SHC
SOLAR HEATING & COOLING PROGRAMME
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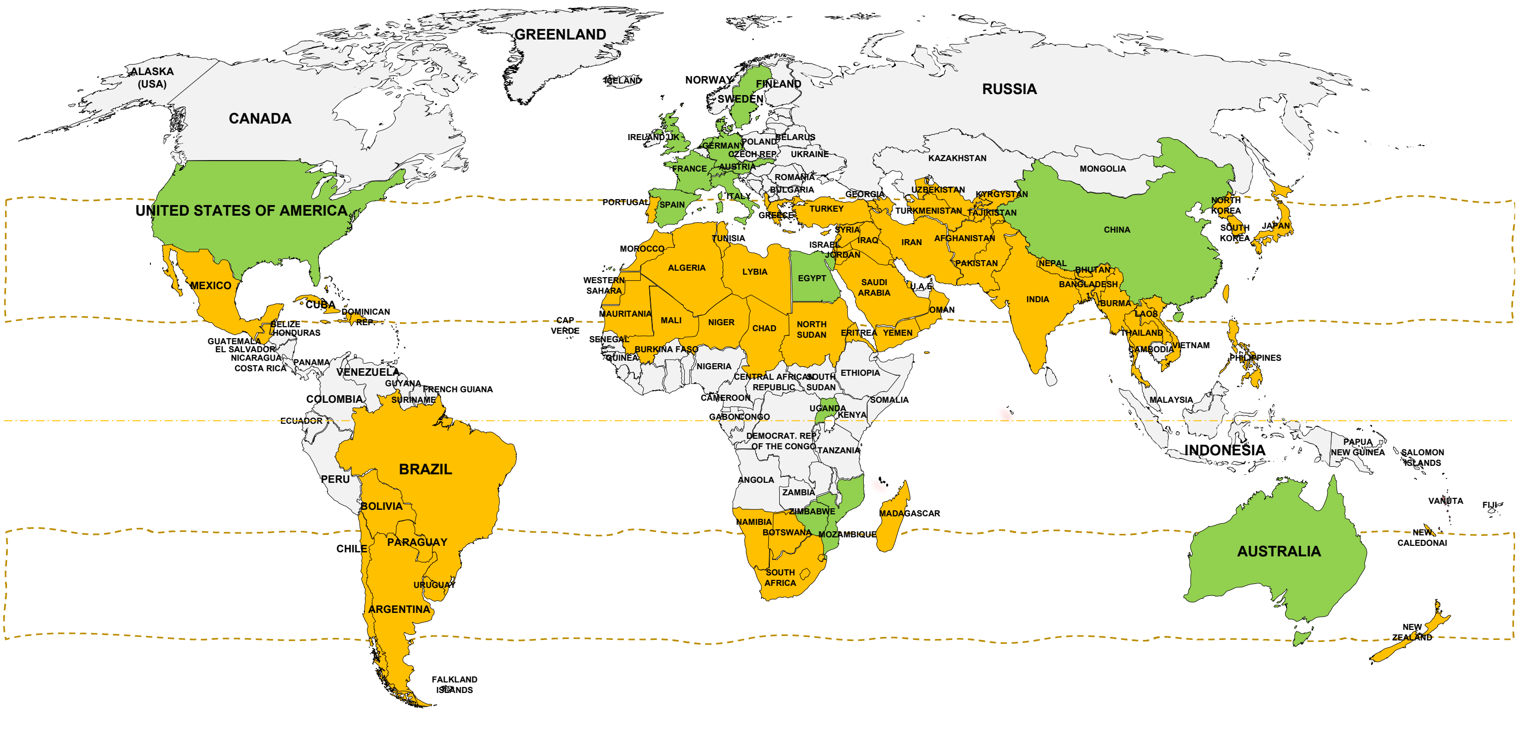
Building and Process Optimization Potential



IEA SHC TASK 65 | SOLAR COOLING FOR THE SUNBELT REGIONS

Technology Collaboration Programme
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SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Building and Process Optimization Potential

This is a report from SHC Task 65: Solar Cooling for the Sunbelt Regions and work performed in Subtask A: Adaption

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Date: 6 July 2023
Report D-A4, DOI: 10.18777/ieashc-task65-2023-0003

Cover photo credit: World map with Sunbelt regions (marked yellow) and the 18 countries of the participating Task 65 experts (marked green), source: Neyer Brainworks & JER

Solar Heating & Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54, 69)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64, 72)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61, 70)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46, 71)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

In addition to our Task work, other activities of the IEA SHC include our:

- SHC Solar Academy
- *Solar Heat Worldwide*, annual statistics report
- SHC International Conference

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Contents

1 Executive Summary

This document is the final report on activity 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 are 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.

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, last part reports a literature review of the of loads, demands, and saving potential that the application of solar cooling systems can provide. Particular attention has been focused on the integration the structure of the buildings and on the saving in terms of energy and economic aspects as well according the different conditions of application.

2 Introduction

The main goal of Activity A4 was to study the potential of energy efficient buildings and processes in Sunbelt regions for new and existing buildings. To do this, the subtask activities was related to studies of other projects. Moreover, another topic that is discussed under this headline is the integration of solar cooling in retrofitted HVAC systems. Depending on the existing conventional HVAC system the integration can be challenging in terms of refrigerants and cold distribution. Cold delivery systems are also of interest to decrease draft of air-based systems and increase thermal comfort in buildings. Best technical solutions for certain situation were cited from technical and economic point of view. Following picture summarizes the diagram flux of the methodology that was followed.

Unfortunately, not all the analysis that were planned provide useful data. The workflow of the expected activities was changed. In particular, the changes concern the study of the analysis of the data of some research projects and the connection of IEA EBC (Buildings and Communities Programme) projects. Regarding this latter, some similar projects were identified and analysed. Unfortunately, as it will be shown, there are not so many recent projects that consider the application of solar cooling systems in buildings. Despite this, the information provided could be used as baseline cases in order to study the potential energy saving achievable by applying solar cooling systems. Figure 1 shows the first flux diagram.

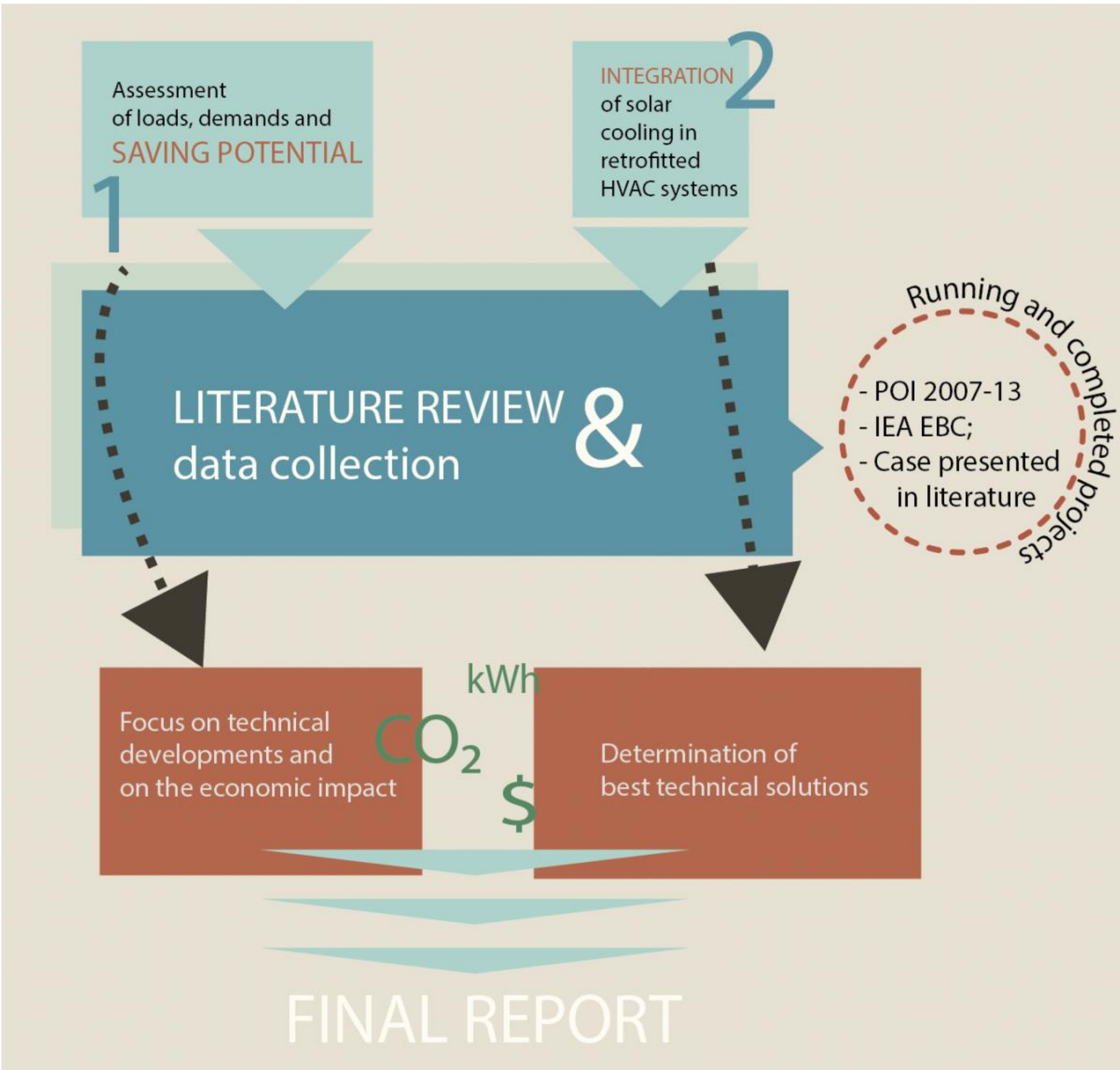


Figure 1: First, planned workflow scheme

3 Running and Completed Projects for Data Supporting

This first part of the study of activity A4 reports many data of buildings. The goal is to understand the potential of energy efficient buildings and processes in Sunbelt regions for new and existing buildings. Depending on the existing conventional HVAC system the integration can be challenging in terms of refrigerants and cold distribution. Cold delivery systems are also of interest to decrease draft of air-based systems and increase thermal comfort in buildings.

