

Integration of Solar Cooling Systems in Buildings in Sunbelt Region: An Overview

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Abstract: This paper presents the results of the activities related to the subtask “Building and process optimization” of the IEA SHC Task 65. The main topic of this activity was the integration of solar cooling in retrofitted HVAC systems. Based on the current conventional HVAC systems, the integration may present difficulties concerning cold distribution and refrigerants. Cold supply systems can also reduce airflow in air-based systems and enhance thermal comfort in buildings. The best technical actions for specific scenarios were mentioned considering both technical and economic aspects. Unfortunately, not all the analyses that were planned provide useful data. Results show that there are few recent projects that consider the application of solar cooling systems in buildings and most of them are based on simulation. Moreover, not much data about the characteristics of the buildings (envelope, other cooling systems, comfort conditions, etc.) are reported in the studies. This is because many of them are more focused on the plants’ configurations, and the performance of the different plants is in general assessed by testing the prototype in a single room. Despite this, the information provided could be used as baseline cases in order to study the potential energy savings achievable by applying solar cooling systems.

Keywords: solar cooling systems; renewable energy sources; integrated RES systems



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1. Introduction

Space cooling is responsible for 16% of the building sector’s final energy consumption in 2021 [1] and the global electricity consumption for space cooling might triple from 2020 until 2050 [2]. In addition, global economic growth, especially in developing countries located in cooling-intensive climates, such as India and Indonesia, will lead to a rapid increase in Air-Conditioning (AC) installation.

Moreover, in public buildings, the energy consumption of heating, ventilation, and air conditioning (HVAC) systems is 40–60% of the total energy consumption of the building [3]. Climate change and the global rise in temperature will cause a further increase in the energy demand for cooling [4]. Actually, AC is the most common active technology for cooling that uses electricity to achieve and maintain adequate indoor comfortable conditions.

Colelli et al. [5] presented a study that focused attention on the impact that mid-century climate change will have on electricity demand accounting for residential AC in poorer, hotter states in India and in cooler countries in Europe. The results presented in [5] show that growing cooling demand could cause peak electricity consumption to increase by two to three times the expected average AC prevalence level in the two regions around 2050.

Thus, energy saving and the reduction in cooling demand are key issues in the design of buildings.

As is known, to do this, it could be useful to provide passive solutions, e.g., natural ventilation [6] or efficient materials for building envelopes [7] in order to reduce artificial cooling consumption. However, this latter can be supported by renewable energy such as solar energy sources. In this light, two main solutions can be adopted. The first and most common solution is to install photovoltaic panels to produce electricity to power traditional systems for cooling. The second one is the implementation of solar thermal systems.

The integration of RES systems in buildings [8] or on a larger scale [9] can provide many advantages, e.g., decreasing dependence on the power grid [10,11], transmission losses, and increasing access to electricity as well, in rural areas [12] or not. Panda et al. [13] presented a review of recent developments in six electrical energy storage (EES) + hybrid power systems (HPS) and three hybrid EES systems. The study encompasses the functioning of HPS in both stand-alone and grid-connected modes and explores the increasing implementation of artificial intelligence (AI)-driven scheduling techniques for assessing optimal HPS operational paradigms.

On the other hand, Hassan and El-Rayes [14] developed an innovative optimization model to maximize the utilization of renewable energy (RE) measures in existing buildings, satisfying specific owner-defined targets for energy consumption reduction while minimizing the associated building upgrade costs. The aim was to assist decision makers in minimizing upgrade expenses by integrating optimal and cost-effective RE measures to achieve at least an 80% reduction in total annual building energy consumption from fossil fuels and cover at least 30% of building water heating energy through solar water heaters.

In this paper, the main results of the specific activity of the IEA Solar H&C PROGRAM, task 65 are presented. The main topic of this activity was the integration of solar cooling in retrofitted HVAC systems with a special focus on solar cooling systems and their application to buildings. Figure 1 shows the block diagram with aspects analyzed in the paper. In particular, the authors investigated first the passive and active measures to reduce cooling demand. A further part shows the influence of the solar cooling integrated systems on the assessment of loads, demands, and saving potential.

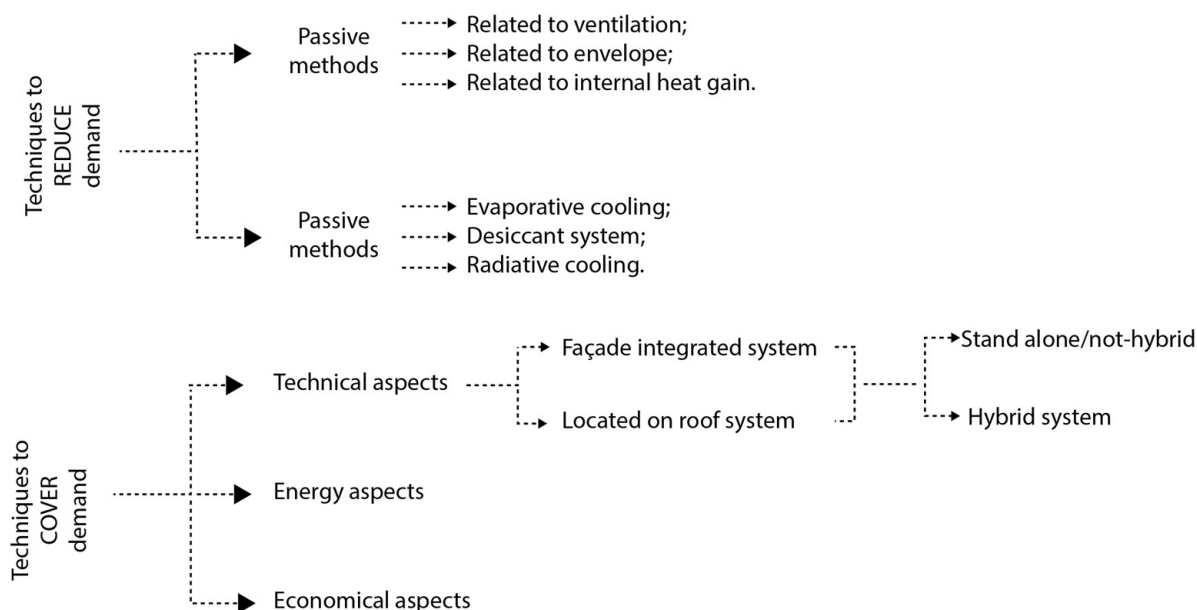


Figure 1. Block diagram with aspects analyzed in the paper.

2. IEA Task 65

As said, the present paper reports the results of activities related to subtask A4 of the IEA Task 65 “Solar Cooling for the Sunbelt Regions”. The task involves 82 people including participants and task leaders. SHC Task 65 is aimed at addressing the cooling and AC needs of the medium- to large-scale market (ranging from 2 kW to 5000 kW). Both solar thermal and PV technologies can be incorporated to support HVAC systems. When appropriately designed and meeting specific boundary conditions, these systems are exceedingly competitive compared to standard reference systems. This project primarily concentrates on harnessing solar energy in Sunbelt regions characterized by diverse boundary conditions (such as sunny and hot, as well as humid climates), situated between the 20th and 40th latitudes in both the northern and southern hemispheres. The adaptation of pre-existing concepts plays a crucial role. To effectively leverage solar heat in the industry and foster the solar thermal market, the integration of solar thermal systems into existing energy supply structures is of paramount importance.

The Task (Figure 2) is organized into four main activities/Subtasks, derived from the described key areas. Subtask A is focused on the *Adaptation* of the plants; Subtask B is on the *Demonstration* topic; Subtask C activities analyzed the *Assessment & Tools*; finally, Subtask D regards the *Dissemination*.



Figure 2. IEA SHC Task 65 Subtask structure [15].

The Sunbelt countries can be divided into sunny, hot-arid or hot-humid climates between the 20th and 40th degrees of latitude in the northern and southern hemispheres. Köppen–Geiger (Geiger 1954) classified the climate into Group A (tropical climates), Group B (dry climates), and Group C (temperate climates). Figure 3 shows a world map which shows the countries inside or touching the Sunbelt [15].

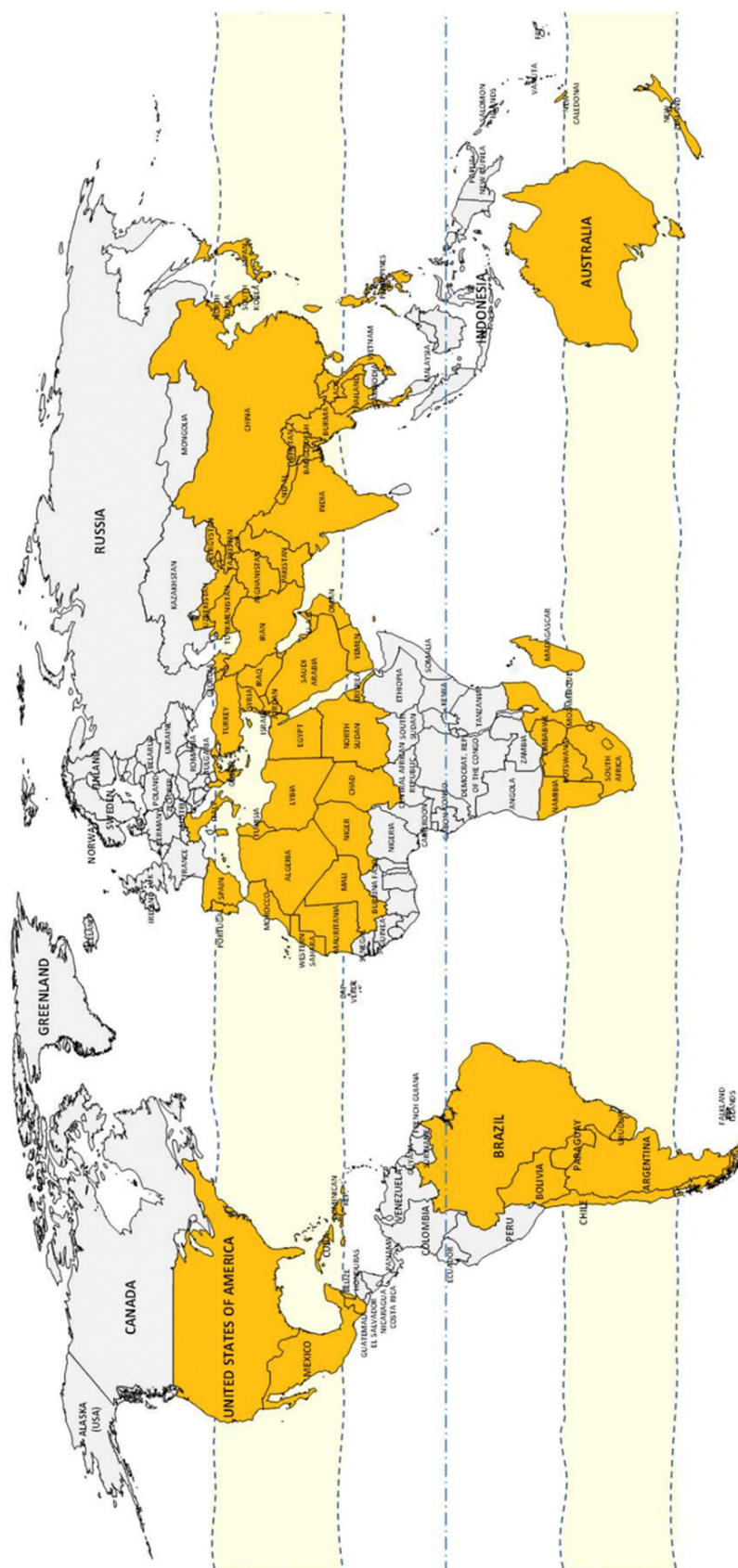


Figure 3. Countries inside or touching the Sunbelt on the northern and southern hemispheres [15].

3. Methodology

This paper reports some results of the activity named A4 “Building and process optimization” of the IEA SHC Task 65 “Solar Cooling for the Sunbelt Regions”. It presents an overview on the relevance of building and process optimization. Several ongoing and completed projects are introduced and results are depicted. In particular, information about completed and running research projects is presented in order to quantify the amount of energy used for cooling systems. Furthermore, main projects related to the IEA EBC (Buildings and Communities Programme) about cooling systems are reported. The main goal of the activity was to investigate the capacity of energy-efficient buildings and operations in Sunbelt areas, considering both newly constructed and pre-existing buildings, as well as the incorporation of solar cooling into revamped HVAC systems.

