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Design and Evaluation Strategies for Solar Cooling Integrated Façades: A case study in a Southern European office building

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ABSTRACT

Integrating solar cooling technologies into building façades can play a crucial role in reducing reliance on conventional cooling systems. However, incorporating various aspects at the early stages of a project can be challenging for designers due to the diverse types of information, steps, and decisions required. This study aimed to develop strategies for design teams to facilitate the early-stage design and evaluation of building façades integrating solar cooling technologies. The strategies were developed using a research-through-design methodology, considering the Spanish context and a proposed evaluation set-up to assess techno-economic feasibility. The development of strategies involved mapping the design and evaluation of solar cooling integrated façades by identifying and relating key processes, inputs, outputs, design decisions, and tools within key design stages. Consequently, a systematic design and evaluation process was carried out, including the identification and assessment of potential integration scenarios for solar electrically driven and thermally driven technologies based on relevant techno-economic criteria. The findings indicate that water-cooled vapor-compression chillers (VCC), combined with photovoltaic (PV) panels as an electrically driven solution, were the most relevant option for the selected case. Additionally, the developed strategies revealed that early-stage decisions significantly impact later processes, as they involve a greater number of steps, required information, and design choices. These strategies serve as guidelines to support designers in adopting a systematic design approach, helping to manage the complexities associated with processing diverse technical and economic information. Providing such structured methodologies to professionals with limited experience in solar cooling technologies is crucial for enabling their broader application.

1. Introduction

Cooling demands in the built environment have been estimated to have a dramatic increase in the coming decades as a result of climate change and the growth in the global population [1–3]. This demand increase can lead to a rise in the use of cooling systems depending on energy generated in power plants in order to meet thermal comfort requirements [2]. Consequently, supporting the use

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of cooling systems relying on renewable energy is becoming more important to reduce greenhouse gas (GHSs) emissions generated from energy consumed by conventional cooling systems.

Producing cooling effect through solar radiations is one of suitable options intended to mitigate challenges related to cooling demand increase in the built environment. The peak cooling demands can be proportional to the solar intensities due to maximum sunlight hours [4,5]. The main advantage of applying such techniques, namely solar cooling technologies, include lowering peak energy demand to reduce costs and being environmentally friendly with no impact on ozone depletion. [5]. Solar cooling technologies, introduced in the 1970s, are designed to produce conditioned air or chilled water using solar energy [6]. These technologies can generate hot water using Solar Thermal Collectors (STC) or produce electricity through Photovoltaic (PV) panels [7]. Accordingly, this highlights two main approaches for converting solar energy into cooling effect: thermally driven processes and electrically driven processes [6–11].

Having an insight into the built environment, building facades present high potential for integrating solar cooling technologies. Such part of the built environment can have a crucial effect on the indoor thermal requirements. At the same time, they can provide a considerable amount of surfaces exposed to solar radiations [12]. The wealth of technical strategies and interdisciplinary knowledge has boosted façade engineering, driving advancements in the building envelope industry [13]. Building façades have become multifunctional components that have an active role in the building energy system. These multifunctional components integrate technologies contributing to energy savings and meeting thermal requirements [14–16]. Although there are different definition in literature related to solar active façades of solar cooling integrated façades [17,18], the following definition can be relevant as it provides more flexibility when it comes into building integration [19]:

> "building envelope systems that include elements using and/or controlling solar radiation to deliver self-sufficient solar renewable electric and/or thermal energy needed to generate cooling effect in a particular indoor environment"

The design and development of solar cooling integrated façades should take into account various aspects, which include the following [20].

- Technical and product (T&P)-related aspects which comprises sizes, performances, efficiencies of components
- Financial (F)-related aspects which are associated with different costs during the product life-cycle
- Process and stakeholder (P&S)-related aspect which include various design and development processes, as well as the roles and responsibilities of various stakeholders during the product life cycle.

