figure 10. Variable refrigerant flow system configuration [24,34]

Table 2. Purchasing prices for RACS and CACS[31] – reference year 2016

System type	Costs [€/unit]
Movable systems	409
Split system (capacity<5kW)	1 051
Multi-split system (capacity>5kW, incL. Single Duct)	1 692
Rooftop system	18 135
Chiller (air-to-water) (capacity < 400kW)	20 768
Chiller (water-t-water) (capacity < 400 kW)	1 676
Chiller (air-to-water) (capacity > 400 kW)	111 370
Chiller (water-to-water) (capacity > 400 kW)	88 033
VRF system	19 720

RACs are most used in the residential sector, while they are also used in the tertiary, particularly in offices. CACs are also used in households but mostly in the tertiary sector [34].

Running costs depend strongly on several factors such as climate conditions and electricity prices (actual values 11 to 24 € cents). Indicative running costs are estimated at 11 €/m²y [40]. Repair and maintenance costs (including refrigerant replacement and servicing expenses) amount to approximately 4 % of an air-conditioning unit investment (including the price paid for the installation). As an indicative disposal cost, a typical price of approximately 33 € is mentioned (for equipment up to 100 kg weight) [34,40].

2.4. Alternative Cooling systems

In this section, the main features (fuel types used, cold sources, reference sink temperatures, variations of main system configurations depending on sectors of use, resources usage, range of capacities installed, application, efficiency level, lifetime, costs - investment, installation, maintenance, reparation, dismantling – noise, specific environmental and health risks, typical applications development trends and TRL) of the alternative SC systems are discussed.

2.4.1. Thermoelectric

Thermoelectric cooling is based on the Peltier effect. A Peltier cooler is composed of semiconductor materials, typically made from bismuth telluride or other similar compounds. When an electric current is passed through the junction of two different semiconductors, a temperature differential arises. As one junction warms up, the other one gets cooler. The cool side drops below room temperature while the warm side is kept at ambient temperature by being connected to a heat sink. The heat sink can also be a coolant fluid which is cooled down by the ambient temperature. During the cooling process, the heat transfer medium of thermoelectric cooling devices does not change phases (single phase (solid)).

Table 3. Main features of thermoelectric cooling [31]

Reference sink temperature	5 – 15 °C
Resource usage	no liquid refrigerant
Energy efficiency	0.18 (maximum theoretical second law efficiency)
Range of capacity installed	up to a few hundred watts
Typical applications	portable refrigerators, car seat air-conditioning, wine cabinets, and spot cooling for electronics
Development trends	research will likely make the efficiency of thermoelectric cooling devices and VC close in local comfort applications such as cooled seats
TRL	4

2.4.2. Thermionic

In thermionic cooling, energetic electrons emit from the surface of the cathode to remove heat and allow the cathode to cool. Thermionic cooling devices' heat transfer medium doesn't change phases during the cooling operation (single phase (solid)).

Table 4. Main features of thermionic cooling [31]

Reference sink temperature	Around 20 °C
Resource usage	no liquid refrigerant
Energy efficiency	Around 50-55% of Carnot efficiency
Range of capacity installed	50 – 500 W
Typical applications	all cooling applications in residential and commercial buildings in different climate regions
Development trends	new materials for embedded applications, but still numerous challenges that limit the development of thermionic cooling
TRL	2

2.4.3. Thermotunnel (Thermotunneling)

Thermotunnel cooling is comparable to thermionic emission cooling (also known as thermotunneling). The difference is that in thermotunnel cooling, electrons do not move back to the emission point due to voltage difference. The heat transfer medium of thermotunnel cooling devices does not undergo a phase change during the cooling process too (single phase (solid)).

Table 5. Main features of thermotunnel cooling [31]

Reference sink temperature	Around 20 °C
Resource usage	no liquid refrigerant
Energy efficiency	55 % of Carnot efficiency
Range of capacity installed	50 – 500 W
Typical applications	All cooling applications in residential and commercial buildings in different climate regions. Thermotunnel cooling devices are currently being developed for small electronics cooling applications.
Development trends	There are still numerous challenging issues that need to be overcome, as seen by the limited prototype development. technology's future development trends are average.
TRL	2

2.4.4. Electrocaloric

According to the electrocaloric refrigeration theory, materials are imposed on an electric field. By modifying the dipolar state of the material, which in turn leads to a change in entropy and a consequent increase in temperature, the material is made to release heat in response to the applied electrical field [41]. There is no working fluid in the electrocaloric systems, the fluid is only a heat carrier but does not undergo any phase change during the cooling process. It is the solid refrigerant (caloric material) that undergoes a solid-solid phase change.

Table 6. Main features of electrocaloric cooling [31]

Reference sink temperature	Around 20 °C
Resource usage	no liquid refrigerant
Energy efficiency	3.7 – 4.9 projected COP
Range of capacity installed	Below 2 kW
Typical applications	All cooling applications in residential and commercial buildings in different climate regions.
Development trends	R&D is currently focusing on manufacturing electrocaloric materials and electrodes. However, the technology is still being developed for HVAC and other cooling applications in buildings.
TRL	2

2.4.5. Electrochemical

An electrochemical cell for cooling purposes compresses a hydrogen working fluid using a proton exchange membrane to drive a VC or metal hydride HP cycle. During the cooling process, the heat transfer medium in electrochemical cooling devices does not change phase (single phase (gaseous)).

Table 7. Main features of electrochemical cooling [31]

Reference sink temperature	Around 35 °C
Resource usage	Hydrogen/refrigerant
Energy efficiency	COP higher than 4
Range of capacity installed	1 kW
Typical applications	Packaged air-conditioning
Development trends	For the technology to be commercialized, extensive R&D is required to better understand its potential energy savings and cost-effectiveness.
TRL	3 – 4

The alternative VC systems (Lorenz-Meutzner cycle, transcritical cycle, S-RAM, Turbo-Compressor-Condenser-Expander HP), no phase change (Stirling/Ericsson cycles, reverse Brayton, Bernoulli cycle, Elastocaloric effect, Barocaloric effect), and phase change ((Metastable) critical flow cycle, Membrane HP) technologies comprise the second group of cooling technologies (mechanical energy) as shown in Figure 2. These technologies are driven by electricity except for Stirling/Ericsson cycles which are driven by thermal energy sources such as natural gas, gasoline, wood, waste heat or high-temperature heat sources. Additionally, they use air as a cold source.

2.4.6. Alternative Vapour Compression systems

Lorenz-Meutzner cycle

The working fluid for the Lorenz-Meutzner cycle is a zeotropic mixture that has a gliding temperature differential during the evaporation and condensation phases [42]. These devices are electrically driven. There is very little data or information available on this technology since it is not currently on the market. Therefore, not much information regarding capacities, applications and development trends.

Table 8. Main features of Lorenz-Meutzner cycle [31]

Reference sink temperature	Around 32 °C
Resource usage	Refrigerant
Energy efficiency	20 % energy savings comparted to standard refrigerators.
Range of capacity installed	Large capacity
Typical applications	Large systems such as domestic refrigerator-freezer.
Development trends	This technology is only studied in the laboratory, but prototypes are in the development stages.
TRL	4

Transcritical cycle

The CO_2 transcritical cycle was proposed to reduce the global warming impact of HFC-based air-conditioning and refrigeration systems. Transcritical systems maintain CO_2 above the critical temperature by cooling it at the gas cooler's inlet without allowing it to condense.

Table 9. Main features of Transcritical cycle [31]

Reference sink temperature	Around 90 °C
Resource usage	Refrigerant
Energy efficiency	Unknown
Range of capacity installed	6 – 12 kW
Typical applications	Centralized commercial systems
Development trends	For the next 20 years, it is anticipated that research interest in the transcritical CO_2 cycle will remain high, with a potential for large-scale commercial applications.
TRL	9

Sanderson Rocker Arm Mechanism (S-RAM)°

This cooling technology uses a unique rocker arm design to transfer heat from the engine to the cooling system, allowing for more efficient cooling and improved performance. It works by using a rocker arm to connect two or more pipes. When the temperature in the space increases, the rocker arm expands, allowing the air to flow freely through the pipes. When the temperature in the space decreases, the rocker arm contracts, restricting the flow of air. By controlling the flow of air in this way, the space can be cooled when necessary. The heat transfer medium of the system does not change phases (single phase (gaseous)).

Table 10. Main features of Sanderson Rocker Arm Mechanism [31]

Reference sink temperature	Around 48.9 °C
Resource usage	Refrigerant
Energy efficiency	Unknown
Range of capacity installed	25 – 300 kW
Typical applications	Packaged rooftop units for commercial buildings.
Development trends	S-RAM cooling technology has seen a number of advancements in recent years. Many of these advancements have focused on improvements in the cooling efficiency of the mechanism. At the moment, the core S-RAM compressor is being tested with heat exchangers, new designs are being developed to increase the efficiency and reduce the size of the heat exchangers.
TRL	3 – 4

Turbo-Compressor-Condenser-Expander heat pump

Turbo-compressor-condenser-expander HP uses a turbine-compressor to compress the refrigerant, a condenser to reject heat to the environment, and an expander to expand the refrigerant and absorb heat from a low-temperature source. The heat transfer medium of the system does not change phases (single phase (gaseous)).

Table 11. Main features of Turbo-compressor-condenser-expander heat pump [31]

Reference sink temperature	55 - 65 °C
Resource usage	Refrigerant
Energy efficiency	SEER of 20 in residential buildings compared to a SEER of 14 as a baseline.
Range of capacity installed	Above 150 kW
Typical applications	Packaged units for commercial buildings.
Development trends	It is expected that this technique will continue to be uncompetitive with vapour compression in the near future since prototypes are still in the development stage and further research and development have to be done.
TRL	3 – 4

2.4.7. Stirling/Eric(c)son cycles

The following technologies have been assigned to Stirling/Ericsson cycles since they have the same principles. The technical characteristics of the cycles are described below in Table 12. The heat transfer medium of the system does not change phases (no-phase change (gaseous)).

Reverse Stirling

The reverse Stirling cycle is a thermodynamic cycle involving a heat engine that is based on the Stirling cycle but operates in reverse [43].

Duplex Stirling

The duplex Stirling machine (or duplex Stirling HP) utilizes a gas-fired Stirling engine's mechanical energy to compress and expand a gaseous refrigerant while transferring it between two chambers [44].

Vuilleumier heat pump (HP)

A Vuilleumier HP produces a warm and a cold side by cyclically compressing and expanding a gaseous working fluid (typically high-pressure helium) using a gas-fired heat engine [28].

Reverse Eric(c)son cycles

The Ericsson engine is based on the Ericsson cycle (reversible cycle).

Besides, reverse Stirling devices are used for cooling electronic sensors and microprocessors. Duplex Stirling devices are available for applications for cryocooling, low-temperature and niche refrigeration. Vuilleumier HP would be appropriate for most of the applications in residential and commercial buildings. Reverse Ericsson devices are used for refrigeration and air-conditioning. The different Stirling/Ericsson cycles are currently under development for the different HVAC applications.

Table 12. Stirling/Ericsson cycles characteristics

System	Reference sink temperature	Energy efficiency	Range of capacity installed
Reverse Stirling	20 – 50 °C [45,46]	COP is around 1	40 – 100 W [47]
Duplex Stirling	approximately 17 °C [48]	COP is around 1	50 W – 20 kW [49]
Vuilleumier HP	500 °C and higher [28]	COP is around 0.8	7.5 – 20 kW [28]
Reverse Ericsson	about 30 °C [50]	Second law efficiency around 3 %	Around 700 W [51]

2.4.8. Reverse Brayton (Bell Coleman cycle)

Reverse Brayton (Bell Coleman cycle) is a modified version of the Brayton cycle, which is an ideal thermodynamic cycle used to describe the operation of a gas turbine engine. The reverse Brayton cycle allows for heat rejection at a lower temperature than in a traditional Brayton cycle, improving the system's efficiency. The heat transfer medium of the system does not change phases (no-phase change (gaseous)).

Table 13. Main features of reverse Brayton (Bell Coleman cycle) [31]

Reference sink temperature	Around 20°C
Resource usage	Refrigerant
Energy efficiency	COP between 0.5 and 0.8
Range of capacity installed	Up to 100 MW
Typical applications	transportation space condition, commercial and industrial refrigeration
Development trends	Recent trends in the development of the reverse Brayton cycle have focused on increasing its efficiency and reducing its cost in different applications such as food freezing applications
TRL	From 5 to 9

2.4.9. Bernoulli cycle

The Bernoulli cycle cooling system uses the principles of the Bernoulli equation to transfer heat. The cycle produces cooling across the nozzle throat by accelerating a working fluid through a converging-diverging nozzle. The heat transfer medium of the system does not change phases (no-phase change (gaseous)).

Table 14. Main features of Bernoulli cycle) [31]

Reference sink temperature	Lower than the indoor temperature
Resource usage	refrigerant
Energy efficiency	Currently low COP (0.1) but improvements up to COP of 2-3 are expected
Range of capacity installed	Very small capacities (few Watts)
Typical applications	Electronics cooling in a first stage, HVAC applications at a longer term
Development trends	Still a developing technology, the capacity and COP are expected to increase
TRL	3-4

2.4.10. Elastocaloric refrigeration

In Elastocaloric refrigeration, pressure is exposed to the Elastocaloric materials, which may be done by compression, tension, bending, or torsion [41]. The Elastocaloric effect is a cooling technology that utilizes the change in temperature of a material when it is subjected to mechanical stress. When an elastocaloric material is stretched, it absorbs heat and cools down, while when it is released from the stress, it releases heat and heats up [52]. The same as barocaloric systems, there is no working fluid in the elastocaloric systems, the fluid is only a heat carrier but does not undergo any phase change during the cooling process.

Table 15. Main features of Elastocaloric refrigeration [31]

Reference sink temperature	Close to the room temperature
Resource usage	Water
Energy efficiency	COP are expected to reach 9 and more
Range of capacity installed	Small capacities (<1kW)
Typical applications	Domestic cooling devices
Development trends	Prototypes are being developed
TRL	3-4

2.4.11. Barocaloric effect

Adiabatic compression, heat transfer (from a cold to a hot heat exchanger), decompression, and heat transfer (from a hot to cold heat exchanger) are the four key processes of the barocaloric refrigeration cycle. the barocaloric effect utilizes the change in temperature of a material when it is subjected to pressure. When a barocaloric material is compressed, it heats up and releases heat, while when it is released from the pressure, it cools down and absorbs heat [53]. The same as electrocaloric systems and elastocaloric systems, there is no working fluid in the barocaloric systems, the fluid is only a heat carrier but does not undergo any phase change during the cooling process.

Table 16. Main features of Barocaloric effect refrigeration [31]

Reference sink temperature	Close to the room temperature
Resource usage	Watter
Energy efficiency	COP around 6
Range of capacity installed	Few watts
Typical applications	cryocoolers
Development trends	Early stages for developing materials and cycles
TRL	4

2.4.12. (Metastable) Critical flow cycle

Using a converging-diverging nozzle, the critical-flow refrigeration cycle provides SC by expanding a liquid refrigerant and absorbing heat from a secondary fluid. The working fluid of critical flow cycle cooling devices undergoes a phase change during the cooling process (two-phase). The mediums used are liquid/gaseous.

Table 17. Main features of critical flow cycle [31]

Reference sink temperature	Around 35°C
Resource usage	Refrigerant
Energy efficiency	1,7 (lab prototype). Could be theoretically improved up to 15
Range of capacity installed	Up to 15 kW
Typical applications	Large commercial chillers are the most promising applications
Development trends	Promising developments for HVAC applications
TRL	3-4

2.4.13. Membrane heat pump

A membrane HP uses a vacuum pump to transfer moisture across a number of membranes to provide cooling and dehumidification. The working fluid of membrane HPs undergoes a phase change during the cooling process (two-phase). The mediums used are liquid.

Table 18. Main features of membrane HP [31]

Reference sink temperature	35°C
Resource usage	water
Energy efficiency	Estimated to be twice higher than conventional VC technologies
Range of capacity installed	3 - 30 kW
Typical applications	Commercial building
Development trends	Being a more environmentally friendly technology, several prototypes are currently being developed
TRL	5-6

2.4.14. Waves transmission/Thermoacoustic

Thermoacoustic cooling works by transforming acoustic energy into thermal energy. The presence of acoustic waves (standing or travelling) expands, and it can be either standing waves or travelling waves. The technology is driven by waste heat, solar heat or other heat. The working fluid of thermoacoustic cooling devices also does not undergo a phase change during the cooling process (single phase). The mediums utilized (e.g. helium, argon, air) are gaseous.

Table 19. Main features of thermoacoustic cooling [31]

Reference sink temperature	25 – 35 °C
Resource usage	refrigerant
Energy efficiency	Theoretical efficiency lower than VC technologies
Range of capacity installed	About 3,5 kW
Typical applications	Portable AC systems
Development trends	Seeking of higher capacities
TRL	4

2.4.15. Magnetocaloric effect

The magnetocaloric effect, which exposes paramagnetic materials to a magnetic field, is the basis for magnetic cooling. For the vast majority of magnetocaloric materials, heating and cooling are caused by magnetization and demagnetization, respectively [41,54]. The heat transfer medium of magnetocaloric cooling instruments does not undergo a phase change during the cooling process too (single phase). The mediums utilized (e.g. gadolinium) are solid.

Table 20. Main features of magnetocaloric effect [31]

Reference sink temperature	Around 25°C
Resource usage	Refrigerant
Energy efficiency	COP has been assessed up to 9 in labs
Range of capacity installed	Low capacities (<3,5 kW)
Typical applications	Mobile refrigerators, medical and commercial
Development trends	Magnetocaloric materials and system design optimization
TRL	4

2.4.16. Desiccant systems

In desiccant cooling systems, desiccants remove water from entering airstreams, which are then cooled by air-conditioners or evaporative coolers. The working fluid of desiccant cooling instruments undergoes a phase change during the cooling process. The mediums utilized are liquid or solid (according to the different systems as described below). Desiccant cooling systems are driven by natural gas, solar heat or waste heat.

The technical characteristics of the different desiccant cooling systems are described below in Table 21.

Evaporative liquid desiccant system

The combination of evaporative cooling with liquid desiccants is known as evaporative liquid desiccant technology. The system typically consists of a liquid desiccant solution that is circulated through a regenerator, where it is heated and regenerated, and a dehumidifier, where it removes moisture from the air [55]. The mediums utilized are liquid.

Ground-coupled solid desiccant system

Ground-coupled fluid systems and solid desiccants are combined in the ground-coupled solid desiccant technology. They utilize the principle of desiccant dehumidification to remove moisture from the air, followed by heat exchange with the ground to cool the air. The mediums utilized are liquid.

Stand-alone liquid desiccant system

In stand-alone liquid desiccant systems, moisture from the air is absorbed using liquid desiccant materials having a strong affinity for water [56]. The mediums utilized are liquid. Compared to solid desiccants, liquid desiccants provide a number of benefits. Since liquid desiccants often have fewer pressure drops, they can be used with low-temperature regeneration [56,57].

Stand-alone solid desiccant system

Stand-alone solid desiccant systems also absorb moisture from the air using solid desiccant materials with a high affinity for water. The mediums utilized are solid.

With the exception of ground-coupled solid desiccant systems and stand-alone liquid desiccant systems, which are only applicable in hot-humid climate zones, all desiccant cooling systems are applicable to all applications for all building types and climate areas [28]. For the next two decades, desiccant cooling systems will not have a high market penetration [6]. Even if evaporative liquid desiccant systems have developed, they have not yet been commercialized, while several institutions are working to develop advanced products for stand-alone liquid desiccant systems [28]. Conventional solid desiccants are still struggling to achieve acceptable cooling performance [58]. The ground-coupled solid desiccant system has been considered a "moderately promising" technology by the DOE and has not yet achieved market penetration [28].

Table 21. Desiccant cooling systems characteristics

System	Reference sink temperature	Range of capacity installed
Evaporative liquid desiccant	20 – 50 °C [59]	moderate capacities of about 35 kW [28]
Ground-coupled solid desiccant	16-21 °C [60]	small capacities about 1 kW [28]
Stand-alone liquid desiccant	regeneration temperature of 60-75 °C [61]	small capacities of about 1.7-5.5 kW [61]
Stand-alone solid desiccant	high regeneration temperature (up to 170 °C) [62]	moderate capacities of about 10 kW [63]

2.4.17. Heat of reaction

Cooling through a chemical process occurs through an endothermic reaction at which heat (energy) is taken in, followed by a drop in temperature. In this case, a reaction (e.g. of two chemical substances) takes in energy from the starting point until the end. The working fluid at chemical cooling does not undergo a phase change during the cooling process (single phase). The mediums utilized are solid/liquid.

Table 22. Main features of heat of reaction [31]

Reference sink temperature	About 30°C
Resource usage	refrigerant (e.g. sodium nitrate or H_2O)
Energy efficiency	unknown
Range of capacity installed	Up to few hundreds watts
Typical applications	Small applications such as portable electronic devices heat management
Development trends	Seems to be limited
TRL	2

2.4.18. Absorption and adsorption cycles

Similar in operation to the VC refrigeration cycle, the key distinction between absorption and adsorption cooling systems is that thermal energy, rather than mechanical work, drives the cycle. Water/ammonia and lithium bromide/water are typical working fluids (sorbent/refrigerant) for absorption systems. and metal chlorides/ammonia, zeolite/water, activated carbon/methanol, zeolite/water, activated carbon/ammonia, silica gel/water, or composite adsorbents for adsorption systems. Sorption cooling systems are driven by natural gas, solar thermal, process steam or waste heat steam.

Table 23. Main features of absorption and adsorption cycles [31]

Reference sink temperature	70 -100 °C and higher
Resource usage	refrigerant
Energy efficiency	COP between 0.4 to 1.2 depending on the cycle configuration
Range of capacity installed	Large range from few kW to dozens of MW
Typical applications	Residential and non-residential buildings
Development trends	development of environmentally benign refrigerant pairs, improved energy efficiency, decreased cost, and scaled-down size
TRL	4-9

2.4.19. Transcritical thermal compression heat pump

Transcritical thermal compression HP is a new technology developed by boostHEAT company driven by gas. It includes a thermal compressor that uses the heat produced by the combustion of gas, not to heat water directly (for example), but to activate a heat pump cycle. It operates using an external point heat source to compress CO_2.

Table 24. Main features of transcritical thermal compression heat pump [31]

Reference sink temperature	High temperature of 700°C
Resource usage	refrigerant
Energy efficiency	COP around 2
Range of capacity installed	17 – 50 kW
Typical applications	Residential and non-residential
Development trends	Increasing of the capacity range
TRL	4

2.4.20. Natural cooling

Natural cooling systems that utilize sensible heat, refer to certain building designs that make an effort to include physical concepts (such as reflection) into the building's envelope in order to reduce the rate of heat transfer into buildings (particularly from the sun). In contrast, natural cooling systems working with latent heat, refer to certain building designs, which attempt to integrate physical principles (e.g. evaporation) into the building´s envelope to remove heat from buildings. Natural cooling solutions can be passive or active cooling measures and they are included in the measures scouting (see Part 3).

2.5. Limits of the study

When looking at the scientific literature regarding space cooling technologies, it is rich in research on the heating sector and conventional VC space cooling technologies, but when focusing on the field of alternative SC technologies, it was found to be not as deeply investigated. There is still a major gap in the knowledge about this field compared to the VC and heating technologies, despite an increasing interest in developing alternative SC technologies.

The limited development observed in certain technologies hinder the acquisition of comprehensive knowledge regarding alternative SC technologies. Consequently, compared to VC technologies, the absence of a large market share for alternative SC technology posed challenges in determining the costs of the systems.

Moreover, owing to ongoing research and development efforts, the precise costs and efficiencies of several of these systems remain undisclosed. A noteworthy technology is thermal driven heat pump (TDHP), which stands as the only competing SC technology with a notable market presence; however, even in this case, comprehensive information remains scarce. In order to enhance the competitive edge of these systems in the market, additional investigation is imperative to conduct a more rigorous analysis of their potential performance and associated costs.

3. Measures Scouting

3.1. Materials and Methods

The objective of the current section is to elucidate the methodologies and materials used to create a comprehensive review of the existing measures that might be adopted to reduce space cooling.

A scientific literature review process has been executed by examining relevant information and data sources: project deliverables, journal papers and conference proceedings have been scouted to assemble and extrapolate useful data. Furthermore, a comprehensive assessment has been conducted, with meticulous attention, to grey literature sources, to acquire pertinent information.

Expert questioning has been performed to cover data lacks in scientific literature as well as grey sources or in presence of not satisfactory information present about some measures. Experts from the external institutions and internally operating in Eurac Research have been contacted and interviewed to gather missing information. The institutions contacted for interviewing process are: i) Eurac Research, ii) Renson; iii) Building Performance Institute Europe (BPIE); iv) Armines. For privacy issues the name and surname of the experts are not reported. The expert interviews have been performed in full compliance with related legal issues treated in the GDPR (General Data Protection Regulation) as well as thoroughly respecting IPRs.
As anticipated before, experts have been contacted to cover missing information. From the scientific sources and grey ones have been emerged that data regarding costs, split in Capex and Opex, energy savings and lifespan are not always available and easily reachable. In summary, all the interviews have been conducted focusing on the aforementioned topics.

A preliminary classification has been performed to subdivide the measures into three main categories: i) active, ii) passive and iii) comfort lifestyle and user behaviour. The term active denotes all measures in which there is a control system that requires a physical form of energy input (excluding the energy of the person operating it), while passive measures do not need it to be implemented. From a research study conducted by the Annex 80's working group [13], a further classification of active and passive measures has been carried out into four categories:

- Reduction of heat gains to indoor environments and people indoors;
- Enhancement of personal comfort apart from cooling whole space;
- Removal of sensible heat from indoor environments;
- Control of latent heat (humidity) of indoor environments.

When considering active measures, the identified solutions cover systems that need a final energy as input (mainly electricity) such as smart glazing systems, adaptive facades, active shading devices and ceiling fan. On the other hand, passive measures include systems which do not directly consume any final energy such as shading devices, evaporative envelope surfaces, sky radiative cooling, ventilated envelope surfaces, thermal energy storage systems, ventilative cooling and nature-based solutions. These measures can also be differentiated according to the application scale, at room and/or building level in one hand, and at neighbourhood/urban scale in another hand. Comfort, lifestyle and user behaviour measures cover actions or strategies that the building occupier does to maintain or resolve their thermal comfort, avoid space overheating, or avoid the space itself that would require space cooling. As Vellei et al. [64] conclude, thermal comfort however not merely the result of a body's thermal balance but is the outcome of a continuous process of adaptation involving three types of self-regulatory actions: physiological, psychological and behavioural. Thus, apart from u:ser actions that are particularly done to maintain comfort by the occupant, adaptation phenomena that is not intentional is also collected, that can also help reduce cooling demand.

These were categorized in the following ones [64]:

1. Behavioural adaptation: refers to all the conscious or unconscious actions that, when the environmental stimuli are perceived as discomforting, a person can take in order to modify the building indoor environment, their personal situation or both of these. These adjustments can be further broken down to personal and environmental adjustments, and their availability, ease and effectiveness depends on building contextual factors;
2. Physiological adaptation: any physiological alteration which happens in response to ambient thermal changes;
3. Psychological adaptation: includes any psychological reaction to sensory information (e.g. habituation, relaxation of thermal expectations, gradual change of preferences, etc.)

According to the aforementioned methodology, 56 measures have been classified: 28 passive measures, 13 active measures and 15 comfort lifestyle and user behaviours measures.

3.2. Passive measures

The next sections explore the main passive measures to reduce cooling loads inside buildings. The energy reduction potential of the passive measures depends on the type of measure, the control method/algorithm, and also the climatic conditions, and building characteristics, including window to wall ratio, surface area/volume, building orientation, thermal mass, functions and internal loads, hence, the effectiveness of a particular system needs to be evaluated on case by case. In the following section energy saving ranges for the literature are provided as general indications.

3.2.1. Shading devices

According to Annex 80’s classification mentioned before [13], shading devices belong in the first category (“Reduction of heat gains to indoor environments and people indoors “) because it reduces the externally induced heat gains to indoor environment. Effective use of solar shading can contribute to the reduction of overheating, space cooling demand and air conditioning use, improved thermal insulation of fenestration and thereby lower space heating and cooling loads in European buildings. Excessive solar gains increase the indoor temperature, which in turn, raise the cooling demand.

Shadings and blinds are used by people for different purposes and can provide combined functions: heat and glare protection, maintenance of adequate visual and thermal comfort conditions on sunny days and reduction of space cooling loads and lighting demands. However, the usage of solar shading is not only dependent on the solar loads on the façade, but are also affected by daylighting preferences, and can serve as devices for providing privacy. Solar shading can provide a reduction of solar loads in the interior entering through a building façade by 10-90%.

The International Energy Agency identifies the importance of solar shading in realizing the potential of energy efficiency in the advanced building envelope and recommends as necessary and of high priority that exterior shading with proper orientation and dynamic solar control should become standard features globally in new buildings and can also be applied to existing buildings. Pilot projects have demonstrated that such systems can enable energy savings up to 60 % for lighting, 20 % for space cooling and 26 % for peak electricity. [65]

There are many types of shading devices of which the most important ones are detailed within this taxonomy:

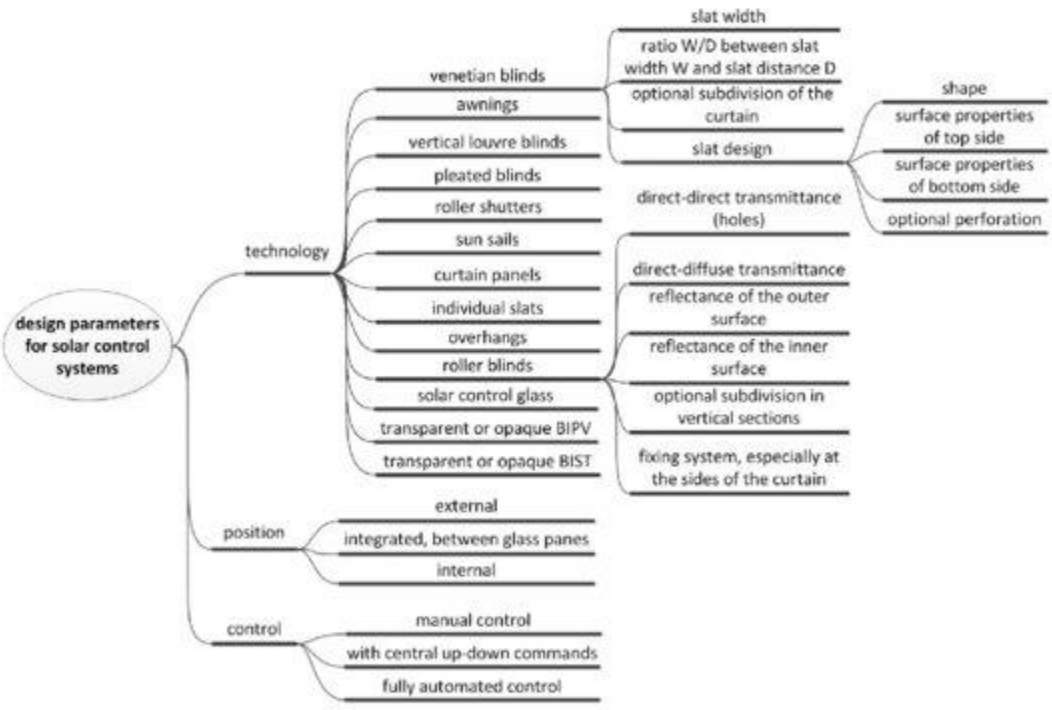


Figure 11. Evaluation criteria for solar-control systems [66]

Venetian blinds

Venetian blinds are shading devices made of horizontal slats that can be rotated for adjusting the daylight penetrating through the glazing system, deciding the amount of incoming sunlight into the environment [67]. They are effective on providing privacy, visual and thermal comfort. Standard venetian blinds have 2.5 cm width, spaced at 2.2 cm vertically and are placed 2.5 cm away from the surface of the glass in commercial construction [68]. Cut-off angle slat angle beyond which no direct solar radiation is transmitted through the slats. Venetian blinds are mainly made of aluminium. They can be placed either internally or externally, or in the cavity of the double-glazed window, or even within double skin façades. The effectiveness of the system highly varies on the position. The highest efficiency in limiting solar loads is achieved when placed on the external face of the building, however the operational hours of these systems can be limited by weather conditions, as it is exposed to wind. Thus, placing it in the cavity can extend the useable hours.

Figure 12. Venetian blinds.

Compared to building without shading devices, venetian blinds can provide 5% of energy savings up to 15%. Their cost highly depends on the material and window dimension: the CAPEX ranges from 10 to 215 euros per modular unit (even more for large windows), while OPEX cannot be easily estimated [69]. The lifetime depends on different factors and it ranges from 5 to 15 years. TRL goes from 7 up to 9.

Drapes

Drapes are window covering made of fabric or other flexible materials suspended vertically to block or filter sunlight, thereby reducing the amount of heat and light entering a room or building. Typically, they are hung from a track or rod above a window and can be opened or closed as needed. They are often used for aesthetic purposes as well as for their functional benefits, which can include energy conservation, increased privacy, and glare reduction. Drapes can affect the thermal and optical properties of a building's envelope. Since drapes are used to reduce the externally induced heat gains to indoor environment, this measure belongs in the first category too defined by Annex 80 [10]. This common passive cooling measure can provide from 5% to 20% of energy savings but may affect the lighting quality inside the room. Their lifetime is from 5 up to 10 years. The cost of commercially available drapes can exhibit a high degree of variability depending on the material and dimension of drapes: CAPEX is typically in the range 100 - € 200 per square meter but can increase up to 300 € per unit for high quality fabrics. OPEX are estimated to stay low around 5 € per year per unit [69]. The TRL is between 7 and 9.

Figure 13. Drapes.

Screens

Screens (or roller shades) are devices made of textile or meshes installed internally with respect to the window to manage daylighting and glare control [68]. Roller shades can be arranged for multiple positions, producing a significant on space lighting, heating and cooling. Sometimes this might be an issue because the useful daylight decreases, causing both visual discomfort and overheating problems.

Figure 14. Screens (or roller blinds).

Considering the classification of measures of Annex 80 [13], this shading device belongs in the first category. The lifetime of screens is approximately between 5 and 10 years [69]. This measure allows to save from 10 % to 25 % of energy compared to buildings without it. The capital expenditure of screens is between 100 and 200 €/unit, while the OPEX is very low (5 €/year) [69]. TRL of roller shades goes from 7 up to 9.

Drop arm awning

This type of shading combines the features of a roller blind and an overhang. The shading elements can be closed or tilted, which allows both ventilation and daylight penetration. It is used as external shading.

Figure 15. Drop arm awning.

Roller and wooden shutters

A roller shutter is a type of external shading typical of central European residential buildings. It consists of aluminum or plastic slats (or sometimes bars or web systems) hinged together, that can be rolled up in front of or above the top frame of the window. Transmission of radiation in the holes between the slats is possible when not drawn totally, but also total black-out can be provided. This type of shading also can serve security and privacy purposes. The reduction of peak solar loads can be up to 90% when fully drawn. Regarding the energy saving potentials, a study by Zwiehoff [70] for single-family house in Rhine-Westphalia concluded that external shutters were found the most effective regarding the cooling demand

and the total demand. The cooling demand reduction of 82 % was achieved, reducing the total energy demand by 38 %. Price is around 70 €/m^2- 100 €/m^2.[69]

Figure 16. Roller shutter in closed position

Wooden shutters are applied mostly in the Mediterranean region. They also consist of slats, which allow some daylight penetration in between. These can be either rotated around their axis, and the sashes may be opened or partially tilted. Their control possibilities are less flexible than venetian blinds.

Figure 17. Shutters

Overhang

An overhang is a horizontal surface that projects over a window for providing shade. According to sun conditions, their shape, typology, depth and height may vary. In temperate climate, a fixed overhang is suitable to shade a window for reducing glare and solar heat gains during warm season but also to allow sunlight entering into the environment for warming it during the heating period [68]. [68]. It was demonstrated by Valladares-Rendón and Shang-Lien Lo that the overhang device system was the most effective passive strategy for decreasing the indoor overheating and lowering the energy for cooling [71]. According to Annex 80's classification mentioned before [13], an overhang belongs in the first category because it reduces the externally induced heat gains to indoor environment. It is estimated that the lifetime of an overhang is between 20 and 30 years. Its TRL is rounded between 7 and 9. Generally, being an overhang an integral component of the building structure, it is difficult to estimate CAPEX and OPEX of the single component [69].