A literature review names different passive and active low-tech solutions to optimize the energy performance of a building. Additionally, the Urban Heat Island effect and mitigation measures are described. The novel Cooling Demand Market Index (CDMI) is furthermore introduced. It gives information where economically speaking, action to cover the increasing demand for cooling is taking place. An additional review highlights different technical and building solutions for space conditioning. Finally, the last part reports a literature review of the loads, demands, and saving potential that the application of solar cooling systems can provide. In particular, the work was focused on the integration of the structure of the buildings and the savings in terms of energy and economic aspects as well according to the different conditions of application.

As said, the main goal of Activity A4 was to assess the potential of energy-efficient buildings and operations in Sunbelt regions, encompassing both new and existing buildings. The integration of solar cooling into retrofitted HVAC systems is discussed under this heading. The feasibility of integration may vary depending on the existing conventional HVAC setup, particularly concerning refrigerants and cold distribution. Implementing cold delivery systems is also of interest to reduce drafts in air-based systems and enhance thermal comfort in buildings. The most suitable technical solutions for specific situations were identified from both technical and economic standpoints. Figure 4 summarizes the diagram flux of the methodology that was followed.

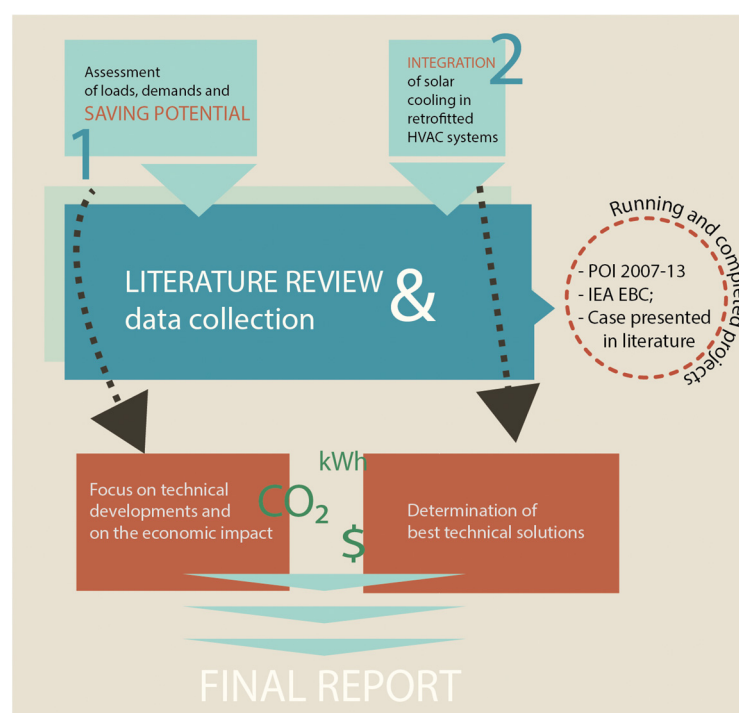


Figure 4. First planned workflow scheme.

Of course, only papers that included case studies located in the Sunbelt Region were investigated. This search was conducted using Scopus, Google Scholar, and Web of Science as the main search engines.

4. Passive and Active Measures to Reduce Cooling Demand

To prepare efficient and environmentally friendly cooling to the user, three principles are to be followed. These are (i) building energy efficiency, (ii) system energy efficiency, and (iii) renewable primary energy supply. The combination of all three principles leads to cost-effective and sustainable cooling solutions with comfort benefits to the user and environmental benefits avoiding GHG emissions for the climate. This section focuses on both passive and active measures to optimize the energy performance of buildings.

4.1. Passive Measures

The demand for cooling energy to operate a building comfortably for the user is dependent on many aspects. It depends on the site, plants, and buildings' characteristics. The International Energy Agency (IEA) outlines that "Improving the energy performance of buildings" is an important topic to be studied to reduce cooling-related energy consumption [2]. In the following section, different aspects which influence a building's energy performance are discussed.

It is important to note that buildings have three heat gains: ventilation, envelope, and internal heat gain. They are related to further characteristics such as opaque and transparent materials and percentage of surfaces, orientation, schedules, end-use, habitants' behavior, and the standard of their comfort conditions [16–18]. Finally, the cooling systems' performances (not considering the alternative passive solutions, such as cooling roofs) widely influence the final consumption, by varying according to the EER, the efficiency of generation, distribution, regulation, and emissions components, the maintenance, and the typology. Regarding the site characteristics, it is important to note that this study is focused on Sunbelt region countries. Many studies are presented in the literature and, for the above-listed reasons, they reported very different results. In this part, some of the studies will be reported to pave the way to understanding which of the consumption of cooling systems is supported or not supported by solar plants, consequently quantifying the savings potential.

Of course, regarding the architecture and design of buildings, they must be adapted to both the users' needs and behavior, but also to their environment and the climate conditions. This also addresses the compactness of a building, which is relevant for the energy exchange between the building and the environment through its envelope. The compactness can be expressed as the ratio between volume and surface [19]. The orientation of a building is important as it impacts solar gains. Façades facing east or west are exposed to solar irradiance at a high zenith angle, whereas façades facing south are exposed to solar irradiance at a lower zenith angle. The orientation must be in line with its design. Directly addressing the solar gains and the design, external shading elements are a good solution to block solar irradiation. Shading devices can be either passive, such as fixed building elements on top of a window, or active, such as lamellas, which prevent solar irradiance on a window only on demand. Active shading devices can be expressed in different ways, such as via tilting, rotating, or folding mechanisms. An overview of active shading systems is presented by Al Dakheel et al. [20]. Authors found that by using active shading systems it is possible to achieve 12 to 50% of savings of cooling electricity consumption. Shading devices are part of the envelope and can play a role in the design of a building. In addition to the block of solar irradiance, shading elements also influence the availability of natural light, which should be considered in building operation.

The quality of windows and glazing elements in the envelope of a building also affect the solar gains, considering the g-value of glazing elements, respectively, the solar heat gain coefficient (SHGC). A high reflection of short-wave radiation is preferred to decrease the solar heat gains. The insulating characteristic of windows, expressed as u-value, is the other

purpose of windows. Windows with high thermal transmittance (high u -value) can lead to convective heat gains if the ambient air is of higher temperature than the indoor air. The window-to-wall ratio (WWR) and the size and number of windows [21,22] are additionally relevant points having an impact on energy performance. The high quality in air tightness of a building envelope is required to reduce the uncontrolled energy transfer, which goes along with uncontrolled air flows. The infiltration strongly depends on the dimension of cracks and gaps in the envelope. Thus, treating not only the air of a building's volume but on top of that an uncontrolled stream from outdoors increases the cooling energy demand of a building. In [23], authors presented a review of passive solar heating and cooling by comparing different systems and found that the use of a double-glazed system can provide a decrease of 9% in heat gain and a reduction in losses by 28% compared to a single-glazed system. The combination of a cool roof, Trombe wall, and thermal insulation can provide 80% of savings in cooling demand. In addition to the temperature itself, low quality of air tightness might also affect the indoor air quality in terms of humidity, as not only gains in energy but also gains in humidity occur.

Using natural ventilation to remove heat and cool down a building is one of the cheapest and easiest ways to decrease the cooling demand of a building. It is affected by both the temperature and pressure difference between indoor and outdoor conditions [24]. Nocturnal ventilation is efficient as the lower temperature during the nighttime cools down the building's mass which then can heat up during the day. Natural ventilation is also a necessity to supply fresh air to the user. This goes along with the risk of heat gains through natural ventilation during the day if it is hot outside. Technologies to improve the potential of natural ventilation are solar chimneys [19] or windcatchers [25], which boost the air mass flow. E.g., Shbailat et al. [26] developed an experimental chimney and installed and tested it in Baghdad. They accounted that in the evaporative cooling mode, the variance in evaporative outlet temperature can range from 4.5 to 7 °C. The average energy saving for the experimental chamber employing evaporative cooling and a solar chimney system decreases as the volume flow rate increases, culminating at the highest attainment of 20% (at $Q = 0.8 \text{ L/m}$).

Of course, the potential of natural ventilation is linked to the thermal mass of a building, based on its construction material [22]. Using nocturnal ventilation, a 24 h temperature variation can be damped by the building. A higher thermal heat capacity of a building results in a slower increase/decrease in the indoor temperature. Concrete or clay have better characteristics to store heat than wood, for example. The thermal mass of a building has the potential to decrease the cooling demand and especially the cooling load of a building, as the material absorbs heat.

The integration of latent heat storages pictured as phase change materials (PCM) may be a tool to enhance the thermal mass of a building. The term PCM refers to a wide variety of materials such as hydrated salts or paraffins. They are characterized by their unique melting point temperature, where they undergo a phase change and absorb and release energy, respectively. When the indoor temperature increases, PCM with a melting temperature of 26° C absorbs heat at that temperature which theoretically prevents an additional temperature rise. It allows the achievement of adequate indoor comfort conditions in terms of temperature and energy savings exceeding 50% [27]. However, the application of PCM in construction face barriers, including the high initial investment costs of PCM, is accompanied by concerns about their low thermal conductivity that can cause limitations in heat transfer, the durability of the phase change cycles over a long period, and the impact of hot weather conditions that could hinder the solidification of PCM [28].

An effective way to reduce heat gains through an opaque envelope is the application of thermal insulation. External insulation not only reduces the heat flux through the construction of walls and roofs but also leads to the fact that thermal mass is even more effective in indoor conditions. Various insulation materials are readily available in the market, including expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), mineral wool, and vacuum insulation panels [24]. In particular, XPS is understood

to be the best insulation material in terms of thermal characteristics and cost. It was demonstrated that a reduction of about 16% in HVAC system energy consumption with a payback period of around 2 years and 29% of return on investment can be achieved.

More environmentally friendly and biomass-based materials such as insulation based on hemp or wood-wool are also available. The application of mineral oil-based materials must be considered critical, considering the life cycle analysis [24].

Roofs often suffer from high solar heat gains throughout the day. Roofs characterized by a high albedo reflect a high share of solar radiation, called “cool roofs”. This might be achieved by using either bright and reflective paints or materials. In [29], results showed a 54% reduction in the cooling energy demand.

There is no uniform definition or minimum albedo for the label “cool roof”. Furthermore, due to exposure to the environment, studies show that solar reflection declines over time. For example, in [30], results indicate that although most of the studies analyzed that roofs after being washed with detergent could be brought to within 90% of their unweathered reflectivity, in some instances, an algicide was required to restore this level of reflectivity.

Green roofs, however, are characterized by the installation of a vegetative layer including plants. Plants theoretically bring a benefit through shading, evapotranspiration phenomena, and additional thermal mass [31]. A study by Jaffal et al. came to the conclusion that the cooling effect of green roofs is primarily based on their insulating effect [32]. They conducted a study for a single-family house with conventional and green roofs in a temperate French climate and found that during the summer season, the fluctuation amplitude of the roof slab temperature was found to be reduced by 30 °C due to the green roof. With a green roof, the summer indoor air temperature was decreased by 2 °C, and the annual energy demand was reduced by 6%.

Thus, green roofs can be substituted by roof insulation focused on reducing the cooling demand of a building. A direct comparison of the named measures is not possible in a unified way. Most of the measures were investigated via software-based simulations. Essentially, most of the studies are based on TRNSYS or EnergyPlus. Despite the methodology of assessment, the building’s design, climate, and occupation are different.