Such multiple aspects are linked to the fact that various social phenomena are connected to multiple bodies of knowledge across different disciplines [21]. However, addressing these aspects at the early stages of a project can be challenging, as it introduces complexities for the design team due to the diverse types of information, steps, and decisions required. This includes considering regulatory and passive measures, weather data, cooling demand, supplementary building services, and façade integration pathways [12,18,22]. Therefore, it has been emphasized that providing design approaches to professionals with limited experience in such technologies plays a vital role in enabling their widespread application [23]. In response, this study aims to develop key strategies for guiding the design and evaluation of solar cooling integrated façades to support broader adoption. These strategies serve as guidelines to help designers adopt a systematic design approach, managing the complexities associated with processing diverse technical and economic information related to both quantitative and qualitative criteria. Providing such structured methodologies to professionals is crucial for facilitating their broader implementation, contributing to the broader goal of sustainable building practices by reducing reliance on conventional cooling systems. The main research question to be investigated in this study is as follows.

- *How to guide the process of designing and evaluating solar cooling integrated façade in order to support the widespread application?*

In order to answer this research question, the development of key strategies guiding the design and evaluation of solar cooling integrated façades is based on a "research through design" methodology considering the development of design alternatives and their evaluation with respect to relevant design criteria. The methodology involves the following.

- Identifying key design stages as a framework for designing solar cooling integrated façades systematically, and also developing the design strategies.
- Proposing an evaluation set-up to assess design scenarios during the case study.
- Designing and evaluating solar cooling integrated façades within a relevant context and selected case, considering/taking into account the two aforementioned points.
- Developing key strategies guiding the design and evaluation of solar cooling integrated façades based on the mapped process through the case study.

Section 2 explains the research approach and methods adopted to develop the aforementioned strategies. Then, section 3 provides the findings related to the case study steps based on the adopted research methodology, which cover the systematic design and evaluation of solar cooling integrated façades. After that, section 4 presents the development of key strategies guiding the design and evaluation of solar cooling integrated façades. Sections 5 discusses the findings obtained from the case study and the developed strategies. Finally, the study ends up with the conclusion section (section 6) that states future research scope.

2. Research approach and methods

To develop key strategies guiding the design and evaluation of SCIFs, the methodology of this study is based on a research through design approach and methods (Fig. 1), which involves gathering and organizing relevant information and mapping key decisions required to design and evaluate solar cooling integrated facades considering the definition of [19]. Hence, the scope of designing such integrated façades assumes having a standalone building envelope systems using and/or controlling solar radiation to deliver self-sufficient solar renewable electric and/or thermal energy needed to generate cooling effect in a particular indoor environment. Therefore, the harvested solar energy by solar collection devised are considered to be used for cooling purposes. The following sections describe research approach and methods adopted to develop the strategies, which include the study context (section 2.1), key design stages (section 2.3), evaluation set-up (section 3.3), and the development of key design strategies (section 2.4).

2.1. Study context

The design and development of building façades integrating solar cooling technologies should consider particular scope and boundary conditions [19]. This include having particular geographic location and climate conditions as well as certain building typology.

2.1.1. Geographic location

Firstly, the strategies consider the application in Southern European regions, which have been identified by experts in the European building industry to be one of the relevant contexts due the urgency in terms of cooling demand requirements [24]. Furthermore, the applicability of various solar cooling technologies, including absorption, adsorption, as well as thermoelectric, in the hot-summer Mediterranean climates tend to be a feasible contexts, according to Prieto et al. [12,25]. Accordingly, for the sake of this study, the Spanish context has been selected. The country has different climate conditions, which cover the predominant Mediterranean feature [26]. Madrid city was the focus of the study which has a cold semi-arid climate according to Köppen-Geiger classification [27].

Spain is ranked as the third country in the European Union (EU), after Malta and Cyprus, in terms of cooling demands. The increase in temperatures in the country has resulted in a greater demand for cooling systems. In addition, the Spanish cooling demand has raised by around 2.6 times during the last four decades [28]. Furthermore, Madrid tends to have large office market and investments. The country had total of €728 million invested on the offices in the first half of year 2023 and it accounted total of €471 million (65 % of total office investment) [29]. In addition, Madrid city had the greatest share (40 %) of European business and professional services which can have a direct relation with office demand [30].