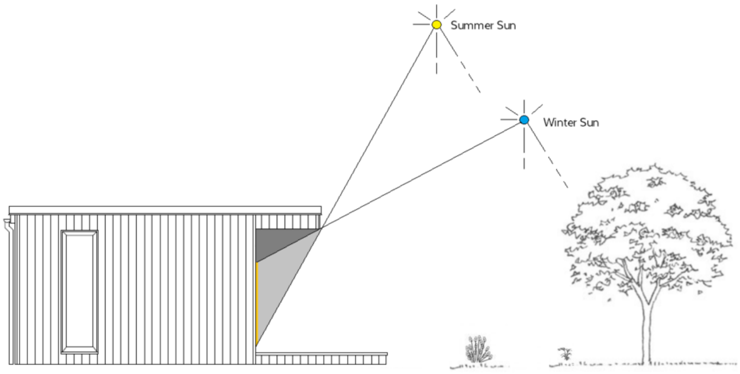


Figure 18. Overhang's operation during cold and warm season.

3.2.2. Building envelope

White roofs

White roofs, sometimes called "cool roofs"; have the capacity to cool the rooftop temperature by comparison with darker roofs since the white painting they are covered increase their albedo value (and then the reflection of solar irradiation). White roofs can decrease the rooftop temperature between 2 to 3 K for each increment of 100 W/m^2 of solar insulations [72]: during very sunny days, the "cool" effect of white roofs reach 30°C. Other research works assessed the cooling capacity of white roofs between 40 to 100 W/m^2 depending on the local climate characteristics [73–76]. This effect allows reducing the space cooling energy consumption of the rooms that located just below the roofs around between 40 to 100 kWh/(m^2.year) of the rooms located below the roofs [77,78] as well as they contribute to mitigate the urban heat island in the neighbourhood [79]. The investment costs of white roofs are estimated around 20 €/m^2.

Green roofs

Green roofs are roofs planted with vegetation on the top of the growth medium (substrate). Green roofs cool the building rooftop by i) absorbing solar radiation, ii) providing evaporative cooling, iii) increasing albedo, iv) providing an insulation layer, v) reducing surface wind speed on the rooftop [80–82]. This measure was designed and developed to promote the growth of various forms of vegetation on the top of buildings, providing aesthetical as well environmental and economic benefits. Green roofs can be classified into i) intensive, ii) semi-intensive and iii) extensive. Intensive green roofs have a thick substrate layer (20-200 cm), wide variety of plants, high maintenance and capital cost, greater weight. Semi-intensive roofs are characterized by a moderate substrate layer and accommodate small herbaceous plants, while extensive green roof system is typically used in conditions where no additional structural support is desired [83]. Because of weight limitations on existing buildings, intensive and semi-intensive green roof systems are only associated to new buildings, whereas extensive green roofs could be also installed on existing ones, subject to a structural reinforcement in most cases. The environmental advantages of green roofs are the storm-water management, decreased energy consumption of buildings, improved water and air quality, decreased noise pollution, longer service life, reduced heat-island effect (UHI). A study conducted by Niachou [84] in Greece revealed that this passive measure can reduce the energy utilized for cooling from 2 % up to 48 % with an indoor temperature reduction up to 4 K. The presence of vegetation on the top of buildings works as an added insulation layer that increases the thermal inertia of the structure when the water content varies [83]. Furthermore, the results of a study conducted on a building in Singapore, indicated that a saving of 1-15 % in the annual energy consumption, 17-19 % in the space cooling load and 17-79 % in the peak space load could be obtained [85]. As anticipated before, green roofs can also mitigate the UHI effect, decreasing ambient air temperature of urban areas, and increasing the albedo from 0.7 to 0.85, which is much higher compared to the one of gravel roof or bitumen (0.1-0.2) [86].

Figure 19. Schematics of different green roof components [83].

The lifetime of a green roof goes from 20 to 30 years, while CAPEX and OPEX are respectively 100-500 €/m^2 and 10-20 €/m^2. The TRL of a green roof is 7-9 [69].

Green façades

Green façades are a similar green infrastructure that that use climbing plants to cover building walls, offering a flexible and adaptable tool for environmental design [87]. If well designed, this kind of measure requires moderate interventions to maintain function over the life cycle and minimal inputs of non-renewable resources [88]. CAPEX of a green façade is between 950 and 1100 euros per square meter, while OPEX is between 25 and 45 euros per square meter. The TRL of a green façade is 7 up to 9 [69].

Roof ponds

Roof ponds use water as an ideal thermal mass to provide passive heating and cooling through indirect evaporative cooling and/or radiant cooling [89]. The element acts as a heat exchanging element which is cooled by evaporation on its surface, longwave radiation to the sky, or both. Moreover, the roof works as a heat sink which absorbs indoor heat and heat penetrating in the building. The internal space is also cooled by radiation and convection since the ceiling is thermally coupled to the roof pond [90]. Driving forces that allow evaporation and radiation are respectively the “difference between vapor pressure at water surface temperature and vapor pressure of surrounding air” and “difference between water surface temperature and effective sky temperature” [89]. The systematic review carried out by Sharifi et al. [89] highlighted several variants of roof ponds: i) open roof ponds; ii) roof ponds with movable insulation; iii) roof ponds with floating insulation; iv) walkable roof ponds; v) roof ponds with gunny bags; vi) shaded roof ponds; vii) ventilated roof ponds.

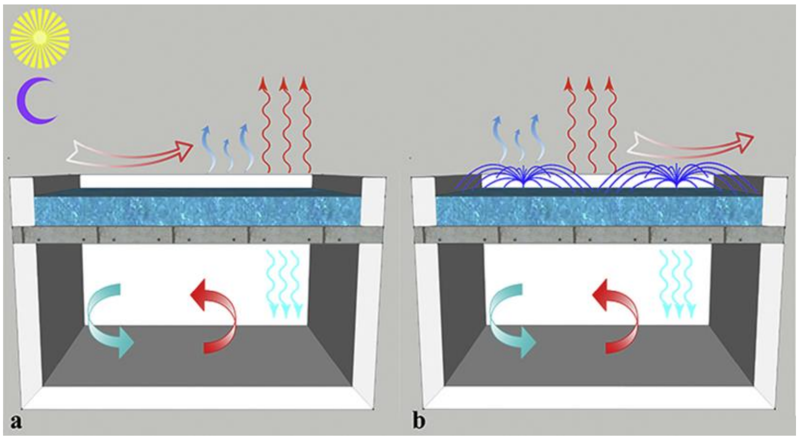


Figure 20. Open roof pond without sprays (a); open roof pond with sprays (b) [89].

An open roof pond is usually supported by a flat concrete roof exposed to ambient environment and can be with or without sprays. For this type of roof is recommended to have a minimum water dept of 30 cm [89]. During daytime the solar heat gains are absorbed by water, then a delay of the indoor peak temperature occurs. Moreover, open roof pond can also provide evaporative cooling benefits: due to solar radiation, water temperature increases until a certain amount of it will be evaporated determining cooling effects [91]. A roof pond with sprays is characterized by a similar structure and thermal behavior, the difference is that water is sprayed over the roof, enhancing heat absorption and evaporative cooling [89]. Roof ponds with movable insulation are another typology of this passive measure. The ponds are placed on rectangular roofs and covered with movable insulation panels. A layer of corrugated metal deck is suitable to provide better thermal coupling with the interior space and enhance nocturnal radiative cooling. Insulating panels can be folding or sliding. Designers recommend the use of highly reflective opaque materials to isolate the pond from solar radiation and prevent water overheating during daytime [89]. During night-time the insulation panels are removed to promote nocturnal radiative cooling [92]. The literature identifies four permutations: i) pond with movable insulation and continuous water spray; ii) pond with movable insulation and night-time-only water spray; iii) pond with movable insulation and no water spray; iv) Skytherm. In the latter system, water is enclosed in transparent polyethylene or PVC bags [89].

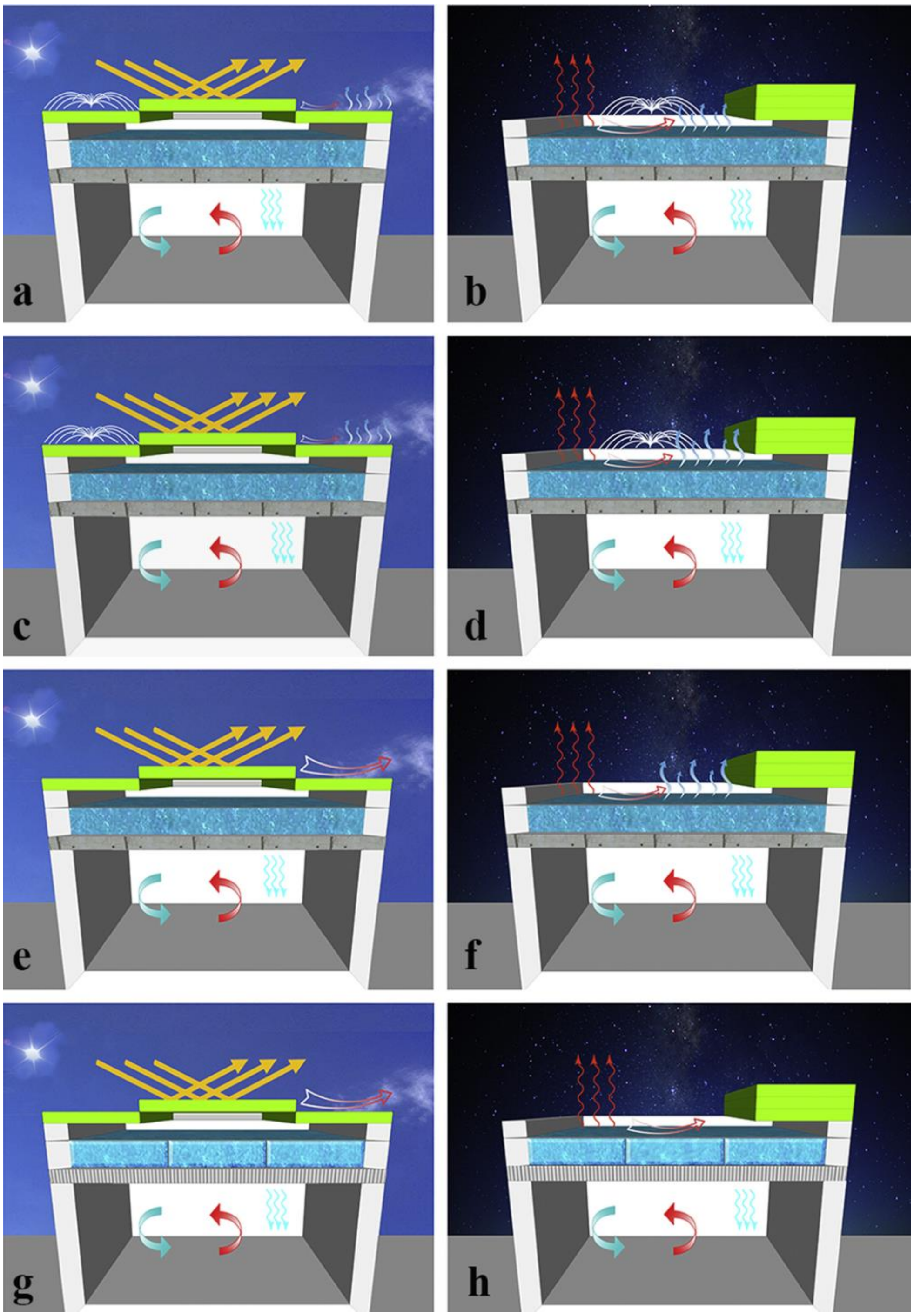


Figure 21. Roof pond with movable insulation and continuous water spray (a and b); roof pond with movable insulation and night-time water spray (c and d); roof pond with movable insulation without water spray (e and f); Skytherm (g and h) [89].

Roof ponds with floating insulation consist in two different roof pond assemblages that utilize floating insulation panels for regulating thermal exchange with the exterior environment. Two typologies of roof ponds with floating insulation are available: energy-roof and cool-roof [89].

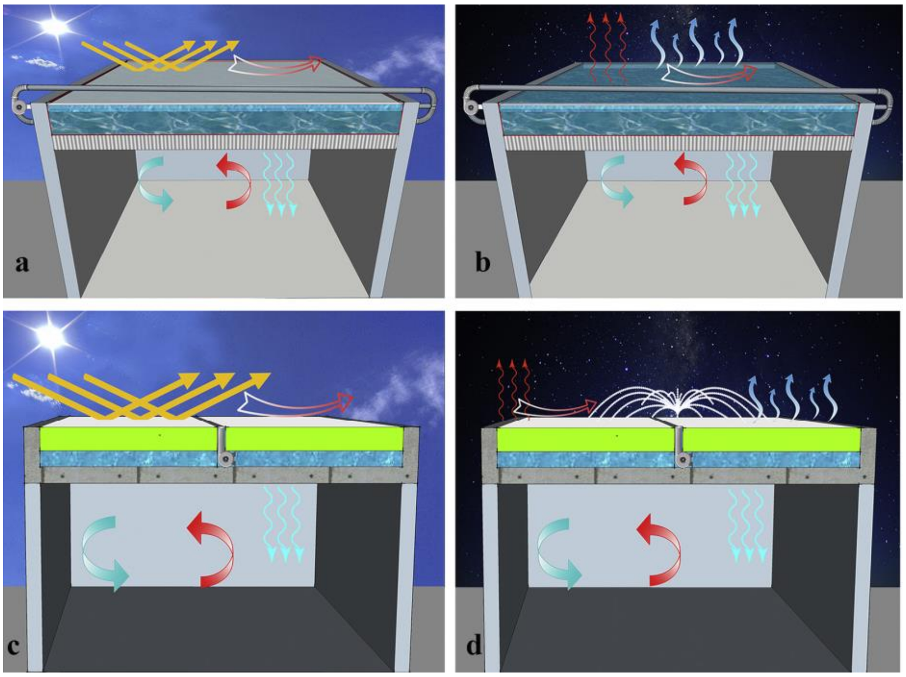


Figure 22. Energy-roof (a and b); cool-roof (c and d) [89].

Finally, walkable roof ponds allow people to walk across the roof surface without disturbing the roof pond's functionality. Under this category, two types of ponds are classified: roof ponds with insulation embedded within them and walkable roof ponds with night water circulation.

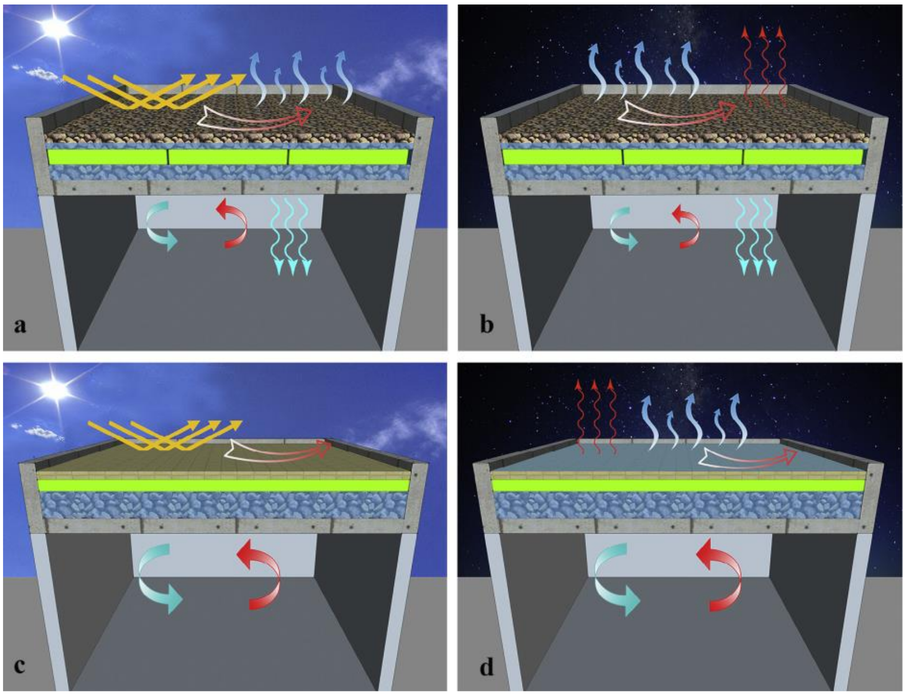


Figure 23. Walkable roof pond with insulation embedded within the pond (a and b); walkable roof pond with night water circulation (c and d) [89].

The two variants are applied to reinforced concrete flat roofs [89]. Roof pond with wet gunny bags (RPWGB) and shaded roof pond with wet gunny bags (shaded RPWGB) are other two typologies of roof ponds characterized by the presence of gunny bags that intercept solar radiation and dissipate part of it through evaporation, convection or nocturnal radiation [93,94]. The lower the temperature of the pond bottom, the more effective the system will be in reducing indoor cooling energy demand [95].

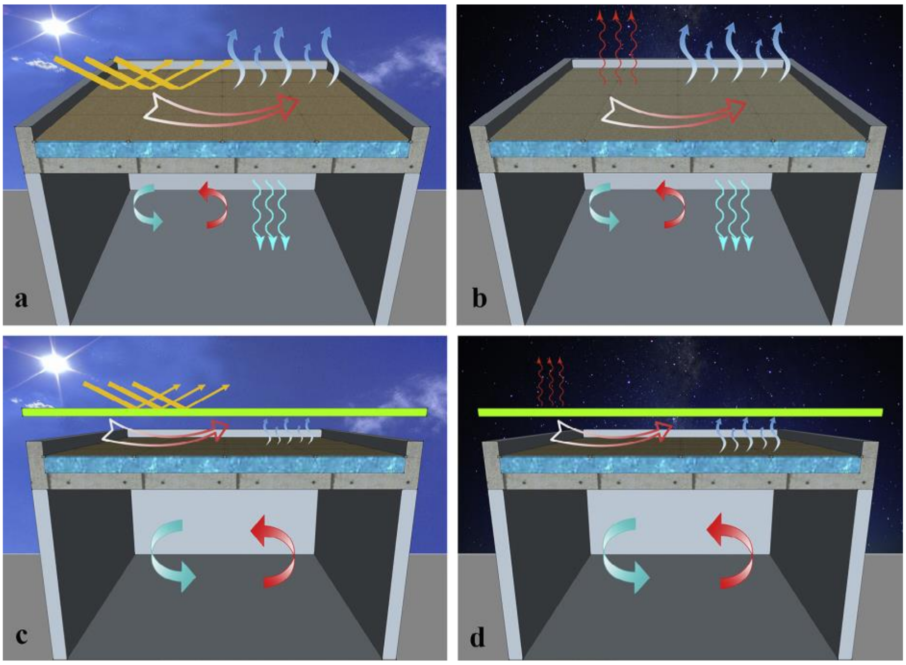


Figure 24. RPWGB (a and b); shaded RPWGB (c and d) [89].

If the roof pond is ventilated, the pond is covered by a permanent insulation layer separated from water by a ventilated cavity [89]. Cooling effect is achieved through convection and evaporation [96], lowering indoor temperature and reducing the amplitude of indoor temperature oscillation. This system is advantageous because it can also be applied to pitched roofs [89].

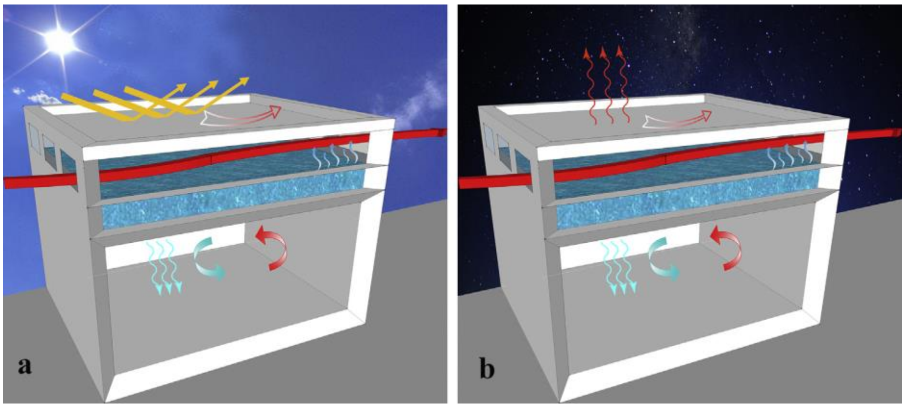


Figure 25. Ventilated roof pond [89].

Shaded roof ponds are covered by shading devices. Operable shadings are closed during the day to minimize solar gains and open at night to provide evaporative and radiant cooling [89].

Other roof ponds designs are considered: shaded roof ponds which are covered by shading devices. Operable shadings are closed during the day to minimize solar gains and open at night to provide evaporative and radiant cooling [89].

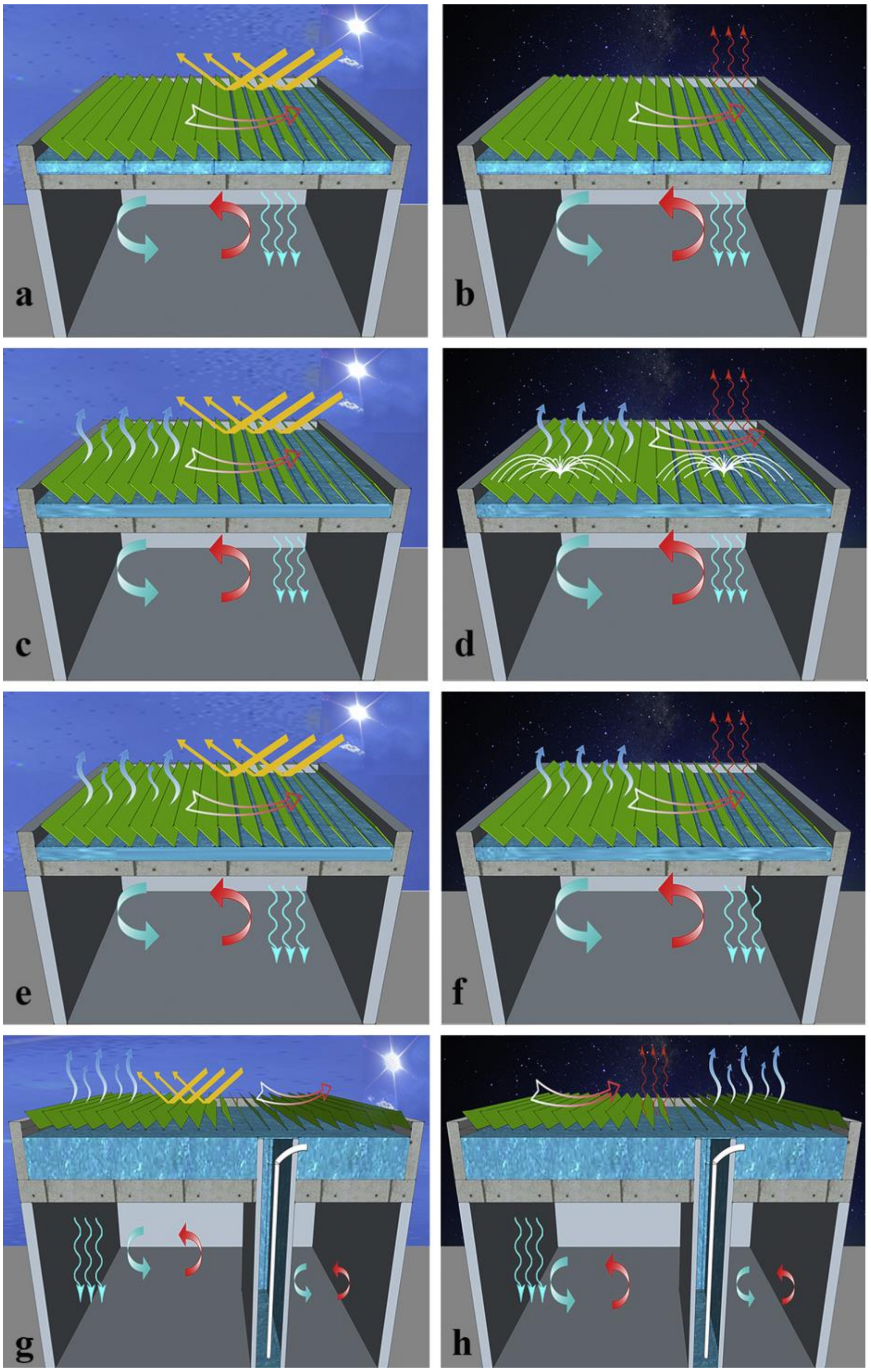


Figure 26. Shaded pond with water enclosed in watertight bags (a and b); shaded pond with water spray (c and d); shaded pond without water spray (e and f); cool-pool (g and h) [89].

Note that, considering the passive/active taxonomy suggested in the report, some roof ponds designs might refer both to active and passive measure since an energy input is required for moving shading devices, sliding or folding insulation or spraying water.

The lifespan of a roof pond could be approximated between 20 and 30 years. The CAPEX and OPEX of this passive measure are respectively between 10000 and 40000 euros and between 100 and 1000 euros per square meter. According to expert interviews, the TRL is still low, from 3 up to 5 [69]. Obviously, because of its important weight, the potential of installing it on existing buildings might be low: structural reinforcement works might be a prerequisite for hosting such an equipment.

Opaque Ventilation Façade

An Opaque Ventilation Façade (OVF) is a multilayer industrialized envelope solution characterized by two opaque layers and a ventilation channel in between. This solution is suitable for both new construction and retrofitting of existing buildings.

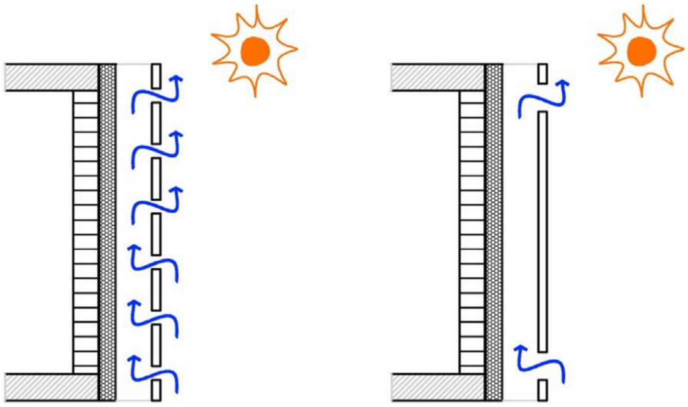


Figure 27. Outer skin types: (1) open joints, discontinuous skin, (2) closed joints, continuous outer skin [97].

The thermal performance of an OVF depends on specific outer parameters, such as the climatic conditions, and on specific design. Several studies demonstrated that the outer skin properties, such as relative roughness and solar radiation coefficient, on the ventilation rate are remarkably important [97]. The external layer is usually composed of modular panels. The joints position and dimensions affect the performance of the façade because they exert an influence on the air pressure [98]. In case of continuous OVF (closed joints), the upward airflow, promoted by the presence of some openings at the bottom and at the top of the cladding, is continuous, homogeneous, and symmetrical along the wall. On the other hand, an open joint OVF enables exterior air to enter and leave the cavity all along the wall, promoting a inhomogeneous and asymmetrical airflow [97]. As a consequence, the ventilation in façades with closed joints is reduced due to the presence of less openings [99,100]. Smaller openings on the façade are preferred in winter to minimize heat losses, whereas larger ones are recommended during warm season in order to avoid overheating and minimize the increase of ventilation rates. For what concern the geometry of the cavity, this must be studied in relation to the amount of solar heat transferred through it and the resulting temperature and ventilation rates produced [97]. The higher is the façade, the greater is the air cavity flow rate and the energy performance improvement [100–102]. Air heat up rapidly because there is a higher temperature gradient along the height of the cavity. The internal skin is typically composed by massive materials (concrete or bricks) combined with insulation ones and provides the thermal resistance to the entire wall [97].

The lifetime of a ventilated façade goes from 20 up to 30 years. According to experts, the CAPEX of this passive measure can be approximated between 250 and 350 euros per square meter. Generally, maintenance costs are not planned. The TRL of a OVF is 7 up to 9 [69].

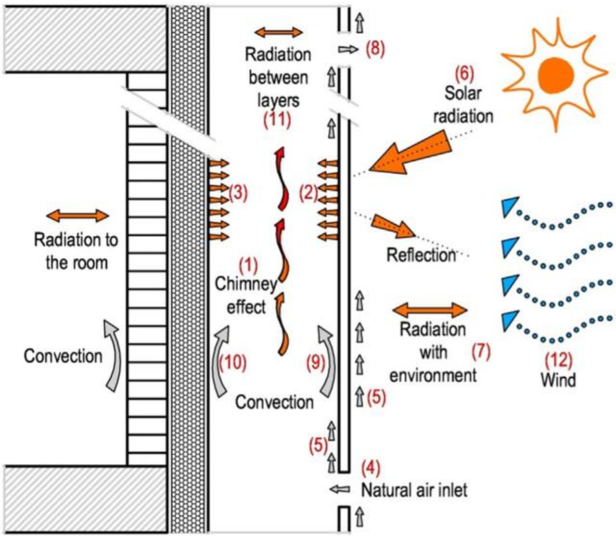


Figure 28. Thermal performance of OVF [97].

Air inside the cavity rises along the whole cavity height (1) gaining heat by conduction from the external layer (2) as well as from the internal wall (3). In the cladding area, the exterior air enters through the bottom openings (4) and keeps rising as it heats up (5) because of solar (6) and environmental (7) radiation. When it reaches a sufficient temperature (higher than environmental temperature), the air begins to exit the cavity (convection). The air closer to the layers rises by the chimney's effect of absorbing heat from the different walls (9, 10). The air movement is also influenced by the radiation between the two layers that make up the cavity (11). Solar radiation is not the only driver for airflow inside the cavity; wind (12) also influences the air movement [97]

Double skin façade

A Double Skin Façade (DSF) is defined as a curtain walling system characterized by a ventilated space between inner and outer layers and openable vents to promote various airpath movements. Compared to a traditional glazing system, itis possible to insert shading devices into the cavity to improve indoor climate [103] and protect them from the external conditions, significantly reducing maintenance costs, and extending the usable hours of the system. DSFs allow for using shading devices in conditions where otherwise it would be hindered, e.g. in high-rise buildings where façades are exposed to severe wind conditions. Ventilation into the façade cavity can be totally natural, mechanical or hybrid. Air movement exploits the buoyancy and chimney effect where the density difference between warmer air inside the cavity and cooler air outside but can also be enhanced by wind pressure differential on the different parts of the building.

Even though DSFs are not a recent measure, they are typically designed to be static, then allowing just one of the several airflow paths available. The presence of operative openings placed on both skins, at the top and at the bottom of the façade, allows five main airflow configurations (see Figure 29): i) exhaust air (EA); ii) supply air (SA); iii) outdoor air curtain (OAC); iv) indoor air curtain (IAC); v) thermal buffer (TB) [103,104]. The cavity can be used as an exhausted duct (EA configuration) to remove solar gains accumulated during warmer season or as a supply one (SA configuration) to provide into the room preheated air in the cavity by means of solar radiation and improve indoor air quality (IAQ) passively. In IAC configuration, the room air is warmed up in the cavity thanks to solar gains and delivered again in the environment at an increased temperature. No fresh air is provided in this case. On the contrary, OAC configuration helps reduce solar loads on the façade by providing ventilation in the cavity. This type is particularly useful when shading is placed in the cavity. Air is taken from the outside, and the air heated up in the cavity thanks to the absorption of solar radiation by the shading and opaque structures, and exhausted again to outdoor environment [105]. Based on the designed fixed configuration, DSFs can belong in the first category defined by the Annex 80 [65].

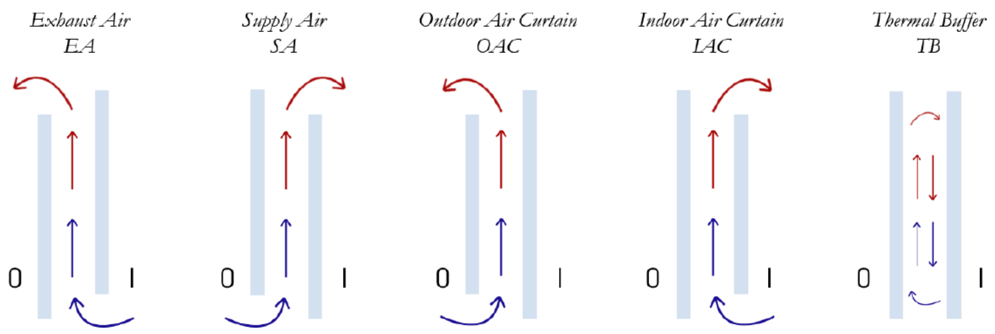


Figure 29. Air-movement strategies of a Double Skin Façade [105].

Ventilated roofs

Ventilated roofs have a similar structure to traditional pitched roofs but are characterized by a ventilated cavity. They need at least a tilt angle greater than 20° to promote forced or natural convection: forced convection is generated by a mechanical device, such as a blower, natural one is generated by the difference of temperatures (buoyancy effect). Airflow passing into the cavity produces an beneficial effect during warm season because it reduces the heat accumulated in the structure and the heat flux transferred through the roof [106]. Several research studies demonstrated that pitched ventilated roofs can achieve an energy saving higher than 30% compared to a traditional roof [107,108].

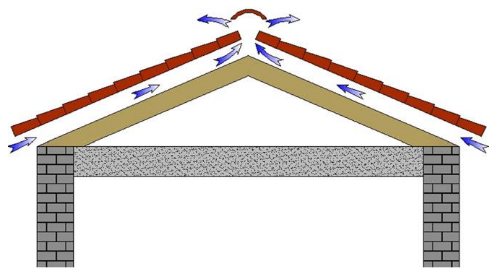


Figure 30. Scheme of a ventilated roof [106].

Thermal mass

Thermal mass is a property of the building to store heat, as either sensible or latent heat, and provide inertia against temperature fluctuations over time. Thermal mass can have a large influence over indoor temperatures, power requirements and occupant comfort [109]. The higher the thermal mass inside the building thermal insulation, the more energy can be stored [110] and a significant reduction of diurnal temperature swings can occur, making the conditions within the building more comfortable [111]. As a consequence, once the heat source is removed, materials with good thermal mass take longer time to release into the environment the heat previously stored [111]. High thermal mass can be achieved choosing the appropriate building materials, such as masonry because its low thermal conductivity allows greater heat storage capacity. The wall may be up to 60% more effective in retarding the heat flow. Thermal mass falls into the second category of Annex 80's measures subdivision [13]. The lifespan of this passive measure coincides with the one of a building structure, approximately between 50 and 100 years. The costs of thermal mass in terms of CAPEX and OPEX depends on several factors, such as materials selection, building design, construction type and location, then it is difficult to provide cost ranges. TRL of thermal mass goes from 7 up to 9.

3.2.3. Phase change materials

Phase change materials (PCMs) are materials capable to absorb and release vast quantity of heat maintaining relatively constant temperature during a phase transition. PCMs manage the energy in different applications by storing the heat during melting/charging phase and releasing it during the solidification/discharging phase, thereby controlling the need for energy [112]. In building field, PCMs positively affect the efficiency of a building shifting the peak-load to the off-peak time. PCMs are generally classified according to their chemical composition: organic, inorganic and eutectic [113]. Each category has a specific range of working temperatures and thermos-physical properties. These classes are further subdivided into sub-categories. Organic PCMs covers paraffin and non-paraffin materials, inorganic PCMs are classified as salt-hydrates, molten salts or metals, while eutectic PCMs are obtained by mixing two or more organics, inorganics, or inorganics with organic PCMs.

According to Annex 80's classification mentioned before [13], an overhang belongs in the first category. The lifespan varies according to the PCM's typology and the number of cycles the material can undergo before losing its ability to retain heat effectively. Paraffin-based PCMs have a lifetime between 10 and 15 years, eutectic PCMs are more durable (between 20 and 30 years) [69]. Even CAPEX and OPEX are variable according to the type of PCM. Approximately, the CAPEX of paraffin-based PCMs is between 0.5 and 2 €/kg, while for eutectic PCMs is between 5 and 15 €/kg. OPEX of paraffin-based PCMs is included between 0.5 and 1 €/kg, for eutectic PCMs is between 2 and 10 €/kg. Generally, the CAPEX is strictly dependent on the volume being purchased, the manufactures and any additional components required for the thermal energy storage system [69]. TRL is rounded among 6 and 8.