The data reported are related to the POI projects and some completed IEA EBC projects.

3.1 POI 2007-13-South Italy

The data presented were analysed in the framework of a research programme "POI ENERGIA 2014e2020" belonging to EU Horizon 2020. It was funded by the Italian Ministry of Economic Development (MISE), Italian Ministry of the Environment (MATTM) and the Unione delle Province d'Italia (UPI). The project was focused on the four Italian regions of the EU Convergence Objective (Campania, Apulia, Calabria, and Sicilia) The aim was to characterise buildings that managed by the Province authorities in terms of their energy performance and thus to elaborate actions for reducing consumption while improving their quality. All the data reported were published in (Beccali et al. 2015).

The goal was to carry out detailed energy audits of all the buildings. This had allowed characterization of the actual building stocks including thermo-physical properties of the envelope, thermal system typologies, lighting, and appliances and energy consumption accounted in utilities invoices.

Based on this data, within the project "POI 2007-13" a decision support tool was developed. It was based on the use of these Artificial Neural Network conceived for a fast prediction of the energy performance of buildings and for a first selection of energy retrofit actions that can be applied. In this light, a database of a large set of data have been developed.

The data concern 151 existing public buildings located in four regions of South Italy and regard information about:

- Weather data;
- Building;
- Plants;
- Consumption.

Regarding the weather data, the information about the heating Degree Days and the solar radiation have been collected (Moreci et al. 2016) (Ciulla et al. 2015).

It is necessary to remind that, Italy is subdivided into six Climate Zones, from A (up to 600 Heating Degree Days (HDD)) to F (over 3000 HDD) (DPR n. 412) (DECRETO). Based on this difference, the schedule of the operating of the heating systems are defined by Italian law. Unfortunately, up to today, cooling season is not defined by Italian laws. It is a significant deficit of the standard because the calculation of conventional cooling demand is based only on thermal energy performance of the building envelope. Following, the HDD that defined the Climatic Zones of the four regions where are locate the analysed buildings:

1. Calabria: from 889 to 2693 HDD, (from B to E Zones);
2. Campania: from 994 to 2651 HDD, (from C to E Zones);
3. Apulia: from 1071 to 1755 HDD, (C and D Zones);
4. Sicilia: from 707 to 2248 HDD, (from B to E Zones).

In order to characterize the buildings, the following parameters were considered:

- use,
- building typology,
- opaque and transparent envelope characteristics,
- floor area,
- room height,
- gross heated volume,
- exposed surfaces,
- S/V ratio,
- heating/cooling system,
- DHW system, monthly thermal and electrical energy consumption, lighting system typology and exploitation of Renewable Energy Sources (RES).

The buildings considered are characterized by different end-uses, but all the buildings are public:

- Office buildings;
- Museums;
- Libraries;
- Congress halls;
- Gymnasium and Sports buildings;
- School buildings.

As well-known, energy demand in buildings depends on a combination of several parameters, such as climate conditions, envelope characteristics, orientation, occupant behavior, and intended use. Indeed, assessing a building's energy performance requires substantial input data describing constructions, environmental conditions, envelope thermo-physical properties, geometry, control strategies, and several other parameters. So, several construction typologies and correlated thermophysical characteristics were studied.

It can be noted that each building was characterized by different compositions and thickness of layered envelope. Regarding the distribution of window glass typologies, the double-glazing is the most common in Apulia and in Calabria, while single glazing is still very frequent in Campania and Sicilia. The most widespread frame material is aluminum, with or without thermal break profiles. As in the case of opaque envelope, in each building there are different shapes and dimensions of windows. In almost all the buildings different plant typologies for the space heating, cooling and hot water production were installed. Figure 2 shows the distribution of the HVAC systems features per region.

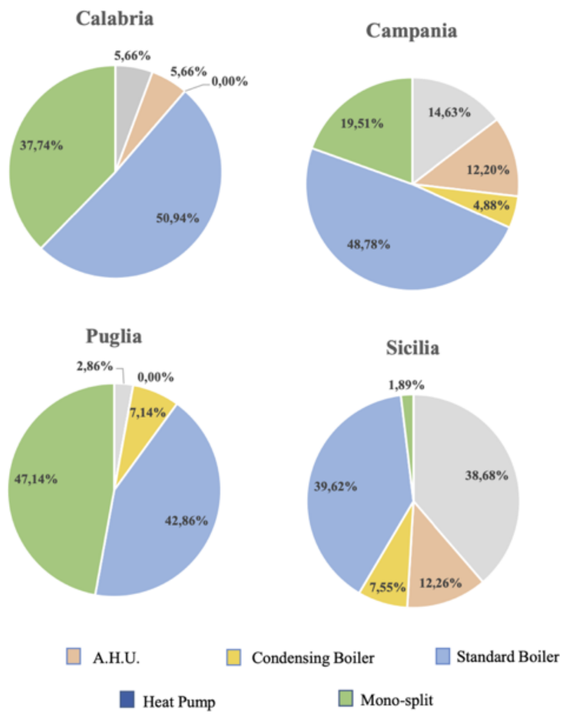


Figure 2: Regional percentage of HVAC system topologies (Beccali et al. 2015)

As it is possible to see from previous figure and tables, the combination of natural gas boiler as generator and regulated through an external climatic probe, a hot water distribution system and radiators as emitting system was the most common space heating system with a global efficiency about 70%. Regarding the cooling systems, the typology with mono-split and all-air systems with an Air Handling Unit (AHU) is the most diffuse. Several buildings use both natural gas and a small electrical boiler for Domestic Hot Water (DHW) production. Following tables show the typologies of heating and cooling systems.

Table 1: Typologies of heating per region (Beccali et al. 2015)

Heating System								
	Generation system					Distribution System		
Region	Centralised Air to Water Heat Pump	All Air System (A.H.U.)	Condensing N. G. Boiler	Standard N.G. Boiler	Mono-split HP	Water Steel/ Copper pipes	Refrigerant pipes (Mono-split HP)	Air Ducts
Calabria	10%	10%	–	90%	67%	90%	13%	67%
Campania	21%	18%	7%	71%	29%	93%	29%	21%
Puglia	5%	0%	13%	79%	87%	84%	8%	87%
Sicilia	80%	25%	16%	82%	4%	90%	16%	82%

	Control system				Emitting system				
Region	External climatic probe	Tele-monitoring	Schedules	Indoor Thermostat	Manual	Fan-coil	Radiator	Air ducts terminals	Air heaters	Mono-Split HP
Calabria	53%	7%	17%	13%	73%	30%	83%	7%	27%	67%
Campania	50%	36%	–	–	61%	75%	82%	11%	32%	57%
Puglia	84%	none	50%	3%	89%	53%	74%	8%	32%	87%
Sicilia	8%	none	–	43%	82%	41%	65%	–	–	82%

Table 2: Typologies of cooling per region (Beccali et al. 2015)

Heating System								
	Generation system					Distribution System		
Region	Centralised Air to Water Heat Pump	All Air System (A.H.U.)	Condensing N. G. Boiler	Standard N.G. Boiler	Mono-split HP	Water Steel/ Copper pipes	Refrigerant pipes (Mono-split HP)	Air Ducts
Calabria	10%	10%	–	90%	67%	90%	13%	67%
Campania	21%	18%	7%	71%	29%	93%	29%	21%
Puglia	5%	0%	13%	79%	87%	84%	8%	87%
Sicilia	80%	25%	16%	82%	4%	90%	16%	82%

	Control system					Emitting system				
Region	External climatic probe	Tele-monitoring	Schedules	Indoor Thermostat	Manual	Fan-coil	Radiator	Air ducts terminals	Air heaters	Mono-Split HP
Calabria	53%	7%	17%	13%	73%	30%	83%	7%	27%	67%
Campania	50%	36%	–	–	61%	75%	82%	11%	32%	57%
Puglia	84%	none	50%	3%	89%	53%	74%	8%	32%	87%
Sicilia	8%	none	–	43%	82%	41%	65%	–	–	82%

The use of DHW is very limited; indeed, there are many buildings that do not have DHW systems. Following, the percentage for each system in each region:

- Central air to water Heat Pump (38.68%) and Standard Natural Gas Boiler (39.62%) in Sicilia;
- Mono-split HP (47.14%) and Standard Natural Gas Boiler (42.87%) in Apulia;
- Standard Natural Gas Boiler in Campania (48.78%) and Calabria (50.94%).