2.1.2. Building typology

The strategies focus on integrating solar cooling technologies into new building construction. Such projects tend to allow a greater degree of design freedom when applying new technologies compared to existing buildings [24,31]. Furthermore, the strategies are intended for office buildings, as they are considered the most relevant building type for such applications compared to residential buildings [32].This building typology typically experiences high heat gains, which result from various sources, including office

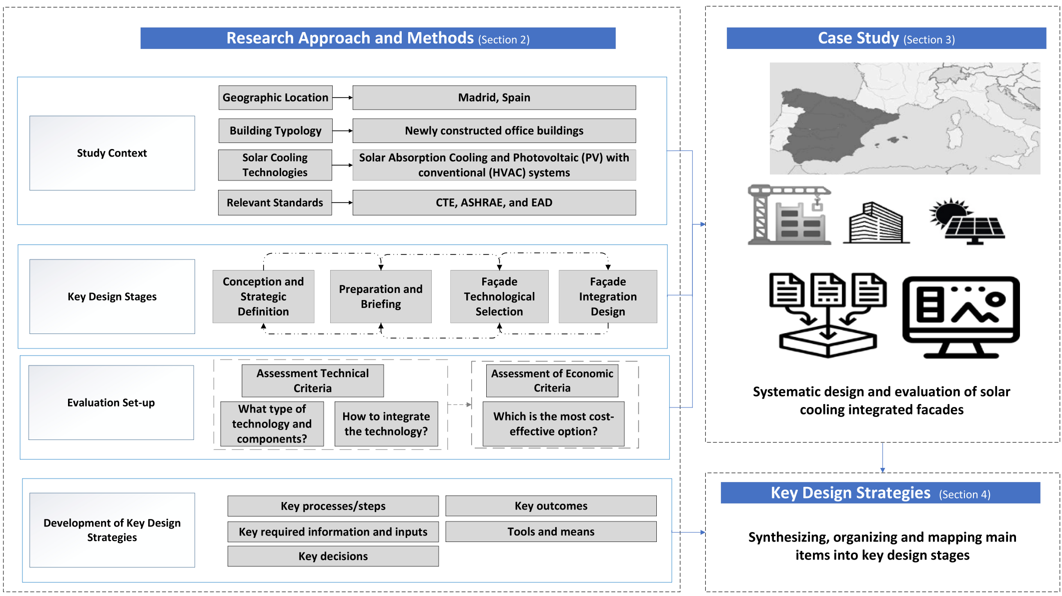


Fig. 1. Research methodology for the development of strategies.

equipment, lighting systems, and building occupants [33]. Additionally, office buildings are particularly relevant since they are primarily used during periods of available solar radiation. Owners and investors of these buildings are also perceived to be more inclined to invest in sustainable solutions compared to other building types, such as residential buildings [32]. Therefore, this study focuses on newly constructed office buildings. It should be noted that previous studies have primarily examined a single, simplified office room, without considering an entire building [12,22,34]. The inclusion of a typical building case in a specific context helps demonstrate the practical applicability of these strategies.

The building industry and office façade typologies are fragmented with various construction materials and systems [35]. Many of existing office buildings tend to have a combination of various façade types and elements, such curtain walls, double façades, shading devices and overhangs. Accordingly, developing the strategies based on a generic typical office with various façade types and elements is an essential to demonstrate its applicability in practice through determining different possibilities for façade integration. The selected building case in a generic office 5-story building (Table 1). The key characteristics of this building is that they take into account the common features of newly constructed office buildings in major European cities [36]. This include that majority of the external walls consist of glazed units attached to a concrete structure, although it the backside of the building consists of mainly opaque walls.

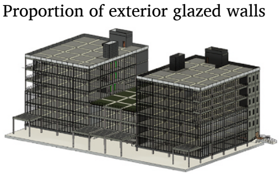
2.1.3. Solar cooling technologies

Since the strategies focus on supporting the process of designing and evaluating solar cooling integrated façades at early project stages, the study involves relevant and available solar cooling technologies. Therefore, sizes, performances and efficiencies are based available components. It was essential to focus on particular technologies to be considered in the process of generating and evaluating scenarios with respect to design criteria. Hence, this study aimed to involve relevant options for solar electrically-driven and thermally-driven technologies. For electrically-driven systems, the use of Photovoltaic (PV) for cooling through coupling it with conventional heating, ventilation, and air conditioning (HVAC) systems provide advantages related construction simplicity and high efficacy. Furthermore, the maturity and advancement of PV technologies was considered as a key factor supporting the widespread integration of electrically-driven solar cooling technologies into façades [24]. For thermally-driven technologies, solar absorption cooling was identified to be a relevant option as the literature pointed out that solar absorption chilling is found to have the highest growth rate compared to all the other solar thermal cooling systems [10]. Solar absorption cooling technologies were found to have relevant technical feasibility in hot summer Mediterranean and hot desertic climate contexts, which indicates their potential for being a promising candidate to be applied at different warm regions [12,25]. Solar absorption chillers are globally popular in the market of solar cooling technologies. This is because of their high coefficient of performance (COP) values compared to other technologies [9].