4.2. Urban Heat Island (UHI)

Another issue which influences a building’s energy performance is its surrounding and its location, respectively. Urban areas characterized by a high building density and a high share of sealed areas, such as parking spaces, suffer from the Urban Heat Island (UHI) effect [33]. This causes in individual cases a number of Cooling Degree Days (CDD) which are 6.5 times higher than in less urban areas [34] and in general have a higher cooling energy demand [35]. The magnitude of a UHI on the building’s energy performance depends on aspects such as urban structure, infrastructure, and topology and is different for each city. Solutions to face UHI are passive cool pavements [36], cool roofs [37], urban green spaces [38], green roofs and green walls installation [39], water bodies and fountains [40], and the adaptation of buildings themselves. Those mitigation options led to a cooling effect of 2 K [41] in daily average summer temperature up to 10 K [38] in maximum temperature difference to UHI temperatures. However, it is hard to compare those mitigation measures as not only do the quantity and quality of the action but also the distance and range of the considered environment, respectively, need to be considered. A study in the USA came to the conclusion that in addition to the lack of public education on UHI, the absence of effective communication between researchers and code writers represents one of the major hindrances in UHI mitigation efforts [42].

4.3. Low-Tech Active Measures

Passive measures are the base methods to optimize a building and to decrease the cooling demand and load. This results in a smaller layout of the cooling system. The

following three technologies are of special interest: evaporative cooling, desiccant system, and radiative cooling.

Evaporative cooling is one of the most efficient ways of cooling and states back to application in the Middle East around 2500 B.C. [43]. This method is based on the cooling effect when water evaporates, changing its phase from liquid to gaseous state. This process requires energy and thus cools down the air by serving as an energy provider. Evaporative cooling can be divided into direct and indirect systems [19] and further separated on its working medium, such as air or water [44]. Direct systems directly cool down the air, whereas indirect systems cool down parts of the construction when water evaporates from its surface. This then leads to a cooling effect of the air on the other side. The operation is limited as dry air requires being able to absorb the water [23]. Desiccant cooling systems include the step of dehumidification via a liquid or solid desiccant, which absorbs moisture from the air [45]. The desiccant must be regenerated via heat, preferably solar heat. The dried air can then be cooled down via evaporative cooling.

The radiative cooling system makes use of radiative heat transfer to the night sky, especially using low-wave infrared radiation [46]. The heat transfer reaches about 60 W/m^2 ($\pm 30\%$). This allows cooling the heat transfer medium down to 5 K [47] or to 7 K [48] below ambient temperature.

5. Integration of Solar Cooling Systems in Buildings: Assessment of Loads, Demands, and Saving Potential

5.1. Energy and Technical Aspects

To evaluate the integration of solar cooling systems in buildings and to develop optimized plant-building systems, not only the aspects related to the frame, the geometry, and the size must be considered. Other parameters affect the outcome of cooling strategies.

In their work, Naderi et al. [49] provided a comprehensive review of state-of-the-art studies on pre-cooling and solar pre-cooling from 2014 to 2021. They asserted that the most influential factors in this field are the electricity tariff [50,51], the thermal mass of the building [52], occupancy, household thermal comfort expectations [53], climatic conditions [54], and the chosen control method [55]. It is not so easy to integrate solar cooling systems into the architecture of buildings, but many researchers studied and analyzed some solutions.

Mortadi and Fadar [56] proposed the study of various solar cooling systems, including photovoltaic thermal (PVT), solar adsorption, and solar absorption, with a focus on their economic viability, environmental impact, and performance in seven climate conditions. The primary goal of their investigation is to find the most adequate system based on specific climate conditions and Solar Fraction (SF) considerations. In the study, an office setting with identical construction and internal loads was chosen to ensure a fair comparison of these solar cooling systems. The authors showed that the PVT cooling system had a high solar coefficient of performance varying from 36 to 52%, depending on the climate condition. The lower discounted payback period was measured in regions with high solar irradiation being lower. Lower levelized cost of cooling values was calculated in sunny locations with high cooling loads varying around 0.056–0.25 €/kWhc for PVC system, 0.069–0.314, 0.1–0.736, and 0.132–0.961 €/kWhc for PVT cooling, solar absorption cooling SABC systems, which could not be recommended in climate regions with low temperature and solar radiation, such as continental (SABC), and solar adsorption cooling (SADC) systems, respectively. It has been demonstrated that the most negative impact on the environment was given by the system that combined a PVT cooling system with an absorption chiller. With solar adsorption cooling and solar absorption cooling, even if the systems have high SF, the lower the levelized cost of cooling, discounted payback period, and greenhouse gases, the higher the positive economic and environmental impact of SF, while lower values of lower levelized cost of cooling and discounted payback period corresponded to high values of ambient temperature and solar radiation. Based on the comprehensive comparative analysis, it can be inferred that the PVT system emerges as a favorable alternative, offering

advantages from both performance and economic standpoints across almost all climate conditions. On the other hand, the SADC and climate cooling systems, despite their environmental benefits, face challenges in terms of economic viability. Nevertheless, these systems may prove to be efficient cooling solutions in regions characterized by higher ambient temperatures and abundant solar radiation.

In another study, Mortadi and Fadar Mortadi [57] investigated solar cooling systems powered by different solar collectors for AC application in a residential building: evacuated-tube collector, parabolic trough collector, flat plate collector, compound parabolic collector, PVT collector, and a new configuration of concentrating PVT collector.

The concentrating PVT collector demonstrated outstanding performance for the absorption cooling system, achieving a solar coefficient of performance of 0.449, 0.428, and 0.414 in cities with diverse climates, namely Marrakesh, Barcelona, and Oslo (not situated in the Sunbelt region), respectively. For the adsorption cooling system, the PVT collector also proved to be the most efficient in Marrakesh (solar coefficient: 0.397) and Barcelona (solar coefficient: 0.386). Tables 1–3 report some information regarding the thermal properties of construction materials, the building’s characterizations, and the characteristics of the selected climatic regions respectively.

Table 1. Thermal properties of construction materials [57].

Elements	Material Layers	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m ³)	Specific Heat (J/kgK)
External walls	Cement plaster	0.02	1.3	1900	1000
	Brick	0.10	0.811	1820	880
	Air gap	0.07	0.02	-	-
	Brick	0.10	0.811	1820	880
	Mortar	0.015	0.719	1700	920
Internal walls	Cement plaster	0.02	1.3	1900	1000
	Mortar	0.015	0.719	1700	920
	Brick	0.10	0.811	1820	880
	Mortar	0.015	0.719	1700	920
	Cement plaster	0.02	1.3	1900	1000
Floor	Plaster	0.0125	0.721	1762	840
	Mortar	0.015	0.719	1700	920
	Reinforced concrete slab	0.15	1.95	2240	900
	Mortar	0.015	0.719	1700	920
	Terrazzo	0.3	1.8	2560	790
Ceiling	Terrazzo	0.3	1.8	2560	790
	Mortar	0.015	0.719	1700	920
	Reinforced concrete slab	0.15	1.95	2240	900
	Mortar	0.015	0.719	1700	920
	Plaster	0.0125	0.721	1762	840
Doors	Wood	0.05	0.15	608	1630

Table 2. Building’s characterizations [57].

Parameter	Value	Unit
Infiltration rate	0.5	Air change per hour
Occupant loads	70	W/person
Equipment loads	7	W/m ²
Lighting loads	10	W/m ²

Table 3. Characteristics of the selected climatic regions [57].

City	Koppen-Geiger Climate Classification	Climate Type	Latitude/Longitude	Altitude (m)
Marrakesh, Morocco	Bsh	Hot arid	31.634/−8.002	459
Barcelona, Spain	Cfa	Warm temperature	41.388/2.17	31
Oslo, Norway	Dfb	Boreal	59.912/10.75	14

As it is possible to see, this last study considered a residential case. Al-Yasiri et al. [58] presented a review of the application of solar cooling and AC systems in buildings and found that real case studies are more commonly installed in commercial buildings rather than residential ones, particularly in buildings with high capacities. However, the majority of these systems are equipped with auxiliary energy systems, especially in facilities that require continuous cooling, such as hospitals and airport lounges.

In a study by Chen et al. [59], they proposed a solar-based cooling and heating system that utilizes solar concentrating collectors, photovoltaics, a double-effect absorption heat pump, and thermal storage. The system is designed for various types of buildings, including offices, hotels, residences, markets, and hospitals. The buildings considered in the study are located in Nanjing, Jiangsu province, China, which is characterized by a region with cold winters and hot summers. The total combined area of these buildings is assumed to be 24,000 m², with a rooftop area of 2000 m².

In comparison to the other building types considered, the hospital exhibits the lowest energy and economic benefits. The energy savings range from 69.4% to 71.8%, and the cost savings range from 64.4% to 65.9%. The solar cooling and heating for the hospital increased by 16.1%-units, whereas for the office and market buildings, the increase was 35.4%-units and 32.6%-units, respectively. This difference is primarily due to the higher total load of the hospital, particularly the heating load. In contrast, the office and market buildings have lower heating demands: the office has zero demand at night due to its special operating schedule, and the heating load during the daytime is reduced due to higher ambient temperatures. Furthermore, both the hospital and hotel have significantly higher heating loads compared to the other buildings, with the cooling load only being lower than that of the market. The Fossil Fuel Savings Ratios of the office, residence, and market buildings are >87%, and the economic benefits are >77% except for the cost saving ratio of the hospital, which is 65.3%. The decreasing order of the solar cooling/heating share (SC/HS) is the residence, office, hotel, hospital, and market (average values from 34.2% to 23.7%). According to the average values of objective indices, the office building is deemed the most suitable for implementing a solar-driven cooling/heating system, primarily due to its intermittent energy consumption pattern. The weights assigned to solar shares, calculated using the coefficient variable method, are greater than 0.77 for all buildings, indicating their significant contribution. Comparatively, the lowest weights are attributed to the cost-saving ratio and fossil fuel savings ratios, with values of 0.10 for the office and market, and 0.08 for the hospital. This discrepancy is primarily because the solar shares hold higher values than the other two criteria, making them the dominant factor in the selection process.

The aim of the research of Comino et al. [60] is to determine experimentally the seasonal coefficient of performance, solar coefficient of performance (SCOP), of a solar desiccant cooling system (SDEC) utilized to control indoor conditions in a research lab room. The SDEC system consisted of a desiccant wheel, an indirect evaporative cooler, and a thermal solar system. The research lab room had an area of 63.8 m³ and was situated in the Plastic Technological Center (ANDALTEC) building in Martos (Jaén), Spain. The indoor conditions in the research lab room were maintained at a set point of 25 ± 1 °C for air temperature and 8 ± 1 g/kg for air humidity ratio (equivalent to 40% relative humidity). Approximately 75% of the seasonal energy consumed by the solar desiccant cooling system to perform cooling and dehumidification processes was derived from thermal solar energy and outdoor air. The authors discovered that the tested system effectively controlled

both the latent and sensible loads of the room utilizing 100% of the outdoor air. Only a minimal amount of auxiliary energy was required to maintain indoor conditions during the analyzed period. A sensible seasonal coefficient of performance value of 2.1 was calculated, indicating that the sensible thermal energy delivered by the solar desiccant cooling system in cooling mode surpassed its electric energy consumption. However, in dehumidification mode for the same period, a seasonal latent coefficient of performance value of 0.5 was observed, which resulted from the dehumidification potential of outdoor air. When the solar desiccant cooling system operated in both dehumidification and cooling modes, the coefficient of performance achieved a value of 2.

5.2. Façade-Integrated Systems

Façade panels deal with the integration of solar systems in building architecture. Noaman et al. [61] took into account passive solar design strategies (PSDSs) coupled with an active solar cooling technology (ASCT) integrated into the façade. The performance of this system was evaluated for three hot climates in the Sunbelt region: humid subtropical, hot semi-arid, and hot desert. Even if the study is more focused on the configuration of the passive strategies, the results are very interesting for this report, because the successful design of the ASCT depends mainly on the use of adequate PSDSs [62]. As demonstrated in [63], approximately 45% of the cooling demands of a building can be attributed to the façade's configuration. Implementing passive systems can be an efficient approach to reduce energy demand for cooling. For example, the average cooling demands for Alexandria, Cairo, and Aswan were significantly reduced to 9.02 kWh, 10.13 kWh, and 12.21 kWh, respectively, after applying the four PSDSs, compared to 19.93 kWh, 22.99 kWh, and 29.48 kWh in the base case. By utilizing the four PSDSs, the deviation in cooling demands between Aswan (in the southernmost part of Egypt) and Alexandria (in the northernmost part) reduced to approximately 35%, whereas the deviation in the base case was around 50% (see Figure 5). These findings demonstrate the potential impact of incorporating passive solar design strategies in the overall energy efficiency of buildings, especially when combined with active solar cooling technologies.