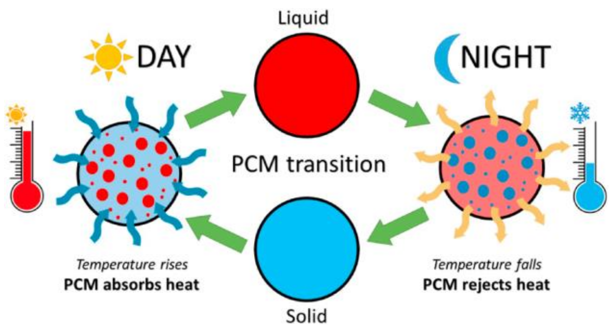


Figure 31. Phase transition of PCMs during hot climates [113].

3.2.4. Natural ventilation strategies

Natural ventilation is a method for supplying fresh air into the building exploiting environmental driving forces such as temperature difference or wind pressure without using any additional mechanical system [114]. The exploitation of natural ventilation in buildings has mainly three scopes: i) maintaining indoor air quality, ii) satisfying thermal comfort and iii) night cooling. The effectiveness of natural ventilation is strictly dependent on climate, temperature differences and wind direction parameters [114]. The design and implementation of natural ventilation in buildings located in climates where normally cooling loads are high, allows to improve the built environment energy efficiency and save costs, adopting active technologies just when is strictly necessary. Two types of natural ventilation occur in buildings basically due to two main driving forces: wind pressure and stack (chimney) effect. Wind-driven ventilation occurs when there is a wind-induced pressure difference, while the buoyancy-driven ventilation is determined by a density difference caused by temperature difference [114]. The main natural ventilation strategies for lowering cooling loads by taking advantage of passive measures belong in the third category defined by the Annex 80 [13] and are explained below.

Night cooling

Night cooling, which may also be called nocturnal convective cooling, consists in ventilating the building during the night to cool down the structural elements [115]. This ventilation strategy allows to satisfy thermal comfort requirements during the first hours of the next day and supplies fresh air to the indoors [114]. Artman et al [116] have evaluated the night cooling potential for different European locations. 60–180 Kh/night cooling potential was estimated for the hottest month of the year, the higher in Northern Europe and lower in Southern parts of the continent.

Night cooling can also be provided through the ventilation system as an active measure. In this case, the annual electrical energy savings up to 8% was shown by Braun and Zhong [117].

Solar chimney

A solar chimney (or thermal chimney) is a vertical shaft that exploits passive solar energy to drive ventilation through a building. The basic driving mechanism of the airflow inside the chimney cavity is thermal buoyancy [118]. During the day, the sun warms up the air into the chimney and due to stack ventilation effect hot air rises through the chimney, creating an upward draft. Fresh air is then drawn into the building through lower openings. Solar chimneys are designed to maximise the stack ventilation [119]. Several factors influence the performance of this passive measure, such as the design and geometrical parameters, including stack height, air gap (chimney depth/width), opening areas, chimney inclination, materials, geographical coordinates as well as the climate and season [118].

The lifespan of solar chimney and night cooling coincides with the lifetime of building, then it could be approximately 100 years [69].

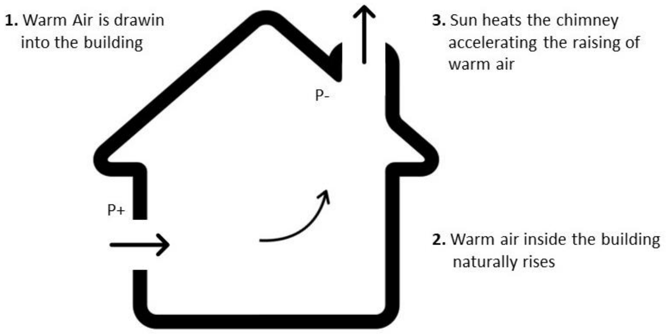
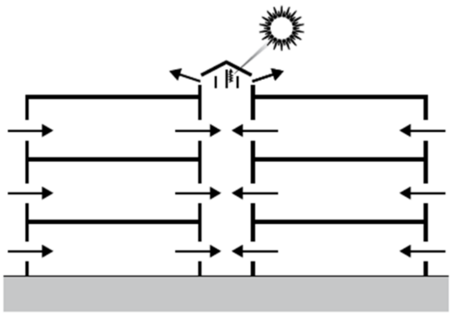


Figure 32. Solar chimney operating principle.

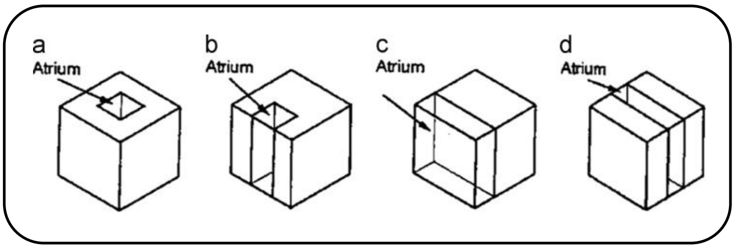
Atrium

Atrium is an open large space within a building, present especially in non-residential building, which has been in use with an increasing trend throughout centuries since ancient times starting in Mesopotamia. Natural ventilation in such buildings plays a crucial role in maintaining acceptable level of thermal comfort and providing optimum quality of indoor circulation air within the building without using HVAC systems. Therefore, atria and courtyards are commonly embedded in some buildings for cooling purposes and ventilation. The scientific literature has identified four different shapes of atrium, each one characterized by a particular environmental advantage chosen according to ambient conditions, daylight performance and expected ventilation. For example, in temperate climates, atrium is directly attached to the building as a glazed façade in order to have more solar heat gains during cold season. On the other hand, in hot and humid climates it better to design centralized or linear atria to minimize temperature fluctuations during hot and moderate seasons [120]. The difference in pressures in the inside and outside environments, caused by wind and buoyancy driven forces, generates the air movement throughout the building [121]. The effectiveness of natural ventilation in atrium is influenced by climatic factors, such as outdoor temperature, wind direction and speed, solar intensity [120].

The lifespan of atrium ventilation might coincide with the lifetime of the building itself, then it could be approximately 100 years [69].



(1)



(2)

Figure 33. Atrium ventilation operating principle (1) and atrium typologies (2).

Single-sided and cross ventilation

Single-sided ventilation is one of the simplest ventilation principles, consisting in ventilating a building through openings. This ventilation strategy might occur at room level or building one. Single-sided ventilation works when the high-pressure due to wind from one side of the building pushes air into the building, while the air then exits on the low-pressure side [119]. Air exchange between the room and the outdoor can occur through a single window (single-sided single opening strategy) or more (single-sided double opening strategy) placed on the same wall at different height [114]. Considering the latter case, the presence of two or more openings on the same façade increases the air difference in pressure among the openings [122].

As single-sided ventilation, cross ventilation consists of air displacement through openings placed on two or more opposite façades. This ventilation strategy is more convenient for spaces with a depth included between 6 and 12 meters [114]. Compared to single-sided ventilation, which relies on the high-pressure gradient on a single façade, this passive ventilation strategy is more effective as it can take advantage of the high-pressure gradient around the entire building [119]. As a result, cross ventilation has a greater air change capacity than other ventilation methods [123]. It is recommended that there should be an acceptable height difference between the inlet and outlet to provide sufficient buoyancy driving force for the no-wind case.

Compared to other ventilation strategies, the lifespan of single-sided ventilation and cross ventilation is strictly dependent to the window's one, then it can be estimated to be between 15 and 40 years [69].

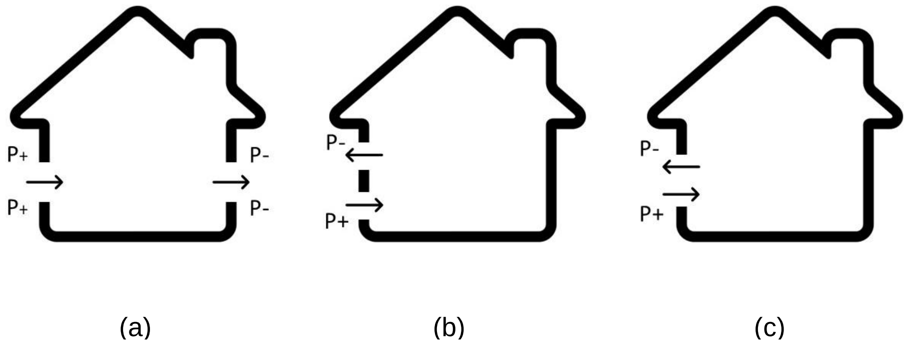
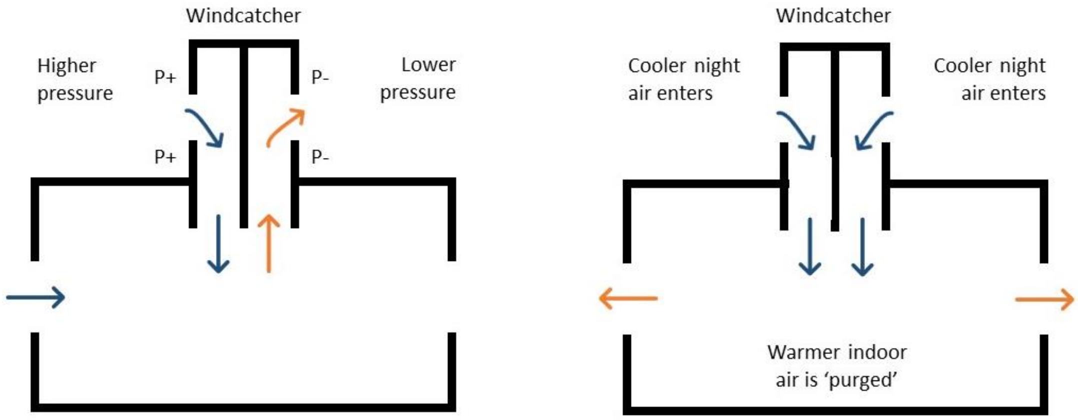


Figure 34. Cross ventilation (a), single-sided double opening, (b) and single-sided opening ventilation (c).

Windcatchers

Windcatchers, also known as wind towers, are a type of natural ventilation system that resembles chimneys and aims to "catch" the outdoor wind to channel the air towards the indoor spaces. The first traditional windcatchers have been built more than 1000 years ago in the hot and arid climate of Iran [119,124]. The main driving force for the ventilation is the pressure difference generated by the wind on the windcatcher structure, while the buoyancy effect plays a minor role [125].



(a) (b)

Figure 35. Pressure zones around a wind structure during windy days (a). Night-time cooling in a building having a windcatcher (b).

Outdoor air from enters the building through the positive pressure side during the day. The air inside the building rises and is drawn out through the negative pressure side of the windcatcher. During night-time, when lower wind conditions are expected, the main ventilation driving force is the temperature difference usually referred as buoyancy-driven or stack ventilation. The cooler air from outside descends into the building due to its higher density. As a result, warm air inside the building is displaced, forcing it to leave through openings. In climates characterized by a large diurnal temperature range, night-time cooling strongly reduces the heat gains accumulated during the day by cooling the thermal mass of the building [119]. The performance of a windcatcher is affected by geometric parameters, such as the tower's height and cross-section, local weather, and external conditions. According to [126], rectangular cross-sections show improved performance than squared one due to the bigger region of flow separation inducing a higher-pressure difference. The larger is the dimension of the openings, the greater the air flow rate passing through them. The lifespan could be approximately 100 years [69].

Staircase, ducted cross and scoop cross ventilation

Staircase ventilation, ducted cross ventilation and scoop cross ventilation are typologies of ventilation applied on a building level that exploit wind-driven force to cool down buildings, improve indoor air quality and reduce the energy consumption of a building by reducing the need for air conditioning. In staircase ventilation the external fresh air is supplied to the indoor by means of openings at different floors, cooling down the entire building, and it is exhausted through the top part of the stairwell. Ducted cross ventilation in buildings uses ducts to bring fresh air into a building and exhausts polluted air outside. It involves installing a series of ducts throughout the building to create a continuous flow of air. Typically, it is used in commercial or larger residential buildings. Scoop cross ventilation gets outdoor air from scoops or openings on the roof and directs it downwards into the building, creating a natural draft that pulls stale air out. Although it is difficult to define the lifespan of those ventilation strategies, it can be roughly estimated that it coincides with the lifetime of the building itself, then around 100 years [69].

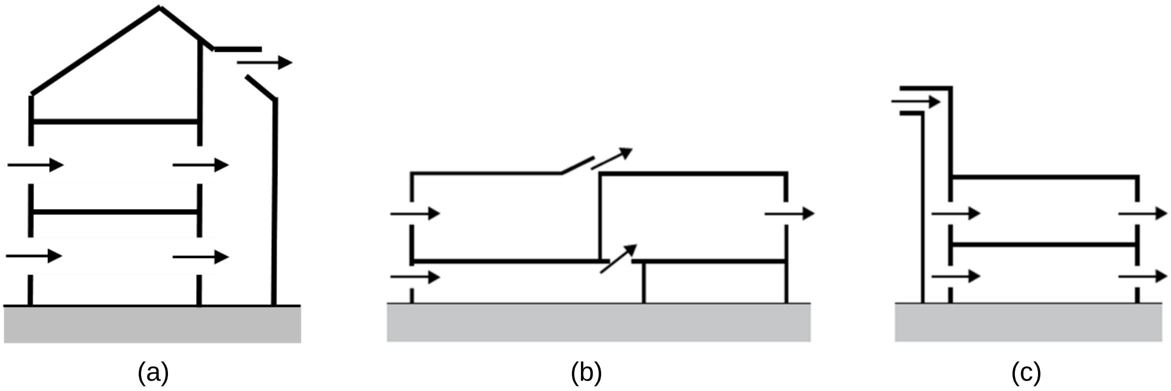


Figure 36. Staircase ventilation (a), ducted cross ventilation (b) and scoop cross ventilation (c).

Trickle vents

Trickle vents (also called background ventilators) are natural ventilation devices that provide background ventilation along with other forms of ventilation and are usually incorporated into window frames. In order to prevent outside dust, insects, and birds from entering, they can optionally be equipped with a perforated aluminium screen on the supply side. Such ventilation device can generally transfer fresh air from outside to the indoor environment by controlling turbulence and wind gusts. Trickle vents are typically controlled manually [114].

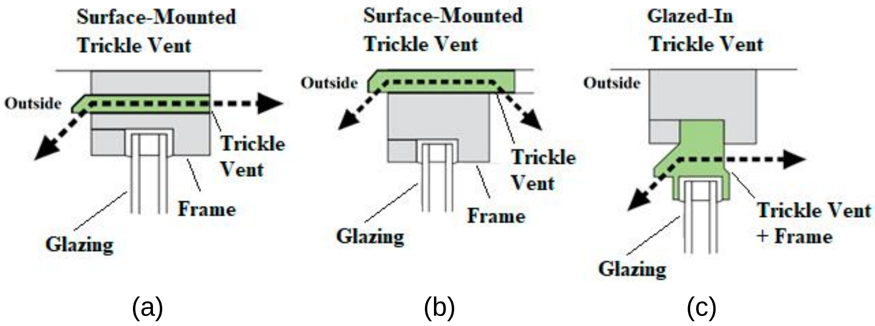


Figure 37. Trickle vents typologies [114].

Windows with integrated trickle vents belongs in the second category defined by the Annex 80 [13]. Their lifetime is between 20 and 30 years. The capital expenditure of this measure is approximately between 50 and 1500 euros per unit, while the operational costs are between 65 and 650 euros per unit [69]. The costs depend on several factors, such as length of the device, colour, product typology.

The capital expenditure and operational costs of ventilative cooling strategies depends on many parameters, such as the engineer's expertise, complexity of design, building size, location and materials used for constructing the building. Therefore, it is difficult to indicate the costs of ventilative cooling strategies. TRL of all ventilation strategies is 7 up to 9 [69].

3.2.5. Urban scale measures

Urban scale measures can reduce the cooling demand by providing a microclimate where the temperature is lower compared to the case without these measures. Some of these measures typically can only be implemented on a larger scale, e.g. during urban planning, or development of a neighbourhood, while other measures need time to achieve its full potential.

Pavement-watering

Pavement-watering is a technique which consists in generating a latent heat flow on otherwise dry surfaces, by sprinkling water onto impervious sidewalk and road surfaces. Pavement-watering can provide temperature reductions of 13°C and 5°C on average during insolation at the pavement surface and 5 cm deep, respectively. The effect on reducing UHI and improving the local microclimate expressed by the Universal Thermal Climate Index (UTCI)-equivalent temperature can be reduced up to 2.8°C [127]

Nature-based solutions (NbS

Nature-based solutions (NbS) can address the challenges of UHI and heat waves, through the provision of cooling service. The most studied interventions are waterbodies and green areas. Increased surface greenery/vegetation provides a cooling effect essentially by blocking solar radiation, while an additional cooling effect is achieved when radiation absorbed by vegetation is dissipated through transpiration from the leaves and/or evaporation from the growing medium. The size, shape of the NbS, and surrounding urban density, alongside the wind patterns created by street canyons may influence how well the cooling effect is transferred from the site to the surrounding neighborhood. [128] Most empirical evidence attribute up to 2 °C cooling effect to green areas.[129] Parks and water bodies can have an effect of a few hundred meters in their surroundings, depending on their size.[130]

Urban vegetation can also contribute to the change of microclimate by creating a wind barrier next to a surface. [131] The use of Green Tree Barrier (GTB) system uses less space than parks, and air temperatures surrounding a row of trees could be reduced by approximately 1 °C, while through careful planning of where GTBs are planted, the ventilation achieved from wind corridors within the urban environments can also be maintained. [131]

Increased surface reflectivity or cool materials

Increased surface reflectivity or cool materials can also be utilized on an urban level. Typical urban materials like asphalt and concrete have albedos in the range of 0.05–0.1 and 0.3–0.4, respectively, where the albedo of reflective surfaces tend to be greater than 0.5. [131] By switching from asphalt to concrete in both residential and high-rise areas a ground surface temperature reduction up to 7.9 °C was shown by [132], however, careful planning is needed so that the use of reflective materials on urban surfaces does not cause adverse effects by radiation being reflected onto adjacent buildings or pedestrians. [131]

Evaporative surfaces

Evaporative surfaces can store stormwater and store thermal energy through evaporating this water. Porous pavers retain water within the cavities, permeable paving materials access water from a sublayer below. However, these solutions require higher maintenance costs and careful planning not to reduce performance of the pavement in dry and freezing conditions. [131]

3.3. Active measures

The following sections detail the main active measures to reduce heat gains to indoor environment and to enhance personal comfort, lowering the cooling loads of buildings.

3.3.1. Suspended particle devices (SPD)

Suspended Particle Devices (SPDs) are a type of smart glazing system that utilize an electrochromic material suspended in a liquid or gel to control the amount of light and heat that passes through a window or glass surface. SPD glazing systems typically consist of two or more panes of glass with a thin layer of the electrochromic material sandwiched between them. The material can be electrically charged to align or disperse tiny particles, thus altering the tint or transparency of the glass [133].

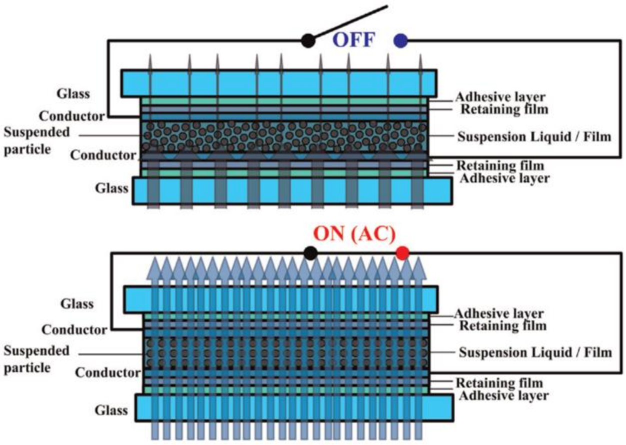


Figure 38. Schematic structure of SPDs in “off” and “on” states [134]

When an electric current is applied, the suspended particles align to create a clear view, while in the absence of an electric current, the particles disperse, making the glass opaque or tinted because they scatter and/or absorb the visible light. This technology allows for dynamic control over the amount of light and heat that enters a building, reducing the need for traditional shading devices or air conditioning systems. Additionally, SPD glazing can be used to regulate privacy, reduce glare, and provide insulation, making it an efficient and versatile option for modern building design. When used to separate indoor and outdoor environments, this measure is able to generate energy savings of 20% to 50% compared to single-pane windows [135].

The physical form of energy input of these devices is electricity, their lifetime is 10-20 years and the TRL is 8 [69]. Focusing on the costs, the CAPEX is currently 90-910 €/m2, with a goal to reach 90-210 €/m2 [136], while their OPEX, mainly related to cleaning, maintaining, replacing components, energy, and monitoring of the system, is €70 - €450 per year [69].

3.3.2. Thermochromic glazing (TC)

Thermochromic glazing refers to a type of active glazing system that changes its optical properties in response to changes in temperature. Specifically, it refers to a material or coating that can transition between transparent and opaque states based on temperature fluctuations. This type of glazing typically contains a layer of thermochromic material that is sandwiched between two layers of glass or plastic. When the temperature rises above a certain threshold, the thermochromic material undergoes a reversible chemical reaction that causes it to darken, thereby blocking out a portion of the incoming light.

Figure 39. Images of outside (upper band) and inside (lower band) views of the same thermochromic glazing system in the clear state (left) and in an intermediate state with a glass surface temperature equal to 39.2 °C (right) [137]

The ability of thermochromic glazing to regulate the amount of heat and light entering a building can led to improved energy efficiency and greater comfort for occupants, reasons because it is becoming an increasingly popular option in the design of modern and sustainable buildings.

The TRL of this measure, which has the potential to yield energy savings for heating and cooling of up to 80 % when compared to conventional glazing systems [138], is 6 to 8. The production cost of a square meter of thermochromic coating is currently €3 to €5 [139], while the OPEX ranges from €45 to €900 [69]. The lifetime of thermochromic glazing is 10-15 years [69].

3.3.3. Electrochromic glazing (EC)

Electrochromic glazing is an active glazing technology that allows the transparency and shading properties of a window or glass surface to be electronically controlled. This technology utilizes a thin coating of electrochromic material, such as tungsten oxide or nickel oxide, that changes its optical properties in response to an applied electrical current.

When an electrical charge is applied to the material, it undergoes a reversible oxidation-reduction reaction, causing the material to darken or lighten in colour. This process changes the amount of light and heat that can pass through the glass, allowing for dynamic control over the amount of natural light and solar heat gain in a building. In the clear state, the glass allows 47 % of the incident solar energy to the building interior, while in the darker state it can lower the solar energy entering the building by 81 % [133].

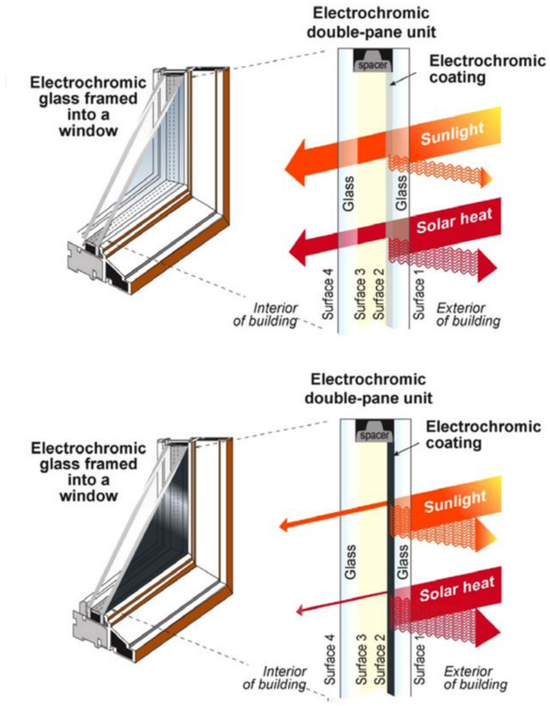


Figure 40. Electrochromic technology in clear and tinted state [140]

Electrochromic glazing systems can be designed to respond automatically to changes in environmental conditions, such as light intensity or temperature, or they can be manually controlled by occupants or building management systems. This technology provides a highly efficient and flexible solution for regulating the indoor environment, reducing the need for traditional shading devices, and improving energy efficiency and occupant comfort in modern buildings. Compared to conventional glazing systems, electrochromic glazing can guarantee energy savings of up to 8% of total energy consumption of a building in a hot climate, while up to 15 % in a cold climate [141].

If installed externally, their lifetime is 5-10 years [142]. Their TRL can vary from 6 to 9, mainly depending on the commercialization potential and regulatory compliance. Considering the cost of this measure, the CAPEX is 980 €/m^2 , while the OPEX is 20.4 €/ m^2 [143].

3.3.4. Liquid crystal glazing (LC)

Liquid crystal glazing is a type of active glazing system that utilizes liquid crystal technology to regulate the amount of light entering a building. This glazing system is constructed using a thin film of liquid crystal molecules, which can be controlled by applying an electric current to them.

In the absence of an electric field, the liquid crystal molecules are randomly oriented and allow light to pass through. However, when an electric field is applied, the molecules align themselves in a specific direction, causing the glazing to switch from transparent to opaque.

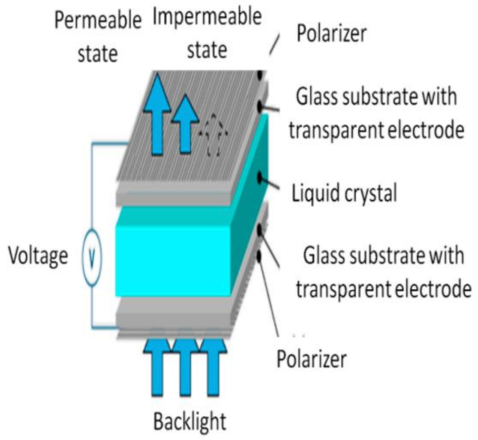


Figure 41. Working principle of LC glazing [144]

The ability of liquid crystal glazing to switch between transparent and opaque states makes it an effective solution for controlling the amount of natural light entering a building. This, in turn, can lead to greater comfort for occupants and improved energy efficiency of 30 % to 40 % compared to conventional glazing systems [69].

The TRL for LC glazing is 6 to 8 and the lifetime is 10 to 15 years. Taking into account the expenses associated with this measure, the capital expenditure (CAPEX), similarly to thermochromic glazing, currently amounts to €90-€910 per square meter, with a future cost goal of €90-€210 per square meter [136]. In addition to this, the ongoing operational expenditure (OPEX) of this measure is €45 to €900 per year [69].

3.3.5. Rotating shading system

Rotating shading systems are adaptive façade components that can be adjusted to control the amount of sunlight and heat entering a building. These systems typically consist of a series of rotating louvers or slats, mounted on the outside of a building, that can be tilted to varying degrees on a vertical or horizontal axis to regulate the intensity and direction of incoming solar radiation.

By adjusting the angle and orientation of the louvers using electric motors, rotating shading systems can optimize daylight levels, reduce glare, and prevent excessive solar gain, thus improving occupant comfort and the building's energy performance, the latest from 15 % to 40 % compared to buildings without shading services [69]. These systems can also be integrated with other building automation systems to respond to changing weather conditions or user preferences in real-time [133].

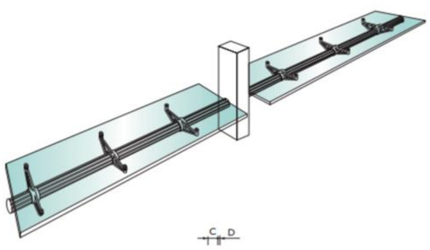


Figure 42. Glass rotating shading systems used at the European Commission Headquartes, Belgium [133]

Depending on the aesthetic preferences, design and performance requirements, rotating shading systems can be made of aluminium, steel, glass, wood or composite materials. The material composition influences also the durability of the system, which can vary from 10-15 years to 15-20 years, but also its cost.

The CAPEX of a modular unit of rotating shading system can significantly vary depending on factors such as materials, complexity size and location, and it can be estimated ranging between €275 and €18.000. The OPEX is characterized by a high variability too: €45 to €900 per year per modular unit. The TRL of these systems is 6 to 9 [69].

3.3.6. Folding shading system

Folding shading systems, also known as adaptive shading systems or kinetic shading systems, are a type of shading technology used in adaptive façades that can dynamically adjust their position to control solar radiation and heat gain within a building. These systems typically consist of an array of individual shading elements or louvers that are connected to a control system and can be individually adjusted to optimize their shading performance based on changing environmental conditions. The system can have two main typologies of movement: translational movement (a linear, bi-dimensional change of shape that allows adjustment levels in the building skins by size-opening variations or by overlapping layers) or rotational movement (tri-dimensional shape change that is performed by a swivel motion in the same axis and/or around different axis) [133].

The movement of the shading elements can be driven by a variety of mechanisms, including motors, pneumatic systems, or shape memory alloys. These systems can also be designed to respond to external sensors, such as light sensors or temperature sensors, to automatically adjust their position based on the prevailing conditions.

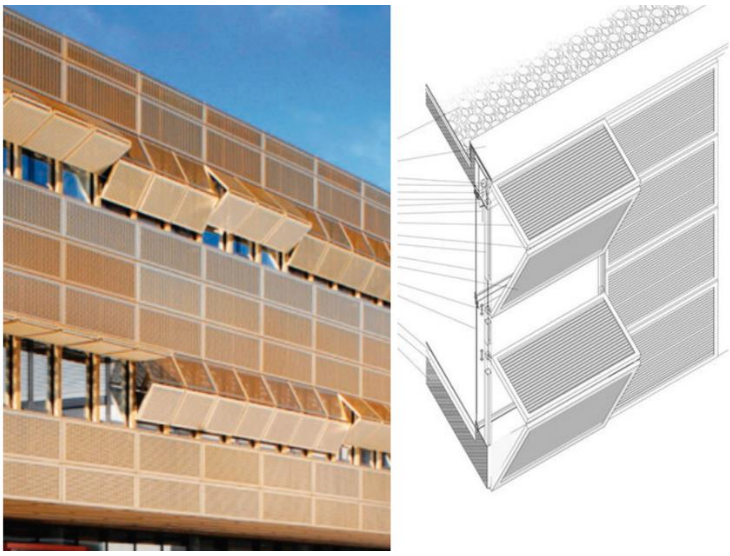


Figure 43. Anodized aluminium vertically folding device at the University of Potsdam, Germany [133]

Folding shading systems provide a number of benefits to building occupants, such as improved thermal comfort, increased natural daylighting, and reduced total cooling load from 8 % to 22 % compared to buildings without shading devices [145]. These systems can also enhance the aesthetic quality of a building façade by introducing movement and variability into its design. However, they can also be complex and require careful engineering and control to ensure optimal performance and durability over time. Because of these reasons, the CAPEX ranges from €2750 to €4500 per modular unit, while the OPEX from €180 to €650 per year per modular unit [69].

The lifetime of this type of shading systems depends on the same factors described for rotating shading systems and can vary from 10 to 20 years. Their TRL is 6 to 9 [69].

3.3.7. PV shading system

PV shading systems, also known as photovoltaic shading systems, are adaptive façade structures that combine solar panels with shading devices to provide both electricity generation and shading to a building or indoor area. These systems typically consist of solar panels mounted on a structure that can be adjusted to provide shade at different times of the day or year. They can be connected to a solar tracking system or an automatic shading device, enabling the system to move in a way that increases the solar panel's electric output, controls incoming solar radiation, or does both.

PV shading systems can be integrated into the design of a building or added to an existing structure such as window shading, roof, semi-transparent windows or façades, and cladding. The shading provided by these systems can also reduce the amount of heat absorbed by a building, resulting in energy savings for cooling of 5% to 15% compared to buildings without shading devices, not including the energy generated by PVs and used by the building. Overall, PV shading systems provide a sustainable and efficient solution for combining solar energy generation and shading to reduce the building’s energy consumption [133].

Figure 44. Photovoltaics panels mounted on external shading devices

The cost of this measure highly depends on the specifics of the system considered: for fixed PV systems in the commercial sector the CAPEX ranges from €18.000 to €36.000, while considering also a tracking system it increases to €36.000 - €65.000. In the case of the residential sector, a fixed system costs €9.000 - €18.000, while a solar-tracking PV shading system can cost €18.000 to €30.000 per installation. The spectrum of operational costs may vary within a range of €90 to €900 per year. The TRL for this measure is 6 to 9 [69].

3.3.8. Algae façade system

Algae facade systems are a type of adaptive facade technology that integrates living microalgae within building envelopes to provide a range of benefits. These systems utilize transparent or translucent panels containing a nutrient-rich aqueous solution in which microalgae are cultured. The microalgae are able to provide various functions including shading, air pollution reduction through photosynthesis, production of biomass for use as a renewable energy source, and thermal insulation.

The algae growing apparatus comprises intake systems that supply CO_2, growing algae, and nutrients, while the discharge systems collect the grown algae and emit O_2. The water that has been heated by the incoming solar radiation and that also contains the algae is then transported via a closed loop system to a separator and a heat exchanger, allowing this system to also reduce the building`s heating generation needs.

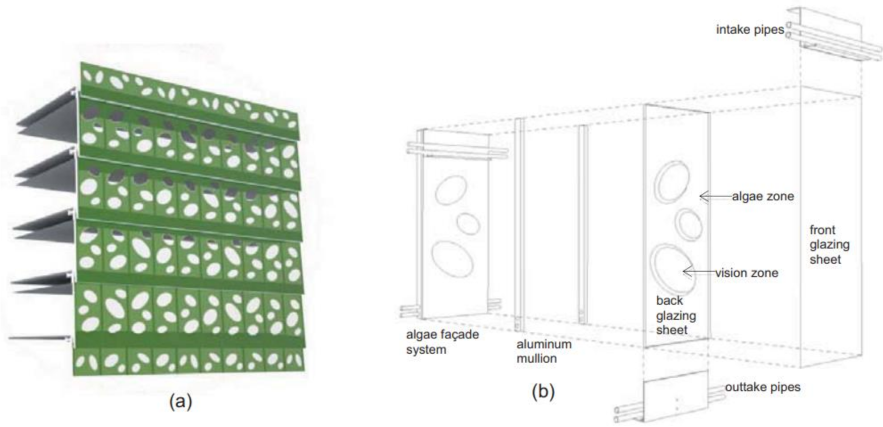


Figure 45. Algae façade building application (a) and system details (b) [146]

Algae facade systems represent a novel and promising strategy for enhancing the environmental performance and sustainability of adaptive facades in modern building design [146]. Their TRL is 6 to 7, meaning they`re not commercially available yet, but with an estimated CAPEX of 2500 €/m^2 and high operational costs [133].

3.3.9. Active venetian Blinds

Active venetian blinds are structured as classic venetian blinds, but they are characterized by the presence of a motor and light and/or temperature sensors that allow the automatic adjustment of the inclination of the slats via winding or unwinding of the cords. This mechanism guarantees to regulate the amount of solar radiation that, when the blinds are mounted outdoor, reaches the inside of the building to increase the comfort of the occupants.

The energy savings obtained with externally installed active venetian blinds can reach 10 % to 20 % compared to buildings with manual blinds. This measure is commercially available and has a TRL of 8 to 9. The CAPEX depends on the specific characteristics of the blinds, and it ranges from €400 to €800 per unit, while the OPEX, which includes cleaning, maintaining, replacing, and repairing of the components, is €30 to €80 per year. Their lifetime is 5-20 years [69].

3.3.10. Roller Blinds

Automated drapes, also known as motorized shades or roller blinds, are designed to provide a convenient and efficient way to control the amount of sunlight entering a room. They work by using an electric motor to move the fabric up or down along a track, which is usually mounted above the window or opening.

The motor, together with a range of incorporated sensors, allows to control and optimize the performance of the drapes. The sensors can include light sensors, which automatically adjust the position of the drapes based on the amount of sunlight entering the room, and temperature sensors, which can be used to regulate the amount of heat entering the space. In addition to this, the motor can be manually controlled by a remote or a wall switch, which allows users to manually adjust the position of the drapes to their desired level of shading. Some motorized drapes can also be controlled through a smartphone app or a home automation system, which allows for even greater flexibility and customization. Some motorized drapes also include features such as timers, which allow users to program the drapes to open and close at specific times of day, and voice-activated controls, which allow users to adjust the drapes using voice commands. In this way, automated drapes can guarantee energy savings of 10-20 % compared to building without shading devices.