2.1.4. Relevant standards

Considering the fact that it is essential to understand key aspects to be considered in the decision-making process for integrating technologies into building façades [18], demonstrated that the design and development of solar cooling integrated façades involve the inclusion of additional functions into façades, which represent a secondary step to be considered when other passive and regulatory measures are unable to meet indoor requirements. Accordingly, the study aims to reduce energy and cooling demand using relevant guidelines. Although there are various guideline that can be applied during the design process, this study involved the use of the Spanish Technical Building Code (CTE) when selecting the U-value of the thermal envelope to align with current construction practices [37]. Although the study focused mainly on of the CTE code as a main standard to establish the reference model, it also involved referring to the ventilation for acceptable indoor air quality standard published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and American National Standards Institute (ANSI) in order to set some ventilation requirements [38,39]. Finally, EAD 090062-01-0404, Kits for external wall cladding mechanically fixed, was adopted as relevant reference standard demonstrate the façade detailing and connections [40].

Table 1
Overview of the selected building case.

Item	Description	Values
Function	Office building (5 story building)	–
Location	Madrid, Spain	–
Altitude	Altitude with respect to sea level	655 m
Ground floor area	Ground has its own same layout	2695.68 m^2
Spaces functions	Generic office areas, store rooms, toilets, dining/drinking areas, and light plant rooms	–
Window-to-Wall Ratio (WWR)	Proportion of exterior glazed walls	55 %
Building Overview		

2.2. Key design stages

The scope developing key strategies guiding design-decisions considers that it supports designers at different early key design stages with guidelines that can enable ending up with a suitable façade solutions. This is due to the fact that the having proper design can avoid many issues as well as ensure proper assembly and operation [24,32]. There are various ways and categorizations of design and construction stages that are available in the literature [41–44]. Hence, it is essential to have a structuring of the key design stages that can be used for the strategies. The structured key design stages are as follow.

1. *Conception and Strategic Definition:* The key outcomes of the conception and strategic definition stage include the possibilities for façade integration. The stage is intended to establish a reference model as a benchmark for investigating different scenarios [17]. Accordingly, it was essential to identify constant parameters to define the basis of the reference model [45]. The assumptions of constant parameters include climate contexts, internal heat loads (occupancy schedule and density), heating, cooling, and air conditioning (HVAC), and air infiltration. Also, establishing the model require identifying construction characteristics of the thermal envelop elements according to national energy saving guidelines.