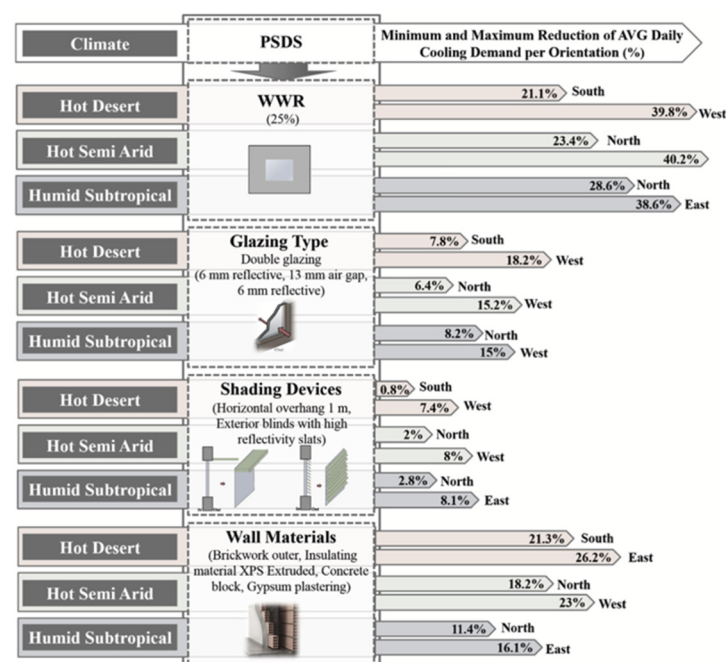


Figure 5. Guidelines for applying the four tested PSDSs to façade in the hot climates [61].

To evaluate the possible production of the ASCT and the amount of incident solar radiation, authors investigated four tilt angles: 90°, 60°, 30°, and 0°. Results found showed

different performances of the ST according to the tilt angle and the city. For instance, the tilt angle of 30° was found to be the best angle in most cases; the 0° angle is the best for the buildings oriented north. It is interesting to see that the tilt angle of 0° seems to be more favorable than 30° for the south orientation in Aswan because solar altitude angles during the summer week reach almost 90° at peak hours. The 0° tilt angle likely allows for better solar capture and utilization during these high solar altitude periods, resulting in improved energy efficiency and performance of solar systems in the region. However, the tilt angle of 60° is better than 90° for all conditions (see Figure 6). This shows that the vertical STC at 90° is not a good option. It should be noted that, particularly for the south and north orientations, there is an improvement in the incident solar radiation at the tilt angles of 60° , 30° , and 0° compared to 90° . In the case of Alexandria, the study observed significant enhancements in solar system performance. For the north orientation, the maximum enhancement reached 214.38%, while for the south orientation, it reached 166.19%. This demonstrates the substantial improvement in solar capture and utilization when the solar systems are optimized for these specific orientations in Alexandria. Furthermore, the study also highlighted variations in performance based on different orientations. For the east orientation in Alexandria, the maximum enhancement reached about 81.95%, whereas for the west orientation, it reached approximately 77.22%. These results indicate that careful orientation and optimization of solar systems can lead to substantial increases in energy efficiency and performance in different locations within Alexandria. Figure 7 shows the final configuration of the integrated façade.

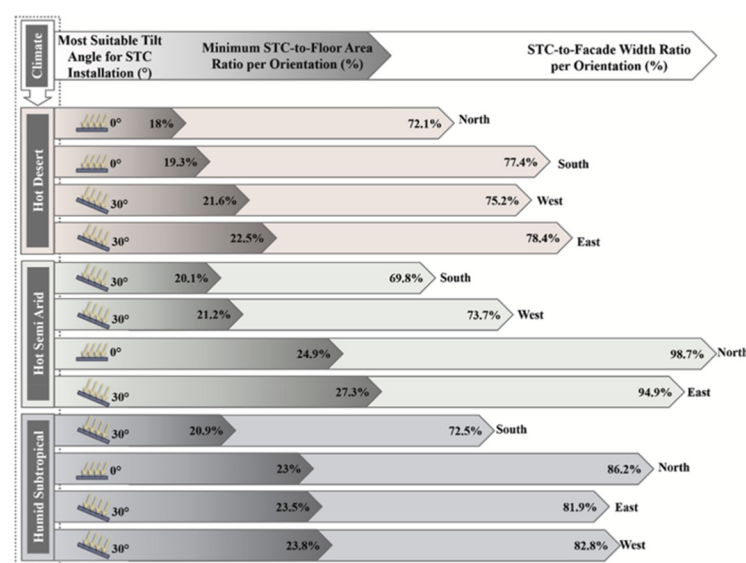


Figure 6. Geometrical design guidelines STC into façade in the hot climates [61].

Alejandro Prieto et al. [64] explored the possibility of applying solar cooling integrated façades as decentralized stand-alone cooling systems applied in different warm regions. They considered applications in Athens, Riyadh, Hong Kong, Lisbon, and Trieste. It should be noted that they considered Singapore as well, but it is not included in the Sunbelt region. In addition, in this case, passive design strategies play a crucial role in reducing cooling demands before incorporating active systems into the building envelope. These strategies include minimizing the window-to-wall ratio, implementing sun shading techniques, using solar control glazing, and utilizing natural ventilation for cooling purposes. By implementing these passive strategies, the cooling demands of the building can be significantly reduced. For this study, the researchers investigated a single office room with an area of 16 m^2 . The room was considered adiabatic for the evaluation, which means that no heat exchange occurs between the room and its surroundings. This simplified setup allows for a detailed analysis of the impact of passive design strategies on cooling demands, providing valuable insights for future applications in larger buildings.

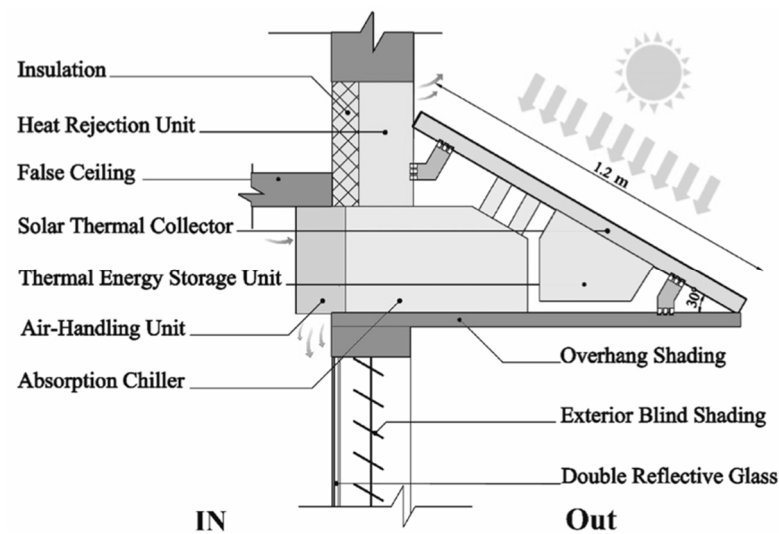


Figure 7. Final configuration of the integrated façade [61].

It is necessary to underline that this case study has been considered just as a reference for the specific assessment at hand and does not claim to represent fully passively optimized scenarios. As evidenced by the results, Lisbon achieved the best outcomes in all orientations, while Hong Kong reported the worst results due to lower solar availability and the highest calculated cooling demands in the simulated scenario. Additionally, it should be noted that, in general, warm-dry climates and east/west orientations are more suitable for solar cooling façade applications compared to humid regions and north/south orientations. The research results indicated that solar thermal technologies hold great performance for both west and east orientations, as the base scenario exhibited significant potential, with theoretical Solar Fraction (SF) reaching 100% in several cases. These findings provide additional evidence supporting the efficacy of passive design strategies and solar cooling applications, particularly in certain climate conditions and orientations. Better performances were noted for warm and dry climates in Athens, Riyadh, and Lisbon, compared to the performance calculated for warm and humid climates (Trieste and Hong Kong). So, for these orientations, solar cooling façade applications could have better performance if installed in temperate climates and dry contexts (e.g., desert) than in extreme and humid climates. Regarding the south applications, locations between the equator and the Tropic of Cancer, such as Hong Kong and Riyadh, have the worst results due to the extreme climate conditions, and the solar radiation contribution is lower when the tilt angle is 90° . The best results for north orientation were obtained from the analysis performed in the case of Lisbon. Table 4 shows some results.

Table 4. Cooling demands for all locations and orientations [64].

Location	Summer Design Week	Orient.	Base Case (No Passive Strategies)	Improved Base Case (With Passive Strategies)		
			Cooling Yearly Demands (kWh (m ² years))	Cooling Yearly Demands (kWh (m ² years))	Cooling Design Capacity (kW)	AVG Daily Cooling in Summer Design Week (kWh day)
Riyadh	20–26 July	South	298.92	92.67	1.19	11.69
		West	336.43	95.11	1.23	12.26
		East	342.14	91.56	1.21	12.26
		North	175.93	84.36	1.16	11.34
Athens	3–9 August	South	231.28	56.00	1.10	10.95
		West	190.69	57.02	1.10	11.27
		East	210.57	54.70	1.08	10.94
		North	94.44	50.21	1.03	10.25
Lisbon	15–21 July	South	224.37	33.01	0.92	7.73
		West	148.25	33.13	0.91	7.86
		East	227.47	33.56	0.90	7.72
Hong Kong	22–28 July	South	246.53	143.99	1.61	13.76
		West	255.69	144.34	1.67	14.15
		East	247.97	135.87	1.62	13.77
		North	186.29	130.87	1.57	13.38
Trieste	20–26 July	South	140.68	40.74	1.26	9.75
		West	110.38	41.12	1.26	9.88
		East	115.28	37.87	1.22	9.51
		North	66.74	36.13	1.18	8.80

According to the findings from the study, different technologies of solar cooling were evaluated. The authors observed that solar electric processes face certain constraints primarily. This is because the efficiency of PV panels is lower if compared to ST collectors. Moreover, the limited efficiencies of thermoelectric modules also contribute to the challenges faced by solar electric processes for cooling applications. However, the study suggests that self-sufficient façade modules for solar cooling could be feasible in east orientations in Lisbon. The east orientation is likely favorable for such applications due to the potential for higher solar exposure and the more effective utilization of solar thermal collectors in this specific location. By leveraging solar thermal technologies in the east orientation, the potential for achieving self-sufficiency in cooling through façade modules is enhanced.

By continuing to analyze applications on façade (Figure 8), Hernandez et al. [65] introduced a novel approach using a honeycomb desiccant block installed within a ventilated façade system. The desiccant material within the honeycomb block is regenerated through the use of a solar air collector, which is also integrated into the façade. This integrated system allows for efficient dehumidification of the air, making it an innovative and sustainable solution for humidity control in buildings. They considered a typical office building (total area of 950 m²), called The Business Entrepreneurship Centre (TBEC). It is located in the Technology Park in Málaga. The main façade is located to the south. Windows are composed of a double layer (4–6–4 mm) and an aluminium frame. The shading system consists of Venetian blinds. It is occupied from 8:00 to 17:00 from Monday to Friday in south zones and from 8 a.m. to 3 p.m. in the eastern zones by a total of 87 people. For the latent load calculation, authors considered a degree of activity of seated/light work, a latent heat of 45 W per person. The system is equipped with two central AHUs used for the distribution of the ventilation air. In the Air Handling Units (AHUs), a cooling coil is activated to reduce the air temperature from the desiccant system. This process ensures that the supply air temperature remains lower or equal to 26 °C, which is the set point comfort temperature in the zones. Additionally, when the desiccant system is not in operation, the cooling coil also plays a role in dehumidifying the ventilation air, further contributing to indoor comfort and humidity control.