The cost of automated drapes depends on the materials and on their dimensions. Their CAPEX ranges from €300 to €500 per unit, while the operational cost is €10 - €50 per year and includes mainly the cleaning. The lifetime of automated drapes is 5-15 years [69].

3.3.11. Automated screens

Automated screens, also known as motorized shading systems or roller shutters, are a type of shading device designed to regulate the amount of solar radiation entering a building or space using an automated mechanism. These screens are typically made of the same materials as classic screens and are installed outside of windows or building facades to provide shade and reduce solar heat gain. The automated mechanism typically involves an electric motor that moves the screen up or down along a track, which is usually mounted above the opening or window. Automated screens can be controlled through a variety of methods, such as remote control, wall switch, smartphone app, or home automation system. They can also be programmed to adjust their position automatically based on environmental factors such as time of day, amount of sunlight, and outdoor temperature.

The performance of these screens can be quantified in terms of their shading coefficient, solar heat gain coefficient, and visual transmittance. This measure can guarantee energy savings of 15 % to 30 % compared to buildings with manual screens [69]. Overall, automated screens provide a flexible and energy-efficient solution for controlling solar heat gain and regulating the amount of natural light entering a space, while also offering a range of customizable options to optimize their performance.

The CAPEX for small applications of automated screens is €400 to €800, while the OPEX is €30-€80 per year. These expenses exhibit significant variability depending on the specific applications considered. Their lifetime is 10-15 years [69].

3.3.12. Ceiling fan

Ceiling fans are a type of electrical appliance mounted on the ceiling of a room, designed to move air within an enclosed space, typically a room or a building, by utilizing the principle of fluid mechanics, in which a rotating, angled set of blades creates a low-pressure zone that draws in air from its surrounding environment, and then distributes it throughout the space. It is primarily used for creating a comfortable living or working environment thanks to the wind chill effect it provides, thereby reducing the perceived temperature in the occupied space: the strength of ventilative cooling effect can be chosen by the user, which has the possibility to select the optimal velocity of the blades.

Ceiling fans are typically powered by electricity and can be controlled by either a pull chain, remote control, or wall switch. The blades of a ceiling fan are commonly made of wood, metal, or plastic and are attached to a central motor. Depending on the model and brand, some ceiling fans can be automated and activated through smartphone apps or voice commands using smart home technology.

Figure 46. Eight blades ceiling fan.

This measure has a typical lifetime of 10 years and can provide energy of up to 50 % on the total cooling load [147]. The costs of a ceiling fan are materials and geometry dependent, meaning it depends on the diameter of the fan and the dimensions of the room in which the measure should be used. Their CAPEX is 50€ to 500 € per unit, while their OPEX can range from 10 € to 40 € per unit per year [69].

3.3.13. Dynamic Double Skin Façade

A dynamic double skin façade (DSF) is defined as a typical double skin façade in which various airpath movements are promoted according to internal and external boundary conditions. The control of openings allows to have a transparent façade that acts responsibly in relation to climatic conditions, optimizing the building's requirements, such visual and thermal comfort and energy efficiency. The achievement of this goal requires a decision-making system able of evaluating the conditions and predicting the best façade configuration to guarantee the established performance [105].

The quantitative costs of this active measure tend to be higher that the passive type since an electrical input is involved, then the cost of actuators must be included. In particular, it has been estimated that the CAPEX of a dynamic DSF is rounded between 600 and 800 euro per square meter, while the OPEX goes from €100 to €250 per year [69]. Compared to a single skin façade, dynamic DSF allows to save up to 10 % of energy savings [148].

3.4. Comfort lifestyle and user behaviour

This section summarises the occupant related actions, behaviour and comfort related phenomena that help avoid or reduce cooling demand. A more detailed analysis of these actions and their effect on the SC demand has been elaborated in *Deliverable 3.2 Analysis of behavioral interventions across Europe.* To maintain the physiological balance of the human organism, the behaviour reactions of the users are induced. Generally, it has been recognized that occupants' adaptive behaviour on passive measures, which are mainly provoked by various environmental conditions, are stochastic but with some predictability through identifying triggering factors. The main aspects are summarized here.

3.4.1. Environmental adjustment

Opening/closing shadings/blinds

As seen in section 3.2.1 shading devices can block up to around 90% of the solar loads on the transparent building surfaces, when operated. In lack of automated systems the manipulation of shadings and blinds is up to the users. Based on the classification of Vellei et al. [64] this is considered a behavioural adaptation that uses environmental adjustment. Researchers have been studying the user behaviour in regards to shading and blind use since the 1970s, however, in their review literature for office buildings had only been found.

While solar shading is an effective measure that can eliminate the SC cooling needs on many locations in Europe, solar shading solutions when left to manual control is known to be less than fully effective in case of office buildings. A study done by the Swiss federal office for energy/Estia SA, Lausanne showed that in an office building, when manual operation was provided, sunscreens were adjusted infrequently: less than 2 movements / blinds / week regardless of the orientation or season. [149] This is due to the fact that the environmental control achieved by shading may have several functions, other than locking heat loads. The occupants can be reluctant to close shading or blinds as they prefer to have sunlight [150]. Suboptimal shading control does not only lead to high space cooling loads, but can also lead to increased lighting energy use. Chen et al. YEAR [151] calculated 18.33% possible SC energy savings with standard shading controls in an office building (shading closed in summer), but only up to 13.87% savings were anticipated when their occupant behaviour model for manual operation was applied. They even concluded that there is a probability of 7.26% that using manual shades may result in an energy increase rather than energy saving in offices.

Blind and shading use is more seasonal than day dependent: the daily adjustments are very rare and the position is kept constant until a discomfort situation occurs The main drivers of shading use defined by Inkarojrit [152] in addition to those environmentally related were identified as physiological (e.g. individual sensitivity to brightness), psychological (e.g. needs for privacy or view) and social (e.g. organization policy) factors. The following list reports the identified triggering variables:

- Illuminance/glare: related to visual discomfort seems to be the major driving factor to modify the blind position. Many studies concluded that “block direct sunlight” was a stimulus to intervene on blinds, others found glare on computer screens and reduce the brightness of work surfaces as a second reason. Where detailed, lowering actions occurred mainly when indoor horizontal illuminance was about 1200 lux, while raisings increased around 200 lux.

- Solar radiation: In one study external illuminance of 15,000 lux was found to be the value at which 50% of venetian blinds were lowered. Differences suggest that users’ behaviours can be very different for similar physical quantities.

- Indoor and outdoor temperature: three studies, reporting temperature stimuli, recorded an increase in blind use when both these temperatures rose. For indoor temperature 26 °C was reported as the limit for lowering blinds

A blind “hysteresis phenomenon” was also highlighted: occupants close blinds at illuminance levels higher than that at which they open them It is suggested that actions on shadings and blinds are partially related to time drivers, but they are highly influenced by occupants’ habits.

Opening/closing windows/doors

Natural ventilation can be operated by the occupants by the means of manipulations on windows and doors. The window is considered as the most common indoor environmental adjustment approach available from surveys performed in the offices [150]. The main functions of opening a window are generating breeze, for fresh air and inducing natural ventilation cooling in summer [150]. It was also shown that occupants use windows more frequently in the transition seasons – the frequency is about 82% in spring and 76% in autumn [150].

Yu et al. study recommends opening windows in transition months to allow natural ventilation, especially at high floors due to the lower outdoor temperatures on higher levels [153]. This is considered as an effective measure to reduce the indoor air temperature and decrease the cooling load in subtropical regions [153].

Meanwhile, opening windows and doors is associated with decreasing CO_2 concentration and improving air quality, in polluted city such manipulation can result in an increase in indoor CO_2 concentrations, and increase in noise pollution. Opening windows in hot months is also not recommended because it was found to increase the cooling load and have a negative impact on cooling load conservation and maintenance of thermal comfort [153].

Stazi et al [154] found a pattern of the interaction with windows in offices that shows temporal distribution: opening is greater at arrival, decreases substantially in intermediate periods and is related to closings before departure. However, they conclude that in residential buildings their use is often a consequence of specific domestic activities, which are usually performed in the same time lapse.

They conclude that temperature and indoor air quality requirements are the main environmental stimuli that trigger window adjustments, but a general agreement on whether the main triggers are indoor or outdoor conditions has not been reached yet. Their findings based on the correlations with environmental parameters compared from previous studies:

- Outdoor temperature: few openings occur when the outdoor temperature is less than 10-15 °C, the percentage increases when the temperature rises over 15 °C until 30 °C, reaching the maximum between 25 °C and 30 °C

- Indoor temperature: people tend to open windows when indoor temperature overcomes 20 °C. Some studies found that when the temperature exceeds about 27 °C openings are reduced to avoid the heat entrance from the outside.

- CO_2 concentration: the variable is mainly related to residential buildings. Many studies found a significant statistical correlation between openings and the CO_2 increasing.

An interesting finding is that for closing actions the outdoor temperature appeared to be main trigger parameter also for closings: when outdoor temperature decreases the probability decreases; but also closing actions are more frequent when the indoor temperature decreases, especially during the heating period.

Natural ventilation through opening the windows not only reduces the heat loads in the building, but helps the occupants feel more comfortable due to air movement. Thus, as described in the adaptive thermal comfort standards higher indoor temperatures up to 30°C are still felt comfortable when natural ventilation is provided, which can eliminate the need for mechanical space cooling technologies.

Drawing curtains

As two previous measures, drawing curtains relates to manual control of environmental parameters through adjustments of coming light. The reasons of using curtains include avoiding glare, blocking solar gain as well as privacy. The 4.7 % of respondents in the Liu et al. study utilized sun shading devices for other reasons, including privacy [150]. The paper also shows that occupants can be reluctant to drawing curtains as they prefer to have sunlight, particularly in winter season [150].

Closing curtains in case of invading sunlight is one of the intuitive and traditional cooling measures. For example, it is included in the Dutch national heat plan among long-term care institutions in Amsterdam and considered as important and feasible measure [155].

Turn/off appliances

Turning on or off appliances allows users indirectly and manually adjust the environment through modifying heat gains. Cooling appliances like air-conditioners and cooling fans are the most popular options with occupants in typical seasons, cooling fans being not as popular due to the limited cooling capacity [150].

One of the driving forces of turning off the appliances can be monetary costs, specifically in residential buildings [156]. Hence, in the office areas the air conditioning is largely used due to money not being the concern [156]. However, the beliefs and attitudes of occupants towards energy use and greenhouse emissions even in the same house can be significantly different, what widely affect the practices [157].

3.4.2. Personal adjustments

Putting on/taking off clothing

Clothing is a tool for personal adjustment as a behavioural adaptation to the environment. It is one of the typical personal controls that allows to maintain thermal comfort. It is considered as the most common thermal adaptive behaviours in summer along with staying in the shade, drinking cold drinks, etc. One wearing more clothes believes that it helps to get warmer and vice versa, Clothing decreases the body’s heat loss. Hence, the wearer can consciously help the body to regulate its proper heat balance under different environment conditions by wearing suitable clothing. Thus, clothing insulation is essential for human thermal comfort [158]. A special application of reducing clothing is for occupants in residential buildings, who can also limit the heating effect of bedclothing. This can result in higher indoor air temperature maintained in bedrooms without losing thermal comfort at night, and consequently, reduced energy use for air conditioning for sleeping environments.

The clothing insulation values vary according to indoor air temperature in each season; however, it is also influenced by the socio-cultural and moral acceptability of the available measures [150]. In addition, adding or reducing clothing is the first measure which occupants turn to in transition seasons in comparison with technical behaviours (e.g., air conditioning) [150]. Relaxing dress codes in institutional environments have been proven to reduce space cooling needs. An example is the CoolBiz campaign in Japan, whereby set points during summer months in public offices were set at 28°C, and office workers were encouraged to wear lighter clothing, and more breathable fabrics during work hours. [159] The initiative has been widely regarded as a success and was reported to avoid from 1 –3 million tonnes of carbon emissions per year.

Providing cool bedclothing [160] and advanced textiles for personal thermal management and energy control, e.g. conductive cooling textiles with enhanced thermal conductivity, active cooling/warming textiles, responsive textiles are emerging in the textile industry.[161]

Changing activity level

Changes in the users´ activity levels are also considered as an adaptive response to the environmental stimuli. The intention behind the behaviour is restoring comfort after a change that produced discomfort [156]. The activity level of the occupants play an important role in the maintenance of specific thermal comfort. The comfort perception and satisfaction are affected by the type of activity as well as the health state and habits [162]. The higher the activity level is, the higher the metabolic rate, which increases the perceived temperature.

Moreover, presence of people induces passive effects on the environment. Occupants' activities may influence the indoor temperature, and in result can have an important influence on the operation of heating and cooling systems and the energy use. Depending on their activity, people release not only various quantities of sensible and latent heat, but also water vapor, carbon dioxide, and other execrations and odorous substances [163].

An example of the reduction of activity levels is implementing a siesta, i.e. resting in the hottest part of the day. Implementing this action needs to be facilitated by the environment of the occupant, which might need socio-cultural changes.

Changing posture of human body

Changing posture of the human body may serve as a personal adjustment tool to affect the personalized ventilation.

The frequent change of an occupant's posture and position, coughing and sneezing behavior provide an opportunity to achieve better thermal comfort with lower energy use [150]. Adaptation through modification of the human´s posture is explained by affecting the heat loss of the body by means of changing the surface area [164]. Occupants may change their postured depending on the surrounding temperatures to achieve a greater thermal comfort.

Moving to a different location

Within the building the thermal environment is not uniform. Different rooms and workstations have different exposure to solar radiation, outdoor weather, and cold airflow from the air conditioner outlet.

Local thermal dissatisfaction due to asymmetrical radiation may occur close to the facades with high solar loads, and also the operative temperature is dependent on the radiative heat gains of the human body. This uneven indoor operative temperature distribution can cause the movement of users inside the space to seek thermal comfort in more comfortable environments.

. Data analysis has shown that taking a break and moving to a cooler location resulted in a 100% satisfaction index; in comparison to decreasing body skin temperature and adjusting room's thermostat, which achieved 5% satisfaction index [165]. Hence, ability of a user to change his or her location is one of the effective tools to regulate personal thermal comfort. To facilitate the free movement of the occupants to meet their comfort needs in institutional buildings, a flexible working environment is suggested, where the desks can be freely selected.

Taking in hot/cold drinks or food

Consuming beverages or water are simple adaptive behaviours that are able improve thermal comfort. Because of the high temperatures body can lose body fluid which is essential for thermal regulation. Hence, hydration is important while being exposed to environmental heat or during physical activity in order to maintain adequate circulating intravascular fluid volume and to aid in conduction processes that cool the body down. Cold fluids ingestion may help to release the heat into the fluid and secrete it out of the body as sweat or urine [166].

Regarding food consumption, it was shown that people tend to eat, on average, 357 kcal less in the warm condition, adjusting for BMI and peripheral temperature being more comfortable and productive than usual in the warm condition [167].

Taking in drinks or food is a simple manual adaptation to the environment which also comes in price. For example, water price comes up to 1.5 USD/m^3 in Hungary and to 1.91 €/m^2 in average Western Europe [168] [169].

Taking a cold shower

On an individual level, taking a cold shower may alleviate heat stress [170]. Thus, such activity can be considered as an adaptation tool to the environment.

However, the research on activity logs of residents found out that turning on fans and turning on air conditioner occurred more often at high temperature ranges in comparison with the "non-mechanical" type of cooling adaptations like changing clothes, taking a shower, going to the basement, going to the porch or yard, leaving the house [171].

Taking a shower also result in consumption of energy and water. Prices of which depend on the country.

3.4.3. Physiological Adaptation

Acclimatization

Acclimatization is a physiological response of human body to maintain its thermal balance. It occurs naturally and poses no additional stress on the environment. Heat adaptation can be achieved by exposure to a hot temperature or by endogenous heat produced during exercise. It often brings a greater regulatory efficiency by lowering mean body temperature during heat stress, however, comes at the cost of a higher water loss [172].

The levels of personal acclimatization may vary and depend on various factors, including BMR, physical activity intensity and duration, and subsequent internal heat generation, the external climatic conditions contributing to heat exchange, level of acclimatization and capacity for dissemination of excess heat to the environment [173]. The study highlights the ultimate thermoregulatory limitation where under a set of external climatic conditions human adequate physiological cooling cannot occur [173].

Habituation

Habituation is a psychological adaptation of humans to the environment without any energy inputs. Past thermal experiences, personal believes and cultural values directly affect thermal response and cognitive assessment of people [174]. Studies support, that thermal sensations of human depend on many factors including psychological such as habits and expectations. Hence, any adjustment is performed not necessarily to adapt to the thermal environment but may also be due to habit [175].

It was shown that habituation of different climatic zone and seasonal changes of the thermal environment, cause physiological adaptation, which in turn is accompanied by subjective adaptation of thermal perception. In addition, preferred temperature is also suggested to change over the course of a day, due to circadian changes of body temperatures [176].

Perceived control

Perceived control is a psychological adaptation as the habituation. Having higher perceived control means that user has more control over its surroundings based on his or her believes.

The study has concluded that subjects with perceived control represented greater acceptance of the thermal environment. Perceived control influences the thermal sensations as well as thermal acceptability [177]. Hence, psychological factors also play an important role in the identification of thermal comfort of occupants.

Torriani et al. also suggests providing perceived control as a strategic tool to affect human thermal perception, to reduce the energy consumption of buildings [177].

Thermal expectations change

One of the psychological factors affecting the thermal of adaptation of human can be their expectations towards the thermal comfort. The concept of “expectation” outlined by Fanger and Toftum as the seventh parameter in the PMV equation suggests that people living in poor thermal environments may believe it is their destiny to be in such environments [178]. In contrast, those living in the better thermal environment may have a higher thermal expectation and become “picky” about the thermal environment.

Following the same logic, the study has shown that is easier and quicker for occupants to adapt to improved comfort conditions than it is for ‘spoiled’ occupants to lower their expectations and adapt to non-neutral indoor climate [179]. Expectations of users may narrow or widen their comfortable thermal sensation range.

3.4.4. Behavioural adaptation

Behavioural adaptation to the changes in the living conditions can be represented by conscious energy savings, which help reduction of energy bills and therefore are a powerful motivating factor.

The reports from households have shown that simple intervention like providing “Home Energy Reports” (Reports) containing, among other things, information about how a household’s electricity usage compares to that of its neighbours can reduce energy demand by 1.8 % on average, with the effectiveness of individual programs ranging from 0.9 % to 2.9 % [180].

Three categories of interventions with a high potential for initiating behavioural adaptation were identified in D3.2, namely:

1. Monetary incentives (i.e.: dynamic pricing) to shift peak load, encourage pre-cooling, and promote energy conservation of SC appliances.
2. Providing feedback and information on energy consumption to promote energy conservation of SC appliances (and other appliances that generate heat loads), encourage setting higher SC set-points, motivate the uptake of natural ventilation (including night-time ventilation), and encourage adaptive health-related behaviours during extreme heat events.
3. Nudging occupants, through social comparisons or default settings, to conserve electricity in their usage of SC appliances (and other appliances that generate heat loads), set higher SC set-points (together with default dress codes that encourage the use of breathable fabrics), motivate the uptake of natural ventilation measures, and adopt efficient shading practices.

3.5. Limits of the study

Regarding active and passive measures, lack of precise information on costs and energy savings due to high variability of the specification of each measure was found to be an additional limit of this study. Notably, dimensions and materials were factors that significantly influenced both capital expenditure and operational expenditure of the described measures. Furthermore, the orientation of the buildings on which these measures were installed emerged as a contributing factor influencing the effectiveness of the cooling installations, yielding varying outcomes.

In the context of space cooling technologies, Technology Readiness Level (TRL) was identified as a significant determinant of the availability of data pertaining to cost and energy savings. This observation applies also to both passive and active measures. Specifically, it is notable in the case of window trickle vents for passive measures and algae facades systems for active measures. The TRL concept plays a vital role in assessing the practicality and maturity of these measures, and its influence is evident in the comprehensiveness and availability of data related to energy efficiency outcomes and economic aspects.

Further studies that address the aforementioned limitations and variables are therefore suggested to enhance the availability of information and promote innovation, optimize energy consumption, reduce environmental impact and improve overall comfort in various settings. In addition to this, the coupling of different solutions could be also addressed for further investigations.

4. Technologies and measures selection

4.1. Approach

After the scouting and review of the space cooling technologies and measures devoted to reducing ambient temperature, the consortium handled a validation process to define a clear set of technologies and measures to face the expected increase in EU space cooling needs. The aim consists in identifying a set of the most relevant technologies and measures that could be deployed now or in the next decade, at a large scale. The outcome of this process wants to feed the CoolLIFE tool's calculation module on technologies and measures as well as the calculation module on economic feasibility.

The process comprises:

- First, each technology and measure that is already or is going to be (in a near future) available has been assessed according to environmental, economic/financial, technical, regulatory, and socio-economic factors. For this first selection round, a qualitative or semi-quantitative assessment is considered.
- Then, a focus is undertaken on applications of the selected technologies and measures. The aim of this step consists in identifying the feasibility of deploying the set of selected technologies and measures on specific target groups. Experts have also been called in to validate the adequacy between the technologies and the application fields.
- Finally, the set of technologies and measures are subject to a cost-benefit analysis (see Part 5 Cost-benefit analysis) and a final selection.

The current part deals with the 2 first steps, whereas the final step is covered in the section 5.

4.2. Selection of technologies and measures

4.2.1. Selection of space cooling technologies

Based on the comprehensive review of SC technologies, a first screening is applied in order to eliminate the not market-ready technologies. For doing so, the TRL index is mostly used and only technologies with a TRL index above 8 (*TRL 8 – system complete and qualified*) are considered. Note that only the technologies with a TRL index equal to 9 are actually and currently available on the market. With a TRL index 8 or below the technologies should be still considered as emerging or promising ones: it should be also highlighted that the CAPEX and OPEX of these technologies are not known and, at best, can only be estimated.

With this first criterion, a reduced set of technologies is identified (see Table 25). Of course, the vapour compression technologies, which are considered as "conventional technologies", are in the scope. But some alternative technologies may also be part of the solution: transcritical cycle using CO2 as refrigerant for instance, the reverse Brayton cycles as well as the absorption and adsorption cycles. The second family of alternative SC technologies which can be considered as available are technologies based on natural convective, evaporative, or latent cooling: active and/or passive technologies integrated into buildings, fans and mobile air coolers for instance, or latent cold storage. Change-phase materials which belong to the “freeze/melt cycle” type are excluded since they are not a mature technology.

Table 25. Selection of SC technologies – technology maturity

	Technology	Basic working principal	Systems	TRL index
Conventional technologies	Subcritical cycle	Vapour compression	Split system Multi-split system Packaged unit Portable unit Rooftop unit Chillers VRF	9
Alternative technologies	Transcritical cycle	Vapour compression	Chillers	9
	Reverse Brayton	No phase change	Turbines	5 - 9
	Absorption and adsorption cycles	Refrigerant and solid sorbent	Chillers	3 -9
	Forced convection	Natural sensible	Fans	9
	Evaporative cooling	Natural latent	Mobile air coolers	9

The next selection step consists in assessing the following factors for each of those technologies, with the aim of identifying any constraint or barrier which could definitively discard a given technology for being implemented into buildings:

- Environmental factors: energy consumption, use of environment, harming substances (HFCs), noise, space occupancy, etc.
- Economic/financial factors: prohibitive costs of investment, installation, maintenance, reparation, and dismantling costs, etc.
- Technical factors: development status of a technology, efficiency, technical, and physical constraints
- Legal/regulatory factors: presence of laws and regulations, which could boost or hamper the deployment of a technology.
- Health factors: possible harming of human health.

Based on the literature review done so far for the SC technologies scouting and feedback from experts' interviews, each factor has been qualitatively assessed (when possible). All the findings have been summarized in Table 27.

Again, conventional technologies have some drawbacks – especially due to the refrigerant – but not enough to be discarded. The promising transcritical cycle technology show great performances and is currently used for supplying negative cooling in commercial or industrial facilities. But these performances decline strongly when supplying positive cooling. As far as we know, the control of the transcritical cycle chillers become also quite tricky when operating at part load. Then, the current technologies are mostly suitable for providing negative cooling at steady-state operating mode.

The reverse Brayton technologies are used since decades for providing cooled water for SC purpose. Their main advantage is that the ambient air is directly cooled by direct expansion in a turbine (without using any refrigerant), before being blowed in the cooled space. They are mainly uses when mechanical force is already available and when risk of refrigerant leakages is great: this is why they have been mainly used in aircraft or trains since decades and there are recent attempts to apply this technology in automobile industry. Their main drawback is the investment cost (compressor and turbine) which is prohibitive for residential and commercial uses by comparison with vapour compression technologies.

The absorption and adsorption technologies already exist since decades and have some advantages by comparison with vapour compression technologies: the refrigerants used – or more precisely the refrigerant mixes – have lower Global warming or Ozone depletion potential. Nevertheless, their relatively low efficiency and the need of high temperature sources as inputs make them more interesting for valorising heat rejections (e.g. steam vapour) in an industrial context than for generating chilled water for direct SC purpose. For space cooling applications, absorptions and adsorptions technologies can be found in bi- or tri-generation facilities coupled with a cooling district network always when a heat source already exists (e.g., from household waste incineration facility).

Eventually, fans and mobile evaporative air coolers dot not supply space cooling but a relative and local thermal comfort, which can be enough to allow building occupants to get the required summer thermal comfort. Being low cost, having very low environment impact and without technical constraint, they are interesting alternatives to space cooling technologies to insure summer comfort.

As a conclusion, the following technologies have been discarded from the selected set of technologies for not being suitable for being implemented at a large scale for space cooling purpose:

- *Transcritical cycle chillers*
- *Reverse Brayton cycle chillers*

The Table 26 shows the final section of space cooling technologies.

Table 26. Final selection of space cooling technologies

	Technology	Systems
Conventional technologies	Subcritical cycle	Split system Multi-split system Packaged unit Portable unit Rooftop unit Chillers VRF
Alternative technologies	Absorption and adsorption cycles	Chillers
	Forced convection	Fans
	Evaporative cooling	Mobile air coolers

Table 27. Multi-criteria assessment of the selected technologies

System	Criteria assessment				
	Environment	Economic / financial	Technical	Legal / Regulatory	Health
Split system **Multi-split system** **Portable unit** **Packaged unit** **Rooftop unit** **Chillers** **VRF**	refrigerant GWP refrigerant flammability	cost-effective solutions meeting nearly 99 % of SC demand	inlet temperature between 25 to 35 °C the installation of packaged units, rooftops, VRF and chillers requires large works on existing buildings.	Limitation of refrigerant charge	refrigerant flammability or potential toxicity of refrigerant Air conditioning might cause health issues due to air drying
Transcritical cycle Chillers	low impacts: substitution to HFC-based solutions: non-flammable and low GWP	working fluid at high pressure (~90-100 bars) low efficiency (1-1.5) at usual temperatures	requires higher inlet temperature (40 - 90°C) system control complexity	-	low toxicity Air conditioning might cause health issues due to air drying
Bell Coleman cycle	no impact (no refrigerant/direct effect)	low efficiency (~0.8) high CAPEX (turbine)	moderate inlet temperature (~20 °C)	-	Air conditioning might cause health issues due to air drying

System	Criteria assessment				
	Environment	Economic / financial	Technical	Legal / Regulatory	Health
Absorption /adsorption cycle **Chillers**	refrigerant GWP (lower than for VC techs) refrigerant flammability	low efficiency (~0.4 – 1.2)	Inlet temperatures between 70 – 100 °C and higher Large capacities requiring spaces to be installed	some adsorption or absorption mix are only for industrial and commercial uses due to toxicity issues	possible toxicity risks in case of prolonged exposure Air conditioning might cause health issues due to air drying
Fans	-	Very low to low CAPEX and OPEX	supply a relative and local space cooling	-	draught might cause health issues
Mobile air coolers	no impact (no refrigerant/direct effect)	-	supply a relative and local thermal comfort	-	Noise-induced tiredness

4.2.2. Selection of measures for reducing space cooling demand

With the same approach than for technologies scouting, a comprehensive screening of active and passive measures for reducing space cooling demand has been carried on, as well as for lifestyle, behavioural or comfort options. Now we select the measures and options which might be deployed at a large scale in the coming years. A similar filtering process is applied (see Table 28) we only select mature technologies first (TRL index above 8). In a second step, we select measures on a multi-criteria assessment basis (see Table 29).

Table 28. Selection of reducing SC demand measures – technology maturity.

	Type of measure	Measure	TRL index
Active measures	Adaptive façade	Rotating shading system	6 – 9
		Folding shading system	6 – 9
		PV shading system	6 – 9
	Smart glazing systems	Suspended particle device	8
		Thermochromic glazing	6 – 8
		Electrochromic glazing	6 – 8
		Liquid crystal glazing	6 – 8
	Shading devices (automated)	Venetian blind	8 – 9
		Drapes	7 – 9
		Screens	7 – 9
Passive measures	Shading devices (manual or stationary)	Venetian Blinds	9
		Drapes	9
		Screens	7 – 9
		Overhang	7 – 9
	Thermal energy storage systems	Phase change materials components	6 – 8
		Thermal mass	7 – 9
	Natural ventilation strategies	Night cooling	7 – 9
		Solar chimneys	7 – 9
		Atrium ventilation	7 – 9

	Type of measure	Measure	TRL index
		Windows opening	7 – 9
		Wind catcher	7 – 9
		Staircase ventilation	7 – 9
	Sky radiative facades	White roofs	7 – 9
	Evaporative envelope surfaces	Green roofs	7 – 9
		Green facade	7 – 9
	Ventilated envelope surfaces	Ventilated roof	7 – 9
		Ventilated facade	7 – 9

We look for measures that can be applied to existing buildings, not only to new constructions. Consequently, measures that would require heavy works on the structure of the buildings should be discarded from the selection. These measures are two kinds: either their effectiveness relies on the design of the building (e.g. atriums, solar chimneys or wind catchers) or the characteristics of structural components of the building (e.g. wall inertia, phase change materials, overhangs). For these reasons, measures relying on thermal energy storage systems, ventilative or evaporative envelope facades and roofs are also discarded from the selection.

Active measures for adaptative façades as well as smart glazing components are expected to achieve significant reduction of space cooling demand (up to 40 % according to the literature). Nevertheless, they are still quite expensive, and, above all, the associated maintenance operations are their weak point. The implementation of such adaptive facades is thus still the privilege of specific and singular buildings (e.g., head offices of major companies or administration).

Finally, the Table 30 shows the final portfolio of the selected measures for the validation process.

Table 29. Multi-criteria assessment of the selected measures

Type of measure	Criteria assessment					
	Measure	**Environment**	**Economic / Financial**	**Technical**	**Legal / Regulatory**	**Health**
Adaptive façade	Rotating shading system	-		Limited lifetime ~15 years Uncertain durability	might conflict building codes / requirements for heritage protection	-
	Folding shading system	-	Very high CAPEX	Complexity in design and control Limited lifetime ~15 years	might conflict building codes / requirements for heritage protection	-
	PV shading system	-	Very high CAPEX	Complexity in control (tracking system) Limited lifetime ~15 years	might conflict building codes / requirements for heritage protection	-
Smart glazing systems	Suspended particle device	-	Maintenance costs are expected to stay high	Limited lifetime (10-20 years)	might conflict building codes / requirements for heritage protection	-
	Thermochromic glazing		Maintenance costs are expected to stay high	Limited lifetime (10-15 years)	might conflict building codes / requirements for heritage protection	-
	Electrochromic glazing		Maintenance costs are expected to stay high	Very limited lifetime (<10 years)	might conflict building codes / requirements for heritage protection	-

Type of measure	Criteria assessment					
	Measure	**Environment**	**Economic / Financial**	**Technical**	**Legal / Regulatory**	**Health**
	Liquid crystal glazing		Maintenance costs are expected to stay high	Limited lifetime (10-15 years)	might conflict building codes / requirements for heritage protection	-
Shading devices automated	Active Venetian blind					
	Automated Drapes	-	-	-		Decrease visual comfort
	Automated Screens					
Shading devices (manual)	Venetian Blinds					-
	Drapes	-	low CAPEX and OPEX	-	-	Decrease visual comfort
	Screens					
	Overhang	-	high CAPEX and OPEX	Integral component of the building, must be integrated in the building design	might conflict building codes / requirements for heritage protection	-
Thermal energy storage systems	Phase change materials components	-	Very high CAPEX and OPEX	Must be integrated in the building structure	-	-
	Thermal mass	-	High CAPEX and OPEX	Integral component of the building	-	-
Natural ventilation strategies	Night cooling	-		Efficiency strongly related to the building geometry or to the existence of mechanical ventilation	-	Possible noise disturbances (especially in cities centre)

Type of measure	Criteria assessment					
	Measure	**Environment**	**Economic / Financial**	**Technical**	**Legal / Regulatory**	**Health**
	Solar chimneys	-	High CAPEX and OPEX	Must be integrated in the building design	-	-
	Atrium ventilation	-	high CAPEX and OPEX	Must be integrated in the building design	-	-
	Windows opening	-	-	Limited potential for tilt-and-turn windows	Restricted/not allowed in some situations for safety reasons	Possible noise disturbances (especially in cities centre)
	Wind catcher	-	high CAPEX and OPEX	Must be integrated in the building design	-	-
	Staircase ventilation	-	-	Must be integrated in the building design	-	-
Sky radiative facades	White roofs	-	Low CAPEX, no OPEX		might conflict building codes / requirements for heritage protection	-
Evaporative envelope surfaces	Green roofs	storm-water management reduced heat-island effect (UHI)	very high CAPEX and OPEX	Extensive green roofs only, structural reinforcement needed in most cases	might conflict building codes / requirements for heritage protection	Decreased noise pollution
	Green facade	reduced heat-island effect (UHI	high CAPEX and OPEX	Structural reinforcement needed in most cases	might conflict building codes / requirements for heritage protection	Decrease visual comfort

Type of measure	Criteria assessment					
	Measure	Environment	Economic / Financial	Technical	Legal / Regulatory	Health
Ventilated envelope surfaces	Ventilated roof	-	high CAPEX and OPEX	Must be integrated in the building design and roof structure	might conflict building codes / requirements for heritage protection	-
	Ventilated façade	-	high CAPEX and OPEX	Shall be installed on façade without any window	might conflict building codes / requirements for heritage protection	Decrease visual comfort

Table 30. Final selection of active and passive measures

	Type of measure	Measure
Active measures	Shading devices (automated)	Active Venetian blind
		Automated drapes
		Automated screens
Passive measures	Shading devices (manual)	Venetian Blinds
		Drapes
		Screens
	Natural ventilation strategies	Night cooling
		Windows opening
	Sky radiative facades	White roofs

4.3. Focus on applications of the selected technologies and measures

According to the type of buildings or end-users, the various selected technologies and measures might be more or less adequate. The aim of this second validation step consists in specifying the adequacy of a give technology/measures to the different buildings' archetypes.

The analysis of this adequacy relies on whether a given technology belongs to the "Room air conditioner" (RAC) systems type or to the "Central air conditioner" (CAC) type (see **Erreur ! Source du renvoi introuvable.**). The choice between the CAC or RAC family is driven by the building situation and configuration as well as the required space cooling needs. Basically, the more the building's size and cooling needs increase, the more the CAC systems are relevant by comparison with the RAC systems. Besides, the implementation easiness will also be a relevant criterion for assessing the adequacy of a given technology with a building.

One should also consider a third system family for distributing space cooling: the district cooling networks. With a very low market share for space cooling in EU (<1%), this kind of infrastructure could play a major role in very dense centres of EU large cities and should be considered as an alternative SC option whatever the chillers type that supply chilled water (vapour compression / absorption / adsorption chillers). Moreover, as it has been mentioned in part 4.2.1, the absorption and adsorption chillers are not so relevant for directly supplying space cooling: they must be connected to a cooling district network. It seems thus more relevant to consider this technology has part of the district cooling solution.

Eventually, in order to describe the buildings stock, we have adopted the buildings' archetypes built in the framework of Hotmaps project [181] (Table 32).