The electrical consumption was studied in relation to the lighting systems and the other electric appliances (printers, computers, photocopiers, lifts) and appliances for DHW production and for HVAC systems installed in the buildings. This data is interesting as well because, as known, electric appliances can be an important heat gain of the building.

The most common lighting sources were:

- Fluorescent;
- Incandescent lamps;
- High pressure sodium;
- Mercury lamps;
- Metal halide lamps;
- Iodide lamps and LED.

In Sicily, the lighting systems are responsible for about 55% of electricity consumption, while in the rest of the regions such lighting systems have a share of approximately 40%.

Finally, the RES plants were studied. They were based only on solar energy. Only in Campania and in Calabria solar thermal systems were installed. PV systems were installed in 7 buildings in Sicily, 2 in Calabria, 11 in Apulia and 9 in Campania. Only in 2 buildings in Campania and in 2 in Calabria are there both PV and thermal solar systems.

Table 3: First, PV systems installed (Beccali et al. 2015)

PV systems installed.

N. PV System	PV peak power [kW_p]			
	Puglia	Campania	Sicilia	Calabria
1	28.35	81.9	3.5	6
2	10.15	51.3	80	10
3	10	27	49	–
4	40	27.5	20	–
5	60	17.1	19.8	–
6	60	199	19.8	–
7	20	3	19.8	–
8	10	2.7	–	–
9	48	49	–	–
10	104	–	–	–
11	90	–	–	–
Average Peak Power	**43.68**	**50.94**	**30.27**	**8.00**

Also the energy end-uses split by regions have been analysed. Figure 3 shows the breakdown of electricity demand in several end-uses.

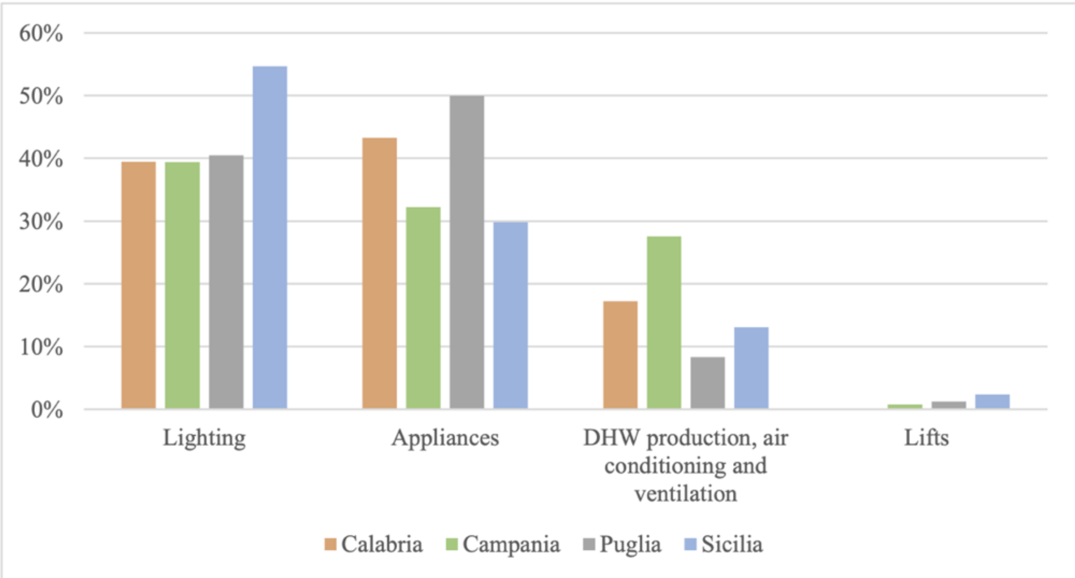


Figure 3: Analysis of electrical consumption per end-use and per region (Beccali et al. 2015)

3.2 Building Energy Efficiency in Nepal

Nepal is one of the fastest urbanizing countries and its population grew from 1990 to 2020 by 61% and is expected to grow by 19% from 2020 to 2050 (United Nations, Department of Economic and Social Affairs, Population Division 2018). An estimated 1 million new homes will be built in the next decade (SWITCH-Asia programme and European Commission). The majority of Nepalese population is living in subtropical climate and topic of space cooling gains more of interest.

The EU funded SWITCH-Asia project BEEN (Building Energy Efficiency in Nepal) addresses this topic, contributing to establish energy efficient building strategies in Nepal (SWITCH-Asia programme and European Commission). This target is followed by design charrettes and software-based building optimization studies, trainings and workshops to skill experts in energy efficient building and setting up guidelines and advice to policy makers. The project started in March 2022 and is running for four years.

3.3 Review of IEA EBC (Buildings and Communities Programme) Useful Projects

In the Strategic Plan 2019 – 2024, presented in 2019 the Energy in Buildings and Communities Executive Committee reported as topic of research activity the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible.

They dedicated many activities to the analysis of cooling system. Actually, there were not completed projects that investigated the application of solar cooling systems in buildings. However, the final repots of these activities reported interesting results and information about the application of other possible retrofit actions on cooling systems and on energy use for cooling. Following, the list of some of the analysed annexes and their description:

- ANNEX 28: Low Energy Cooling Systems (1993 - 1997)
- ANNEX 36: Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures (1999 - 2003)
- ANNEX 37: Low Exergy Systems for Heating and Cooling (1999 - 2003)
- ANNEX 52: Towards Net Zero Energy Solar Buildings (2008 - 2014)
- ANNEX 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (2008 - 2013)
- ANNEX 59: High Temperature Cooling and Low Temperature Heating in Buildings (2012 - 2016)

The reports related to the above-listed Annexes were analysed. The aim of Annex 28 project was to provide design tools/guidance on the application of low energy cooling technologies to buildings. To do this, authors studied some technologies for cooling system, such as night cooling (natural and mechanical ventilation), ground cooling (air), ground cooling (water), evaporative cooling (direct and indirect), desiccant and evaporative cooling, slab cooling (air), slab cooling (water), displacement ventilation and chilled ceilings. As it can be noted, this activity was carried out more than 25 years ago and, unfortunately, solar cooling plants were not included, but the report includes a useful review of the main technologies that can be applied to retrofit solar cooling.

The Annex 36 aimed at develop tools for retrofit concepts to support the decision maker to evaluate integrated construction, installation and lighting measures by promoting promote energy and cost-efficient retrofit measures. To do this, researchers developed a 'concept adviser' to analyse existing buildings and their economic efficiency. By studying high solar heat gains in educational buildings and the relating parameters (glare problems, overheating problems) they carried out an overview of retrofitting scenarios referring to solar control and cooling techniques, including shading systems, cooling systems and air conditioning systems.

During the activities of Annex 37 following topics were investigated: potentials for replacing high valued energy (e.g. fossil fuels and electricity) by low valued energy sources, application of existing technologies and components for low exergy heating and cooling in buildings, low exergy solutions in buildings by case studies.

The topic investigated during the activities of the Annex 52 was more general, but, as well in this case, the results are useful to investigate the energy of buildings. In particular, the objective of the project was to study current net-zero, near net-zero and very low energy buildings and to develop a common understanding, a methodology, tools, innovative solutions and industry guidelines.

The outcomes of Annex 53 include the development of a methodology for analysis of building energy use and, in particular, to develop methodologies and technologies for long term monitoring of the energy use in buildings by including information about the six factors directly influencing building energy use (climate, building envelope, building services and energy systems, Building operation and maintenance, occupants' activities and behaviour, and Indoor environmental quality). Similar to the POI project, a very useful database to define a reference structure was developed.

Finally, the ANNEX 59 activities had the aim to study how to achieve high temperature cooling and low temperature heating by reducing temperature differences in heat transfer and energy transport process and, so, how to avoid unnecessary offset of cooling and heating, dehumidification and humidification, mixing losses of cold and hot fluids, or unnecessary or inappropriate transfer losses due to heat exchange, in commercial buildings, such as offices and buildings containing large enclosures.

4 Literature Review of application of Solar Cooling in Buildings

4.1 Passive and Active Measures to Reduce Cooling Demand

Space cooling is responsible for 16% of buildings sector final energy consumption in 2021 (IEA 2022) and the global electricity consumption for space cooling might triple from 2020 until 2050 (Dean et al. 2018). In addition, global economic growth, especially in developing countries located in cooling-intensive climate, such as India and Indonesia, will lead to a rapid increase of Air-Conditioner (AC) installation.

To prepare efficient and environmentally friendly cooling to the user, three principles are to follow. 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 benefit avoiding GHG emissions for the climate. This section puts focuses on both passive and active measures to optimize the energy performance of buildings.

4.1.1 Passive Measures

The demand of cooling energy to operate a building comfortably for the user is dependent on many aspects. 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 (Dean et al. 2018, p. 78). In the following section, different aspects which influence on a building's energy performance are discussed.