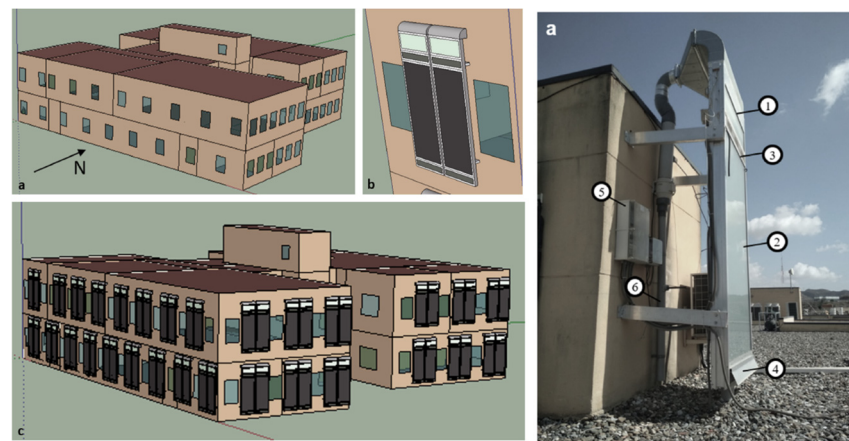


Figure 8. (a) the building; (b) desiccant façade detail; (c) detail of a desiccant system unit installed in the south and east façades [65].

The results of this study are particularly interesting for this task because they included as well the assessment of comfort conditions in terms of humidity values. To do this, the supply air temperature was set at 26° C and the relative humidity was set at 45–60%. From the results, it can be noted that there is a relation between the latent load removed by the façade and the solar radiation it receives. By simulating the conventional system considering the same daily condition, in the south office, the humidity value was very high. The desiccant façade system effectively provides latent load values without the need for excessive overcooling, ensuring more than 90% comfort in the south and east orientations. In contrast, conventional systems require adjustments to the cooling coil's set point air temperature to meet humidity requirements and achieve satisfactory comfort results. With a set point of 26 °C, the desiccant façade system maintains humidity comfort during typical summer days with high ambient humidity. Occupants in the cooling season experience humidity comfort conditions for more than 92% of the time in the south and east façades, while conventional systems only achieve less than 31% comfort in these orientations.

Regarding energy consumption, the fans used in the desiccant façade system play a significant role. However, in conventional systems, the heat pump consumption increases as the supply air temperature decreases, leading to potential inefficiencies in achieving comfort. Overall, the desiccant façade system proves to be highly efficient in maintaining humidity comfort levels without excessive cooling, offering better comfort performance than conventional systems. While there are energy consumption considerations, the desiccant façade's benefits in achieving humidity comfort make it an attractive option for specific orientations and climatic conditions.

5.3. Hybrid Systems: Solar Cooling Systems Integrated with Other Plants

Another interesting aspect to consider regarding the use of solar cooling systems in buildings is the integration of them with other energy sources. Sun et al. [66] evaluated a system for cooling and heating with an absorption chiller that uses gas and solar energy as sources. When solar hot water temperature is low or solar energy is not sufficient, the system operates in gas-fired mode (double effect). Of course, the use of solar energy had priority over gas that can be used only as a backup. The year-round operation of the solar and gas-fired system in two buildings (1000 m²) of a hotel in Changle, Shandong, China was closely monitored and analyzed. The authors who studied the operating parameters of the hybrid solar/gas-fired absorption system tested for a whole year from October 2012 to September 2013. By using the gas/solar-driven absorption system, a savings of 49.7% can be achieved compared with the gas-fired absorption system. Results show that in real operations, solar energy cannot supply the heating and cooling demand, while the solar/gas-fired absorption system could supply all the heating, cooling, and hotel hot

water needs for a building by reducing the energy consumption of a conventional gas-fired absorption system by 49.7%.

5.4. Economic Issues

As said, another aim of this subtask was to study the economic aspects of the application of the solar cooling system in buildings.

Bataineh and Taamneh [67] conducted an economic analysis of adsorption and absorption systems. To do this, they analyzed many case studies presented in the literature. The authors noted that the initial cost of the adsorption system was higher if compared to a conventional system. Results of this study show that the high initial cost of the system and its low performance had a key role in the main significant commercial growth of this technology. The system efficiency and cost can increase by combining different system configurations, collector types, and climate data. According to the results of this study, the size of the system, the long adsorption/desorption time, the high cost of adsorption chillers, and low performance of the adsorption chiller are the main factors that limit commercialization of solar adsorption systems.

Wu et al. [40] developed a method to optimize façade integrated solar cooling systems in terms of technical and financial performance. They assessed four systems: (a) a single-stage absorption chiller, (b) a vapor compression cycle chiller driven by semi-transparent photovoltaics arrays, (c) an adsorption chiller, and (d) a vapor compression chiller coupled with organic Rankine cycle driven by evacuated tube solar collectors. Then, they compared them with a conventional electric vapor compression chiller. They carried out the analysis for different Australian cities. In their research, they applied a financial study. One of the main issues for solar cooling systems is the high investment cost [68] which includes equipment costs, design and installation costs, maintenance cost and operating expenses, and equipment replacement. So, mainly for renewable energy systems, it could be necessary to calculate life cycle costs (capital, operation, and maintenance costs) to make long-term decisions. All calculations were conducted for a project lifetime of 20 years. The cooling technologies are compared based on UCC which represents the life cycle cost for one kWh of cooling, analogous to the levelized energy cost used in the analysis of electricity generation [69] that was determined as follows.

$$UCC = \frac{ALCC (\$ \text{yr}^{-1})}{\text{Cooling supplied } (kWh_r \text{ yr}^{-1})} \quad (1)$$

$$UCC = \frac{LCC}{Pa} \quad (2)$$

$$Pa = \left(\frac{1}{1+d} \right) \left(\left| \frac{1}{1+d} \right|^t - 1 \right) / \left(\frac{1}{1+d} - 1 \right) \quad (3)$$

$$d = \left(\frac{1+D}{1+i} \right) - 1 \quad (4)$$

$$LCC = IC + \sum_{n=1}^t Cr \frac{1}{(1+d)^n} \quad (5)$$

where Pa is the present worth factor, t is lifetime (year), d is the real discount rate, D is the nominal discount rate, i is the inflation rate, IC is the initial cost of the system (\$), and Cr is for each single future cost (\$) to take into account all the operating cost over 20 years that was assumed to be constant for each year except replacement cost occurred. Results demonstrated that nowadays, solar cooling technology is still less cost-competitive compared to conventional cooling systems (at least 50% higher than conventional systems). Among the solar cooling systems, the PV system emerges as the most economically viable option, closely trailed by the organic Rankine cycle (ORC) combined with a vacuum-compression chiller (VCC), adsorption, and single-stage absorption systems. However, this

pattern is not distinctly evident in tropical climate regions. In such zones, the single-stage absorption chiller system proves to be only 21% more expensive than the most affordable PV system. As a result, the duration of the cooling season emerges as a pivotal determinant for selecting the appropriate system. In terms of system performance, the PV system delivers the highest Solar Fraction (SF), followed by the ORC combined with VCC chiller, adsorption, and single-stage absorption systems. Tables 5 and 6 show main results.

Table 5. Initial and life cycle costs [40].

Item	System	Darwin	Brisbane	Perth	Sydney	Adelaide	Canberra	Melbourne
Initial cost (\$)	Conventional	189,424	176,199	192,686	188,333	199,682	151,005	176,674
	PV	583,572	320,358	507,933	504,272	432,380	298,357	375,281
	ORC-VCC	491,888	451,479	483,815	469,043	490,258	414,412	431,049
	AD	442,109	398,971	443,645	418,277	455,187	372,423	392,079
	AB1	503,634	463,925	506,727	489,467	518,283	427,157	455,144
Specific cost (\$ kW _r ^{−1})	Conventional	712	728	708	713	701	763	727
	PV	2641	1732	2199	2345	1779	1865	1876
	ORC-VCC	2256	2508	2122	2255	2132	2726	2449
	AD	2028	2217	1946	2011	1913	2450	2228
	AB1	2310	2577	2222	2353	2178	2811	2586
ALCC (\$ a ^{−1})	Conventional	78,192	52,362	49,921	42,664	42,394	29,761	34,995
	PV	74,757	37,135	58,351	57,861	49,959	34,539	43,357
	ORC-VCC	96,271	67,370	77,277	70,640	69,530	56,458	60,250
	AD	101,398	67,603	76,291	69,902	71,510	57,292	60,150
	AB1	111,125	76,906	84,961	77,964	77,881	62,295	66,561
UCC ((\$ kWh ^{−1})	Conventional	0.14	0.15	0.17	0.18	0.21	0.22	0.24
	PV	0.21	0.24	0.29	0.39	0.38	0.41	0.45
	ORC-VCC	0.23	0.40	0.41	0.47	0.60	0.81	0.77
	AD	0.21	0.38	0.39	0.46	0.63	0.81	0.73
	AB1	0.23	0.44	0.43	51	0.70	0.91	0.82

Table 6. Cost data assumption applied [40].

Item	System	Darwin	Brisbane	Perth	Sydney	Adelaide	Canberra	Melbourne
Solar field (\$ m ^{−2})	PV	750 [70]	750	750	750	750	750	750
	ETC	314	314	314	314	314	314	314
Cooling tower (\$ kW _r ^{−1}) [71]	Conventional	24	25	24	25	24	28	25
	PV	27	29	26	27	25	31	27
	ORC-VCC	28	28	26	26	26	30	28
	AD [72]	27	27	25	27	25	27	27
	AB1	26	25	25	25	25	28	26
Solar Thermal driven chiller (\$ kW _r ^{−1})	ORC-VCC	695	695	695	695	695	695	695
	AD	616	579	616	673	616	579	616
	AB1	1505	1505	1751	1751	1751	2099	1751
Electricity driven chiller (\$ kW _r ^{−1})	Conventional	243	294	275	280	267	326	293
	PV	200	337	301	313	293	360	324
	ORC-VCC	168	345	317	322	312	369	352
	AD	168	357	322	338	309	369	352
	AB1	168	341	322	322	309	369	352
ORC (\$ kW _m ^{−1}) [72]	ORC-VCC	5000	4668	5000	4882	4882	4792	5000
Maintenance cost (\$ kW _r ^{−1})	Conventional	14	15	14	14	14	15	15
	PV	33	24	29	30	24	26	26
	ORC-VCC	34	37	33	34	33	40	40
	AD	35	38	33	34	33	42	42
	AB1	41	45	39	41	38	49	49
Business electricity price (\$ kW _r ^{−1}) [73]	N/A	0.30	0.31	0.33	0.37	0.47	0.27	0.32

Bellos and Tzivanidis [74] investigated solar cooling systems in ten different cities for a typical building of 100 m² floor area. The analysis was supported by simulations

performed by using the commercial software TRNSYS. Various combinations of collectors and storage tank volumes were compared and studied with the aim to determine the optimum combination which leads to the minimum levelized cost of cooling (LCOC). The best results were found in the cases located in Phoenix (LCOC of 0.0575 €/kWh) and Abu Dhabi (LCOC of 0.0590 €/kWh). On the contrary, Rome, Madrid, and Thessaloniki are the less suitable locations. Furthermore, locations with high cooling loads and high solar potential are the most suitable locations for installing solar cooling. In addition, it is proved that higher collecting is associated with a greater optimum storage tank.

Narayanan et al. [75] studied a solar absorption cooling system implemented in a student residential building in Australia (subtropical climate region) by focusing attention on technical, economical, and environmental aspects. They analyzed initial investment costs (the purchase price of the product acquired), the maintenance cost, and operational costs associated with both reference and solar cooling systems. The authors found that the configuration had yearly operational savings of \$1477 compared with vapor compression chiller with a payback period of 15.8 years. In observing the life cycle cost, it was found that the solar cooling system cost was approximately \$58,000, whereas the reference cooling system was approximately \$73,500.

Balaras et al. [76] conducted a state-of-the-art analysis of solar-assisted cooling and AC technologies by presenting some results of the project SACE (Solar Air Conditioning in Europe). Solar AC holds great potential for substantial primary energy savings. Especially in southern European and Mediterranean regions, solar-assisted cooling systems can achieve primary energy savings ranging from 40% to 50%. The related cost of saved primary energy is estimated at approximately 0.07 €/kWh under the most favorable conditions. These findings highlight the significant benefits and cost-effectiveness of implementing solar-assisted cooling technologies in areas with abundant solar resources, such as southern European and Mediterranean regions.