Table 31. RAC / CAC classification

Room air conditioners (RAC)	Central air conditioniers (CAC)
Fans	Rooftop
Portable	VRF
Split	Chillers
Multi-split	
Package unit	

Table 32. Buildings archetypes

Residential	Services sector
Single family houses	Offices
Terraced houses	Trade
Multi-family houses	Education
Appartement blocks	Health
	Hotel and restaurants

Then, we propose to figure out the adequacy of the selected technologies and measures with the different archetypes with the following 3 level scale: adequate, possible but less adequate, not adequate. The adequacy level is assessed regarding the following criteria:

- Availability of the systems/measure on the market regarding the targeted building (and their actual cooling needs)
- Easiness of installing the system or implementing the measure in existing buildings
- Effectiveness of the system for space cooling
- Cost-effectiveness of the system/measure

4.3.1. Adequacy residential buildings - technologies

In that respect (see Table 33), large systems such rooftops, VRF, chillers become relevant for collective – and especially the largest – buildings, as well as for district cooling which requires affording high connection and extension costs. On another issue, portable units, mobile evaporative air cooler and fans do not provide air conditioning but a relative thermal comfort, sometimes at the cost of a deterioration in acoustic comfort (portable units).

Table 33. Adequacy table technology – buildings' archetype – Residential sector (where: ++ = adequate, + possible but less adequate, 0 = not adequate)

Systems unit	Single family houses	Terraced houses	Multi-family houses	Appartement blocks
Portable	+	+	+	+
Split	++	++	++	++
Multi-split	+	+	++	++
Packaged	+	+	+	+
Rooftop	0	0	+	+
VRF	0	0	++	++
Chillers	0	0	0	+
District cooling	0	0	+	++
Fans	++	++	++	++
Mobile evaporative air cooler	+	+	+	+

4.3.2. Adequacy residential buildings – measures

Regarding measures (see Table 34**Erreur ! Source du renvoi introuvable.**) that aim at decreasing solar radiations into the building, internal devices (Venetian blinds, drapes) are considered as less efficient that external devices (screens), since internal devices do not provide an efficient protection against infrared heat waves radiations. Moreover, the cost of system itself (automated devices) and their installation costs can be an obstacle to their adoption by households.

On a different level, cooling space strategies based on natural ventilation (night cooling) or windows opening are less obvious to implement in large buildings as multi-family houses and appartements blocks, in which the arrangement of housings is not necessarily suitable for cross-ventilation strategies. Finally white roofs are especially efficient to decrease cooling needs of the spaces which are located just below the roofs: in large buildings, only the last floor takes advantage of this measure.

Table 34. Adequacy table measure – buildings' archetype – Residential sector (where: ++ = adequate, + possible but less adequate, 0 = not adequate)

Systems unit	Single family houses	Terraced houses	Multi-family houses	Appartement blocks
Venetian blinds	+	+	+	+
Drapes	++	++	++	++
Screens	++	++	++	++
Active Venetian Blinds	+	+	+	+
Automated drapes	+	+	+	+
Automated screens	+	+	+	+
Night cooling	++	++	+	+
Windows opening	++	++	+	+
White roofs	++	++	+	+

4.3.3. Adequacy non-residential buildings – technologies

For non-residential buildings, the adequacy analysis shall consider the buildings size and make a distinction between small-medium (Table 35)**Erreur ! Source du renvoi introuvable.** and large buildings (Table 36), mainly for cost-effectiveness considerations of the systems. Moreover, for sanitary reasons, the buildings from the health sector favour centralized systems by comparison with RAC.

Table 35. Adequacy table technology – buildings' archetype – Non-residential small/medium buildings (where: ++ = adequate, + possible but less adequate, 0 = not adequate)

Systems unit	Offices	Trades	Education	Health	Hotels and restaurants
Portable	0	+	0	0	0
Split	++	++	++	0	++
Multi-split	+	+	+	0	++
Packaged	+	+	+	0	0
Rooftop	+	+	+	++	++
VRF	+	+	+	+	++
Chillers	+	+	+	+	0
District cooling	0	0	0	+	0
Fans	++	++	++	+	++
Mobile evaporative air cooler	+	+	+	0	+

Again, large systems become relevant for collective the largest buildings, whereas single split systems, portable or mobile systems are adequate for cooling offices small, hotels, restaurants and shops for instance. Because of noise disturbances, portable units can also be discarded for cooling places where this constraint can downgrade the final use such as offices, health, education or hotels.

Table 36. Adequacy table technology – buildings' archetype – Non-residential large buildings (where: ++ = adequate, + possible but less adequate, 0 = not adequate)

Systems unit	Offices	Trades	Education	Health	Hotels and restaurants
Portable	0	0	0	0	0
Split	0	0	0	0	0
Multi-split	++	++	++	0	++
Packaged	+	+	+	+	+
Rooftop	++	++	++	++	++
VRF	++	++	++	+	++
Chillers	++	++	++	++	++
District cooling	++	++	+	++	++
Fans	+	0	+	0	+
Mobile evaporative air cooler	+	+	+	0	0

4.3.4. Adequacy non-residential buildings – measures

Regarding measures, in contrast with housings, blinds, drapes and screens are very less relevant for several commercial sectors since lighting quality has a direct impact on the activities productivity (mainly offices and education) or general living quality (hotels and restaurants) (see Table 37 and Table 38).

Besides, for sanitary or safety reasons, windows opening is not allowed or restricted in other sectors (especially for health and education sectors which reduces the adequacy of natural ventilation measures for these sectors). Night cooling might not be possible where windows cannot stay opened when the building is closed (for obvious safety reasons) without a ventilation system that allows free cooling such as rooftops or air-handling units, which supposes that the buildings are large enough to afford such systems. If we consider that such systems are systematically installed in large buildings, night cooling through mechanical ventilation shall be considered as a relevant measure to implement.

White roofs are considered as a relevant option for small/medium buildings or larger low-rise buildings (typically malls buildings, or, to a less extent, some educational buildings).

Table 37. Adequacy table measure – buildings' archetype – Non-residential small/medium buildings (where: ++ = adequate, + possible but less adequate, 0 = not adequate)

Systems unit	Offices	Trades	Education	Health	Hotels and restaurants
Venetian blind	+	+	+	+	
Drapes	+	++	+	++	+
Screens	0	++	0	++	0
Active Venetian Blinds	0	0	0	0	0
Automated drapes	+	+	+	+	0
Automated screens	0	0	0	+	0
Night cooling	0	+	+	+	+
Windows opening	+	+	+	++	0
White roofs	++	++	++	++	++

Table 38. Adequacy table measure – buildings' archetype – Non-residential large buildings (where: ++ = adequate, + possible but less adequate, 0 = not adequate)

Systems unit	Offices	Trades	Education	Health	Hotels and restaurants
Venetian blind	+	+	+	+	
Drapes	+	+	+	++	+
Screens	0	0	0	+	0
Active Venetian Blinds	++	+	+	+	+
Automated drapes	+	+	+	+	+
Automated screens	0	0	0	+	0
Night cooling	++	++	++	++	++
Windows opening	+	+	+	+	0
White roofs	0	++	++	+	+

5. Cost-benefit analysis

5.1. Materials and Methods

A cost-benefit analysis (CBA) of the set of technologies and measures already identified and selected in the previous sections will provide a detailed assessment of their implementation feasibility. Due to the lack of information available on the service sector, the study will focus on the residential sector. It will be performed at a dwelling stock level and from a societal point of view.

5.1.1. Configurations and scenarios definition

To consider the European demand diversity, the CBA method is based on a combination of two parameters: district archetype and climate zone.

Four district archetypes will be retrieved from [182]: *large housing*, *old urban centre*, *dense urban district*, and *urban periphery*. A choice was made to exclude from this typology the *high-rise buildings* and the *industrial area*, as the current study is focused on residential buildings. *Rural area* has also been excluded because of the high concentration of cooling needs in urbanised area.

Marty et al.[182] identified district archetypes from all the Ile-de-France districts based on a clustering method using multiple parameters, such as height of buildings, building density, age, greenery, and net inhabitant density. The district segmentation is based on Statistical Information Aggregation Units (IRIS) defined by the French National Institute of Statistics and Economic Studies (INSEE).

The four district archetypes selected are all located in Ile-de-France, France. Two are located inside Paris, another one is in Bagneux, and the last one is in Anthony. Therefore, each district has its own population density value. To adopt a European perspective, certain local characteristics of these districts will be changed or ignored.

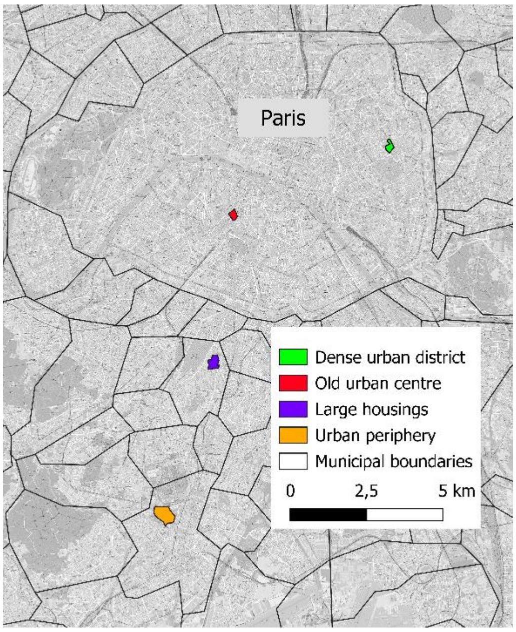


Figure 47. Map of the four district archetypes [182].

The climate zones at the European scale, will be defined based on the cooling degree days (CDD) annual values. Three climate zones were identified and presented below (less than 20 CDD, between 20 and 130 CDD, more than 130 CDD). To comply with the European standard EN14825 [1], the meteorological files associated with these climates will be those of Athens, Strasbourg and Helsinki, all three located in the above-mentioned zones. The reference year will be 2030, based on forecast files (Data source *Meteonorm* V8). The projection scenario of climate change selected is the intermediate emissions one, SSP2-4.5, considering a radiative forcing of 4.5 W/m² in 2100, equivalent to a global averaged temperature higher by 2.1 °C to 3.5 °C compared to the end of the 19th century [183].

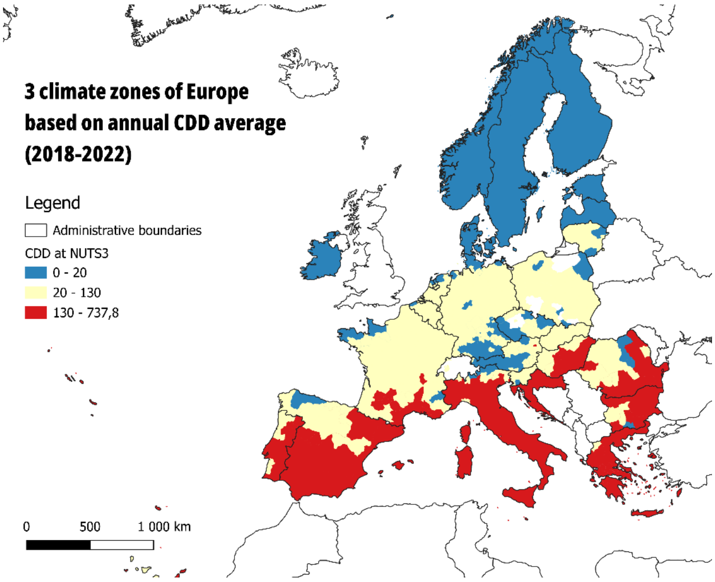


Figure 48. Map of the three climate zones defined for the CBA [184].

Architectural characteristics will also be associated with each climate zone to reflect the diversity of buildings across the continent. Those data will be retrieved from the Hotmaps project [181].

This method produces a matrix of twelve configurations (four district archetypes and three climate zones). Based on local population density values for the whole continent (in inhabitants per km²) and the geographical location, each point on the European territory could then be associated with a type of district archetype and a climate. It will then be possible to observe regional disparities and obtain average European results.

Each configuration will be simulated with Smart-E, the simulation platform of Mines Paris – PSL [185]. These simulations will provide reference levels of thermal discomfort.

Regarding the adequacy analysis provided in the section 4.3 and with the sake of brevity for the CBA, we selected the following types of technologies and measures to be considered in the CBA framework for the residential sector:

Table 39. Technologies and measure types selected for CBA for the residential sector.

Technologies	Measures
Portable unit system	Shading device (manual/automated blinds, screens and drapes)
Single and multi-split	Ceiling fan
Variable Refrigerant Flow	Opening/closing windows (incl. night cooling)
District cooling	White roof

Afterwards, in each configuration, the selected technologies, and measures, listed below, will be simulated in three scenarios: 30 %, 60 % and 90 % of dwellings equipped with the technology or measure. In each scenario, the most uncomfortable dwellings will be equipped first.

In all, 288 simulations were carried out, plus 96 reference simulations. Each simulation will enable indicators to be assessed with a view to comparing the technologies and measures selected. The indicators retrieved are listed below.

Table 40. Indicators obtained at the end of each simulation.

Indicators	unit
Amount of technologies or measures installed	-
Total contracted power	kW
Cooling produced	kWh/y
Electrical consumption	kWh/y
thermal discomfort	°C · h · occupant (above comfort temperature)
Noise discomfort inside	dB · dwelling · y
Noise discomfort outside	dB · dwelling · y
CO_2 emissions	tCO_2e

5.1.2. Costs and benefits calculation method

When assessing costs in the context of the CBA, a distinction is made between internal and external costs. Internal costs are those directly supported by individuals living in the dwellings. These are the capital expenditure (CAPEX) and operational expenditure (OPEX) of the solutions studied. Internal costs are retrieved from previously presented work.

The implementation of a scenario also has social and environmental consequences that need to be considered. These consequences, known as externalities, will be estimated, and valued, using available methods, such as revealed preference method. In the scope of this work, the externalities considered are:

- thermal discomfort inside the dwellings,
- noise discomfort from inside and outside,

- GHG emissions during the use phase and due to power production,

In this analysis, thermal discomfort will always be considered as a benefit. Indeed, the results will be presented in comparison to the baseline scenario. The implemented technologies and measures reduce thermal discomfort, resulting in a quantifiable benefit. In some cases, noise discomfort may be reduced compared with the reference scenario and will then be counted as a benefit.

Therefore, four categories of cost or benefit will enable the completion of the CBA: CAPEX, OPEX (operating and maintenance), External costs, and Thermal discomfort benefit.

To summarize the results of the CBA, two indices will be employed: the Benefit-Cost Ratio (BCR) and the Net Present Value (NPV), which summarise the results of the CBA. The equations of the two indices, recovered and adapted from [186] are presented below.

$$BCR = \frac{\sum_{i=t_0}^{t_0+T} \frac{\mathbf{B}_i}{(1+a)^i}}{I_0 + \sum_{i=t_0}^{t_0+T} \frac{\mathbf{C}_i}{(1+a)^i}} \qquad NPV = \sum_{i=t_0}^{t_0+T} \frac{\mathbf{B}_i - \mathbf{C}_i}{(1+a)^i} - I_0 \qquad (5.1)$$

Where: a: discount rate, B_i: benefits achieved in year i, C_i: costs in year i, t_0: year of implementation, T: time duration in years, I_0: initial investment.

When the BCR is higher than 1 or when the NPV is a positive value for a scenario, it means that this scenario fulfils the cost-benefit criteria and can be, theoretically, implemented.

The time duration will be equal to the lifetime assumed of each technology or measure, presented below, in order not to disadvantage the most durable solutions.

Table 41. Technologies and measures lifetime.

Technologies and measures	Lifetime
Portable unit system	10 years
Single and multi-split	12 years
Variable Refrigerant Flow	15 years
District cooling	30 years
shading DEVICE; ceiling fan; white roof	10 years

5.1.3. Simulation hypothesis

Before presenting the simulation results, it is necessary to elucidate several modelling assumptions.

Building envelope

The architectural features of the modelled buildings are derived from those of real districts located in Île-de-France. However, to ensure representativeness of the results at the scale of the European continent, certain characteristics will be adjusted.

In each district in Île-de-France, the topographical database from the French National Geographic Institute (IGN) delineates the distribution of residential dwellings within each building type (SFH, MFH, AB). Hence, it is possible to associate, based on this distribution, each dwelling in the district with a specific building type.

To avoid calculating averages based on architectural values, particularly the U-values, a reference country was selected for each climatic zone: France, Greece, and Finland. When changing from one climate zone to another, parameters were adjusted.

The distribution of construction periods in the modelled building stocks is based on the distribution of construction periods in the national building stocks of the considered countries. U-values of walls, windows, floors, and roofs will be assigned according to the type of building and the period of construction allocated. These are national values taken from the data available in the Hotmaps project repository [181]. Since window surface area has a significant impact on the thermal performance of the building in summer, it will be adapted according to the climate zone. The window-to-floor area ratios of reference buildings will be retrieved from the Ambience project [187] for Finland, France and Greece. In the same way, the type of building and the period of construction have made possible to assign an appropriate ratio to each dwelling.

Europe also presents a diversity in the number of inhabitants per dwelling. The total number of inhabitants in each district will be adjusted on the basis of Eurostat data on the average number of inhabitants per dwelling: 2.6 for Greece, 2.2 for France, and 1.9 for Finland [188].

Technologies efficiency

In order to compare different active systems for satisfying building cooling needs, it is essential to accurately assess their efficiency. In this study, the energy efficiency ratio (EER) will be the key indicator for efficiency. It will be used as the ratio between the cooling power and the electric power input.

The EER value then depends on the operating conditions, and particularly on ambient temperature [189]. Thus, to enable different models of the same system to be compared with each other, the SEER "has been developed based on typical temperature and corresponding load distributions over a year and the EER/load curve of the system given by the manufacturers" [190]. The European standard EN14825 [1] distinguishes various SEER according to operating modes. Especially, SEERon only accounts for times when the system is switched on and operates in normative conditions.

While it's important to keep these definitions in mind, the comparative work in this study will be based on dynamic building thermal modelling. For this reason, it would be too imprecise to use single system efficiency values. Instead, temperature-dependent efficiency functions will be exploited.

To ensure that these functions can be used to compare all the systems studied, they will be defined according to the method presented below for room-air-conditioners, VRF and district cooling networks.

Room-Air-Conditioners functions

In the framework of the Ecodesign study ENTR Lot 6 "Air conditioning and Ventilation Systems" [191], temperature-dependent EER, or EER(T), functions have been defined for all the main categories of systems based on vapor compression. The latter, based on correlations derived from the 4-point EER between 20 and 35 °C of a large set of machines, provides the shapes of the functions in this section. The temperature considered is the air temperature at the condenser.

As the purpose of this study is to evaluate the consequences of current choices, the efficiency values of system used will be the ones of the European sales average for 2020. To recover those values, the method will use the forecast data from the Heat RoadMap project [190].

The two RAC considered in the scope of the present study are portable unit systems and split systems. For this section, it will be assumed that portable systems have a capacity of 2.5 kW and split systems have a capacity of 5, 10, or 15 kW.

Portable systems

For portable systems, the average function proposed in the scope of the Ecodesign study, is as follow:

$$\begin{cases} \boldsymbol{EER(T = 35) = 2.1} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 \times (T - 35)\right) \; ; \; T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \; ; \; T < 35\,°C} \end{cases} \tag{5.2}$$

Here, T is the air temperature at the condenser, the inside air temperature in °C.

For portable systems, the Heat RoadMap project provides the EER evolution over the year at nominal conditions, i.e., at 35 °C for the air temperature at the condenser. Thus, the required function is immediately achievable. The European sales average EER value of portable system at 35 °C is 2.8, therefore, the EER(T) function for portable system that will be used in the following is:

$$\begin{cases} \boldsymbol{EER(T = 35) = 2.8} \\ \boldsymbol{EER(T) = 2.8 \times \left(1 - 0.03 \times (T - 35)\right) \; ; \; T > 35\,°C} \\ \boldsymbol{EER(T) = 2.8 \; ; \; T < 35\,°C} \end{cases} \tag{5.3}$$

The effect of the infiltration generated by this system and the heat gains for which it is responsible will be added to the thermal model without being considered in the EER function.

The additional infiltration generated will be assumed to be equal to the air flow generated by the system, considered to be constant during operation and equal to 200 $m^3/(h \cdot kW)$ [192]. Heat gains are assumed to be equal to the power consumption of the system.

Split systems

For split systems, the average function is as follow:

$$\begin{cases} \boldsymbol{EER(T) = -0.0035 \times T^2 + 0.0434 \times T + 5.609 \; ; \; 20\,°C \le T \le 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 \times (T - 35)\right) \; ; \; T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 20) \; ; \; T < 20\,°C} \end{cases} \tag{5.4}$$

Here, T is the air temperature at the condenser, the outside air temperature in °C. The SEER value for this precise function is 4.

Because the Heat RoadMap project provides the SEER evolution, it's slightly more complicated to obtain the desired function. It is necessary to precisely define the link between a function and the associated SEER value.

Firstly, to the equation above, a single value of SEERon can be associated using equation (6) of the 5.6 section of the standard EN14825 [1], copied below, and the number of hours per bin corresponding to the reference cooling season (Table F.2 of the standard). Applying this method, the SEERon value obtained is 4.26.

$$\boldsymbol{SEER_{on}} = \frac{\sum_{j=1}^{n} \boldsymbol{h_j} \times \boldsymbol{P_c(T_j)}}{\sum_{j=1}^{n} \boldsymbol{h_j} \times \left(\frac{\boldsymbol{P_c(T_j)}}{\boldsymbol{EER(T_j)}}\right)} \tag{5.5}$$

Where:

- *j: the bin number*
- *n: the total number of bins*
- *T_j: the bin temperature, in °C*
- *h_j: the number of bin hours occurring at the corresponding bin temperature T_j*
- *$P_c(T_j)$: the cooling load for the corresponding bin temperature T_j, in kW. Determined by multiplying the design load value of the system (here 5 kW) with the part load ratio for each corresponding bin.*

To pass from SEERon to SEER, it is necessary to assess the power consumption of the system on thermostat-off mode, standby mode, crankcase heater mode and off mode. The following equation, derived from equation (5) of section 5.5 of the standard, can provide this consumption:

$$\boldsymbol{P_{off}} = \boldsymbol{P_{design}} \times \boldsymbol{H_{CE}} \times \left(\frac{\mathbf{1}}{\boldsymbol{SEER}} - \frac{\mathbf{1}}{\boldsymbol{SEER_{on}}}\right) \tag{5.6}$$

Where:

- *P_{off} : the power consumption of the system on thermostat-off mode, standby mode, crankcase heater mode and off mode over a year, in kWh ;*
- *P_{design}: the design cooling load of the unit, in kW ;*
- *H_{CE}: the number of equivalent active mode hours for cooling, equal to 350 h [1].*

Assuming a 5 kW cooling capacity and knowing that equation (5.4) is associated to a SEER of 4, the value of P_{off} is 26.96 kWh. This value will be assumed constant, regardless of technical developments.

With all these elements, it is now possible to adjust the value of the y-intercept of the polynomial of equation (5.4) (between 20 and 35 °C) so as to obtain the function corresponding to the 2020 European sales average, related to a SEER value of 6.15 (for split capacity above 5 kW). Since this value cancels out when the calculation standards presented in EN14825 are followed, the final EER(T) function of split units does not depend on the installed capacity, as long as it is above 5 kW. Whatever the installed capacity, the equation below will be applied.

$$\begin{cases} \boldsymbol{EER(T) = -0.0035 \times T^2 + 0.0434 \times T + 8.09 \ ; \ 20\,°C \leq T \leq 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 \times (T - 35)\right) \ ; \ T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 20) \ ; \ T < 20\,°C} \end{cases} \tag{5.7}$$

Variable Refrigerant Flow functions

The only centralised-air-conditioner that will be considered here is the variable refrigerant flow system, with a 70 kW assumed capacity. The average function is as follow [191] :

$$\begin{cases} \boldsymbol{EER(T) = 11\,690 \times T^{-2.336}\ ;\ 20\,°C \leq T \leq 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 \times (T - 35)\right)\ ;\ T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 20)\ ;\ T < 20\,°C} \end{cases} \tag{5.8}$$

Here, T is the air temperature at the condenser, the outside air temperature in °C. The SEER value for this precise function is 4.3.

The same method used previously for split and based on EN14825 will be used. However, it must be underline that, for air conditioners with a cooling capacity over 12 kW, the value of H_{CE} depends on the climate: 300 h for Helsinki, 600 h for Strasbourg and 900 h for Athens.

For instance, for the Strasbourg climate, the function is:

$$\begin{cases} \boldsymbol{EER(T) = 15\,014.7 \times T^{-2.336}\ ;\ 20\,°C \leq T \leq 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 \times (T - 35)\right)\ ;\ T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 20)\ ;\ T < 20\,°C} \end{cases} \tag{5.9}$$

With SEER = 5.16.

District cooling network function

For district network, the cooling production is assumed to be assured by water-to-water chiller. For these systems, the average function, depending on outside temperature, is as follow:

$$\begin{cases} \boldsymbol{EER(T) = -0.0175 \times T^2 + 0.8794 \times T - 5.4802\ ;\ 20\,°C \leq T \leq 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 \times (T - 35)\right)\ ;\ T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 20)\ ;\ T < 20\,°C} \end{cases} \tag{5.10}$$

This function is associated with a SEER of 4.85. Average 2020 sold water-to-water chiller with a cooling capacity over 400 kW had a 6.59 SEER. Since this function depends on the outdoor air temperature and not on the water temperature at the condenser, there is no method for precisely obtaining a new function from the latter SEER. Each point of the function for the chiller under consideration will be derived from the equation above, multiplied by 1.36 $\left(\frac{6.59}{4.85}\right)$. The following equation is obtained:

$$\begin{cases} \boldsymbol{EER(T) = -0,0238 \times T^2 + 1,1949 \times T - 7.4487\ ;\ 20\,°C \leq T \leq 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 35) \times \left(1 - 0.03 * (T - 35)\right)\ ;\ T > 35\,°C} \\ \boldsymbol{EER(T) = EER(T = 20)\ ;\ T < 20\,°C} \end{cases} \tag{5.11}$$

This function only takes compressor consumption into account. Pump consumption and losses should also be considered.

Losses

Losses along the network will be assumed constant as the pipe network is considered to be buried deep enough to be surrounded by soil at a constant temperature.

They will be set at 3 % of the power withdrawn from buildings connected to the network [193].

Pump consumption

Hereafter, only the pump consumption of the primary cold-water circuit will be taken into account, the eventual other circuits downstream in the heat flow after the chiller and upstream before the substation will be excluded.

Pump consumption of the primary circuit varies widely according to the flow rate of water through the pipes. For its estimation, the following equation will be used [194] :

$$\boldsymbol{P_{pump}} = \frac{\dot{\boldsymbol{V}} \times \Delta \boldsymbol{p}}{\boldsymbol{\eta}} \tag{5.12}$$

Where:

- P_{pump}: *The pump consumption, in W*
- $\dot{V}$: *the cold-water flow in the pipes, in m³/s*
- Δp: *the pressure difference before and after the pump, in Pa*
- η: *the pump efficiency, assumed to be 0.9.*

Moreover [194]:

$$\Delta \boldsymbol{p} = \boldsymbol{\lambda} \times \frac{\boldsymbol{l}}{\boldsymbol{d}} \times \frac{\boldsymbol{\rho}}{\boldsymbol{2}} \times \boldsymbol{v}^2 \tag{5.13}$$

Where:

- λ: *the pressure loss coefficient, determined by the Haaland correlation using the Reynolds number value and ε = 0.2 mm, for steel pipes.*
- l: *the length of the network, in m*
- d: *the diameter of the pipe, in m*
- ρ: *the water density, equal to 1000 kg/m³*
- v: *the water speed, in m/s, with a max value of 2 m/s.*

Therefore, by fixing the network characteristics (length, cooling capacity) and assuming a temperature difference of 5K between outgoing and return water, the diameter of the pipe can be defined. The entire network is considered to be a single pipe with fixed dimensions.

At each simulation time step, the quantity of cold to be produced is used to obtain the water flow rate and the water velocity. In this way, the pressure difference can be determined (Eq.(5.13)), and hence pump consumption (Eq. (5.12)).

However, to avoid having to model the entire network, it is possible to deduce the relation between the ratio between pump consumption and compressor consumption and the partial load of the water distribution network, based on the set characteristics.

Smart-E application

Reasoning at the dwelling level on Smart-E model, at each timestep, the hourly cooling needs are known, Qd (in kW). To get the cooling production needs for the network to deliver it to this dwelling, Qn, the value of Qd must be multiplied by 1.03 to account for the losses. An assumption of losses equal distribution among customers is made.

Then, assuming that the district network is dimensioned for an outside temperature of 35 °C, the partial load of the water network, Plw, is assumed to be linearly dependent on outside temperature.

$$\boldsymbol{Plw = \frac{T - 16}{35 - 16}} \tag{5.14}$$

With T being the outside temperature, in °C.

For a 10 MW cooling capacity and 5 km long district network, the following relation has been identified.

$$\boldsymbol{r = 0.0531 \times Plw^2 + 0.0191 \times Plw \,; T \leq 35\,°C} \tag{5.15}$$

Where r and Plw as dimensionless ratio (between 0 and 1).

Above 35 °C, the cooling production remains constant, Q_p is constant and the correlation of equation (***5.15***) is unapplicable. The following equation can be easily demonstrated for all network configurations:

$$\boldsymbol{r(T) = r(35\,°C) \times \frac{EER_{Chiller}(T)}{EER_{Chiller}(35\,°C)} \,; T > 35\,°C} \tag{5.16}$$

The total electricity consumption for the network to deliver the dwelling, Q_{tot}, is calculated with the following equation.

$$\boldsymbol{Q_{tot} = Q_c + Q_p = Q_c \times \left(1 + \frac{Q_p}{Q_c}\right) = \frac{Q_n}{EER_{Chiller}} \times (1 + r) = \frac{Q_d \times 1.03}{EER_{Chiller}} \times (1 + r)} \tag{5.17}$$

Said differently, the district network efficiency can be defined as:

$$\boldsymbol{\eta_{DC}(T) = \frac{EER_{Chiller}(T)}{1.03 \times (1 + r(T))}} \tag{5.18}$$

EER(T) graphical representation

Based on the above-mentioned reasoning, the efficiency functions EER(T) are represented for a temperature range of 17 °C to 40 °C, representing inside temperature for portable systems, outside temperature for split systems, VRF and for the district cooling network. The latter is assumed to be a 10 MW capacity with a 5 km length.

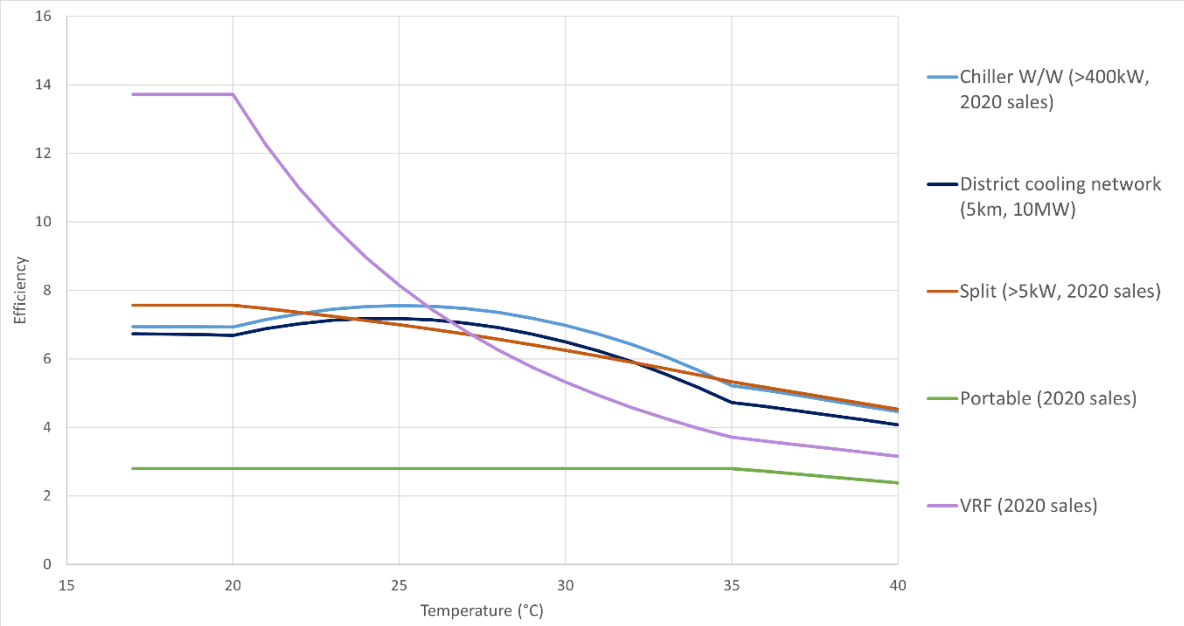


Figure 49. Temperature dependant efficiency functions of cooling systems

These functions will be used for the rest of the study. Nevertheless, a sensitivity study of the method for cooling networks yields the following graph, which confirms the assumption made for the EER function.

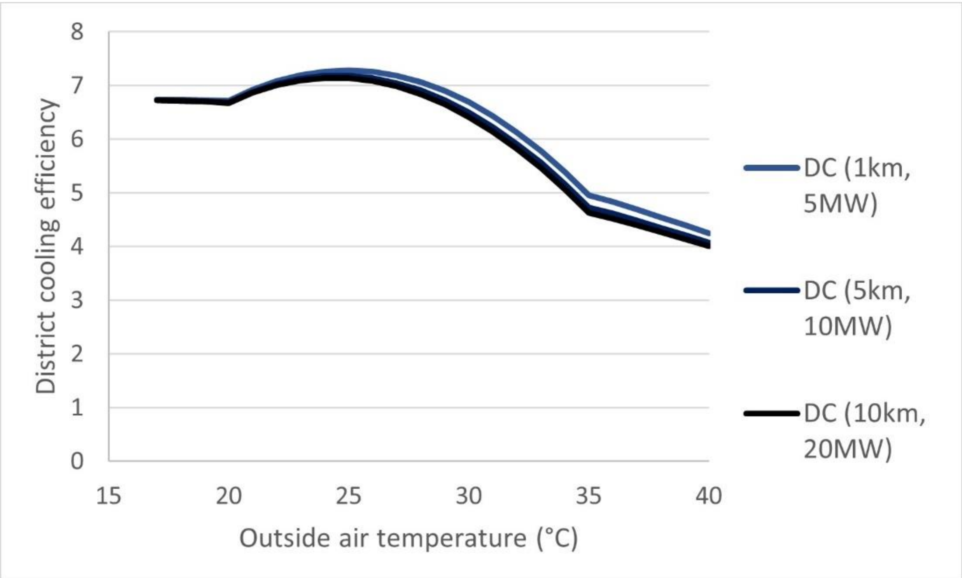


Figure 50. Temperature dependant efficiency functions of different cooling network dimensions

Measures control scenarios

Shading device

Shading devices help in reducing the thermal gains brought into the dwelling by sunlight through windows. Concurrently, they filter light and reduce interior illuminance.

Cellai et al. [195] conducted an evaluation work of the summer reduction factor on solar gains of diverse shielding systems in four European cities (Milan, Florence, Berlin and Athens). They assumed no shielding systems on North façades. Because of their thermal performance and visual assets [196], the simulated shading system is venetian blind. At a blind angle of 60°, their summer reduction factor on solar gains, average among the four European cities above mentioned and the East, South and West façades, is 72 %.

It can be assumed that the solar gains reduction factor is equal to the lighting reduction factor as the shading device selected doesn't discriminate between wavelengths. Therefore, a 72 % reduction factor of solar gains and daylighting will be applied.

The use of blinds will be determined by the external illuminance on the façade using the function derived from the work of Alessandrini et al. [197].

$$Use = \begin{cases} 0.643 \times light + 7\ ; light \leq 28\ klux \\ 0.278 \times light + 17.2\ ; light > 28\ klux \end{cases} \tag{5.19}$$

Where *Use* is the rate of use of shading device (in %) and *light* is the external lighting on the façade (in 1 000 lux). Therefore, it integrates an occupancy scenario.