Regarding the architecture and design of buildings, they have to be adapted to both the user needs and behaviour, but also to its 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 to surface (Pacheco et al. 2012). The orientation of a building is important as it impacts solar gains. Facades 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 is 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. (Al Dakheel and Tabet Aoul 2017). Shading devices are part of the envelope and can play a role in the design of a building. Besides 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 solar heat gain coefficient (SHGC). A high reflection of short-wave radiation is preferred to decrease the solar heat gains. The insulating characteristics of windows, expressed as u-value, is the other purpose of windows. Windows with a high thermal transmittance (high u-value) can lead to convective heat gains if the ambient air is of higher temperature than the indoor. The window-to-wall ratio (WWR) (Shree et al. 2023) and the size and number of windows (Friedrichsen 2018) are additionally relevant points having impact on the 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 outdoor increases the cooling energy demand of a building (Gupta and Tiwari 2016). Besides 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 get rid of heat and to cool down a building is one of the cheapest and easiest way to decrease the cooling demand of a building. It is affected by both the temperature and pressure difference between indoor and outdoor conditions (Elaouzy and El Fadar 2022). 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 (Pacheco et al. 2012) or windcatcher (Jomehzadeh et al. 2017), which boost the air mass flow.

Of course, the potential of natural ventilation is linked to the thermal mass of a building, based on its construction material (Friedrichsen 2018). Using nocturnal ventilation, a 24h temperature variation can be damped by the building. A higher thermal heat capacity of a building results in a slower increase/ decrease of 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 paraffines. They are characterised by their unique melting point temperature, where they undergo phase change and absorb, respectively release energy. When the indoor temperature increases, PCM with a melting temperature of 26° C absorbs heat at that temperature which theoretically prevents an additional rise in temperature (Zeinelabdein et al. 2018). However, the application of PCM in the construction faces barriers, such as high investment costs of PCM (Zeinelabdein et al. 2018), long-term stability of phase change cycles, limitation in heat transfer due to low thermal conductivity of PCM itself, and especially the impact of hot weather conditions which may prevent the PCM from solidifying (Souayfane et al. 2016).

Effective way to reduce heat gains through 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 the thermal mass is even more effective to the indoor conditions. There is a wide range of insulation materials available on the market, of which expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), mineral wool or vacuum insulation panels (Elaouzy and El Fadar 2022) are the most applied. 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 (Elaouzy and El Fadar 2022).

Roofs often suffer from high solar heat gains throughout the day. Roofs characterized with a high albedo reflect a high share of solar radiation, called “cool roofs” (Romeo and Zinzi 2013). This might be achieved either using bright and reflective paints or materials. There is no uniform definition or minimum albedo for the label “cool roof”. Furthermore, due exposure to the environment, studies show that the solar reflection declines during time (Akbari et al. 2005).

Green roofs however, are characterised by the installation of a vegetative layer including plants. Plants theoretically bring a benefit through shading, evapotranspiration phenomena, and the additional thermal mass (D’Orazio et al. 2012). A study by Jaffal et al. came to the conclusion the cooling effect of green roofs is primarily based on its insulating effect (Jaffal et al. 2012). Thus, green roofs can be substituted by roof insulation focusing to reduce 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. Mostly, most of the studies are based on TRNSYS or EnergyPlus. Despite the methodology of assessment, also the building’s design, climate and occupation are different.

4.1.2 Urban Heat Island (UHI)

Another issue which influences a building's energy performance is its surrounding, its location, respectively. Urban areas characterised by a high building density and high share of sealed areas, such as parking spaces, suffer from the Urban Heat Island (UHI) effect (Su et al. 2021). This causes in individual cases to a number of Cooling Degree Days (CDD) which is 6.5 times higher than in less urban areas (Moustris et al.) and in general to higher cooling energy demand (Boudali Errebai et al. 2022). The magnitude of an 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 (Kolokotsa et al. 2018), cool roofs (Governatori et al. 2022), urban green spaces (Semenzato and Bortolini 2023), green roofs and green walls installation (Iaria and Susca 2022), water bodies and fountains (Wu and Zhang 2019)and adaption of buildings itself (Garshasbi et al. 2020). Those mitigation options lead to a cooling effect of 2K (Garshasbi et al. 2020) in daily average summer temperature up to 10K (Semenzato and Bortolini 2023) 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, respectively range of considered environment. A study in the USA came to the conclusion that besides the lack of public education on UHI also the lack of effective communication between researchers and code writers is one of the greatest barriers in UHI mitigation (Wang et al. 2021).

Figure 4: Problem and potential solution to UHI. Source: Adapted from (The Global Commission on Adaption 2019)

4.1.3 Low-Tech Active Measures

Passive measures are the base to optimize a building and to decrease the cooling demand and load. This results in a smaller layout of the cooling system. 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. (Duan et al. 2012). 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 serving as energy provider. Evaporative cooling can be divided into direct and indirect systems (Pacheco et al. 2012) and further separated on its working medium, such as air or water (Yang et al. 2019). Indirect 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 cooling effect of the air on the other side. The operation is limited as dry air is required being able to absorb the water (Gupta and Tiwari 2016). Desiccant cooling systems include the step of dehumidification via a liquid or solid desiccant, which absorbs moisture from the air (DAOU et al. 2006). The desiccant must be regenerated via heat, preferably solar heat. The dried air can then be cooled down via evaporative cooling.

Radiative cooling system makes us of radiative heat transfer to the night sky, especially using low-wave infrared radiation (Vall and Castell 2017). The heat transfer reaches about 60 W/m² (±30%) (Vall and Castell 2017) This allows to cool the heat transfer medium down to 5K (Ito and Miura 1989) to 7K (Ezekwe 1990) below ambient temperature.

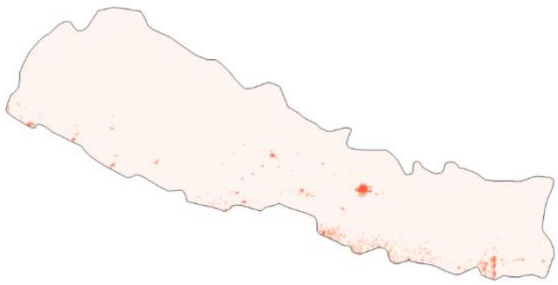
4.1.4 Cooling Demand Market Index (CDMI)

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 (Campbell et al. 2018). Those factors are also identified by the International Energy Agency in the “Future of Cooling” report (Dean et al. 2018).

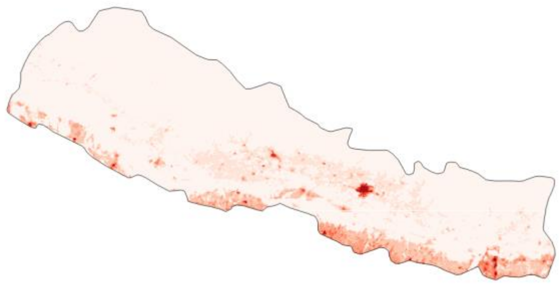
The CDMI developed by Strobel et al. (Strobel et al. 2023) is GIS-based indicator to identify increasing economical demand for cooling applications on a global scale. Based on scenarios for future demographic, climatic, and economic development, the CDMI locates the increase of demand for cooling applications. 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 (van Vuuren et al. 2011) while the SSPs picture future socioeconomic developments (O'Neill et al. 2017).

For Nepal for instance, the cumulative CDMI for 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 5 presents two maps for the Nepalese CDMI, one the left for 2020 and 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.



CDMI for Nepal, 2020



CDMI for Nepal, 2050 SSP1-2.6

Figure 5: CDMI results for Nepal for 2020 and for 2050, scenario based on SSP1 and RCP2.6

4.2 Assessment of Loads, Demands and Savings Potential

The energy demand for cooling of buildings is related to many different parameters. They depend on site, plants, and buildings characteristics.

Buildings have three heat gains: envelope heat gain, ventilation heat gain, 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' behaviour and their comfort conditions standard. 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. Regards the site characteristics, it has to remind that this study is focused on Sunbelt region countries, so. Many studies are presented in literature and, for the above-listed reasons, they reported very different results. In this part, some of them will be reported in order to pave the way to understand which are the consumption of cooling systems supported or not-supported by solar plants and consequently quantify the savings potential.

To evaluate the integration of solar cooling systems in buildings and to develop an optimized plants-building systems, not only the aspects related to the frame, to the geometry and to the size have to be considered. Other parameters affect the outcome of cooling strategies. Naderi et al. (Naderi et al. 2022), in particular, presented a state-of-the-art studies in the field of pre-cooling and solar pre-cooling covering the period 2014 to 2021. They affirmed that the electricity tariff (Nelson et al. 2019) (Tabares-Velasco et al. 2019), the thermal mass of the building (Kishore et al. 2020), occupancy and household thermal comfort expectations (Stopps and Touchie 2021), climate (Turner et al. 2015), and the control method (Romaní et al. 2018) are the most influential factors.