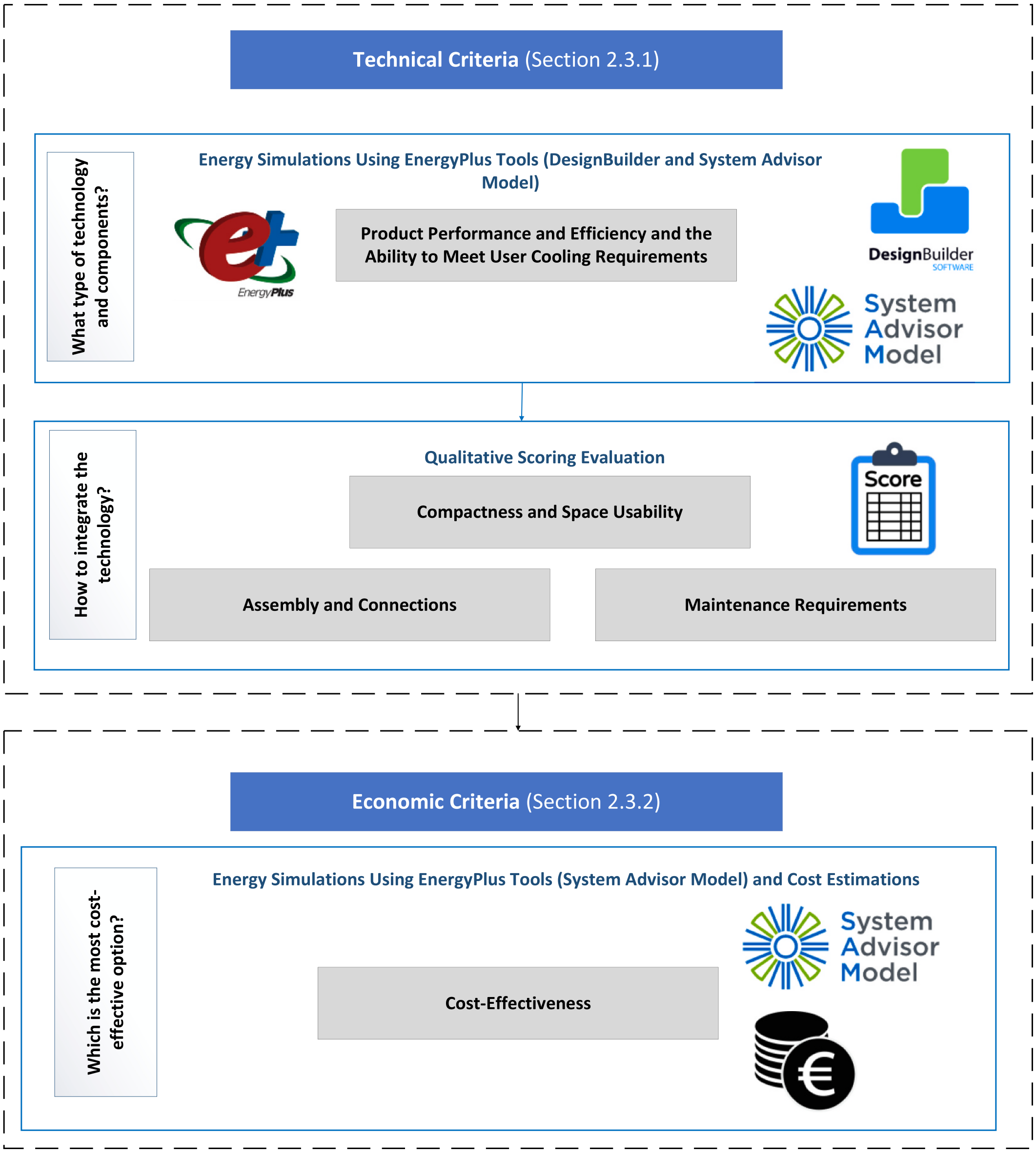


Fig. 2. Multi-stepped evaluation methodology.

2. *Preparation and Briefing:* This stage aimed to assess the feasibility of the generated possibilities considering relevant design criteria related to key aspects affecting façade integration.
3. *Façade Technological Selection:* This stage aims to select the relevant architectural façade technology, based on the outcomes of the preparation and briefing phase, namely technical and economic feasibility.
4. *Façade Integration Design:* This stage aims to presents the detailed design of integrating the selected technology into the façade considering the characteristics of key elements as well as relevant reference standards for component connections [46].

Although that these stages may not be linear as the nature of the design process can depend on regular feedbacks [47], such structuring facilitates having a framework for designing solar cooling integrated façades systematically, and also developing the design strategies.

2.3. Evaluation set-up

To assess the feasibility for façade integration during early design stages, it is crucial to have an evaluation setup that can enable an appropriate comparison of different design alternatives with respect to relevant criteria. This section explains the proposed evaluation set-up to assess design scenarios during the case study. The scope of the proposes evaluation setup consisted of a techno-economic assessment methodology [48–50], corresponding mainly to T&P-&F-related as they can be assessed and compared with certain criteria. The stepped-methodology adopted consisted of two parts, which aimed to assess the technical (section 2.3.1) and economic (section 2.3.2) criteria, respectively. Considering this design-based research, it was essential to have a well-established compilation of parameters, requirements, measurable criteria, and indicators using both quantitative and qualitative techniques [51,52]. Fig. 2 and Table 2 provide an overview of the design evaluation setup and criteria, which are described in the following subsections. The established requirements were primarily based on relevant literature, incorporating lessons learned from professionals working in the façade and/or solar industries [24,53]. The assessment of technical and economic criteria is described in Sections 2.3.1 and 2.3.2.