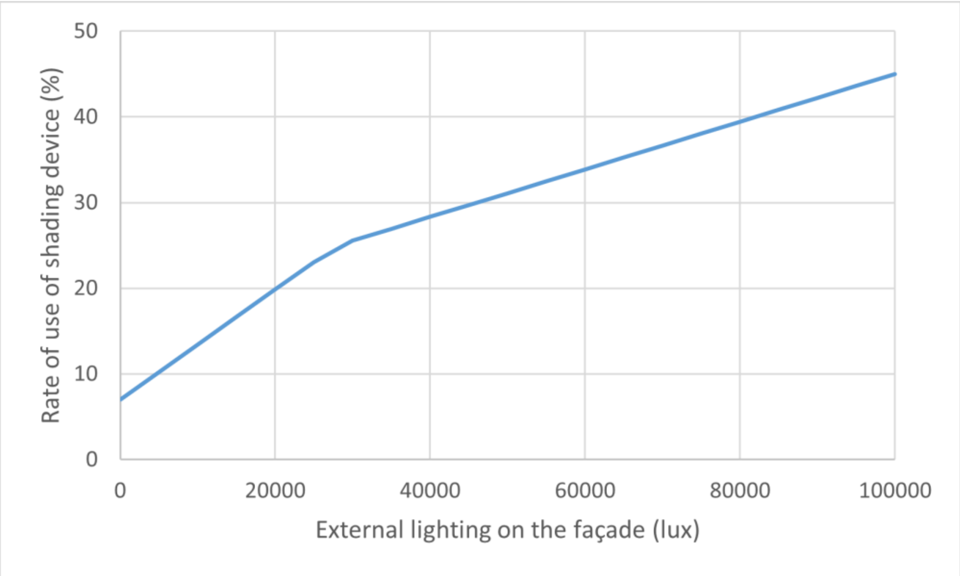


Figure 51. Shading device use depending on the external lighting [197].

Humphreys & Nicol [198] highlight the fact that the use of blinds is uncorrelated to outside or inside temperature. To ensure that the technologies and measures put in place are used realistically, this observation will be taken into account and the use of blinds will depend solely on this parameter.

Ceiling fan

Fans have a negligible impact on indoor temperature. However, when the occupant moves into the air velocity field they produce, the increase in air speed at the surface of their body leads to an increase in heat exchange between them and the surrounding air. This phenomenon results in a reduction in the temperature felt. The intensity of this effect depends on several parameters, but it will be assumed to be constant and will be reflected by an increase in the comfort temperature set in Smart-E when the fan is switched on. This increase in comfort temperature must be based on an estimate of the fan effect in equivalent degrees. This corresponds to the difference, in front of a fan, between the actual temperature and the temperature felt, leaving aside the effect of humidity. A brief review of the literature on the topic yielded the following values: 2.3 °C cooling sensation with a speed of 1 m/s [199] , at maximum with ventilation, a “corrective power” of 3 K is not unreasonable [200], and the upper acceptable temperature increase of 2.9 °C [201].

However, for the effect of increasing heat exchange between indoor air and the human body to be of interest, the air must be at a sufficiently lower temperature than the surface of the human body. If the air being blown in is hot, the fan is ineffective. In one of his works, Givoni, 1998, estimated that at indoor air temperatures of 33 °C and above, the effect of a fan was no longer of interest [202].

Consequently, in Smart-E dwellings equipped with a fan, the occupant will switch it on when the indoor temperature is between its summer comfort temperature and 33 °C. In these situations, the acceptable temperature will rise by 2 °C to 3 °C depending on the dwelling. It will be assumed that occupants will use the fans anytime they encounter thermal discomfort.

The consumption of a ceiling fan in operation will be constant at 30 W [203].

Opening/Closing windows

When the temperature inside a dwelling exceeds its summer comfort temperature and it is hotter inside than outside, the occupants systematically open the windows. When the indoor temperature is slightly below the comfort temperature of the dwelling but still higher than the outdoor temperature, a fraction of the occupants will open their windows. This fraction linearly depends on the indoor temperature, following the relationship proposed by Grignon-Massé [186]. Therefore, the implementation of this measure do not follow any pattern such as night time ventilation: : consequently, night ventilation is an implicit option of opening/closing windows when the internal/external air temperatures conditions are met.

Since they have a sound-damping effect, opening windows in noisy neighbourhoods can contribute to residents' indoor noise discomfort. Even if this aspect of interior comfort plays an important role and will be considered in this study, it is not significantly correlated with window-opening behaviour [204]. Indoor air quality is also a comfort factor affected by the opening of windows. Although studies have already identified that this factor plays a part in the window-opening behaviour [205], the impossibility of assessing the composition of indoor air and the decision not to use a fine fluid mechanics model ruled out the inclusion of air quality in the parameters for controlling the opening of windows.

It is assumed that the use of fans does not affect the control of windows, if both actions can be done simultaneously.

White roofs

Roof colour has a significant impact on the energy consumption of buildings. It affects the way solar heat gain is absorbed by the roof surface before being transmitted to the dwelling’s interior. By default, the albedo of building roofs is set to the 'aged black' albedo of 0.15 [206]. For white roofs, the albedo is based on the 'new white' albedo, set at 0.8. Painting a roof white is seen as a new measure on an existing building.

Internal costs assessment

Generalities

Since all the price values collected do not date from the same year and it is necessary to reason at constant costs to obtain comparable results, all costs dating from before 2020 will be deflated and brought back to values in €2020 on the basis of the consumer price index (CPI) data made available by the Organisation for Economic Co-operation and Development data management services. A distinction will be made between costs associated with common household consumption and those specific to energy consumption.

Nevertheless, since the choices being considered have consequences over several successive years, it is necessary to update the costs or benefits forecast for the future in order to compare them with today's ones. This process is summarised in the choice of a value for the discount rate that will be assigned annually to each future cost or benefit.

Commissioned and published by the European council for an energy efficient economy, a 2015 study reported the discount rates applied by the Member States in cost-optimality calculations. They conclude that, on average, the European discount rate is 3.3 % from a social perspective [207].This value will be used throughout this study.

Even if it is always necessary to reason on the basis of constant costs, any changes in costs in the future due to inflation will be neglected. This choice is justified by the adoption of a societal point of view and is consistent with the recommendations of the ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects [208].

Here too, a distinction will be made between everyday consumption products and energy consumption. The price of electricity will be assumed to rise by 1.5 % per year. This assumption will be retrieved from Grignon-Massé’s thesis [186].

Technologies

The cost of purchasing and maintaining portable, split and VRF unit systems has already been identified in technology scouting part. As the sizing of portable systems depends little or not at all on the size of the dwelling, their cost per dwelling can be estimated immediately. This is not the case for the other technologies identified.

For the other technologies identified, the cost per dwelling depends on the size/amount of unit installed. The unit sizing will be based on the estimate proposed by Dittmann et al., 2017 [190] and listed below. These values were obtained by means of a correlation based on national CDD values, projected for 2020. The correlation is shown below the table.

Table 42. Cooling technology sizing per country [190]

Country	Sizing (power by dwelling surface)
France	111 W/m²
Greece	178 W/m²
Finland	74 W/m²

$$\boldsymbol{Sizing} = \mathbf{1.2} * \left(-\mathbf{6.81} * \mathbf{10^{-5}} * \boldsymbol{CDD^2} + \mathbf{0.163} * \boldsymbol{CDD} + \mathbf{56.6}\right)\ \boldsymbol{W/m^2} \tag{5.20}$$

For this precise correlation, the CDD values are on an 18 °C base, population weighted average of main cities and the forecast is based on RCP4.5 scenario.

For split system, three available unit sizes will be considered: 5 kW, 10 kW, and 15 kW.

Given that, in practice, systems are often oversized when installed, it will be assumed that dwellings for which the product sizing per floor area is less than 5 kW will be allocated this system size. It will be the same for 10 and 15 kW. Dwellings with larger area than the one associated with 15 kW will be equipped with a 15-kW system.

The cost of split unit installation will be the one retrieved for “single split” for 5 kW split and for “multi-split” for 10 and 15 kW.

For VRF system, the total amount of units at a district scale will be equal to the sum of the size (in kW) associated with each dwelling, divided by 70 kW and rounded up to the nearest unit. In the scope of this study, the VRF units have a 70 kW assumed capacity. The total cost will be derived from this number of units and the cost of one unit.

For district cooling installations, the cost estimate will be made from the user’s point of view. Based on a very conventional pricing model, a distinction is made between the variable cost (representative of the cold cost) and the fixed cost (including amortisation of the investment for the entire network). The variable cost is proportional to the cold removed from the dwelling (in kWh). Both costs are paid by the user to the network operator. Financial transfers through condominiums are neglected in this approach.

To obtain results comparable to those associated with individual systems, the variable cost will be based on the cost of electricity. It will be assumed that the operator charges the user only the price of the electrical consumption associated with his consumption. The total network efficiency has already been estimated and the electricity price will be the Eurostat electricity price for non-household consumers in the Euro area.

Since the purpose of this study is to estimate the assets and drawbacks of different solutions based on the characteristics of typical districts, it was essential to assess a fixed cost related to density. Work Package 2 of the European Stratego project (2014-2016) [209] aims to quantify the potential for district heating and cooling in EU member states. From *District heating and cooling* of Frederiksen and Werner (2013) [210], they derived the curve shown below, in the 2007 cost level.

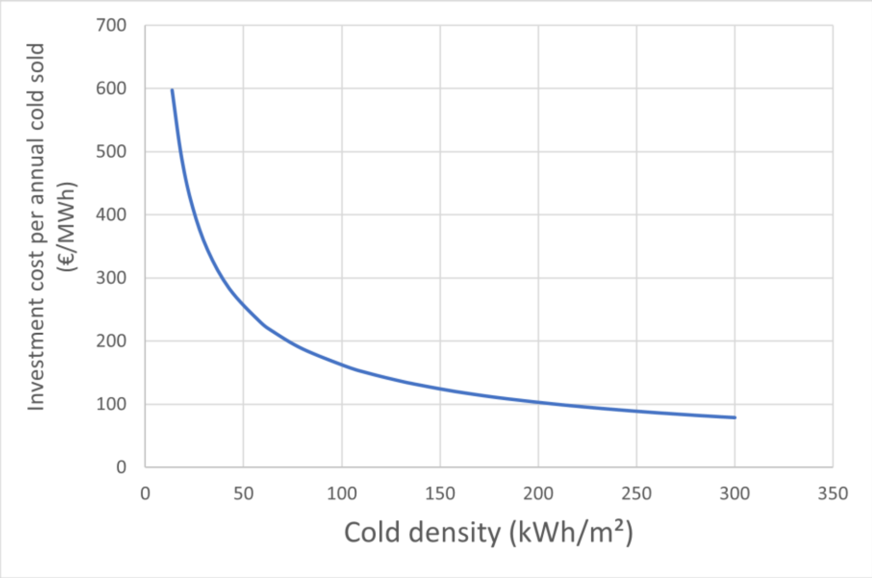


Figure 52. Specific investment cost per cold annually sold as function of the cold densities related to the corresponding land area [209].

This result will be taken as a first approximation of the investment capital for the construction of the district network. Therefore, it excludes the distribution maintenance cost and implies the assumption that a network bordering the district already exists.

For each district type and each scenario, the district's land area and the amount of cooling delivered to it can be estimated. Thanks to the curve above mentioned, the investment cost can be retrieved.

The cost of the installation inside the buildings (i.e., sub-stations, hydraulic networks, room units) that are connected to district cooling, has been assessed, as a first-order estimate, being at the same order of magnitude as the installation cost of Rooftop units [31] Moreover, an annual maintenance cost equal to 4 % of the initial investment (purchase and installation) is assumed for district cooling [211]

Measures

The costs for purchasing and maintaining the passive measures will be taken from the scouting work presented earlier. An average price is used in cases where the results are presented in the form of a range of costs rather than a single value. For ceiling fans, given that the OPEX value obtained includes energy consumption, it is assumed that maintenance is equal to the value obtained for OPEX minus 10 $€_{2023}$/unit. This assumption will make it possible to obtain non-constant electricity consumption for ceiling fans that depend on the dwelling characteristics and the operating time.

Externalities assessment

Heat rejection and Urban Heat Island effect

Due to the high thermal inertia of dense urban centres and the shelter from the wind caused by the height of the buildings there, the temperature in city centres is often higher than the one found, at the same time, in the surrounding rural area. This effect, known as the urban heat island (UHI) effect, has long been widely studied [212].

Since they are based on a classic thermodynamic cycle, conventional cooling production technologies reject the thermal energy that they evacuate from the cooled spaces. This energy is often released outside the space and nearby. For more than a decade, studies have pointed out that the use of air conditioners can influence outdoor temperatures in cities [213]. In addition, the effect of the UHI also influences air conditioning consumption in cities [214].

The feedback effect described here between UHI effect and air conditioning consumption is taken into account in this study by means of correlations already identified in the scientific literature. The study, published in 2017 by Theeuwes, Steeneveld, Ronda, and Holtslag, titled "A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe" [215] established a correlation between geographic and meteorological data and the maximum temperature difference between the interior and exterior of an urban area over a day (UHImax). This correlation was assessed on fourteen cities across Europe.

In the scope of this study, the value of UHImax will be estimated on each simulated day by this correlation.

$$\mathbf{UHI_{max}} = \left(\mathbf{2} - \mathbf{SVF} - \mathbf{f_{veg}}\right) \times \sqrt[4]{\frac{\mathbf{S} \times \mathbf{DTR^3}}{\mathbf{U}}} \tag{5.21}$$

Where:

- *SVF: the sky view factor, in %*
- *f_{veg}: the vegetation fraction, in %*
- *S: the daily average solar radiation, in W/m²*
- *DTR: the diurnal temperature range at the rural site (Tmax − Tmin), in K*
- *U: the daily average wind speed, in m/s*

This correlation allows the integration of the simulated district diversity in assessment of the UHI effect. However, any potential local efforts to increase green spaces will not be considered, and the values for vegetation fraction, the proportion of green district area, will be derived from the real districts located in Île-de-France.

The sky view factor (SVF) value will also be derived from the real districts. The method used relies on the assumption that the SVF is everywhere equal to its value in the middle of a street with the average dimensions of the district. The equation used was proposed by Oke [212].

$$\boldsymbol{SVF_{mid-canyon}} = \boldsymbol{cos}\left(\mathbf{atan}\left(\mathbf{2} \times \frac{\boldsymbol{H}}{\boldsymbol{W}}\right)\right) \tag{5.22}$$

Where H is the height of the building and W the width of the street.

Since districts under study are located in France, the average footprint-weighted height of each district can be easily retrieved from the IGN topographical database[2]. However, the street width evaluation requires to make assumptions.

From the topographical database, the total area of buildings and courtyard footprint can be obtained. By subtracting this area to the total district area, ones get the area of the streets, parks, and places. As all these spaces contributes to heat dissipation, they will be considered together as the “street area”. In addition, the topographical database provides street length value. The average street width is then

[2] The French topographical database is available online https://www.data.gouv.fr/fr/datasets/bd-topo-r/

obtained, dividing the street area by the total street length. Using the equation (5.22), an average SVF value, characteristic of every typical district, can be estimated.

Furthermore, a significant advantage of the Theeuwes et al. correlation is that the heat rejections resulting from air conditioning use can be factored into estimating the magnitude of the UHI effect. Indeed, Theeuwes et al., 2017, specify that "if the amount of anthropogenic heat release is known, it could be added to S" [215].

In addition to solar gains, the value of S will be composed of thermal contributions related to road traffic and air conditioning heat release. The estimation of the contribution attributable to traffic is based on the Pigeon et al. paper [216]. For an old urban centre and based on measurements, it provides estimates of thermal power contributions by different types of roads. The study takes into account traffic daily variation by proposing an average surface heat release and a value associated with the daily traffic peak. Given that the Theeuwes equation only incorporates a daily average value of anthropogenic contributions, the average value proposed by Pigeon et al. will be retained.

Pigeon et al. distinguishes between downtown roads, major roads, and motorway rings. One of the assumptions of the present study is to exclude local characteristic consideration of the real districts when they do not represent regional or continental realities. Consequently, any potential major roads and motorway rings located on the periphery of the real districts will not be taken into account. For each case, the retained value will be 5.5 W/m² for 100 m of street within 100 m per 100 m cells [216]. Thus, the estimation of traffic contribution will integrate street density within the district.

The assessment of air conditioning heat release will focus on RACs only. Indeed, as VRF outside units are located on the building roof and district cooling are managing heat dissipation through latent heat or discharge into nearby water bodies, only portable and split units can have a significant effect on the UHI.

For split units, the heat released will be estimated by summing the cooling produced to the power consumption (in W). For portable unit, the same reasoning will be followed. Nonetheless, as the condenser and the evaporator are packaged in the same unit, this type of system is responsible for heat gains, assumed to be equal to power consumption. Therefore, only the cooling produced (in W) will be considered as heat released due to portable unit use.

For split and portable units, the heat release will be divided by the total unbuilt area of the district to get a value in W/m², averaged over the day and added to S.

It is already known that the value of the UHI effect is not constant throughout the day [217]. To obtain an hourly outdoor temperature meteorological file dependent on heat rejections, it is necessary to disaggregate this daily UHImax for each hour of the day.

With this aim in mind, the following equation can be used, suggested by Yang et al. [218] :

$$\mathbf{UHI_h = UHI_{max} \times \left(0.5 \times \sin\left(\pi \times t_i - \frac{\pi}{2}\right) + 0.5\right)} \tag{5.23}$$

Where UHI_h is the hourly intensity of the UHI effect, and t_i the hour of the day.

This equation is only valid over extended periods. Therefore, UHImax values should be obtained over a week through a rolling average. This approach maintains a distinct UHImax value for each day and smooths out short-term temporal variations.

Subsequently, it is possible to generate a new meteorological temperature file, and it necessitates rerunning the thermal simulation. To optimize the trade-off between low simulation computation time and accurate results, the order of simulation is as follow:

- UHI assessment based on the rural zone weather file (Data source Meteonorm V8) of the selected city, and district characteristics (without heat emissions),
- first simulation run using this UHI-integrated weather file and retrieval of the units' heat releases,
- second UHI assessment using the obtained heat releases, creating a final weather file,
- second simulation run using this updated weather file incorporating the heat releases.

This method allows for estimating air conditioning overconsumption associated with the UHI effect. Although a more detailed estimation could be achieved with a third UHI assessment, preliminary runs have shown that the results are sufficiently accurate after the second assessment.

Even though the latest version, V8, of Meteonorm Software includes files that consider the UHI effect in several European cities, the decision was made to set them aside and instead utilize the geographical characteristics of the four studied districts and the estimated heat releases.

Thermal discomfort

As detailed above, the use of air conditioners can affect the outdoor temperature of an urban district. However, in this study, only the indoor comfort of the dwellings will be considered. Indoor discomfort is an externality accounted for in this work. In order to assign it a monetary value or internalize it, Grignon-Massé suggests a value of 0.6 €/°C·h per occupant [186]. He based this on a literature review concerning tertiary buildings and an estimation for the residential sector. This value will be reused as is.

To obtain a district discomfort value in degree-hours per occupant, at each time step, the difference between the indoor temperature of each dwelling and its summer comfort temperature will be, summed over the whole year, expressed in °C · h, and multiplied by the number of occupants. The total sum for the entire district will provide a thermal discomfort value to be multiplied by the selected monetary value.

Noise discomfort

Noise discomfort is an externality linked to the use of air conditioners and already identified by the European legislator [219]. As for thermal discomfort, it will be considered only indoors for this study.

Firstly, a distinction will be made between discomfort caused by indoor noise and discomfort caused by outdoor noise, which penetrates indoors through the windows. The noise generated indoors, primarily attributable to the portable systems with the compressor located indoors, will be addressed in a dedicated paragraph at the end of this section. The remainder of this section pertains to the noise produced by the outdoor units of split and VRF systems.

For this assessment, Grignon-Massé's thesis and other studies [220,221] highlighted the relevance of using a threshold in decibels at which noise discomfort can be counted. This threshold being dependent on the surrounding outdoor noise, it remains open to discussion.

The outdoor noise is evaluated at the scope of a district. In this configuration, a simplified study of systems' influence on the surrounding noise of the district will often result in an average discomfort value found to be below the determined discomfort threshold. The discomfort estimated with this method would result to be null.

However, even a single air conditioning unit can generate noise discomfort. Therefore, a more detailed method for noise discomfort assessment is necessary. The methodology, presented below, will be based on geometrical sound dissipation simplified models, taking into account reverberations and average geographical properties.

Geometry

To account for the particularity of European urban district, two models of outdoor areas will be developed: the multi-family buildings model and the single-family house model.

The first model is designed to assess noise levels in neighbourhoods where multifamily houses and apartment blocks predominate. It is divided into two zones: the building street and the building courtyard.

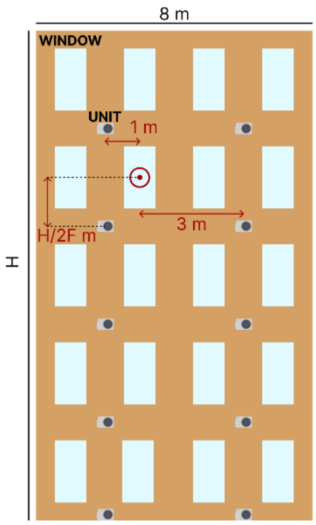


Figure 53. Base façade geometry of the first noise model

These two zones are based on the same façade geometry presented in Figure 53. The dimensions, window and outside units' possible locations are represented. The façade is composed of four columns of windows. The saturation level of outdoor units is assumed to be of one outdoor unit every four windows, i.e., half of the available locations. Outdoor units can be placed randomly but there are always two possible locations on the floor.

The street zone is made up of two rows of A facades arranged face-to-face and separated by W metres. The courtyard zone is composed of B facades arranged on a square of W metres side.

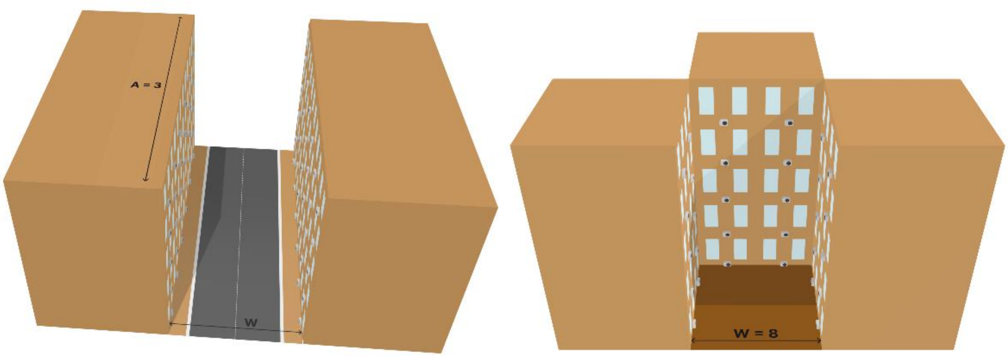


Figure 54. Visualisation of the building street zone (left) and the building courtyard zone (right) of the first noise model.

Even though the illustrations have identifiable dimensions (as H, building height, and F, number of floors) for clarity, the use of models will incorporate the average dimensions of the studied districts.

The second model is designed to assess noise levels in neighbourhoods where single-family houses predominate. As they rarely form courtyard, it will only be composed of a street zone, composed of the symmetrical façade geometry presented below. The street zone is characterized by a W meter width and a S meter space between two houses.

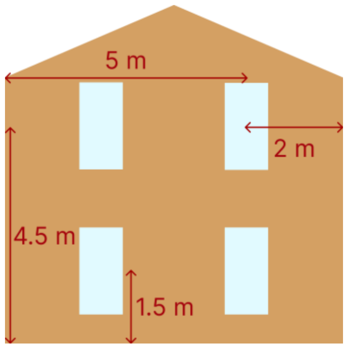


Figure 55. Base façade geometry (left) and visualisation of the street zone (right) of the second noise model.

When using this model, the number of floors is neglected, and the façade geometry never changes. The outdoor units of split systems are assumed to be systematically placed between two houses, as is customary and often recommended.

Subsequently, the noise produced by the split units is shielded by the walls of the two houses that flank it. Therefore, it will be assumed that each split unit can only disturb the houses in front of it. A simple geometric calculation allows for the determination of which windows can directly be affected by the noise from a unit placed opposite. This often leads to every window of the two closest opposite houses.

The outdoor units of VRF systems, which also generate noise, are placed on the roof, in the middle of the facade, and set back by 5m. The saturation level is represented by one system per facade. In the first model, they affect all windows facing the street in the street zone, but none of the windows in the courtyard zone, assumed to be shielded by the roof. In the second model, they also affect all windows facing the street.

Sound calculations

In each model, the sound level is estimated at each window from the sum of the sound intensities resulting from the units placed in the model. Window and units are reduced to points in a three-dimensional coordinate system.

At a given window, the sound intensity produced by a system is estimated from the sound level using the equation below:

$$\boldsymbol{L = L_{P_{sys}} + 10 \times \log_{10}\left(\frac{Q}{4 \times \pi \times r^2}\right)} \qquad (5.24)$$

Where L is the sound level at the given window point (in dB(A)), Lp_{sys} is the sound power level of the unit (in dB(A)), r is the distance between the window and the unit (in meter), and Q the sound directivity factor [194].

The sound power level of the unit is a unique value for the whole district. For split system, it is equal to the average of 62 dB(A) for 5 kW split and 66 dB(A) for 10 and 15 kW split [222], weighted by the number of each in the district. For VRF, the sound level of a unit is 82 dB(A) [192].

The sound of the units is supposed to evolve in the free field but in a different space depending on whether it is a unit on the façade or on the ground. In the first case, the sound evolves in a half-sphere (Q = 2) in the second, the sound evolves in a quarter-sphere (Q = 4).

For each system at the given window, the sound level is estimated and the resulting total sound level for that window is obtained with equation (***5.25***).

$$\boldsymbol{L_{window} = 10 \times \log_{10}\left(\sum_{i}^{units} 10^{\frac{L_i}{10}}\right)} \tag{5.25}$$

At the end of this calculation, carried out for each window, a value of pressure level per window is retrieved.

The sound pressure level value selected is the day-evening-night noise indicator, or L_{den}, taken from the Directive 2002/49/EC on Environmental Noise [223]. Therefore, for each window, L_{window} will be increased by 0 (7 a.m. to 7 p.m.), 5 (7 p.m. to 11 p.m.) or 10 dB(A) (11 p.m. to 7 a.m.). This allows for accounting only the noise generated by air conditioning systems by penalising it if it takes place in the evening or at night.

Based on this definition and the EEA recommendations [224], uncomfortable windows are considered to be those for which the L_{den} is greater than 55 dB(A).

The noise discomfort indicator Ndis, associated with a configuration, is evaluated using equation (***5.26***).

$$\boldsymbol{N_{dis} = \frac{\sum_i^n \left(L_{den_i} - 55\right)_{,\ L_{den_i} > 55dB}}{n}} \tag{5.26}$$

Where n is the total amount of windows.

With this method, the noise discomfort caused by a single unit can still be assessed, even though it will result to be very low.

Sensitivity analysis

The final result, Ndis, the average noise discomfort at a window, depends on various parameters including the penetration rate of air conditioning units. A brief sensitivity analysis identified a dependency of Ndis on the street length. This can be explained by two effects:

- Edge effects: windows at the ends of streets are more comfortable and they are proportionally numerous on smaller streets.
- Long distance effects: an uncomfortable window will also be disturbed by distant systems which are more present, at equal penetration rates, on long streets.

The dependence of Ndis on the width of the street is explained by the proximity of the systems located in front. The noise discomfort in the courtyard seems to be poorly sensitive to its dimensions. Moreover, for the same number of windows, the courtyard is more uncomfortable than the street. However, the courtyard appears to be less uncomfortable than longer street for the same penetration rate.

These two observations, which could contradict a logical approach of the problem, seem to indicate that the phenomenon of sound reverberation must be integrated into the Ndis calculation.

Sound reverberation

The phenomenon of sound reverberation can be integrated into the calculation of Ndis by adding a term to equation (5.24), in order to get the following equation [225].

$$L = L_{P_{sys}} + 10 \times \log_{10}\left(\frac{Q}{4 \times \pi \times r^2} + \frac{4 \times (S - A_{eq})}{S \times A_{eq}}\right) \tag{5.27}$$

Where S is the total surface of the volume studied (in m²), and A_{eq} is the equivalent area of absorption (in m²), defined as:

$$A_{eq} = \sum_{i}^{st} \propto_i \times S_i \tag{5.28}$$

Where α is the absorption coefficient of a defined surface i, st the total number of surface type, and S is the real area of the surface (in m²).

Using the following α coefficient and assuming that each window has a dimension of 0.9 × 1.8 m², the equivalent area of absorption for the two zones can be retrieved.

Table 43. Absorption coefficient used in the noise models [225].

Surface type	α coefficient at 125 Hz
Concrete masonry / Tarmac	0.01
Opening	1
Glass (thick pane or double-paned)	0.15
Brick (unglazed)	0.02
Gravel	0.25

Taking into account that all the windows are closed all the time, the share of the glass surface for the two zones is constantly equal to 28.52 %.

An interesting point to note is that the uncertainty of Ndis related to the placement of outdoor units among their possible positions is significantly reduced when considering the reverberant field. Indeed, the intensity of reverberation is not dependent on the system's location.

Another widely identifiable difference due to the integration of reverberation is the dependence of the result on the dimensions of the yard. The yard is also systematically more uncomfortable than the street for comparable dimensions.

Ambient noise assessment

In addition to the noise caused by air conditioning systems, other sources of environmental noise contribute to noise discomfort. All these sources will form an ambient noise assessed in this study, independent of the solutions being investigated. It is essential to consider this ambient noise, especially to observe the effect of various technologies and measures on noise discomfort more clearly.

Among all these sources, the European Environment Agency has repeatedly emphasized that road traffic is the most dominant source [224]. Therefore, the assessment of the ambient noise will be limited to the noise from all sources associated with transport.

It is quite challenging to establish a correlation between the already defined characteristics of the four district archetypes and the ambient noise in these districts. The works conducted on this topic has shown unconvincing correlations [226,227].

Therefore, this assessment will rely on local ambient noise data for Île-de-France, finely modelled by the regional noise observatory, BruitParif[3]. The average noise values from transportation in the four studied districts are presented below. The motorway in the *urban periphery* district will not be included in the area average calculation, which is based solely on areas where buildings can be found.

Table 44. L_{den} indicators for the sound level associated with cumulative transport noise in the four studied district [228].

District	Lden (dB(A))
Old urban centre	62.7
Dense urban district	59.2
Large housings	59.5
Urban periphery	62.5

They will be used in the method for the remainder of the study. Since these are weighted average values according to the day-evening-night method, they will be added, as constant values, to the Lden values found for air conditioning noise.

Cost evaluation method

At each simulation time step, the number of air-conditioning systems emitting noise to the outside and the number of dwellings with opened windows will be counted.

The number of systems will allow to deduce a time-dependant penetration rate. Depending on the building type predominance of the district and its characteristics, the method presented above will lead to a Ndis value. This value will be unique for the second model but, for the first one, Ndis value will be different in the street zone than in the courtyard zone. Then, for the first model, an average value of Ndis will be calculated weighted by the façade length of street and courtyard in the district.

Therefore, an equal installation and operation of the AC systems among street and courtyard side of the building is assumed.

[3] BruitParif is the observatory of noise in Ile de France Region operating under the status of association https://www.bruitparif.fr/

The Ndis value will be multiplied by the number of dwellings with opened windows. All the values obtained in this way at each time step are then averaged over the year. The average found is then multiplied by 25 €/dB(A) per dwelling per year to obtain the social cost induced by the noise [186].

In addition to these considerations, the noise generated inside dwellings by portable systems will be taken into account. A value of 63 dB(A) for the sound power level will be used [222]. With an approximate indoor reverberation time of 0.5s and the use of the Sabine formula, it is possible to account for sound reverberation. The noise will be assumed to be constant when the system is turned on, and the running time period will allow the calculation of the discomfort cost. Indoor noise produced by other air-conditioning systems will be excluded.

GHG emissions

The GHG emissions are another externality accounted. Two sources of emissions will be assessed in the scope of this study, the refrigerant fluid leaks during use phase (direct emission) and the one caused by power consumption (indirect emission). The estimation of GHG emissions will be limited to the use phase.

Regarding refrigerant leaks from air conditioning systems, the estimation is based on several assumptions. Firstly, the assumption put forth by Grignon-Massé of a 3 % leakage of the total system refrigerant charge per year will be adopted for portable, split, and VRF systems. Secondly, the refrigerant charge for each of these systems will be based on the same system archetypes used previously [222]. Finally, the types of refrigerants used will be R290 for portable systems and R410A for others.

The indirect emissions associated with electricity consumption strongly depend on the considered electricity mix. Three values will be considered, one for each previously defined climate zone. The following values, retrieved for 2020, will be used: 57 gCO2e/kWh (France), 453 gCO2e/kWh (Greece), 65 gCO2e/kWh (Finland) [229].

The cost of one tonne of CO_2 emitted depends on the prospective scenario considered. The value of 100 €/tCO2e will be used.

5.3. Results

Due to the limitations of this study with regards to the parameters available at continental European level, this section will focus primarily on the results based on French data, and present results in detail. The aggregated results of the further climates are included in Section 5.3.7.

5.3.1. Reference scenarios

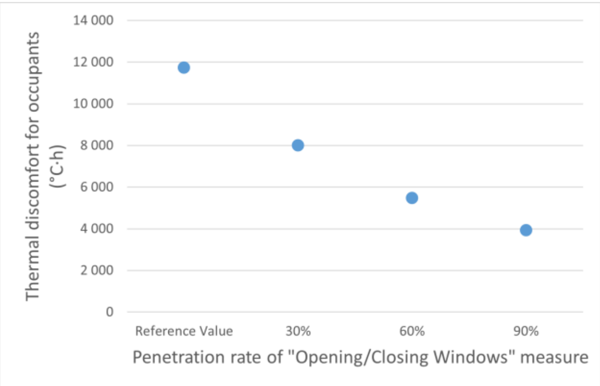
The first results of the cost-benefit analysis to be presented are those of the reference scenario. Assuming that no technology or measure is implemented in the building stock, simulations make it possible to obtain values for thermal and noise discomfort that will serve as a basis for comparing the benefits provided by the solutions considered.

Table 45. Preliminary reference scenario results.

Indicators	unit	Old urban centre	Dense urban district	Large housings	Urban periphery
Thermal discomfort for occupants	°C·h	11 735	12 166	11 599	10 747
Noise discomfort from windows	dB(A)·dwe·y	0	0	0	0

Thermal discomfort varies from one district archetype to another, depending on the characteristics of the dwellings within it. Noise discomfort is null since it is assumed that the occupants can't open the windows and that, when they are closed, they do not allow outside noise to pass through.

By gradually including the possibility of opening windows in 30 %, 60 % and 90 % of the most uncomfortable dwellings in the stock, these discomfort values can be expected to change. For the Old urban centre located in France, the results are show below.



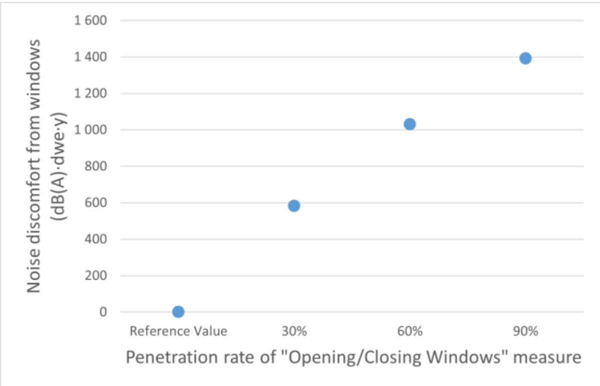


Figure 56. Thermal (left) and noise (right) discomforts in Old urban centre district located in France depending on ventilation penetration rate.

As detailed in the section 5.1, the results are averaged over the entire building stock to ensure a reliable comparison between districts. Letting more dwellings with the ability to open and close their windows will decrease thermal discomfort and increase noise discomfort based on outside ambient noise. The rates of decrease/increase of these trends are greater with lower penetration rates. This can be explained by the fact that it is initially the most uncomfortable dwellings that are equipped. These dwellings tend to make greater use of the solutions put in place than those equipped last.

As this measure has no internal costs or externalities other than those already presented, its cost-benefit analysis is limited to the internalisation of thermal and noise discomfort costs. With the chosen value of of 0.6 €/°C·h per occupant disturbed, the benefit in terms of thermal discomfort provided by a penetration rate of 90 % is 8 493 € per dwelling per year. With a value of 25 €/dB(A) per dwelling disturbed per year, the loss in noise discomfort in the same scenario is 36 € per dwelling per year. The monetary values are averaged over the whole building stock.