In 1998, Lamp and Ziegler [77] gave an overview of the European research on solar-assisted AC up to 1996 and said that collectors with efficient outputs in the range of 100–150 °C will become available in the near future at reasonable costs. However, to realize significant energy savings, the use of highly efficient chillers is essential. Hence, advancements and innovations are expected primarily from the chiller technology sector. In 2003, Tsoutsos et al. [78] presented a study of the economic feasibility of solar cooling technologies by performing the economic evaluation of two types of solar cooling systems, namely an absorption system and an adsorption system. In this case, results show that due to their high investment costs, these solar cooling systems would only be marginally competitive with standard cooling systems at the current energy prices. Karagiorgas et al. [79] investigated the application of renewable technologies in the European tourism industry and identified a large number of solar thermal systems but only a few solar cooling systems. Different heat-driven cooling technologies are available on the market, particularly for systems of above 40 kW, which can be used in combination with solar thermal collectors. The main obstacles for largescale application, in addition to the high first cost, are the lack of practical experience and acquaintance among architects, builders, and planners with the design, control, and operation of these systems.

Xu et al. [80] compared three layouts, traditional solar absorption-subcooled compression hybrid cooling system (SASCHCS), SASCHCS with the cool energy buffer including and excluding the shift of solar cooling power, which are compared technically and financially based on the 8760 h annual simulation, and the parametric analysis of the best layout was implemented. Finally, three layouts are optimized by the genetic algorithm. It is displayed that the SASCHCS with the cool energy buffer excluding the shift of solar cooling power is the best and 11.4% of compressor work is saved. Additionally, its least payback period is 4.69 years and the maximal net present value is CNY 2.88 million, respectively. The authors evaluated a large cold storage located in subtropical Guangzhou. The solar absorption-subcooled compression hybrid cooling system (SASCHCS), in which the cooling output of the absorption subsystem served as the subcooling power of the compres-

sion subsystem, is promising to be the better layout for cold storages. The higher annual energy saving for the layout without the shift of solar cooling output was 322.47 MWh (81 kWh/m²). Energy saving was 11.4% compared with the reference system. Compared to the other two solutions in the optimal case, its annual energy saving/net present value is 68.2%/62.7% and 41.8%/51.6%.

In the study above cited, Mortadi et al. found that the PVT collector is the most cost-effective one for absorption/adsorption systems, with levelized cost of cooling in the order of €0.106/0.111, €0.137/0.142, and €0.287/0.313 per kWh, and discounted pay-back period of 11.25/11.43, 15.23/14.94, and 24/25.63 years in Barcelona, Marrakesh, and Oslo, respectively. Moreover, the evacuated-tube collector was found to be the most “environmentally-friendly” collector, since it allows reducing greenhouse gas emissions, especially in boreal climate with a life cycle climate performance of 5.86/5.99 tCO₂ for absorption/adsorption systems.

5.5. Cooling Demand Market Index (CDMI)

The global demand for space cooling is increasing globally. Main drivers to this development are according to Campbell et al. (i) global warming and increased temperature, (ii) population growth, (iii) income growth, and (iv) urbanization [81]. Those factors are also identified by the International Energy Agency in the “Future of Cooling” report [2].

The CDMI developed by Strobel et al. [82] is a GIS-based indicator to identify increasing economical demand for cooling applications on a global scale. Based on scenarios for future demographic, climatic, and economic development, the CDMI locates the increase in demand for cooling applications. The economic development, portrayed as the Gross Domestic Product (GDP) per capita, is assessed as the driving factor, as the demand for cooling applications is predicted to be placed in countries with developing economies, especially India and Indonesia. The CDMI forecasts are based on widely applied scenarios: the Representative Concentration Pathways (RCP) and the Spatial Socioeconomic Pathways (SSP). The RCPs picture different scenarios for climate change [83] while the SSPs picture future socioeconomic developments [84]. For Nepal, for instance, the cumulative CDMI for the total country will rise by 200% to 350% from 2020 until 2050. The variation is based on the combined scenario of SSP and RCP. Figure 9 presents two maps for the Nepalese CDMI, one on the left for 2020 and one on the right for 2050 for a scenario based on SSP1 and RCP2.6. Demand for cooling applications is especially going to increase in the regions of low altitude close to the Indian border and in the metropole area of Kathmandu.



Figure 9. CDMI results for Nepal for 2020 and for 2050, scenario based on SSP1 and RCP2.6.

6. Discussion

The present review investigated the application of solar cooling systems in buildings in the Sunbelt region. The following table shows the summary of the main studies analyzed.

Review papers typically report the majority of cases, capturing valuable information from various case studies. Consequently, key details and specific characteristics of the systems mentioned in this class of papers are not included in the Table 7.

Table 7. Summary of main studies cited.

Study	Paper Typology	Real/Simulation	System Typology	Results and Main Outputs
Al-Yasiri et al., 2022 [58]	Review	Various	Overview of solar cooling and air-conditioning systems (SCACSs) used for building applications.	-
Balaras et al., 2007 [76]	Review	Various	Solar-assisted cooling in Europe.	-
Bataineh and Taamneh 2016 [67]	Review	Various	Solar sorption systems.	-
Bellos and Tzivanidis, 2017 [74]	Experimental	Simulation	Single-stage absorption chiller operating with the LiBr-H ₂ O working pair is coupled with evacuated tube collectors and this system produces the demanded cooling load for a typical building of 100 m ² floor area.	Levelized cost of cooling: <i>Abu Dhabi</i> : 0.0575 €/kWh <i>Phoenix</i> : 0.0590 €/kWh <i>Rome</i> : 0.2125 €/kWh <i>Madrid</i> : 0.1792 €/kWh <i>Thessaloniki</i> : 0.1771 €/kWh
Chen et al., 2022 [59]	Experimental	Simulation	A solar-based cooling and heating system is proposed here employing solar concentrating collectors, photovoltaics, double-effect absorption heat pump, and thermal storage.	Energy saving: 73.3% Cost saving: 64.2% energy COP: from 5.87 to 7.56
Comino et al., 2020 [60]	Experimental	Real setup	Solar desiccant cooling systems (SDEC) utilized to control indoor conditions in a research lab room.	Sensible seasonal coefficient of performance: 2.1 was obtained. Seasonal latent coefficient of performance: 0.5. Total seasonal coefficient of performance: 2.
Desideri et al., 2009 [68]	Experimental	Design calculation	Absorption chiller coupled to solar flat plate collectors.	-
Fernández Hernández et al., 2020 [65]	Experimental	Pilot scale prototype + simulation	Honeycomb desiccant block placed inside a ventilated façade. The regeneration of the desiccant material is carried out by a solar air collector, which is also integrated in the façade.	- Occupants experience humidity comfort conditions: 92% of the time in south and east façades. - The fans used in the desiccant façade system play a significant role. - It proves to be highly efficient in maintaining humidity comfort levels without excessive cooling, offering better comfort performance than conventional systems. - The desiccant façade's benefits in achieving humidity comfort make it an attractive option for specific orientations and climatic conditions.

Table 7. Cont.

Study	Paper Typology	Real/Simulation	System Typology	Results and Main Outputs
Lamp and Ziegler 1998 [77]	Review	Various	Solar cooling by sorption systems.	-
Marwan Mokhtar et al., 2010 [69]	Experimental	Simulation	Different solar collector/chiller system (e.g., evacuated tube collectors, flat plate collectors, Fresnel, linear Fresnel concentrator, multicrystalline photovoltaic cells, etc.).	-
Mortadi and El Fadar, 2021 [56]	Experimental	Simulation	Solar absorption, solar adsorption, photovoltaic, and photovoltaic thermal cooling systems.	Photovoltaic thermal cooling system SCOP values: 36% to 52%, depending on climate. Photovoltaic cooling system levelized cost of cooling: 0.056–0.25 €/kWh, depending on climate.
Mortadi and El Fadar, 2022 [57]	Experimental	Simulation	Absorption and adsorption cooling systems powered by different solar collectors, namely flat plate collector, evacuated-tube collector, compound parabolic collector, parabolic trough collector, photovoltaic thermal collector, and a new configuration of concentrating photovoltaic thermal collector, for air-conditioning application in a residential building.	PVT for absorption cooling COP: Marrakesh: 0.449 Barcelona: 0.428 Oslo: 0.414 PVT for the adsorption cooling COP: Marrakesh: 0.397 Barcelona: 0.386 Oslo: 0.351 Levelized cost of cooling: Marrakesh: €0.106/0.111 per kWh Barcelona: €0.137/0.142 per kWh Oslo: €0.287/0.313 per kWh Discounted payback period: Marrakesh: 11.25/11.43 years Barcelona: 15.23/14.94 years Oslo: 24/25.63 years
Naderi et al., 2022 [49]	Review	Various	Pre-cooling and solar pre-cooling covering the period 2014 to 2021.	-

Table 7. Cont.

Study	Paper Typology	Real/Simulation	System Typology	Results and Main Outputs
Narayanan 2021 [75]	Experimental	Simulation	Solar absorption cooling technology in student residential building in Australia's subtropical climate region.	Energy saving (compared with vapor compression chiller): \$1477. Payback period: 15.8 years. Life cycle cost of the solar cooling: \$58,000. Life cycle cost of the reference cooling system: \$73,500. CH₄ saving (compared with vapor compression chiller system): 0.003-ton. N₂O saving (compared with vapor compression chiller system): 0.001-ton. CO₂ saving (compared with vapor compression chiller system): 2 tons.
Nelson et al., 2019 [50]	Experimental	Simulation	Solutions of precooling and thermal energy storage (TES): sized for 6 locations. TES capacity: 10.55 kW (3 tons) and 73.85 kWh for Phoenix, 3.52 kW (1 ton) and 14.08 kWh for Los Angeles, and 5.28 kW (1.5 tons) and 26.40 kWh for Kona.	Precooling + TES reduction in energy use: 75.6% and 78.5% for Phoenix, 36.9% and 37.9% for Los Angeles, and 60.7% and 64.4% for Kona. TES system reduction daily on-peak demand (compared with the baseline cooling strategy across all three locations): 11.1–55.8%. TES system reduction on-peak electricity consumption (compared with the baseline cooling strategy across all three locations): 11.5–54.6%. Precooling set back strategy reductions in annual on-peak demand: <i>Phoenix</i>: 38.3% <i>Los Angeles</i>: 51.5% Annual on-peak energy use: <i>Phoenix</i>: 26.2% <i>Los Angeles</i>: 7.0%

Table 7. Cont.

Study	Paper Typology	Real/Simulation	System Typology	Results and Main Outputs
Noaman et al., 2022 [61]	Experimental	Simulation	Passive solar design strategies (PSDSs), and then integrating an active solar cooling technology (ASCT) into the façade. Three hot climates, namely, humid subtropical, hot semi-arid, and hot desert. Four PSDSs, window-to-wall ratio (WWR), glazing type, shading devices, and wall material were sequentially applied to the façade. Then, an absorption chiller driven by a solar thermal collector (STC) was integrated into this passively designed façade.	Energy saving: 43.5–65.7%
Prieto et al., 2018 [62]	Experimental	Simulation	Passive cooling strategies in commercial buildings from warm climates.	Mean cooling demand saving: warm-dry climates: 22–50% (review) and 26–33% (simulation). warm-dry climates: 12–33% (review) –2–22% (simulation).
Prieto et al., 2018 [64]	Review	Various	Self-sustaining solar cooling façade modules on office or commercial buildings.	-
Shbailat and Nima, 2021 [26]	Experimental		Solar chimneys.	Average energy saving for test room with evaporative cooling and solar chimney system decrease with the increase in volume flow rate to reach the maximum value 20% with $Q = 0.8 \text{ L/m}$.
Sun et al., 2015 [66]	Experimental	Real experimental setup	A system for cooling and heating based on an absorption chiller that can be driven by both gas firing and solar hot water was proposed and built. A system for cooling and heating based on an absorption chiller that can be driven by both gas firing and solar hot water was proposed and built.	Gas use saving (compared with the conventional gas-fired system): 49.7%.

Table 7. Cont.

Study	Paper Typology	Real/Simulation	System Typology	Results and Main Outputs
Tsoutso et al., 2003 [78]	Experimental	An absorption type using H ₂ O–LiBr as working fluids, and an adsorption system using silica gel–water.	An absorption system and an adsorption system.	-
Xu et al. 2021 [80]	Experimental	Simulation	Solar absorption-subcooled compression hybrid cooling system (SASCHCS).	Annual energy saving for the layout without the shift of solar cooling output: 322.47 MWh (81 kWh/m ²). Electricity saving: 11.4%. Peak Payback time period: 4.69 years. Peak net present value: CNY 2.88 million.