Talking about the integration of the solar systems in buildings architecture, it is of course the façade panels. Noaman et al. (Noaman et al. 2022) took into account a 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 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 application of the appropriate PSDSs (Prieto et al. 2018b). Indeed, as shown in (Pino et al. 2012), the configuration of the facade is responsible for approximately 45% of the cooling demands of the building. The application of passive system could be an efficient action to reduce the energy demand for cooling. Just as sample, the average values of the cooling demands for Alexandria, Cairo, and Aswan became 9.02 kWh, 10.13 kWh, and 12.21 kWh, respectively, compared to 19.93 kWh, 22.99 kWh, and 29.48 kWh for the same cities in the base case. After applying the four PSDSs, the deviation in the cooling demands between Aswan (in the southernmost part of Egypt) and Alexandria (in the northernmost part) became approximately 35%; the deviation for the base case was approximately 50%.

In order to evaluate the possible production of the ASCT the amount of incident solar authors investigated four tilt angles: 90°, 60°, 30°, and 0°. Results found shown different performance 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 case; the 0◦ angle is the best for the buildings oriented to north. It is interesting to see that the tilt angle of 0◦ seems to be better than 30◦ for the south orientation at Aswan because the solar altitude angle in the summer design week reaches almost 90◦ at the peak sun hours.

Nevertheless, the tilt angle of 60◦ is better than 90◦ for all conditions. 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 Alexandria, the maximum enhancement reached 214.38% and 166.19% for the north and south orientations. Regarding the different performance according to the location, in Alexandria the maximum values reached about 81.95% for the east orientation and 77.22% for the west orientations; In Cairo, the maximum values were 89.24% for the east orientation and 58.82% for the west orientations; in Aswan the maximum values of 78.43% for the east orientation and 70.18% for the west-oriented.

However, it was difficult for the absorption ASTC driven by the vertical STC to meet the cooling demands for almost all the cases. This is because the vertical STC requires a large area, which exceeds the available facade area.

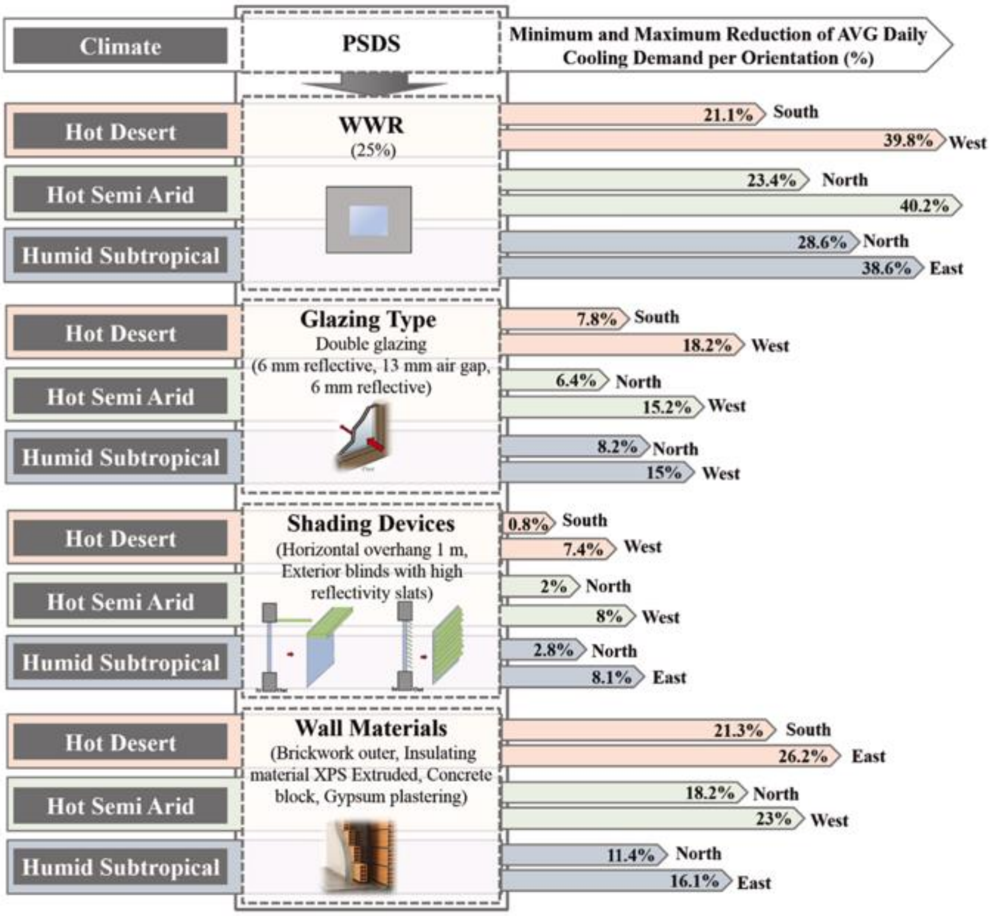


Figure 6:Guidelines for applying the four tested PSDSs to façade in the hot climates (Noaman et al. 2022)

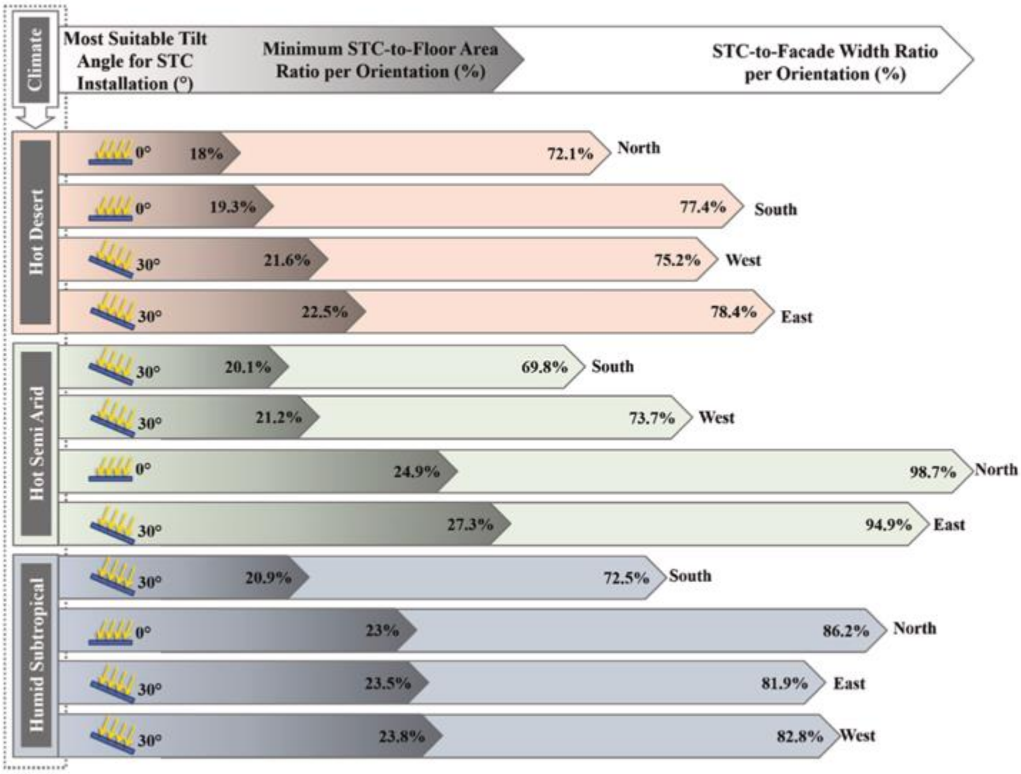


Figure 7: Geometrical design guidelines STC into façade in the hot climates (Noaman et al. 2022)

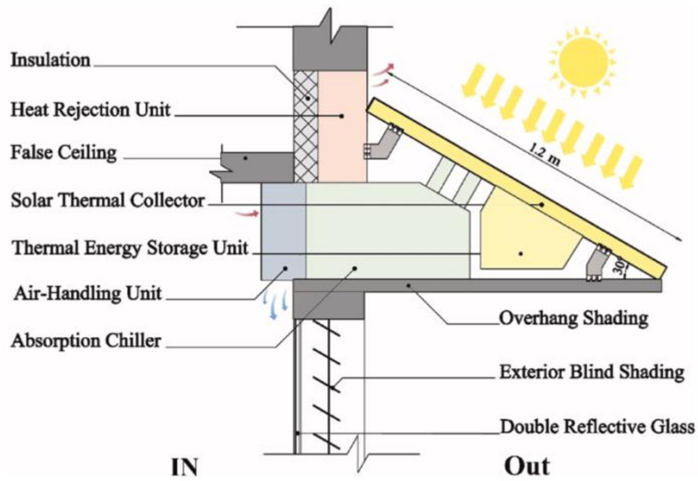


Figure 8: Final configuration of the integrated façade (Noaman et al. 2022)

Alejandro Prieto et al. (Prieto et al. 2018a) explored the possibility to apply solar cooling integrated facades, as decentralized self-sufficient cooling modules on different warm regions. They considered application in Riyadh, Athens, Lisbon, Hong Kong, and Trieste. It has to be reminded that they considered as well Singapore, but it is not included in Sunbelt region.