In view of these results and the specific characteristics of this measure, it seems appropriate to include it in the reference scenario that will be used for the technologies and other measures under consideration. Indeed, without this measure, thermal discomfort is considerable. This might affect the reliability of the comparison. Moreover, the cost-benefit analysis suggests that it is highly advantageous to introduce this measure. Finally, openable windows are widely used in European buildings, and more specifically in the residential sector. The main exception is large high-rise buildings, due to safety concerns that would be difficult to circumvent.

For all these reasons, the remains of this analysis will be based on the assumption that the measure “opening/closing windows” will be implemented in every dwelling as a new reference scenario. In other words, the “reference scenario” on the following will be equivalent to a 100 % penetration rate of opening-windows measure.

The results of this reference scenario are listed below.

Table 46. Reference scenario results.

Indicators	Unit	Old urban centre	Dense urban district	Large housings	Urban periphery
Thermal discomfort for occupants	°C·h	3 629	3 684	3 264	4 048
Noise discomfort from windows	dB(A)·dwe·y	1 485	1 408	847	943

The thermal discomfort values shown are expressed in °C·h of discomfort. They are weighted by the number of occupants in the uncomfortable dwellings and are therefore comparable from one district to another.

The observed differences in noise discomfort take into account: the number of dwellings in the neighbourhood, the proportion of dwellings that open their windows and external ambient noise. The proportion of dwellings with their windows open is more or less identical between districts (between 19 and 22 % over the year). It is above all the number of dwellings in the stock (ranging from 583 dwellings in the urban periphery to 1669 in the Dense urban district) and the difference in ambient noise that explain this disparity. In order to be able to compare the districts more fairly, the monetary values presented below will be given per dwelling.

5.3.2. Thermal discomfort reductions

By implementing the various technologies and measures identified in the four districts, a reduction in the thermal discomfort indicator is expected in all scenarios, with a greater reduction the higher the penetration rate. These results, obtained with the French set of parameters, are presented below.

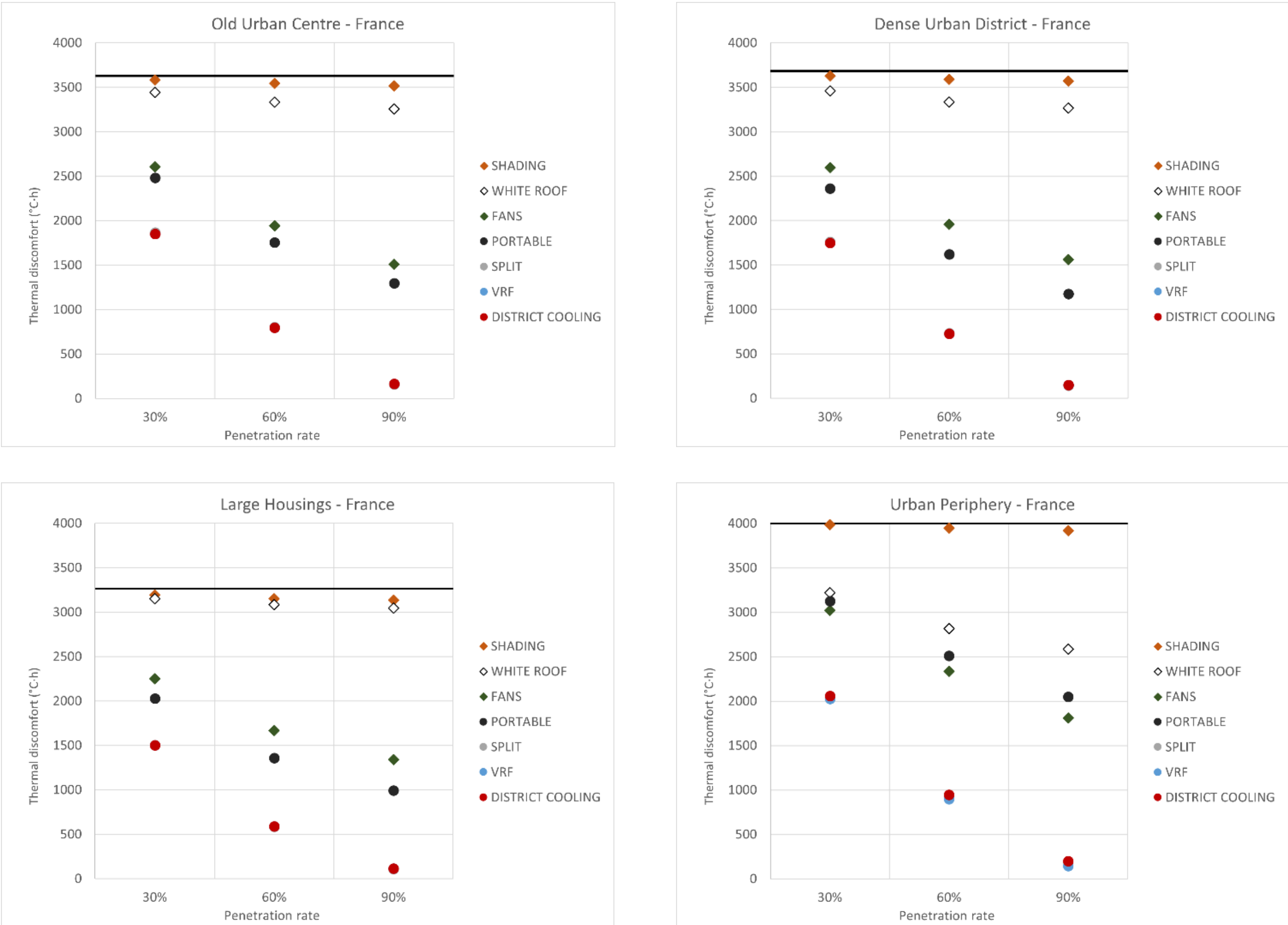


Figure 57. Thermal discomfort in the four district archetypes located in France depending on the penetration rate of the solution considered.

The position of the x-axis indicates the thermal discomfort obtained in the reference situation, presented in Table 46.

The solution that results in the least reduction in calculated thermal discomfort is the shading device (venetian blind). This observation holds true across all district archetypes and appears to be independent of the geographical context. The reason that seems to justify this limited effect is related to the control assumptions. Based on a literature review, the selected control assumption implies that only a small percentage of dwellings with blinds installed will actually use them. For Old Urban Centre with a penetration rate of 90 % of the “Shading device” measure, only 9.2 % of all dwellings are using blinds on average over the periods where cooling needs of the building stock is non-null.

The use of white roofs remains of limited interest but superior to shading devices. The reduction in thermal discomfort appears to be linked with the average number of floors in the district. While the Old Urban Centre and Dense Urban District consist of buildings with an average of 6 floors, this number increases to 11 for Large Housings and decreases to 2 for the Urban Periphery. The roof surface that can be painted is limited in very tall district, and it is not surprising to observe that this measure has a more significant effect in a district primarily composed of Single-Family Houses (SFH).

The effect of fans does not appear to be strongly linked with the district archetype. However, it is the measure studied that consistently demonstrates the most significant effect in terms of reducing thermal discomfort. This can also be explained by the fact that extreme temperatures are rarely encountered in this climate zone. Indeed, the outdoor temperature exceeds 33 °C only during 4 % of the time when thermal discomfort might be experienced. Situations where fans are not effective in reducing thermal discomfort, i.e., when the indoor temperature exceeds 33 °C, occur only rarely.

Portable air conditioning systems have the least significant effect among the studied technologies. This observation can be attributed to their low energy efficiency and their effects on internal heat gains and infiltrations.

Split systems, VRF, and district cooling network have comparable effects on thermal comfort. Indeed, their marks on Figure 57 are almost always inseparable. However, in the Urban Periphery, VRF systems demonstrate higher effect compared to splits and district cooling network. In this district, it is challenging to share the use of a VRF system across multiple houses. Therefore, with one system per house, the installations are largely oversized, allowing for a slightly greater reduction in thermal comfort by providing significant cooling power during peak demand periods.

5.3.3. Noise discomfort effect

In addition to their effect on thermal discomfort, the solutions considered have an effect on occupants' noise discomfort. These effects are presented below. As in the previous section, the x-axis is located at the reference discomfort level (bold line in Figure 58).

In the reference situation, the occupants open the windows, resulting in "outside noise" discomfort. Here, only the noise discomfort experienced by the occupants of the dwellings is assessed. Outside noise should be understood as noise coming from the outside through the windows and "inside noise" as noise coming from the inside. The sum of the two is presented above.

In this study, the only source of indoor noise considered is that produced by portable air-conditioning systems. It is therefore zero for all other solutions. For this reason, but also because of their low efficiency, portable systems are the ones whose use causes the most noise discomfort, in all scenarios. The more these systems are installed, the less occupants open their windows, so the more outside noise is reduced. However, the increase in their penetration rate leads to an increase in inside noise. Overall, the first effect is not enough to counterbalance the second, and the installation of additional portable systems always produces more noise discomfort.

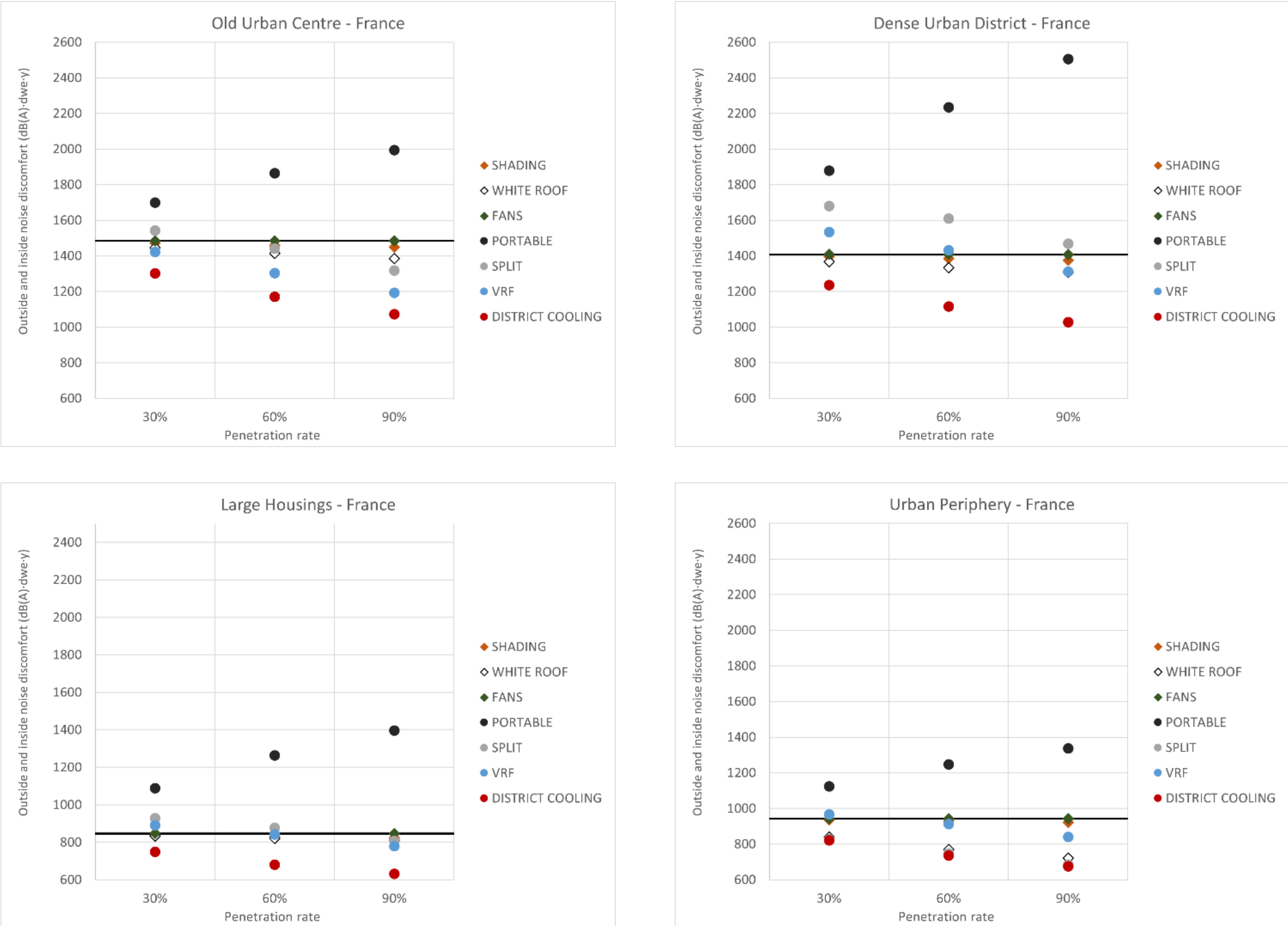


Figure 58. Outside and inside noise discomfort in the four district archetypes located in France depending on the penetration rate of the solution considered.

The trend is reversed with the other technologies studied. The more widespread the technologies, the more occupants close their windows and the less they are disturbed by outside noise, including the one produced by the systems themselves. Installing an air-conditioning system in another dwelling leads to two contrary effects on noise discomfort: increasing outside noise and allowing the occupant to keep the windows closed more often. These result in the possibility, in some cases, to draw a curved line of noise discomfort against the penetration rate with the three dots presented above.

The effect of cooling network at 30 % penetration rate is already positive. This is allowed by the assumption that this system does not produce any outside sound. Therefore, district cooling is the most interesting solution, in all scenarios, regarding noise discomfort. Split and VRF systems, which produce outside sound, give intermediate results. VRF systems are often more interesting than split systems. Even if the sound power of a VRF outdoor unit is greater, there are fewer of them for the same number of dwellings connected, and their location on the roof reduces the effect. This observation is reversed in Urban Periphery, since for an SFH, there are the same number of VRFs as split units for one dwelling connected.

The effect of the measures on noise discomfort is slight. This is mainly because they don’t produce noise and due to their limited impact on thermal discomfort, which consequently limits their effect on window opening. This is confirmed by the significant effect of white roofs on noise discomfort in the

Urban Periphery, in line with their effect on thermal discomfort. Fans do not affect noise discomfort as it was assumed that this measure do not affect window opening at all.

5.3.4. Costs

To be able to accurately assess the benefits of one solution over another, it is necessary to add cost considerations to the analysis. Even a solution with a limited impact may be worthwhile if it also comes at a lower cost.

Internal costs

Internal costs, covering CAPEX and OPEX, are valued as cumulative discounted cash flow over the lifetime of each solution considered. They are presented below for each solution and divided, in each case, by the number of dwellings in the district. The values presented are therefore in € per dwelling.

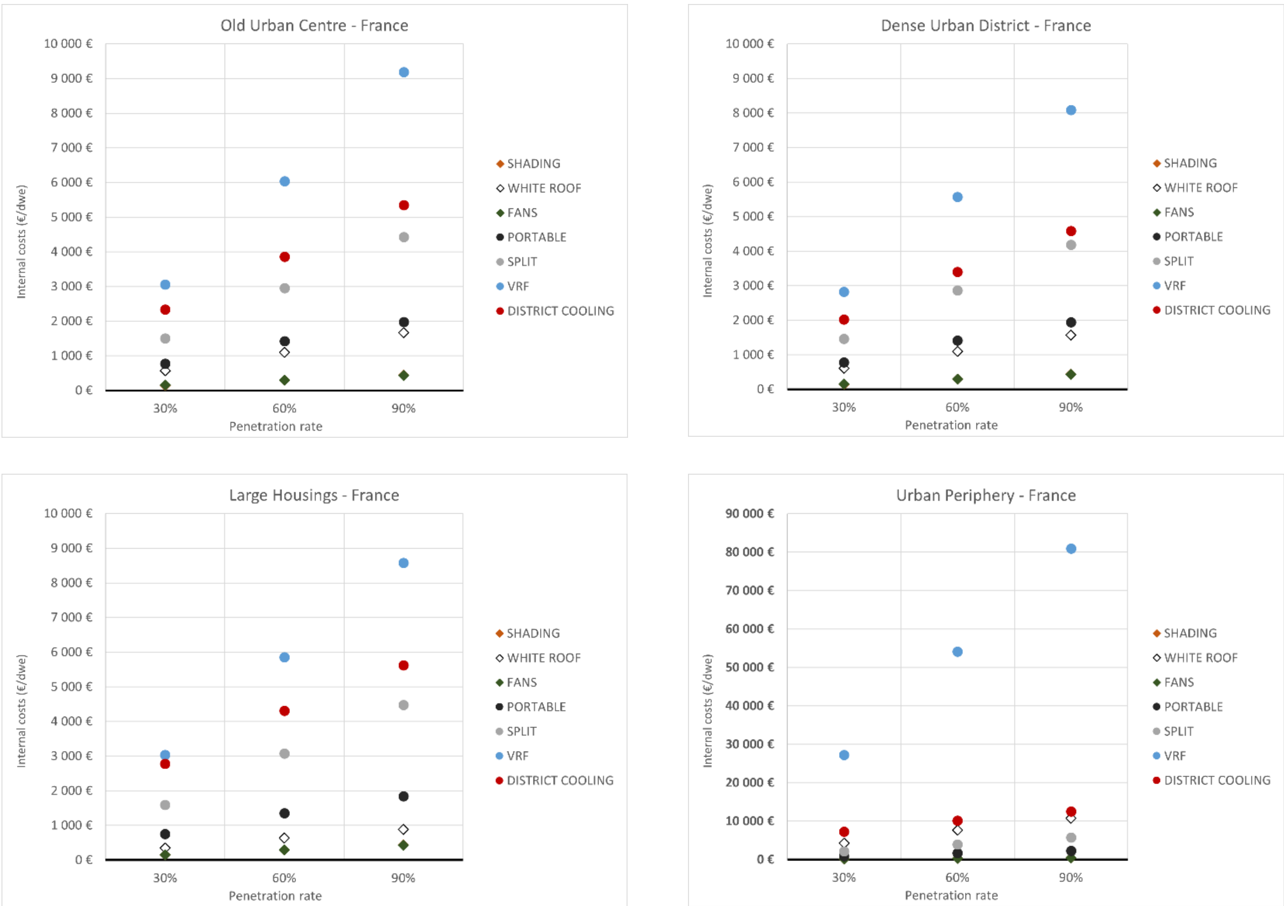


Figure 59. Internal costs (CAPEX and OPEX) of the solutions considered in the four district archetypes located in France depending on their penetration rate.

At a first glance, these costs evolve linearly with the penetration rate. In every scenario, VRF systems are the more expensive option, also related to their high installation cost, in €/kW, compared to the other technologies. District cooling and split systems are, respectively, in second and third position. Portable systems are, as expected, the cheapest technology. In Urban Periphery, the cost of VRF systems becomes considerable due to the SFH they comprise, and the cost of district cooling network is higher due to low density.

The measures include white roofs, always more expensive than fans and blinds, placed in near equality. In the Old Urban Centre, Dense Urban District, and Large Housings districts, all the measures are cheaper than the technologies. In Urban Periphery, due to the large surface area per dwelling, the white roof measure requires a higher value of internal cost, superior to the one of split and portable units.

These results were anticipated considering the costs found in the first two parts of this report. Here too, it can be noted that results for the white roof depends on the average building height.

External costs

As in the case of the 'Opening/Closing windows' measure, internalizing externalities significantly favours thermal discomfort. It remains the main, if not the sole, benefit and often renders the costs associated with noise discomfort and direct and indirect GHG emissions negligible in terms of magnitude.

Under these circumstances, it is more meaningful to present results to illustrate this imbalance rather than raw values. The graph below provides a zoomed-in view for the Old Urban Centre results of the cumulative discounted cash flow of external costs over the lifetime of each solution considered.

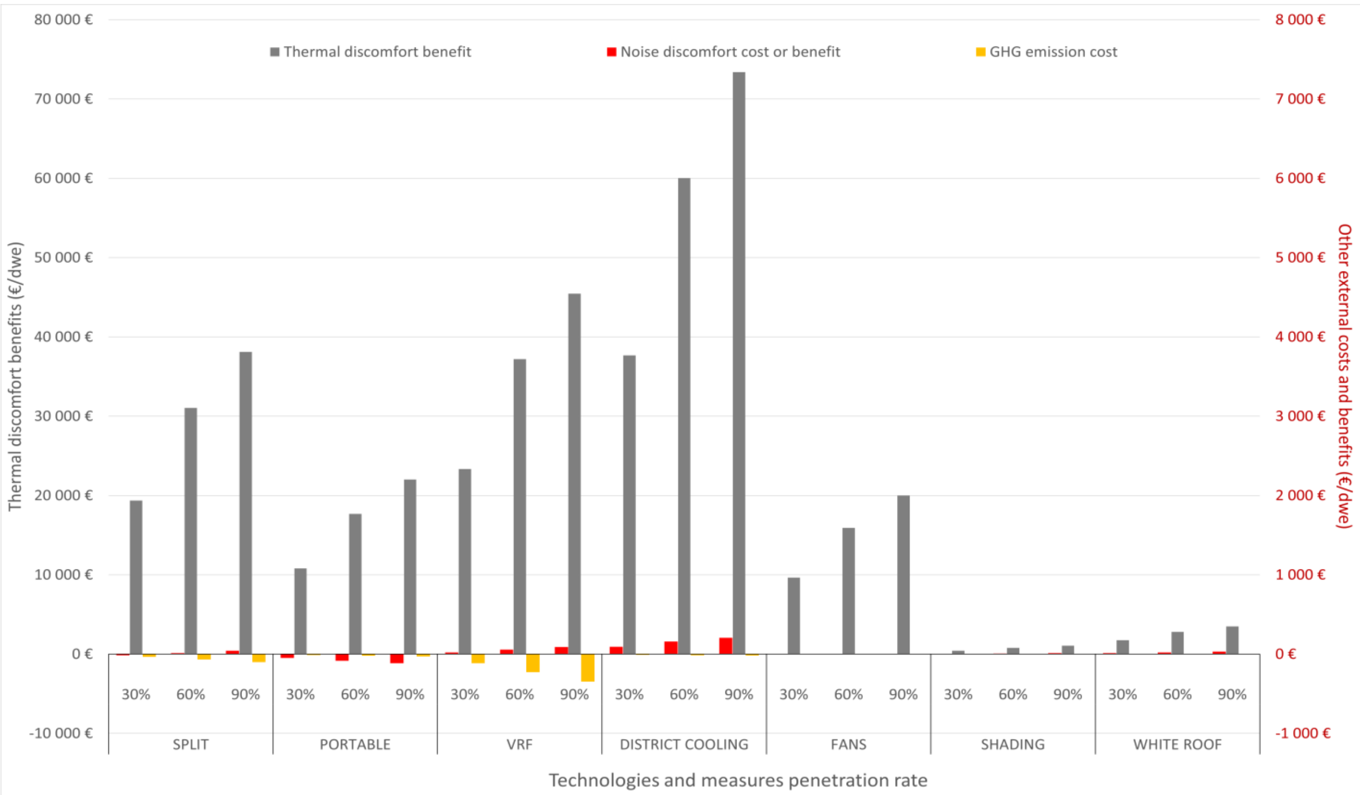


Figure 60. External costs of the solutions over their lifetime in Old Urban Centre district located in France depending on their penetration rate.

With a two-axis graph and a ratio of 1 to 10 between the thermal comfort benefits one and the other, it is possible to measure the imbalance between these values. On average, in the Old Urban Centre, the benefit derived from reducing thermal discomfort is 200 times greater than the other external costs, considered in absolute value and fans excluded.

By summing these cost and benefit values, it is therefore consistent to observe that the ranking of solutions from most to least favourable is the same as identified in the analysis of Figure 57. The split and VRF systems do not end up on par with district cooling due to their different assumed lifetime.

5.3.5. Benefit-cost ratio

Based on all the already presented data, it is possible to evaluate the two indicators of the cost-benefit analysis, the benefit-cost ratio (BCR) and the net present value (NPV).

The BCR of the discounted values over the lifetime of each solution are presented below. Apart from a single case, all the BCR values are greater than 1, which means that each of the solutions studied can theoretically be implemented. Indeed, the technologies and measures under study are all viable and proven solutions. The implementation of VRF systems in Urban Periphery constitutes an exception at high penetration rate.

In every scenario, the fan emerges as the solution with the highest BCR. It stands out as the measure having the most significant effect on thermal comfort and one of the least costly solutions. The district cooling network, despite its internal costs, has a long lifetime, which is reflected in the highest BCR values among all the technologies studied in many scenarios. Portable units despite the high value of their externalities and their low efficiency, have an interesting BCR and are often placed second, or even first, thanks to their low installation cost. The split systems strike a good balance between a relatively low cost and a significant reduction in thermal discomfort. VRF systems have always the lower BCR values due to their high CAPEX and especially their installation cost. White roof and shading device have BCR values located between 1.7 and 6.

The BCR values of VRF and district cooling decrease in the Urban Periphery due to the evolution of their costs in this district. They are inferior to 1 for VRF in this district with 60 % and 90 % penetration rate with values of 0.98 and 0.81 respectively.

All solutions, have lower BCRs as their penetration rate increases, except for district cooling in Urban Periphery. This can be explained by the previously mentioned assumption that favours the installation in the most uncomfortable dwellings. Each additional solution installed in a new dwelling will have less thermal discomfort to reduce, while its cost remains substantially the same. A more detailed analysis of the BCR dependence on the penetration rate could determine an optimal penetration rate, depending on the modelling assumptions.

For the district cooling network, each connected dwelling, even if only slightly uncomfortable, helps increase the density, a central element in evaluating the overall cost of the network. However, the cost of installing the equipment in buildings and dwellings takes often precedence over the cost of the distribution network, except for Urban Periphery. Dependence on the district remains visible, but the influence of the penetration rate is limited when all costs are taken into account.

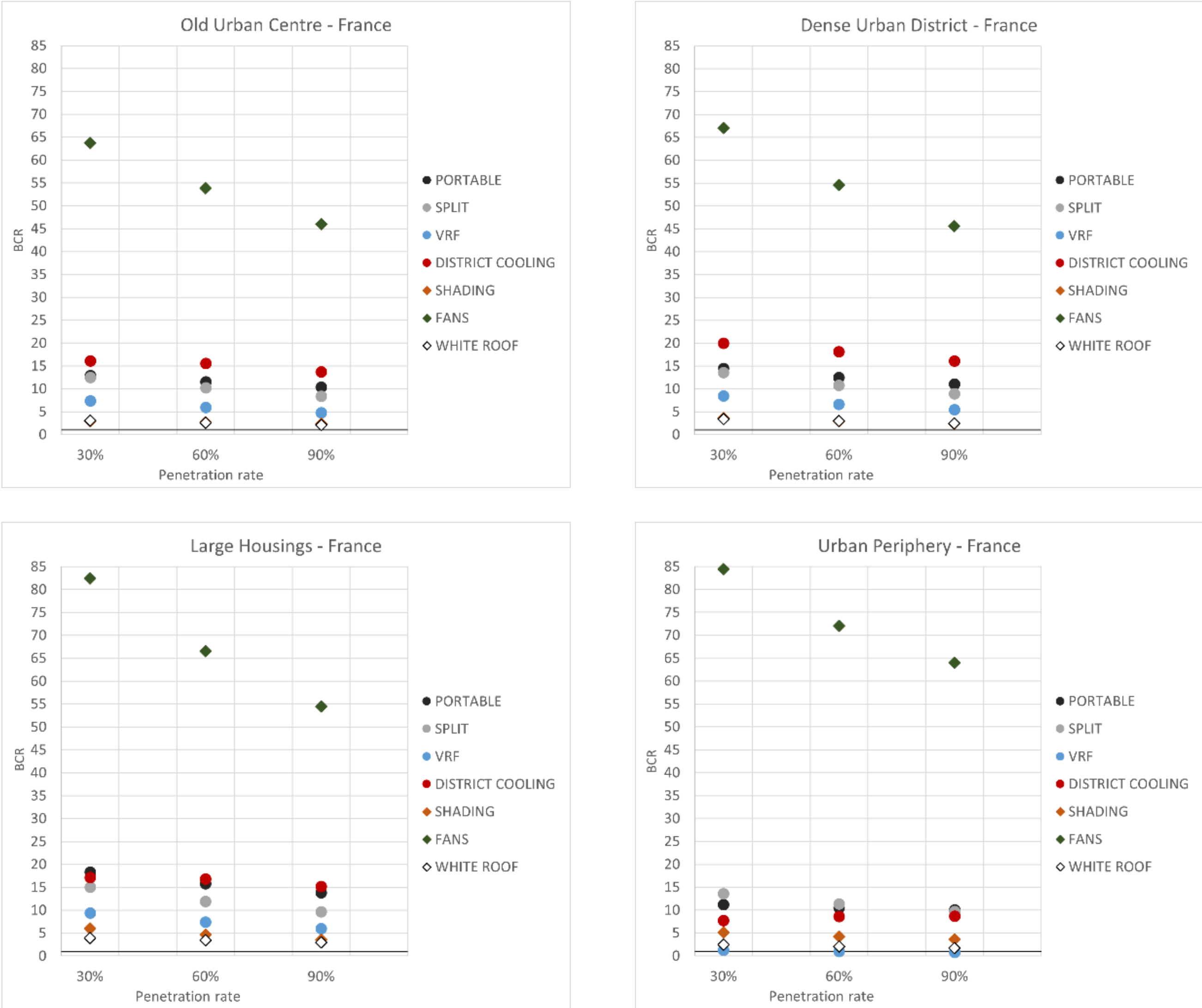


Figure 61. BCR results for all the solutions considered in the four district archetypes located in France depending on their penetration rate.

5.3.6. Net present value

The NPV is the result of the sum of all evaluated costs. It represents the theoretical benefit that could be derived from each solution. Since the cost associated with thermal discomfort is very significant, the results for Old Urban Centre in Figure 62 show the same ranking of technologies and measures to the one based on externalities (Figure 60).

The results for the district cooling in Urban Periphery show the highest benefits. This is related to the fact that, in this district, the average reference thermal discomfort is the highest, coupled with the long lifetime of the district cooling. Over this entire period, this solution will accrue a greater benefit. The only two negative results were also found in the Urban Periphery district. These are the same two scenarios that had negative BCRs: VRF at 60 and 90 %. In line with the previous section, it appears that these solutions should not be implemented in theory.

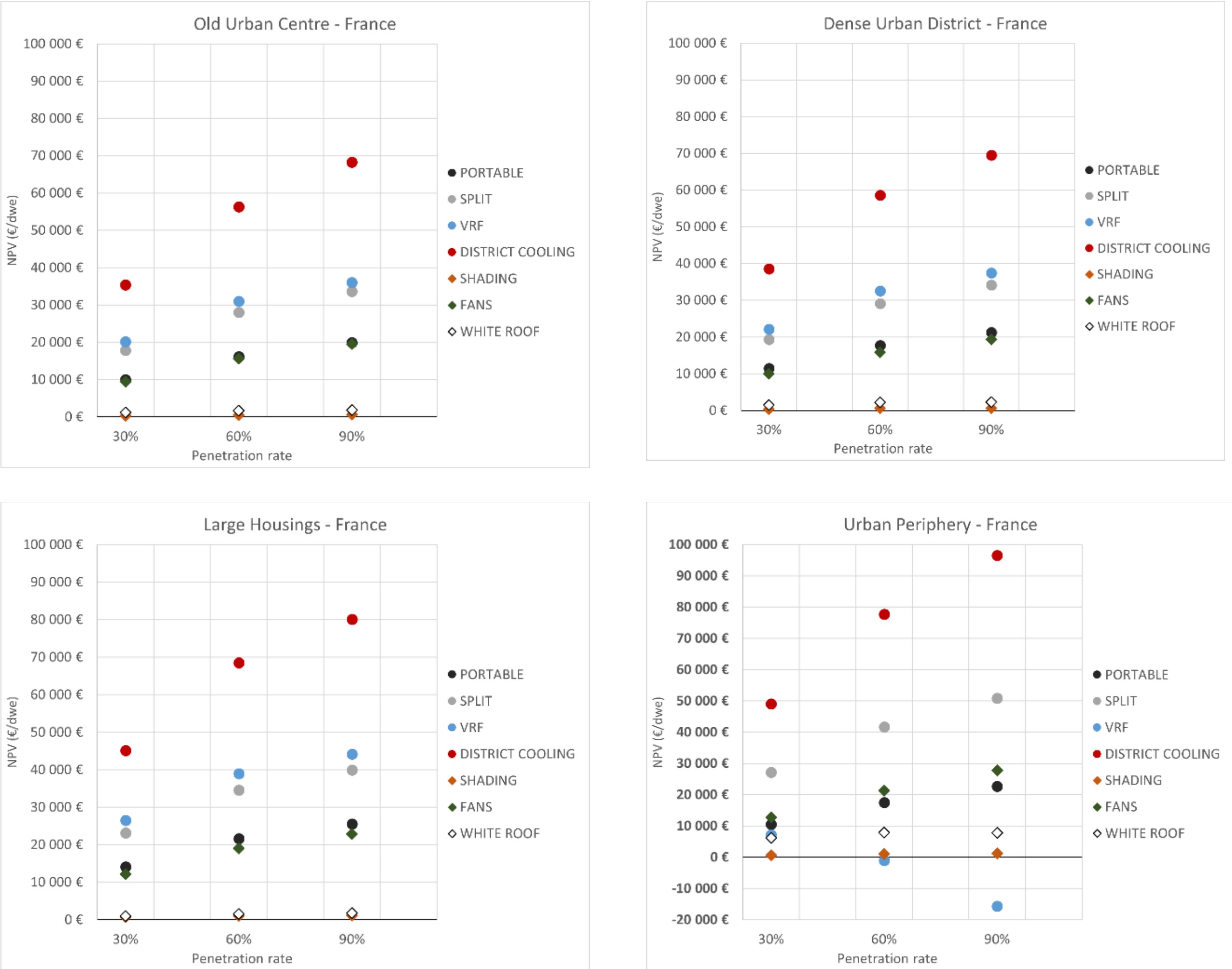


Figure 62. NPV results for all the solutions considered in the four district archetypes located in France depending on their penetration rate.

5.3.7. Climate zones

By changing from one climate zone to another, the weather files, the construction years, the U-values, the window surfaces, the sizing of technologies, and the population density have been modified.

Regarding the reference discomfort values, they are higher the further south they are assessed. As more dwellings are allowed to open their windows, thermal discomfort decreases and noise discomfort increases. With the Athens weather file, these trends are more pronounced than with the Strasbourg file and even more so than with the Helsinki file. The warmer the climate, the more frequently windows are opened by occupants, intensifying the impact on discomfort values.

Using the same reasoning as above, with reference scenarios in which all dwellings can open their windows, the discomfort reference values are given in Table 47.

Table 47. Reference scenario results for all climate zones.

Locations	**Helsinki**		**Strasbourg**		**Athens**	
Discomfort (°C·h or dB(A)·dwe·y)	**Thermal**	**Noise**	**Thermal**	**Noise**	**Thermal**	**Noise**
old urban centre	808	959	3 629	1 485	21 469	3 226
dense urban district	846	933	3 684	1 408	21 614	3 077
large housings	806	584	3 264	847	20 511	1 973
urban periphery	837	601	4 048	943	23 456	2 025

All the technologies and measures installed in the different configurations have proportionally greater effects on thermal discomfort values the cooler the climate (Table 48). In more temperate climates, thermal discomfort is less often caused by extreme temperatures. In these climates, space cooling can more often be managed by any type of system. The difference between climates is even more noticeable for systems that struggle to provide comfort in extreme heat, such as portable systems and fans.

Table 48. Percentage reduction in thermal discomfort based on reference values and induced by the installation of each technology and measure, averaged over all districts and penetration rates.

	Helsinki	**Strasbourg**	**Athens**
Split	-77,3 %	-75,4 %	-69,4 %
Portable	-61,1 %	-48,6 %	-29,0 %
VRF	-77,2 %	-75,7 %	-70,2 %
District cooling	-77,0 %	-75,4 %	-69,9 %
Fans	-57,8 %	-44,1 %	-13,2 %
Shading	-5,6 %	-2,5 %	-1,6 %
White roofs	-5,8 %	-12,7 %	-6,5 %

This effect is slightly counterbalanced by the difference in solar irradiance between climates. This mainly impacts the effects of albedo modification. White roofs are less interesting in Finland than in France because there are less solar heat gains. By way of illustration, the weather file used for this zone indicates a global horizontal irradiance (in W/m²) reduced by 20 % compared to Strasbourg's weather.