Most of the papers refer to the last decade. The number of papers is very limited. It is because it would seem that the technology of solar cooling needs more improvements and further study.

However, it was demonstrated that the application of solar cooling systems, mainly if coupled with other passive techniques, can achieve significant energy savings. Unluckily, authors of the reviewed papers reported the energy saving in different terms, so it is not possible to make a comparison in a direct, simple, or immediate way. Moreover, as it is possible to see, most of the studies were based on simulation results. Furthermore, the scale of application is different. Some of the presented systems were tested in actual test case studies but considering a single room. Other studies have shown results based on whole building application.

Finally, another critical aspect is related to the fact that not much data about the characteristics of the building (such as about envelope, other cooling systems, comfort conditions, etc.) are reported in the studies. It is because many of them are more focused on the plant's configurations, and the performance of the different plants is in general assessed by testing the prototype in a single room. Related to this latter, it must be noted that the studies that tested the system on a whole system considered only simulation data. The study analyzed reported different results and conclusions by demonstrating that the performance of the solar cooling systems is related by the different characteristics such as opaque and transparent materials and percentage of surfaces, orientation, schedules, end-use, habitants' behavior, and the standard of their comfort conditions. Finally, the cooling systems' performances (not considering the alternative passive solutions, such as cooling roofs) widely influence the final consumption, by varying according to the COP (EER), the efficiency of generation, distribution, regulation, and emissions components, the maintenance, and the typology. All of these aspects, of course, influence as well the economic impact and the related costs of the installation, operation, and maintenance. According to this, some results of authors that focused their attention on the economic aspects were reported.

7. Conclusions

This paper presents the results of the activities related to subtask A4. In the first part of the report, some data of a completed project were reported. They were useful to understand the energy consumption of typical public buildings with different end-use results.

The second part reported information related to the application of factors influencing a building's cooling energy demand and different solar cooling plants in buildings. A lot of passive measures to optimize the energy performance of a building are identified in the review, such as shading elements, windows quality, or insulation. Those parameters are identified in the literature and assessed in their ability to decrease the cooling demand. However, studies show different results are assessments of measures which are hard to compare as different boundary conditions are considered.

The main output of this research is that the topic of solar cooling system integration in buildings needs more investigation for the following reasons:

- Most of the studies are based on simulation;
- The studies based on real experimental setups considered as samples a single simplified room and not the whole buildings;
- Many papers did not present the thermal and geometric characteristics of the buildings and it makes a complete analysis more difficult.

Starting from these points, the following conclusions are reached based on the discussions in this paper:

- Passive measures can widely reduce the energy demand for cooling and some of them can be cheap and easy to be applied (e.g., natural ventilation to remove heat and to cool down a building is one of the cheapest and easiest ways to decrease the cooling demand of a building);

- The mitigation of the Urban Heat Islands (UHI) could be a great measure to reduce cooling demand;
- From the economic point of view, the integrated systems are not sustainable, but optimization of the design (e.g., orientation and the use of simplified structure) can improve the performance;
- The cooling demand is going to increase worldwide driven by socioeconomic and climatic developments, of which the rising economic growth in developing countries is the main driver.

In further work, a similar analysis will be conducted by including a larger area to expand the set of the case study and do more analysis and considerations.

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References

1. IEA (2022): Space Cooling. Edited by OECD/IEA. Paris. Updated on September 2022. Available online: <https://www.iea.org/reports/space-cooling> (accessed on 19 June 2023).
2. Dean, B.; Dulac, J.; Morgan, T.; Remme, U. The Future of Cooling. Opportunities for energy-efficient air conditioning. With assistance of Thibault Abergel, Matteo Craglia, Crai Hart, Zoé Hungerford, Peerapat Vithayasrichareon. Edited by IEA Publications. International Energy Agency 2018. Available online: <https://www.iea.org/reports/the-future-of-cooling> (accessed on 8 June 2023).
3. Li, W.; Gong, G.; Ren, Z.; Ouyang, Q.; Peng, P.; Chun, L.; Fang, X. A method for energy consumption optimization of air conditioning systems based on load prediction and energy flexibility. *Energy* **2022**, *243*, 123111. [CrossRef]
4. Khourchid, A.M.; Al-Ansari, T.A.; Al-Ghamdi, S.G. Cooling Energy and Climate Change Nexus in Arid Climate and the Role of Energy Transition. *Buildings* **2023**, *13*, 836. [CrossRef]
5. Colelli, F.P.; Wing, I.S.; Cian, E.D. Air-conditioning adoption and electricity demand highlight climate change mitigation–adaptation tradeoffs. *Sci. Rep.* **2023**, *13*, 4413. [PubMed]
6. Bamdad, K. Cool roofs: A climate change mitigation and adaptation strategy for residential buildings. *Build. Environ.* **2023**, *236*, 110271. [CrossRef]
7. Hwang, R.L.; Chen, W.A. Identifying relative importance of solar design determinants on office building façade for cooling loads and thermal comfort in hot-humid climates. *Build. Environ.* **2022**, *226*, 109684. [CrossRef]
8. Beccali, M.; Bonomolo, M.; Di Pietra, B.; Leone, G.; Martorana, F. Solar and heat pump systems for domestic hot water production on a small island: The case study of Lampedusa. *Appl. Sci.* **2020**, *10*, 5968. [CrossRef]
9. Guarino, S.; Buscemi, A.; Ciulla, G.; Bonomolo, M.; Brano, V.L. A dish-stirling solar concentrator coupled to a seasonal thermal energy storage system in the southern mediterranean basin: A cogenerative layout hypothesis. *Energy Convers. Manag.* **2020**, *222*, 113228. [CrossRef]
10. Di Lorenzo, G.; Rotondo, S.; Araneo, R.; Petrone, G.; Martirano, L. Innovative power-sharing model for buildings and energy communities. *Renew. Energy* **2021**, *172*, 1087–1102. [CrossRef]
11. Martirano, L.; Araneo, R.; Ruvio, A.; Leonowicz, Z.; Rezmer, J. A microgrid with PV production and energy storage for an university building. In Proceedings of the 2017 IEEE 14th International Conference on Networking, Sensing and Control (ICNSC), Calabria, Italy, 16–18 May 2017; pp. 31–36.
12. El Hassani, S.; Charai, M.; Moussaoui, M.A.; Mezrhab, A. Towards rural net-zero energy buildings through integration of photovoltaic systems within bio-based earth houses: Case study in Eastern Morocco. *Sol. Energy* **2023**, *259*, 15–29. [CrossRef]
13. Panda, A.; Dauda, A.K.; Chua, H.; Tan, R.R.; Aviso, K.B. Recent advances in the integration of renewable energy sources and storage facilities with hybrid power systems. *Clean. Eng. Technol.* **2023**, *12*, 100598. [CrossRef]
14. Hassan, A.A.; El-Rayes, K. Optimizing the integration of renewable energy in existing buildings. *Energy Build.* **2021**, *238*, 110851. [CrossRef]
15. Neyer, D.; Jakob, U. Solar cooling for the Sunbelt Regions—a new IEA SHC task. In Proceedings of the EuroSun 2020, Online, 1–3 September 2020; International Solar Energy Society: Freiburg im Breisgau, Germany, 2020; Volume 2020, p. 13.

16. Liu, C.; Xie, H.; Ali, H.M.; Liu, J. Evaluation of Passive Cooling and Thermal Comfort in Historical Residential Buildings in Zanzibar. *Buildings* **2022**, *12*, 2149. [\[CrossRef\]](#)
17. Bekele, M.T.; Atakara, C. Residential Building Energy Conservation in Mediterranean Climate Zone by Integrating Passive Solar and Energy Efficiency Design Strategies. *Buildings* **2023**, *13*, 1073. [\[CrossRef\]](#)
18. Lozoya-Peral, A.; Pérez-Carramiñana, C.; Galiano-Garrigós, A.; González-Avilés, Á.B.; Emmitt, S. Exploring Energy Retrofitting Strategies and Their Effect on Comfort in a Vernacular Building in a Dry Mediterranean Climate. *Buildings* **2023**, *13*, 1381. [\[CrossRef\]](#)
19. Pacheco, R.; Ordóñez, J.; Martínez, G. Energy efficient design of building: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3559–3573. [\[CrossRef\]](#)
20. Al Dakheel, J.; Tabet, A.K. Building Applications, Opportunities and Challenges of Active Shading Systems: A State-of-the-Art Review. *Energies* **2023**, *10*, 1672. [\[CrossRef\]](#)
21. Shree, V.; Goyal, N.; Saxena, A.; Bhattacharyya, S.; Dwivedi, A.; Goel, V. Assessment of thermal loading in energy-efficient buildings: Parametric review on the window design aspects. *J. Therm. Anal. Calorim.* **2023**, *148*, 2703–2718. [\[CrossRef\]](#)
22. Friedrichsen, S. *Nachhaltiges Planen, Baue und Wohnen*; Springer: Berlin/Heidelberg, Germany, 2018.
23. Gupta, N.; Tiwari, G.N. Review of passive heating/cooling systems of buildings. *Energy Sci. Eng.* **2016**, *4*, 305–333. [\[CrossRef\]](#)
24. Elaouzy, Y.; El Fadar, A. Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112828. [\[CrossRef\]](#)
25. Jomehzadeh, F.; Nejat, P.; Calautit, J.K.; Yusof, M.B.M.; Zaki, S.A.; Hughes, B.R.; Yazid, M.N.A.W.M. A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. *Renew. Sustain. Energy Rev.* **2017**, *70*, 736–756. [\[CrossRef\]](#)
26. Shbailat, S.J.; Nima, M.A. Possible energy saving of evaporative passive cooling using a solar chimney of metal foam porous absorber. *Energy Convers. Manag.* **2021**, *12*, 100118. [\[CrossRef\]](#)
27. Zeinelabdein, R.; Omer, S.; Gan, G. Critical review of latent heat storage systems for free cooling in buildings. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2843–2868. [\[CrossRef\]](#)
28. Souayfane, F.; Fardoun, F.; Biwolé, P.H. Phase change materials (PCM) for cooling applications in buildings: A review. *Energy Build.* **2016**, *129*, 396–431. [\[CrossRef\]](#)
29. Romeo, C.; Zinzi, M. Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy Build.* **2013**, *67*, 647–657. [\[CrossRef\]](#)
30. Akbari, H.; Berhe, A.A.; Levinson, R. *Aging and Weathering of Cool Roofing Membranes*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2005; Available online: <https://escholarship.org/uc/item/3qb8j3k7> (accessed on 25 August 2023).
31. D'Orazio, M.; Di Perna, C.; Di Giuseppe, E. Green roof yearly performance: A case study in a highly insulated building under temperate climate. *Energy Build.* **2012**, *55*, 439–451. [\[CrossRef\]](#)
32. Jaffal, I.; Ouldboukhite, S.; Belarbi, R. A comprehensive study of the impact of green roofs on building energy performance. *Renew. Energy* **2012**, *43*, 157–164. [\[CrossRef\]](#)
33. Su, M.A.; Ngarambe, J.; Santamouris, M.; Yun, G.Y. Empirical evidence on the impact of urban overheating on building cooling and heating energy consumption. *iScience* **2021**, *24*, 102495. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Moustris, K.P.; Zacharia, P.; Larissi, I.K.; Nastos, P.T.; Paliatsos, A.G. Cooling and Heating Degree-Days Calculation for representative Locations within the greater Athens Area, Greece. Department of Mechanical Engineering, Technological Educational Institute of Piraeus. Rhodes, Greece. Available online: <https://www.researchgate.net/publication/233776116> (accessed on 18 August 2023).
35. Boudali, E.F.; Strebel, D.; Carmeliet, J.; Derome, D. Impact of urban heat island on cooling energy demand for residential building in Montreal using meteorological simulations and weather station observations. *Energy Build.* **2022**, *273*, 112410. [\[CrossRef\]](#)
36. Kolokotsa, D.D.; Giannariakis, G.; Gobakis, K.; Giannarakis, G.; Synnefa, A.; Santamouris, M. Cool roofs and cool pavements application in Acharnes, Greece. *Sustain. Cities Soc.* **2018**, *37*, 466–474. [\[CrossRef\]](#)
37. Governatori, M.; Cedillo-González, E.I.; Manfredini, T.; Siligardi, C. Solar reflective properties of porcelain tiles for UHI mitigation: Effect of highly reflective frits in the engobe's formulation. *Mater. Today Sustain.* **2022**, *20*, 100255. [\[CrossRef\]](#)
38. Semenzato, P.; Bortolini, L. Urban Heat Island Mitigation and Urban Green Spaces: Testing a Model in the City of Padova (Italy). *Land* **2023**, *12*, 476. [\[CrossRef\]](#)
39. Iaria, J.; Susca, T. Analytic Hierarchy Processes (AHP) evaluation of green roof- and green wall- based UHI mitigation strategies via ENVI-met simulations. *Urban Clim.* **2022**, *46*, 101293. [\[CrossRef\]](#)
40. Wu, Z.; Zhang, Y. Water Bodies' Cooling Effects on Urban Land Daytime Surface Temperature: Ecosystem Service Reducing Heat Island Effect. *Sustainability* **2019**, *11*, 787. [\[CrossRef\]](#)
41. Garshasbi, S.; Haddad, S.; Paolini, R.; Santamouris, M.; Papangelis, G.; Dandou, A.; Methymaki, G.; Portalakis, P.; Tombrou, M. Urban mitigation and building adaptation to minimize the future cooling energy needs. *Sol. Energy* **2020**, *204*, 708–719. [\[CrossRef\]](#)
42. Wang, C.; Wang, Z.; Kaloush, K.E.; Shacat, J. Perceptions of urban heat island mitigation and implementation strategies: Survey and gap analysis. *Sustain. Cities Soc.* **2021**, *66*, 102687. [\[CrossRef\]](#)
43. Duan, Z.; Zhan, C.; Zhang, X.; Mustafa, M.; Zhao, X.; Alimohammadisagvand, B.; Hasan, A. Indirect evaporative cooling: Past, present and future potentials. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6823–6850. [\[CrossRef\]](#)