As well in this case, passive design strategies, such as a reduced window-to-wall ratio, the application of sun shading, solar control glazing, and the use of ventilation for cooling purposes are judged as a necessary step to decrease cooling demands, before integrating active systems into the building envelope. In order to conduct this study, they considered only a single office room of 16 m2, considered adiabatic for the purpose of the evaluation.

It is necessary to underline that this case study has been considered just as a reference for the assessment at hand and do not claim to be fully passively optimised scenarios.

The evidence of it is the fact that Lisbon comprises the best results in all orientations, while the worst results are reported for Hong Kong, due to less solar availability and the highest calculated cooling demands for the simulated scenario.

It has to be noted that, in general, warm-dry climates and east/west orientations are better suited for solar cooling facade applications, compared to humid regions and north/south orientations. In particular, for west and east orientations, the results from the base scenario shown promising potential for solar thermal technologies, reaching a theoretical SF of 100% in several cases. Better performances were noted for warm and dry climates (Athens, Ryadh, and Lisbon, compared to the performance calculated for warm and humid climate (Trieste and Hong Kong). So, for this orientations, solar cooling facade applications could have better performance if installed in temperate climates and dry context (e.g. desert) than 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. It is because the climate is very extreme and the solar radiation is lower in case of tilt angle is 90°. Best results for north orientation were obtained from the analysis carried out by selecting Lisbon as location. Following table shows some results.

Table 4: Simulated cooling demands for all orientations and locations considered in the assessment (Prieto et al. 2018a)

Location	Summer Design Week	Orient.	Base Case (No Passive Strategies)	Improved Base Case (With Passive Strategies)		
			Cooling Yearly Demands (kWh/m^2 year)	Cooling Yearly Demands (kWh/m^2 year)	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
		North	72.72	27.65	0.85	7.27
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 different technologies of solar cooling, authors found that, solar electric processes are more constrained due to the lower efficiencies of PV panels compared to solar thermal collectors, and limited efficiencies of thermoelectric modules. So, self-sufficient facade modules could be feasible on east orientations in Lisbon. By continuing to analyse application on façade, Hernandez et al. (Fernández Hernández et al. 2020) presented a honeycomb desiccant block placed inside a ventilated facade with a regeneration of the desiccant material carried out by a solar air collector, also integrated in the facade.

As case study a typical office building, called The Business Entrepreneurship Centre (TBEC) in the Technology Park in Málaga (longitude 4.49 W, latitude 36.67 N) was considered. It consists of two floors above-grade, with a total area of 950 m2. The building accommodates various space types: offices, meeting rooms, auxiliary rooms, etc. The main facade orientation of the building is to the south. Windows have aluminium frame and double layer (4–6-4 mm). Internal venetians blinds are used for shading in each window. Regarding the occupancy schedule, a total of 87 people works from 8:00 to 17:00 in south zones and from 8:00 to 15 p.m in eastern zones, from Monday to Friday. Considering a degree of activity of seated, light work, a latent heat of 45 W per person is considered for latent load calculation. Two central AHUs distribute the ventilation air in each zone. A cooling coil is activated in the

AHUs in order to decrease the air temperature from the desiccant system, ensuring that the supply air temperature is lower or equal to 26° C (the set-point comfort temperature in the zones) and also dehumidifying the ventilation air when desiccant system is not operating.

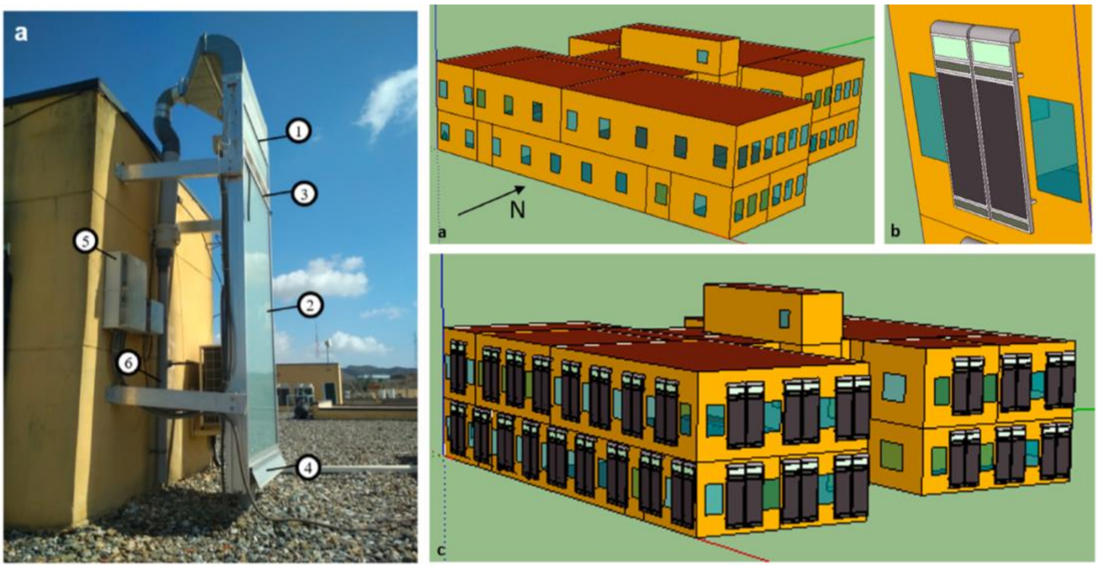


Figure 9: a) Lateral view of the experimental prototype: 1. Desiccant module. 2. Solar air collector. 3. Process dampers. 4. Regeneration dampers. 5. Controller logic (PLC). 6. Fan. b) Scheme of the measurement system and the Building geometry model: a) The building. b) Desiccant façade detail. c) Detail of a desiccant system unit installed in south and east façades. (Fernández Hernández et al. 2020)

The results of this study are particular interesting for this task because they included as well the assessment of comfort condition in terms of humidity values. To do this, 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 which receives. By simulating the conventional system considering the same daily condition, in the south office, the humidity value was very high.

The desiccant façade can provide latent load values without having to overcooling the zone with a percentage higher than 90% of comfort in south and east orientations. For conventional systems, it is necessary to adapt the set point air temperature of the cooling coil to the humidity requirement of the zones in order to obtain good comfort results. The desiccant façade, with a setpoint of 26°C, can maintain the humidity comfort in a typical summer day with high ambient humidity. The percentage of time that occupants spend in humidity comfort conditions in cooling season is greater than 92% in south and east façades (less than 31% with conventional system). In terms of energy consumption, the consumption of the fans used for desiccant façade system are significant, but, in conventional system, the heat pump consumption increases when the supply air temperature decreases.

Mortadi and Fadar (Mortadi and El Fadar 2022b) proposed the investigation of different solar cooling systems: solar absorption, solar adsorption, photovoltaic and photovoltaic thermal (PVT) cooling systems on the basis of performance, economic and environmental aspects. The main objective is to identify the most favorable system depending on climate condition and Solar Fraction (SF). A typical office was considered with the same construction and internal loads to fairly compare these systems, under seven different climate conditions, in terms of key performance, economic and environmental indicators. The results could enable to identify the suitable solar cooling technology for each climate. Authors demonstrated that the PVT cooling system had a high solar coefficient of performance ranging from 36 to 52%, depending on the climate condition. In regions with high solar irradiation there were measure lower discounted payback period. Lower levelized cost of cooling values were calculated in sunny locations with high cooling loads, varying in the range of 0.056–0.25 €/kWh_c for PVC system against 0.069–0.314, 0.1–0.736 and 0.132–0.961 €/kWh_c for PVT cooling, solar absorption cooling SABC systems could not be recommended in climate regions with low temperature and solar radiation, such as continental (SABC) and solar adsorption cooling (SADC) systems respectively. PVT cooling system combined with absorption chiller had the most negative impact on environment. Solar adsorption cooling and solar absorption cooling even if the systems have high SF. The lower levelized cost of cooling, discounted payback period and greenhouse gases the higher is 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. In the light of this comparative analysis, one can conclude that PVT system could be a good alternative from performance and economic perspective in almost all climate conditions. On the other hand, in spite of their environmental benefits, the SADC and climate, due to their economical unprofitability. However, they could be efficient cooling systems in regions with higher ambient temperature and solar radiation.

In another study, Mortadi and Fadar (Mortadi and El Fadar 2022a) investigated solar cooling system powered by different solar collectors for air-conditioning application in a residential building: flat plate collector, evacuated-tube collector, compound parabolic collector, parabolic trough collector, PVT collector and a new configuration of concentrating PVT collector. The proposed concentrating PVT collector performed the best for absorption cooling system with a solar coefficient of performance of 0.449, 0.428 and 0.414 in Marrakesh, Barcelona and Oslo (not included in Sunbelt region) cities, characterized by hot arid, warm temperate and boreal climates. PVT collector was the best performance for adsorption cooling system in Marrakesh and Barcelona cities with a solar coefficient of performance of 0.397 and 0.386, respectively.