By rerunning all the simulations, the BCR values shown below were obtained.

Figure 63. BCR results for all the solutions considered in the four district archetypes and the three climate zones depending on their penetration rate.

Looking at the values on the y-axes, the results generally indicate an increase in BCR values for warmer climates. Not surprisingly, it is more appropriate to install space cooling technologies and measures in the warmest areas of the continent.

In line with the findings presented earlier, portable air-conditioning systems have relatively lower BCR values than other technologies in warmer areas, for all districts. On the contrary, BCR values for split systems increases. This difference between these two technologies is also due to the fact that splits come in a variety of sizes, making them more adaptable to different climates.

The study carried out on the three climate zones still ranks fans as the technology or measure with the highest BCR value. This remains true even in warmer climates, although their use ceases to be useful above 33 °C, based on the assumptions used.

In Strasbourg's climate, it was found that the outdoor temperature exceeds 33 °C only during 4 % of the time when thermal discomfort might be experienced. This percentage rises to around 23 % for the Athenian climate. Based on this indicator alone, one might therefore expect lower BCR for fans in this context. This is not what has been observed and can be explained by the increase in the number of hours during which fans can be useful over the year. In temperate climate zone, 10 % of hours in the year fall in temperatures between 25 and 33 °C. In hotter climate, it is 26 %. The increase in this number of hours, combined with the increase in the reference thermal discomfort, and an internal cost remaining constant, results in higher fan interest in warmer climate zone.

Shading devices are less interesting in Finland, also linked to their declining use. Nevertheless, their BCR values never clearly fall below 1.

Due to the weak solar irradiance in Finland white roofs never appear to be a measure "to be implemented", as the BCR value of this measure is always below 1. It is important to note that this measure can also be the source of higher heating consumption during heating periods. However, this effect wasn't quantified here as these periods are outside the scope of this study. This effect can theoretically be observed in all climate zones, but it is more prevalent in zones with longer heating periods.

To better understand the effect of climate zone on the technologies and measures under study, NPV values are presented below.

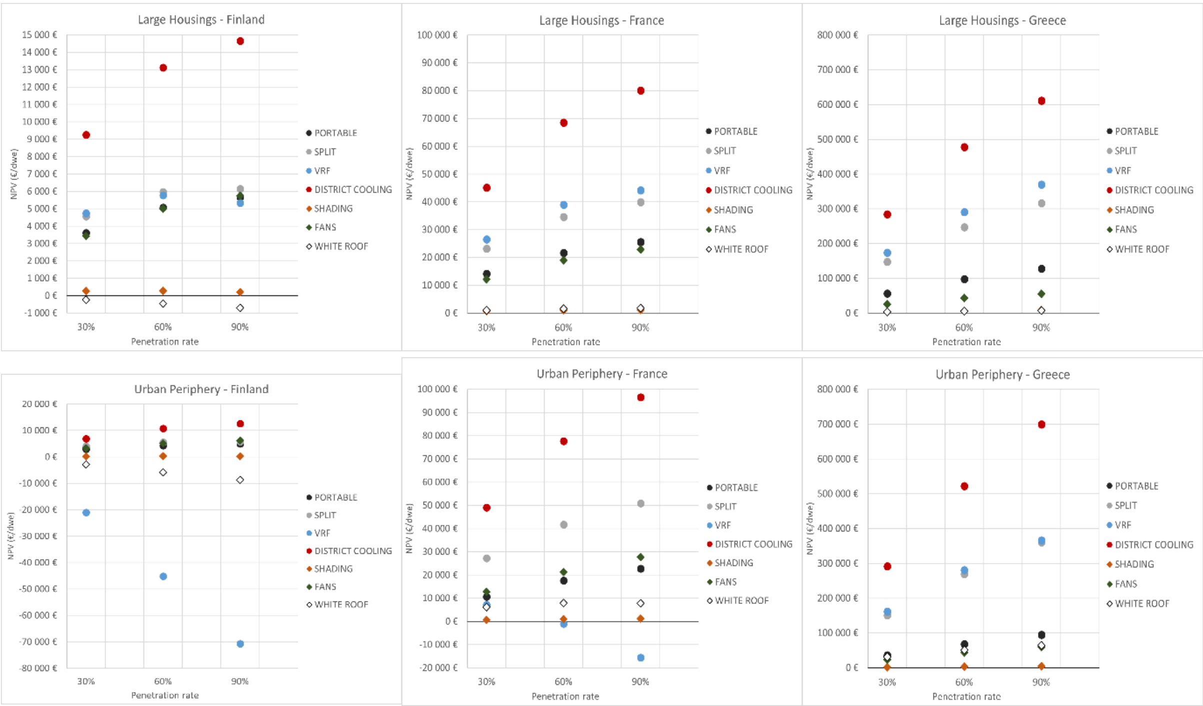


Figure 64. NPV results for all the solutions considered in the four district archetypes and the three climate zones depending on their penetration rate.

The NPV results for Greek climate leads roughly to the same conclusion presented above for France. However, two limitations can be listed to this statement. Firstly, fans result with lower NPV in Greece than in France: since the climate conditions are warmer, the fans' ability to reduce thermal discomfort is lower. Secondly, VRF systems do not get impacted by the high number of SFH in Urban Periphery in Greece, in relation to the high thermal discomfort in this zone.

For Finland, three elements can be pointed out. Firstly, fans achieved higher NPV values, competing with split and VRF systems. Secondly, the inadaptability of white roofs in this climate zones is confirmed by the NPV results. Lastly, NPV values for VRF follow a bell curve against penetration rate for the three districts where they are positive. This is explained by the very significant additional cost of installing systems in dwellings where thermal discomfort is initially low.

5.3.8. Preliminary conclusions

Overall, the district cooling network presents significant advantages. It is quieter, has a high efficiency, and mitigates the urban heat island effect. These advantages make it the best technology or measure evaluated in this study based on NPV and, is very often the best technology based on BCR.

Fans are often very effective in reducing perceived thermal discomfort. They are also not expensive. These findings, combined with the assumption of their use being correlated with thermal discomfort, make them the most suitable measure for reducing cooling needs, according to NPV. Based on BCR, fans are the best option among technologies and measures.

In a broader sense, within the scope of this study, it is important to emphasize that thermal discomfort is the driving force behind the implementation of a technology or measure, and it is also the predominant factor in its monetary evaluation. It might be interesting to evaluate the sensitivity of the results to the thermal discomfort cost.

With the assumption made for the thermal discomfort value (0.6 €/°C·h per occupant), the NPV might be considered less informative than the BCR because with such a high benefit value, the sum tends to dominate the other evaluated costs and is highly dependent on the cost of thermal discomfort. On the other hand, the BCR is more sensitive to the changes in each of these evaluated costs and the ranking of solution based on it doesn't highly depends on the thermal discomfort cost.

5.4. Discussion

It seems important to set out a few points for discussion about the CBA: firstly, the modelling method and secondly, the valuation of externalities.

5.4.1. Modelling method

The thermal and noise modelling choices, on which the results of this analysis are based, were thought out on a neighbourhood scale. The results come from averages over the entire building stock. This makes it possible to observe disparities between district archetypes. For this reason, some situation particularities cannot be observed.

For instance, localisation of dwellings in the district are neglected. In a dense urban area, the white roof measure seems to be of relative relevance as these results are averaged. In practice, it is most relevant for dwellings located under roofs. An analysis focused on these dwellings would undoubtedly lead to other conclusions.

Additionally, the particularities linked to the use of the residential dwellings are neglected. Some occupants of residential dwellings are more sensitive than others to certain externalities. The local effects of noise or heat island concentration at the level of a sensitive occupant are an important element of the district planning.

Finally, the focus on residential sector sets aside the specific features of the service sector. The requirements for spaces open to the public, those linked to the health sector and the architectural features of certain industrial and commercial buildings are some of the factors that influence the results of the cost-benefit analysis.

Average considerations lead to average recommendations and cannot be appropriate to every situation. Moreover, we only consider technologies and measures one by one, which obviously exclude the potential synergies between the selected technologies and measures. In particularly, when reducing space cooling demand with a combination of measures, one can expect a reduction in technologies cost-effectiveness.

5.4.2. Valuation choices

After the modelling phase, each indicator was assigned a monetary value. These values are the result of choices. It is relevant to observe the sensitivity of the CBA results to these values. To avoid an excessive number of graphs, this section will focus on the results obtained for France. The choice was made to focus on: the cost of thermal discomfort, the cost of noise discomfort, the electricity price forecast, and the consideration of the service sector.

Thermal discomfort cost

Following the preliminary conclusion, the graphs below present the NPV values for all solutions in Old Urban Centre located in France, with four values of thermal discomfort cost: 0.02, 0.1, 0.6, and 6 €/°C·h per occupant.

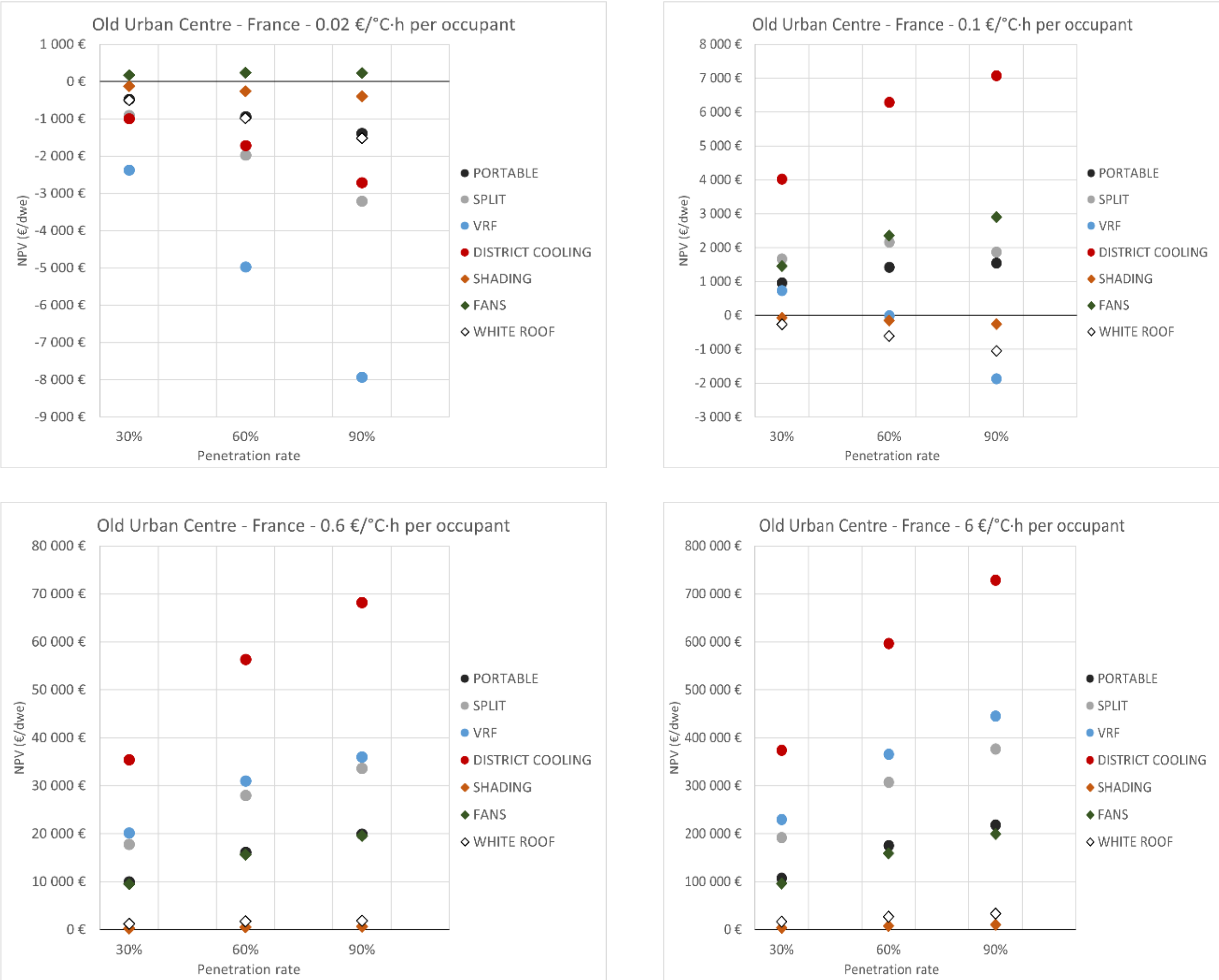


Figure 65. NPV results for all the solutions considered in Old Urban Centre located in France depending on their penetration rate and on the thermal discomfort cost.

The choice of the thermal discomfort cost appears to be crucial not only in the selection of measures 'to be implemented' or 'not to be implemented', i.e., NPV positive or negative, but also in the ranking of solutions from most to least interesting. The higher the cost of thermal discomfort, the more decisive this criterion becomes. Beyond a certain value, it seems that thermal discomfort no longer influences the ranking of solutions, with the influence of all other parameters being sidelined. In view of Figure 65, the set value of 0.6 €/°C·h per occupant already seems to be a high value.

This observation highlights the importance of determining an appropriate value for the cost of thermal discomfort. The literature that was used to determine it is relatively dated, and it would be prudent to anticipate a revaluation of the cost of this externality in the coming years.

Noise discomfort cost

With 0.6 €/°C·h per occupant, the graphs below present the BCR values for all solutions in Old Urban Centre located in France, with four values of noise discomfort cost: 0, 25, 250, and 1 000 €/dB(A) per dwelling per year.

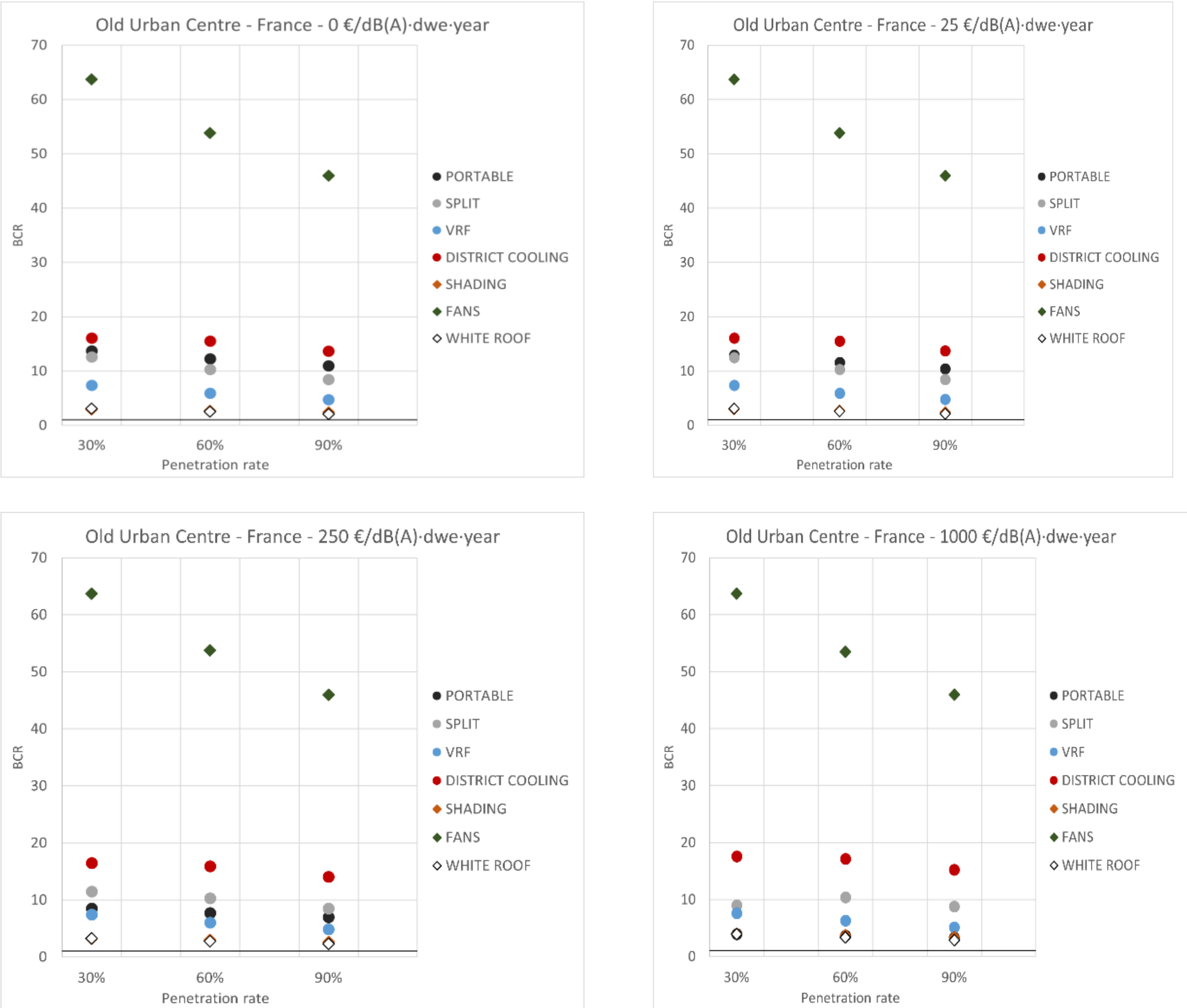


Figure 66. BCR results for all the solutions considered in Old Urban Centre located in France depending on their penetration rate and on the noise discomfort cost.

In line with the conclusions drawn from Figure 58, the increase in the cost of noise discomfort lowers the BCR of solutions that cause noise discomfort and increases the BCR of solutions that enable it to be limited. In areas that are more sensitive to noise discomfort, portable air-conditioners should be avoided.

Electricity price forecast

Recently, electricity prices have evolved significantly, and in this context, it would be interesting to observe the influence of this parameter on the results. Based on the same climate zone, the results below show the BCR values for four estimations of electricity price change: 0.5 %, 1.5 %, 5 %, and 20 %.

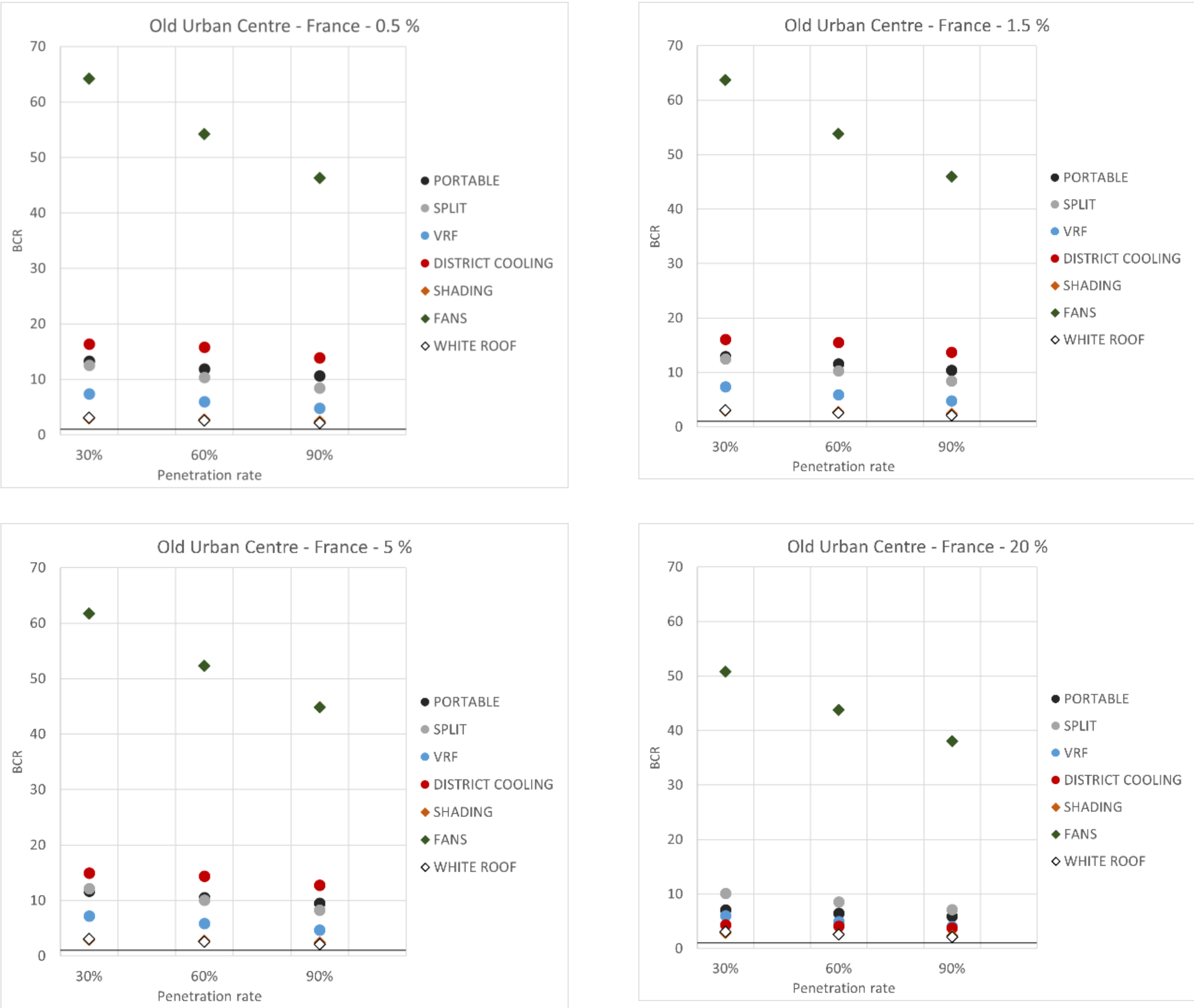


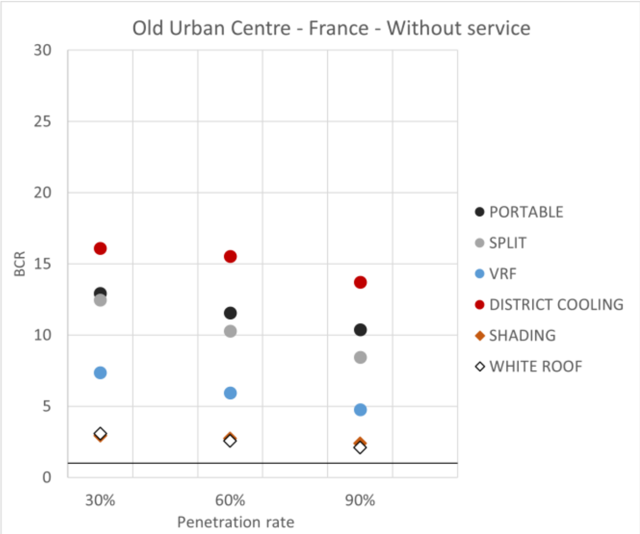
Figure 67. BCR results for all the solutions considered in Old Urban Centre located in France depending on their penetration rate and on the electricity price forecast.

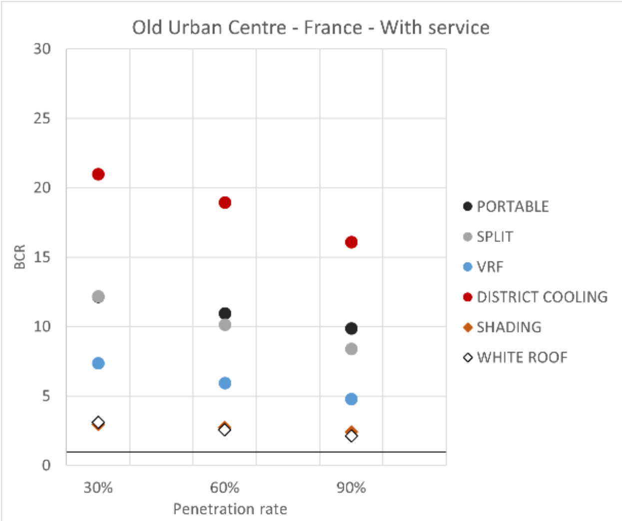
As expected, the assumption regarding the evolution of electricity prices mainly affects the active solutions due to the significant electricity consumption they generate. This factor should be taken into account to compare active and passive solutions effectively.

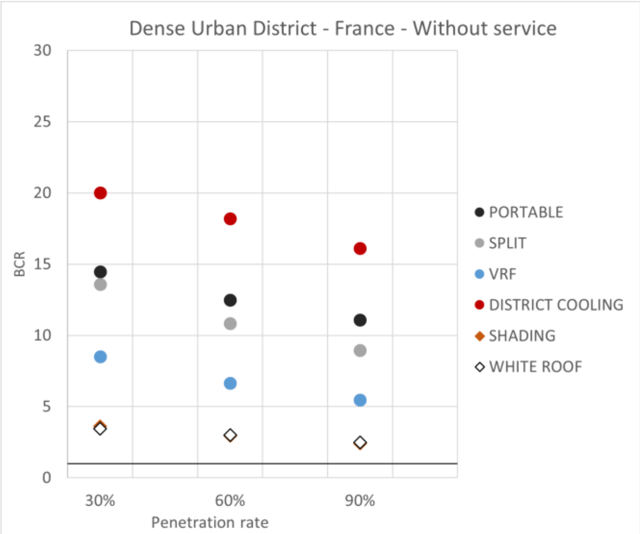
In accordance with the observation made in the previous section, NPV doesn't depend on electricity price forecast with a thermal discomfort cost of 0.6 €/°C·h per occupant.

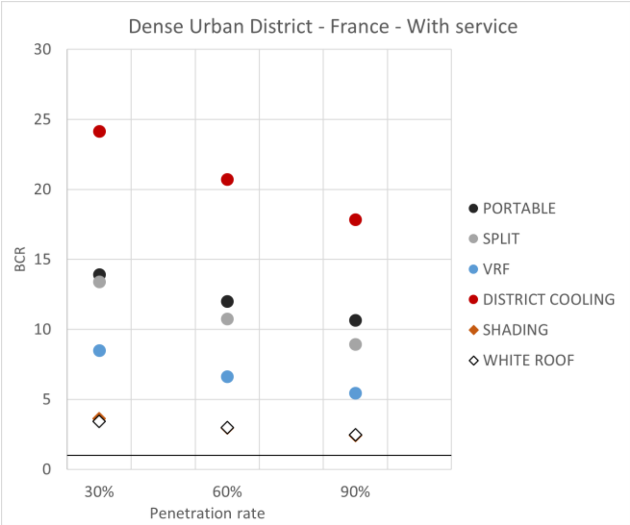
Service sector consideration

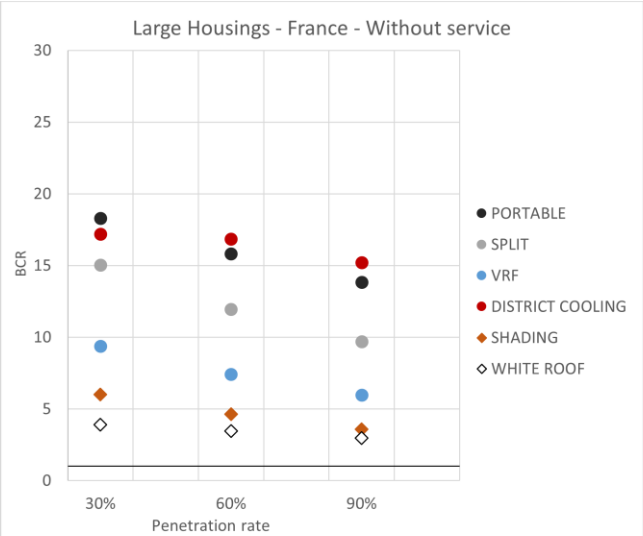
As a result of the identified limitations of this study, this section proposes a partial consideration of the tertiary sector present in the studied district archetypes. This consideration will be limited to adding the heat emissions produced by space cooling consumption in this sector and the increase in space cooling density, which is significant for the district cooling network. These two elements will be based on the assumption that, in all configurations, the space cooling demand of the tertiary sector is twice as high as that of the residential sector.

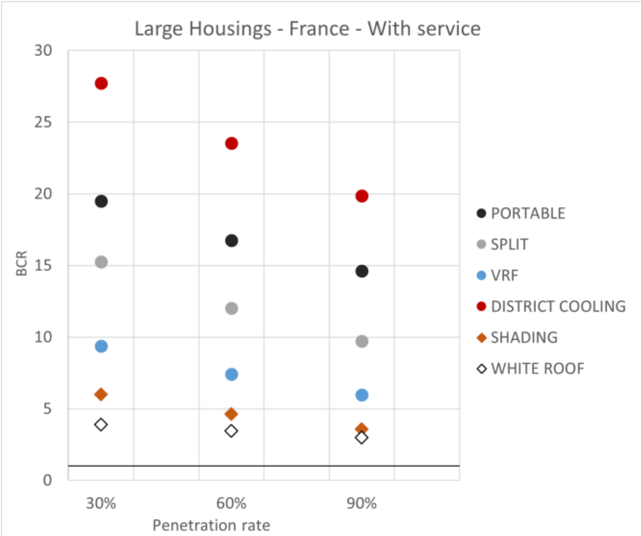

Old Urban Centre - France - Without service
BCR
30
25
20
15
10
5
0
30%
60%
90%
Penetration rate
PORTABLE
SPLIT
VRF
DISTRICT COOLING
SHADING
WHITE ROOF


Old Urban Centre - France - With service
BCR
30
25
20
15
10
5
0
30%
60%
90%
Penetration rate
PORTABLE
SPLIT
VRF
DISTRICT COOLING
SHADING
WHITE ROOF


Dense Urban District - France - Without service
BCR
30
25
20
15
10
5
0
30%
60%
90%
Penetration rate
PORTABLE
SPLIT
VRF
DISTRICT COOLING
SHADING
WHITE ROOF


Dense Urban District - France - With service
BCR
30
25
20
15
10
5
0
30%
60%
90%
Penetration rate
PORTABLE
SPLIT
VRF
DISTRICT COOLING
SHADING
WHITE ROOF


Large Housings - France - Without service
BCR
30
25
20
15
10
5
0
30%
60%
90%
Penetration rate
PORTABLE
SPLIT
VRF
DISTRICT COOLING
SHADING
WHITE ROOF


Large Housings - France - With service
BCR
30
25
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90%
Penetration rate
PORTABLE
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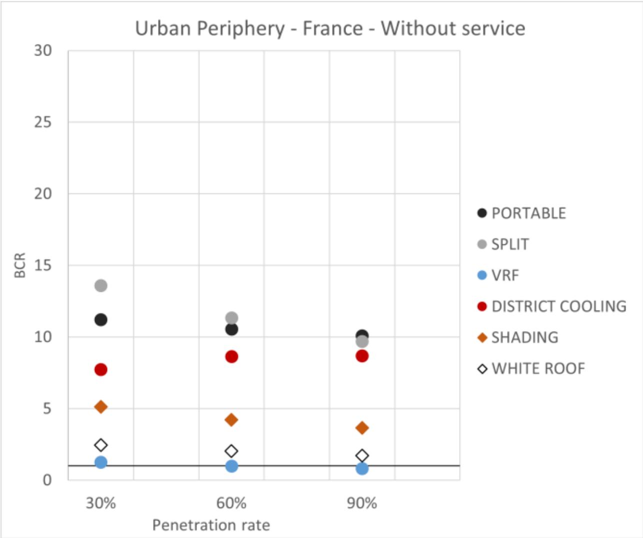
SHADING
WHITE ROOF



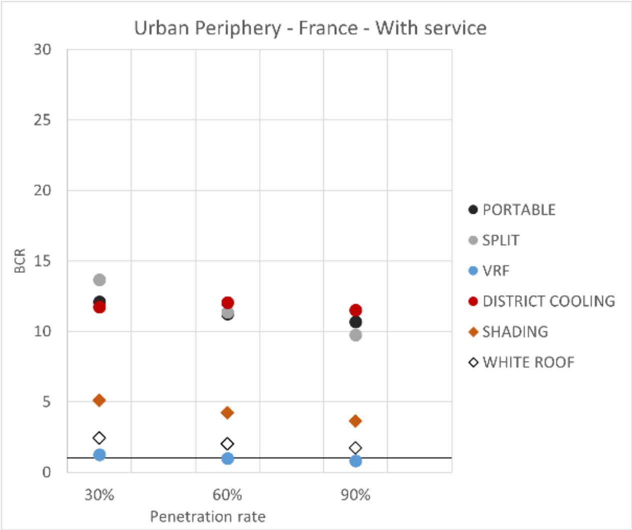


Figure 68. BCR results for all the solutions considered in the four district archetypes located in France depending on their penetration rate and on the service sector consideration, fans excluded.

This assumption will therefore only have consequences on the results for split systems, portable systems and district cooling network. For all the districts, located in France, the Figure 68 shows the BCR values with and without service sector consideration. In order to see the results more in detail and as the fans are not impacted by this assumption, fans will be excluded from the graphs.

These results allow us to conclude that the presence of the tertiary sector in a district has a second-order impact on the RACs consumption, although it adds to anthropogenic emissions and thus to the intensity of the urban heat island effect.

They also show that integrating the tertiary sector into district cooling networks is a key factor in its ratio between benefits and costs. By sharing the investment cost for the distribution network installation, the internal cost decreases for the residential sector, making the system more appealing for all.

6. Conclusion

The study carried out aims to analyse currently deployed space cooling technologies, active and passive measures, as well as comfort, lifestyle and user behaviours in order to provide a comprehensive understanding of the most promising solutions to tackle the increase in space cooling demand. Those solutions can be adopted to face the rapid growth of cooling needs that cities, buildings and people are experiencing due to the increase of global temperatures. This is crucial to identify alternative space cooling methods and their related potential, providing information and data about space cooling demand reduction strategies.

In order to handle this objective, a wide scientific and technical literature review has been carried out and supplemented by feedback from academic and industry experts.

This study provides a comprehensive picture of conventional and alternative space cooling technologies, with the assessment of their main characteristics, namely their efficiency, capacity range, applications, and market maturity. This work shows that conventional technologies will not face any promising competitors in the short or medium term thanks to their cost-efficiency and scalability, despite their poor environmental performance (due to the refrigerant use).

Among the active measures, ceiling fans continue to exhibit superior cost effectiveness. This assertion comes from the technology's maturity, widespread adoption, demonstrated energy savings, and comparatively lower costs. Conversely, alternative active measures face hurdles primarily associated with high capital or operational expenditures, typically lower energy savings, and limited market availability owing to their technology readiness level (TRL). Further research is therefore recommended to explore future developments that can lead to higher performance and market diffusion of smart glazing systems and adaptive facades especially in non-residential applications. Exploring the creation of new active measures through the automation of existing passive technologies holds also promise and warrants further investigation in the field of active measures for space cooling.

This survey also highlights the main passive measures to reduce cooling needs inside buildings, to mitigate users' request of space cooling and to decrease electricity use. Of all the passive measures identified, most have a fairly high TRL, highlighting that they are strategies already widely used in the market or mature enough to be implemented in the field. Additionally, there are still some measures that present a rather low TRL value. For example, roof ponds and windows with integrated trickle vents present a TRL between 3 and 5, indicating that the concept is only being tested or validated in industrially relevant fields. As previously highlighted, the main bottleneck encountered was the definition of quantitative costs. In particular, the cost of the various passive ventilation measures was complicated to collect as these strategies depend not only on geometric and material factors but also on the designer's experience.

A set of measures and technologies has been extracted from the aforementioned portfolio and identified as best available technologies and measures to face thermal discomfort in residential and non-residential sectors. The report shows that the ranking among this technologies and measures set may change regarding the urban context, the climate and the occupants' sensitivity of thermal and noise discomforts. Based on considerations at a district level, the present work does not investigate the several forms of diversity we may found among the population: diversity of occupants' behaviour, of sensitivity regarding noise and thermal discomfort, of location within the district/building, etc. Further works that could be undertaken by considering such diversities may discuss the present findings.

While acknowledging the presence of uncertainties and limitations, this report serves as an exemplary piece of scientific literature that elucidates relatively uncommon technologies, measures, and behaviours aimed at enhancing personal comfort through cooling. The document provides valuable insights into the aforementioned subjects, contributing to the understanding and exploration of innovative approaches in the pursuit of improved cooling strategies.

Furthermore, the information contained in this report has been structured to be fed to WP5 of CoolLIFE, aimed at providing a user-friendly, interactive and open-source tool and knowledge hub for relevant and quality-controlled space cooling related data.

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