44. Yang, Y.; Cui, G.; Lan, C.Q. Developments in evaporative cooling and enhanced evaporative cooling—A review. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109230. [\[CrossRef\]](#)
45. Daou, K.; Wang, R.; Xia, Z. Desiccant cooling air conditioning: A review. *Renew. Sustain. Energy Rev.* **2006**, *10*, 55–77. [\[CrossRef\]](#)
46. Vall, S.; Castell, A. Radiative cooling as low-grade energy source: A literature review. *Renew. Sustain. Energy Rev.* **2017**, *77*, 803–820. [\[CrossRef\]](#)
47. Ito, S.; Miura, N. Studies of Radiative Cooling Systems for Storing Thermal Energy. *J. Sol. Energy Eng.* **1989**, *111*, 251–256. [\[CrossRef\]](#)
48. Ezekwe, C.I. Performance of a heat pipe assisted night sky radiative cooler. *Energy Convers. Manag.* **1990**, *30*, 403–408. [\[CrossRef\]](#)
49. Naderi, S.; Pignatta, G.; Heslop, S.; MacGill, I.; Chen, D. Demand response via pre-cooling and solar pre-cooling: A review. *Energy Build.* **2022**, *272*, 112340. [\[CrossRef\]](#)
50. Nelson, J.; Johnson, N.G.; Chinimilli, P.T.; Zhang, W. Residential cooling using separated and coupled precooling and thermal energy storage strategies. *Appl. Energy* **2019**, *252*, 113414. [\[CrossRef\]](#)
51. Tabares-Velasco, P.C.; Speake, A.; Harris, M.; Newman, A.; Vincent, T.; Lanahan, M. A modeling framework for optimization-based control of a residential building thermostat for time-of-use pricing. *Appl. Energy* **2019**, *242*, 1346–1357. [\[CrossRef\]](#)
52. Kishore, R.A.; Bianchi, M.V.A.; Booten, C.; Vidal, J.; Jackson, R. Modulating thermal load through lightweight residential building walls using thermal energy storage and controlled precooling strategy. *Appl. Therm. Eng.* **2020**, *180*, 115870. [\[CrossRef\]](#)
53. Stopps, H.; Touchie, M.F. Perceptions of thermal conditions in contemporary high-rise apartment buildings under different temperature control strategies. *Sci. Technol. Built Environ.* **2021**, *27*, 1492–1504. [\[CrossRef\]](#)
54. Turner, W.J.N.; Walker, I.S.; Roux, J. Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass. *Energy* **2015**, *82*, 1057–1067. [\[CrossRef\]](#)
55. Romani, J.; Belusko, M.; Alemu, A.; Cabeza, L.F.; Gracia, A.; Bruno, F. Control concepts of a radiant wall working as thermal energy storage for peak load shifting of a heat pump coupled to a PV array. *Renew. Energy* **2018**, *118*, 489–501. [\[CrossRef\]](#)
56. Mortadi, M.; El Fadar, A. Performance, economic and environmental assessment of solar cooling systems under various climates. *Energy Convers. Manag.* **2022**, *252*, 114993. [\[CrossRef\]](#)
57. Mortadi, M.; El Fadar, A. Cost-effective and environmentally friendly solar collector for thermally driven cooling systems. *Appl. Therm. Eng.* **2022**, *217*, 119234. [\[CrossRef\]](#)
58. Al-Yasiri, Q.; Szabó, M.; Arıcı, M. A review on solar-powered cooling and air-conditioning systems for building applications. *Energy Rep.* **2022**, *8*, 2888–2907. [\[CrossRef\]](#)
59. Chen, Y.; Hua, H.; Xu, J.; Wang, J.; Lund, P.D.; Han, Y.; Cheng, T. Energy, environmental-based cost, and solar share comparisons of a solar driven cooling and heating system with different types of building. *Appl. Therm. Eng.* **2022**, *211*, 118435. [\[CrossRef\]](#)
60. Comino, F.; Castillo, G.J.; Navas-Martos, F.J.; Ruiz de Adana, M. Experimental energy performance assessment of a solar desiccant cooling system in Southern Europe climates. *Appl. Therm. Eng.* **2020**, *165*, 114579. [\[CrossRef\]](#)
61. Noaman, D.S.; Moneer, S.A.; Megahed, N.A.; El-Ghaffour, S.A. Integration of active solar cooling technology into passively designed facade in hot climates. *J. Build. Eng.* **2022**, *56*, 104658. [\[CrossRef\]](#)
62. Prieto, A.; Knaack, U.; Auer, T.; Klein, T. Passive cooling & climate responsive façade design. *Energy Build.* **2018**, *175*, 30–47. [\[CrossRef\]](#)
63. Pino, A.; Bustamante, W.; Escobar, R.; Pino, F.E. Thermal and lighting behavior of office buildings in Santiago of Chile. *Energy Build.* **2012**, *47*, 441–449. [\[CrossRef\]](#)
64. Prieto, A.K.U.; Auer, T.; Klein, T. Feasibility Study of Self-Sufficient Solar Cooling Façade Applications in Different Warm Regions. *Energies* **2018**, *11*, 1475. [\[CrossRef\]](#)
65. Fernández Hernández, F.; Jiménez, N.; Juan, P.; Atienza-Márquez, A.; Cejudo López, J.M.; Carrillo Andrés, A. An experimental and numerical model of a desiccant façade. A case of study of an office building in different weather conditions. *Energy Build.* **2020**, *224*, 110255. [\[CrossRef\]](#)
66. Sun, H.; Xu, Z.; Wang, H.; Wang, R. A Solar/gas Fired Absorption System for Cooling and Heating in a Commercial Building. *Energy Procedia* **2015**, *70*, 518–528. [\[CrossRef\]](#)
67. Bataineh, K.; Taamneh, Y. Review and recent improvements of solar sorption cooling systems. *Energy Build.* **2016**, *128*, 22–37. [\[CrossRef\]](#)
68. Desideri, U.; Proietti, S.; Sdringola, P. Solar-powered cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications. *Appl. Energy* **2009**, *86*, 1376–1386. [\[CrossRef\]](#)
69. Mokhtar, M.; Ali, M.T.; Bräuniger, S.; Afshari, A.; Sgouridis, S.; Armstrong, P.; Chiesa, M. Systematic comprehensive techno-economic assessment of solar cooling technologies using location-specific climate data. *Appl. Energy* **2010**, *87*, 3766–3778. [\[CrossRef\]](#)
70. Nordin, N.; Rahman, H. Sizing and economic analysis of stand-alone photovoltaic system with hydrogen storage. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *93*, 012068. [\[CrossRef\]](#)
71. CTS. Cooling Tower Price List. 2018. Available online: http://www.coolingtowersystems.com/cooling_twr_price.php (accessed on 10 February 2018).
72. Lemmens, S. A perspective on costs and cost estimation techniques for organic Rankine cycle systems. In Proceedings of the 3rd International Seminar on ORC Power Systems, Brussels, Belgium, 12–14 October 2015; pp. 12–14.

73. OTER. Comparison of Australian Standing Offer Energy Prices August 2017. Office of the Tasmanian Economic Regulator: Hobart, Australia, 2017.
74. Bellos, E.; Tzivanidis, C. Energetic and financial analysis of solar cooling systems with single effect absorption chiller in various climates. *Appl. Therm. Eng.* **2017**, *126*, 809–821. [\[CrossRef\]](#)
75. Narayanan, R.; Harilal, G.K.; Golder, S. Feasibility study on the solar absorption cooling system for a residential complex in the Australian subtropical region. *Case Stud. Therm. Eng.* **2021**, *27*, 101202. [\[CrossRef\]](#)
76. Balaras, C.A.; Grossman, G.; Henning, H.; Infante Ferreira, C.A.; Podesser, E.; Wang, L.; Wiemken, E. Solar air conditioning in Europe—An overview. *Renew. Sustain. Energy Rev.* **2007**, *11*, 299–314. [\[CrossRef\]](#)
77. Lamp, P.; Ziegler, F. European research on solar-assisted air conditioning. *Int. J. Refrig.* **1998**, *21*, 89–99. [\[CrossRef\]](#)
78. Tsoutsos, T.; Anagnostou, J.; Pritchard, C.; Karagiorgas, M.; Agoris, D. Solar cooling technologies in Greece. An economic viability analysis. *Appl. Therm. Eng.* **2003**, *23*, 1427–1439. [\[CrossRef\]](#)
79. Karagiorgas, M.; Tsoutsos, T.; Drosou, V.; Pouffary, S.; Pagano, T.; Lara, G.; Melim Mendes, J. HOTRES: Renewable energies in the hotels. An extensive technical tool for the hotel industry. *Renew. Sustain. Energy Rev.* **2006**, *10*, 198–224. [\[CrossRef\]](#)
80. Xu, Y.; Li, Z.; Chen, H.; Lv, S. Techno-economic evaluation and analysis of solar hybrid cooling systems with cool energy buffer for cold storages. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101270. [\[CrossRef\]](#)
81. Campbell, I.; Sachar, S.; Kalanki, A.; Solving the Global Cooling Challenge. How to encounter the Climate Threat from Room Air Conditioners. Edited by Rocky Mountain Institute. 2018. Available online: https://rmi.org/wp-content/uploads/2018/11/Global_Cooling_Challenge_Report_2018.pdf (accessed on 25 August 2023).
82. Strobel, M.; Jakob, U.; Streicher, W.; Neyer, D. Spatial Distribution of Future Demand for Space Cooling Applications and Potential of Solar Thermal Cooling Systems. *Sustainability* **2023**, *15*, 9486. [\[CrossRef\]](#)
83. Van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F.; et al. The representative concentration pathways: An overview. *Clim. Chang.* **2011**, *109*, 5–31. [\[CrossRef\]](#)
84. O'Neill, B.C.; Kriegler, E.; Ebi, K.L.; Kemp-Benedict, E.; Riahi, K.; Rothman, D.S.; van Ruijven, B.J.; van Vuuren, D.P.; Birkmann, J.; Kok, K.; et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* **2017**, *42*, 169–180. [\[CrossRef\]](#)

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