Table 5: Thermal properties of construction materials (Mortadi and El Fadar 2022a)

Elements	Material layers	Thickness (m)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Specific heat (J/kg.K)
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	0.03	1.8	2560	790
Ceiling	Terrazzo	0.03	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 6: Building's characterizations (Mortadi and El Fadar 2022a)

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 7: Characteristics of the selected climatic regions (Mortadi and El Fadar 2022a)

City	Köppen-Geiger climate classification	Climate type	Latitude/ Longitude	Altitude (m)
Marrakesh, Morocco	Bsh	Hot arid	31.634/ –8.002	459
Barcelona, Spain	Cfa	Warm temperate	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. (Al-Yasiri et al. 2022) presented a review of solar cooling and air-conditioning systems (SCACSs) used for building applications and found that, in real case studies, SCACSs are in- stalled for commercial buildings more than residential ones with high capacities. However, most of them are provided with auxiliary energy systems, especially for those who continually need cooling, such as hospitals, airport lounges, etc.

Chen et al. (Chen et al. 2022) proposed a solar-based cooling and heating system employing solar concentrating collectors, photovoltaics, double-effect absorption heat pump and thermal storage for different types of buildings (office, hotel, residence, market, and hospital). The buildings are located in Nanjing in the Jiangsu province of China, which is characterized with cold winter and hot summer region. It was assumed that the total areas of these buildings are 24,000 m^2 with rooftop area of 2,000 m^2.

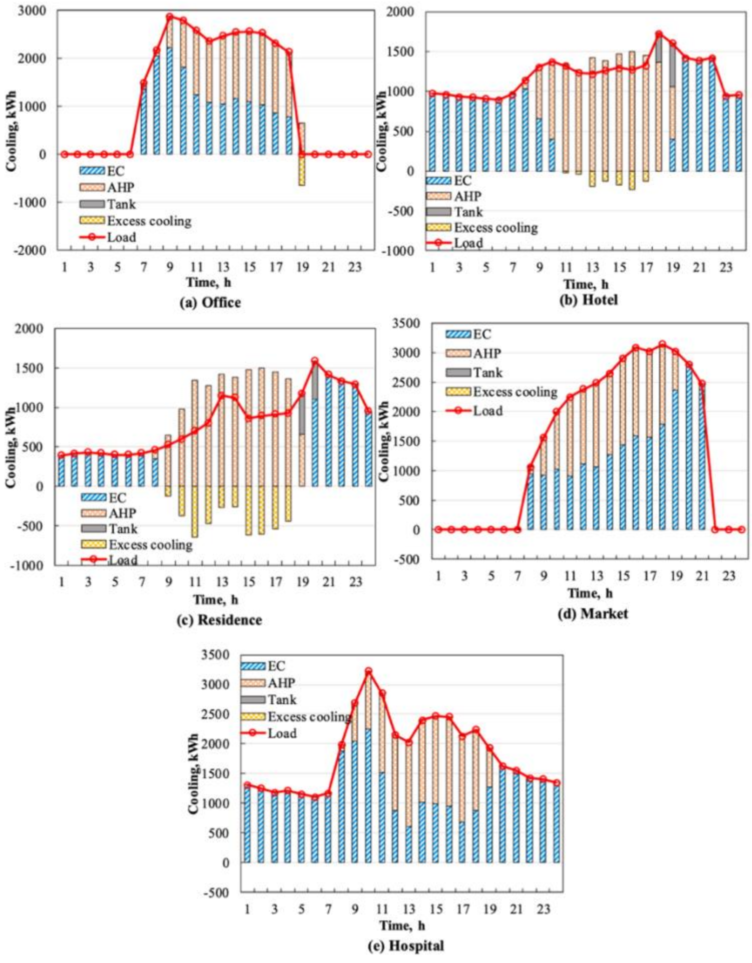


Figure 10: Output of devices in different building types during a typical cooling day: (a) Office; (b) Hotel; (c) Residence; (d) Market; (e) Hospital. (Chen et al. 2022)

Compared to the other building types, the hospital has the lowest energy and economic benefits, which varies from 69.4% to 71.8% for the energy savings, and from 64.4% to 65.9% for the cost savings. The corresponding solar cooling and heating is increased by 16.1%-units, while the solar cooling and heating system of the office and market are increased by 35.4%-units, and 32.6%-units, respectively. This is mainly because of the higher total load of the hospital, especially the heating load, while the heating demand of the office and market are lower: the demand at night is 0, due to the special operating schedule, and the heating load in the daytime is lower for higher ambient temperatures. The heating load of the hospital and hotel is much higher than the that of the other buildings, and the cooling load is only lower than the demand 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 hospital, which is 65.3%. The decreasing order of the Solar cooling/heating share (SC/HS) is the office, residence, hotel, market, and hospital, with average values from 34.2% to 23.7%. Based on the average values of objective indices, the office building fits the best for employing a solar-driven cooling/heating system, due to the intermittent energy consumption. The weights of solar shares, calculated by the coefficient variable method, are > 0.77 for all the buildings, while the lowest weights of the cost-saving-ratio and Fossil Fuel Savings Ratios are 0.10 for the office and market and 0.08 for the office. This is mainly because the solar shares are values higher than the other two criteria.

The aim of the research of Comino et al. (Comino et al. 2020) is to determine experimentally the seasonal coefficient of performance, solar coefficient of performance (SCOP), of a Solar desiccant cooling systems (SDEC) system composed of a desiccant wheel, an indirect evaporative cooler and a thermal solar system, to control indoor conditions in a research lab room. It has an area of 63,8 m3 and was located in a building of the Plastic Technological Center (ANDALTEC) in Martos (Jaén), Spain. The set point indoor conditions for the research lab room were set at 25 ± 1 °C for the air temperature and 8 ± 1 g/kg for the air humidity ratio (40% for the relative humidity). The 75% of the seasonal energy consumed by the solar desiccant cooling systems to carry out the cooling and dehumidification processes came from thermal solar energy and outdoor air.

Authors found that the tested system was able to independently control the sensible and latent loads of the room using 100% outdoor air. Just a low amount of auxiliary energy was required to maintain indoor conditions in the period analysed. A sensible seasonal coefficient of performance value of 2.1 was calculated because the sensible thermal energy delivered by the solar desiccant cooling systems, in cooling mode, was higher than its electric energy consumption. On the contrary, a 0.5 value of seasonal latent coefficient of performance was found in dehumidification mode for the same period caused by the dehumidification potential of outdoor air. When the solar desiccant cooling systems operated in dehumidification and cooling mode, the coefficient of performance achieved a value of 2.

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. (Sun et al. 2015) evaluated a system for cooling and heating based on an absorption chiller that can be driven by both gas firing and solar hot water. It works in gas fired mode (double effect) when solar energy is not enough or solar hot water temperature is low. The design and operation strategy are to use solar at first and gas fired as a backup, thus fossil energy saving is obvious. Year-round operation of the system was recorded and analysed in a commercial 5 stars hotel located in Changle, Shandong in China. The absorption chiller, the solar collectors and the vacuum water boiler were manufactured and installed by the local company. Furthermore, the hotel had two buildings. The larger building had an overall floorage of 14,332 m^2 the smaller ones was 10,000 m^2. The heating and cooling of the smaller building was fulfilled by the system described in the cited paper. The larger building adopted a conventional gas fired double effect absorption chiller. The operating parameters of the hybrid solar/gas fired absorption system were tested for a whole year from October 2012 to September 2013. The gas consumption of the two systems were also recorded for comparison. Compared with the gas fired absorption system, the gas/solar driven absorption system can save 49.7% of the gas consumption. Authors noted that in real operations of the heating and cooling supply are complex processes which can hardly be afforded by simply solar energy. The hybrid solar-gas fired absorption system is able to supply all the heating, cooling and hotel hot water needs for a building. The operation is stable and reliable. Solar energy is able to reduce the energy consumption of a conventional gas fired absorption system in a large extent. The gas consumption of the hybrid energy system has a 49.7% energy saving ratio compared with the conventional gas fired system.

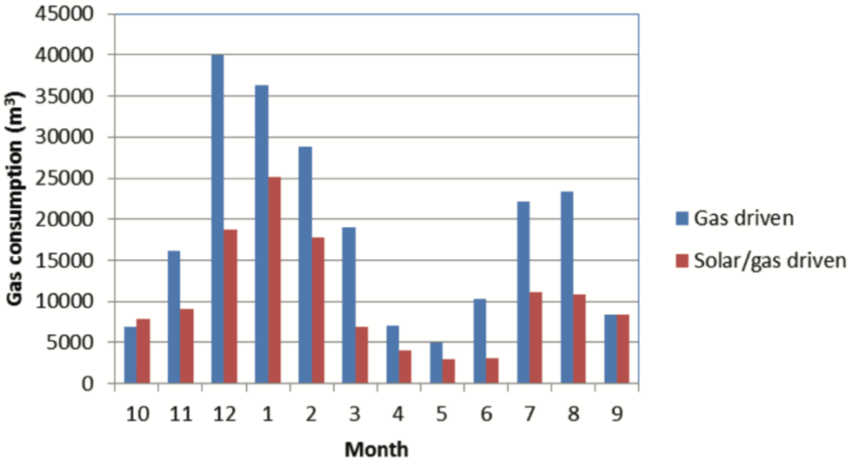


Figure 11: Gas consumption of the hybrid energy system and the conventional system (Sun et al. 2015)

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

Bataineh and Taamneh (Bataineh and Taamneh 2016) conducted an economic feasibility for absorption and adsorption systems. To do this, they analysed many cases study presented in literature. As in most of the cases, the solar systems have a high initial cost and low operational cost. Authors noted that the initial cost of the adsorption system is high compared to conventional system. Results of this study shown that the high initial cost of the system and low performance had a key role on the main significant commercial growth of this technology. The system efficiency and cost can be improved by carefully combining different system configurations, collector type, and climate data are made (i.e. single-effect chiller system with an evacuated tube collector outperforms multi-effect absorption chillers coupled with concentrating collectors when the percentage of direct normal irradiant is low). According to the results of this study, the long adsorption/desorption time, the size of the system, high cost of adsorption chillers, and low performance of the adsorption chiller are the main factors that limits commercializing of solar adsorption systems.

Wu et al. (Wu and Zhang 2019) investigated a consistent approach for optimising and comparing façade integrated solar cooling systems in terms of technical and financial performance. Four systems (a vapour compression cycle (VCC) chiller driven by semi-transparent photovoltaics (STPV) arrays, a single-stage absorption chiller, an adsorption chiller and a vapour compression chiller coupled with organic Rankine cycle (ORC) driven by evacuated tube solar collectors) were assessed and compared with a conventional electric vapour compression chiller. They carried out the analysis for different Australian cities. In their research they applied a financial study. High investment cost has been identified as one of the main market barriers for solar cooling systems (Desideri et al. 2009). To make long- term decisions, it is essential to take into account life cycle costs (capital, operation and maintenance). This is particularly relevant for renewable energy systems that generally have higher initial cost and lower operating cost. The total cost of a cooling system includes equipment costs, design and installation cost, maintenance cost and operating expense. Equipment cost also includes the cost of equipment replacement throughout the life time of the system. The objectives of the financial analysis are to analyse lifetime energy savings in terms of the financial value of each solar cooling system investigated. All calculations were conducted for a project life time of 20 years. The cooling technologies are compared based on UCC that represents the life cycle cost for one kWh of cooling, analogous to the levelized energy cost used in the analysis of electricity generation (Mokhtar et al. 2010) that were determined by using the following Eqs.:

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

$$ALCC = \frac{LCC}{Pa}$$

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

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

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

where *Pa* is present worth factor, t is lifetime (year), d is the real discount rate, D is nominal discount rate, i is inflation rate, IC is 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. Financial results indicated that at current conditions, solar cooling technology is still less cost competitive compared to conventional cooling systems (at least 50% higher than conventional system). Among the solar cooling systems, PV system is the most cost-effective one followed by ORC coupled with VCC chiller, adsorption and single-stage absorption system. In tropic climate zone, this trend is not obvious. The single-stage absorption chiller system is only 21% high than the cheapest PV system. Therefore, the length of cooling season is a key factor for the system selection. In terms of system performance, PV system can provide the highest SF, followed by ORC coupled with VCC chiller, adsorption and single-stage absorption system.

Table 8: Initial and life cycle costs (Wu and Zhang 2019)

Item	System	Darwin	Brisbane	Perth	Sydney	Adelaide	Canberra	Melbourne
Initial cost ($)	Conventional	189,424	176,199	192,686	188,333	199,682	151,005	176,674
	PV	583,572	320,358	507,933	504,272	432,380	298,357	375,281
	ORC-VCC	491,888	451,479	483,815	469,043	490,258	414,412	431,049
	AD	442,109	398,971	443,645	418,277	455,187	372,423	392,079
	AB1	503,634	463,925	506,727	489,467	518,283	427,157	455,144
Specific cost ($ kWr^{-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 9: Cost data assumption applied (Wu and Zhang 2019)

Item	System	Darwin	Brisbane	Perth	Sydney	Adelaide	Canberra	Melbourne
Solar field ($ m^{-2})	PV	750 [1]	750	750	750	750	750	750
	ETC	314 [2]	314	314	314	314	314	314
Cooling tower ($ kWr^{-1}) [3]	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	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 [4]	616	579	616	673	616	579	616
	AB1 [5]	1505	1505	1751	1751	1751	2099	1751
Electricity driven chiller ($ kW_r^{-1}) [6]	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}) [7]	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 ($ kWh^{-1}) [8]	N/A	0.30	0.31	0.33	0.37	0.47	0.27	0.32

Bellos and Tzivanidis (Bellos and Tzivanidis 2017) 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. They considered different combinations of collecting areas and storage tank volumes are investigated in order to determine the optimum combination which leads to the minimum levelized cost of cooling (LCOC). According to the final results, Abu Dhabi and Phoenix are the most suitable locations with levelized cost of cooling equal to 0.0575 €/kWh and 0.0590 €/kWh respectively, while Rome, Madrid and Thessaloniki are the less suitable locations with 0.2125 €/kWh and 0.1792 €/kWh and 0.1771 €/kWh respectively. Moreover, they found that the locations with high cooling loads and high solar potential are the most suitable locations for installing solar cooling. Furthermore, it is proved that higher collecting is associated with a greater optimum storage tank.

Narayanan et al. (Narayanan et al. 2021) investigated the feasibility of implementing solar absorption cooling technology in student residential building in Australia's subtropical climate region. The feasibility study allows the user to determine if the solar cooling system is technically, economically and environmentally sustainable in the long term. They analysed: initial investment costs, maintenance cost, and operational cost associated with both reference and solar cooling system. The initial investment cost is simply the purchase price of the product acquired. The maintenance cost associated with the product can be difficult to predict as there are various factors to be considered, such as the type of refrigerant used, the regularity of equipment maintenance, rate of usage, and unpredictability of randomised equipment breakdown. In particular, they found that the configuration had yearly operational savings of $1,477 in comparing vapour compression chiller, and the payback period was 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. (Balaras et al. 2007) conducted a short overview on the state-of-the-art and potential of solar-assisted cooling and air conditioning technologies in Europe by describing the main results of the EU project SACE (Solar Air Conditioning in Europe). A group of researchers from five countries has surveyed and analyzed over 50 solar-powered cooling projects in different climatic zones.

Commercial application of solar energy for air conditioning purposes is relatively new. Lamp and Ziegler (Lamp and Ziegler 1998) gave an overview of the European research on solar-assisted air conditioning up to 1996. Tsoutsos et al. (Tsoutsos et al. 2003) presented a study of the economic feasibility of solar cooling technologies. Karagiorgas et al. (Karagiorgas et al. 2006) 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, beside 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. For smaller scale systems, there is no market available technology.

A parametric study was carried out as part of the SACE project in order to examine the current cost situation for solar-assisted air conditioning technology. In addition, the influence of improvements in the cost-performance of components such as solar collectors or thermally driven chillers or desiccant systems as well as the influence of subsidies on the economic situation was studied, and recommendations for future work were identified.

In conclusion, they affirmed that for southern European and Mediterranean areas, solar assisted cooling systems can lead to primary energy savings in the range of 40–50% with a related cost of saved primary energy lies at about 0.07 h/kWh for the most promising conditions.

Xu et al. (Xu et al. 2021) (Xu et al. 2021) 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, 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 2.88 million CNY, respectively. A typical large cold storage located in the subtropical Guangzhou is considered as the case study. 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 compression subsystem, is promising to be the better layout for cold storages.

They found that the maximum annual energy saving for the layout without the shift of solar cooling output is 322.47 MWh (81 kWh/m2), which saves 11.4% of electricity energy compared with the reference system. Compared to other two solutions in the optimal case, its annual energy saving/net present value is 68.2%/62.7% and 41.8%/51.6% more than that of traditional layout and the one with the shift of solar cooling power, respectively.

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 payback period of 11.25/11.43, 15.23/14.94 and 24/25.63 years in Marrakesh, Barcelona and Oslo cities, respectively. Besides, evacuated-tube collector is found to be the most "environmentally-friendly" collector, since it allows reducing greenhouse gases emissions especially in boreal climate with a life cycle climate performance of 5.86/5.99 tCO_2 for absorption/adsorption systems.

5 Conclusions

This report presented the information collected during the activities related to activity A4. In the first part of the report some data of a completed project were reported. They were useful to understand which can be the energy consumption of typical public buildings with different end use.

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 literature and assessed in their ability to decrease the cooling demand. However, studies show different results are assessments of measures are hard to compare as different boundary conditions are considered. The impact of Urban Heat Islands (UHI) is introduced and potential mitigation measures are presented. Also for this topic, solutions are hard to compare as the UHI is individually for each location and the measures follow different approaches.

Unfortunately, focussing on solar cooling applications, some critical issues were found. First of all, no many data about the buildings characteristics (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 are in general assessed by testing the prototype in a single room. Related to this latter, it has to be noted that the studies that tested the system on a whole system considering simulation data.

The study analysed reported different results and conclusion 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' behaviour and their comfort conditions standard. 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, operating and maintenance. According to this, some results of authors that focused their attention on the economic aspects were reported.

In addition, the novel Cooling Demand Market Index (CDMI) is introduced and results for the country of Nepal are shown. 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.

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