2.3.1. Technical criteria

The step of evaluating technical feasibility can involve various parameters. For instance, Prieto et al. [53] qualitatively evaluated different technologies in terms of potential façade integration. The aspects were based on the suitability of the technology in addressing key product-related barriers defined by the authors. These aspects included performance, physical integration, feasibility of integrating the system into façade modules, durability and maintenance, aesthetics, and availability. On the other hand, Hamida et al. [24] identified various aspects from qualitative interviews that were perceived as either supporting factors or concerns related to the façade integration of solar electrically-driven or thermally-driven technologies. Aspects identified and covered included aesthetic acceptability, applicability in different climate conditions, costs, product end-of-life, fire safety, lifespan, maturity and advancement, periodic maintenance, product performance and efficiency, sizes, and working principles. Considering these various aspects, it was essential to synthesize them into relevant evaluation criteria. Hence, a total of four evaluation criteria were adopted to assess technical feasibility, evaluated in two phases, as follows.

2.3.1.1. What type of technology and products?. This phase considers the first design criterion, namely product performance and efficiency, as well as the ability to meet user cooling requirements. This criterion is assessed using the Solar Fraction (SF) as an indicator (Table 2). The SF is one of the most commonly used metrics for evaluating the technical feasibility of solar cooling-integrated façades [12,22,54]. This indicator is calculated by dividing two main parameters: the cooling effect delivered by the selected technology and

Table 2
Overview of design criteria and requirements involved in the multi-stepped evaluation methodology.

Main Steps	Investigation Type	Criteria	Indicators	Unit	Required/ Recommended Value or Score per Indicator	Key Tools
T&P- Related Aspects: Technical Criteria	What type of technology and components?	Product Performance and Efficiency and the Ability to Meet User Cooling Requirements	Solar Fraction (SF)	Unitless	SF ≥ 1 (Required)	Energy simulations using EnergyPlus tools (DesignBuilder 7.0.2.006 and System Advisor Model (SAM) 2023.12.17)
	How to integrate the technology?	Compactness and Space Usability	Qualitative Evaluation	Level	A-C (Recommended)	Qualitative scoring and rating technique to translate qualitative criteria into quantifiable measures
		Assembly and Connections	Qualitative Evaluation	Level	A-C (Recommended)	
		Maintenance Requirements	Qualitative Evaluation	Level	A-C (Recommended)	
F-Related Aspects: Economic Criteria	Which is the most cost-effective option?	Cost-effectiveness	[a] Life-Cycle Cost (LCC_{AW})	€/year	Lowest LCC_{AW} (Recommended)	Energy simulations using EnergyPlus tools (System Advisor Model (SAM) 2023.12.17) and Cost Estimations
			[b] Levelized Cost of Cooling (LCOC)	€/kWh/ $year_{summer}$	Lowest LCOC (Recommended)	

the cooling demand of a particular indoor environment. This type of analysis serves as a numerical method to determine the required surface area to meet the building's cooling demand. It also facilitates the comparison of different scenarios and technological configurations in terms of their ability to provide the self-sustaining solar energy needed to generate cooling in a specific indoor environment at early design stages. However, previous studies have used a simplified equation to assess the SF, considering only losses in components related to cooling generation while neglecting losses associated with storage and distribution components [12,22,55]. It should be noted that storage and distribution components have been identified as having a critical effect on energy loss in solar cooling systems, depending on various factors, including how properly insulation is applied to the components [56]. Therefore, improving the accuracy of SF assessment should ensure a more precise representation of energy losses by incorporating all stages, including generation, conversion, storage, and distribution. Equations (1) and (2) indicates the detailed calculations for all parameters needed to assess the SF. The SF value was assessed considering daily solar availability as key input and daily cooling demands during the summer design week, which involves the most crucial period in summer season according to the weather data file. Scenarios having an SF value one or more are considered in phase 1.2.

Table 3
Qualitative scoring matrix for evaluating the compactness and space usability, assembly and connections, and maintenance requirements.

Level (Status): Score	Key Features of Different within Each Level for the Criteria		
	Compactness and space usability	Assembly and Connections	Maintenance Requirements
Level A (Extremely acceptable): 1.00	• Rooftops only, compact sizes of solar collection devices, and extremely simple structural support requirements to install components, • Rooftops only, moderate compactness of solar collection devices, simple structural support requirements to install components, or • Façade only, compact sizes of solar collection devices, extremely simple structural support requirements to install components	• Rooftops and façades and no use of hydraulic components among the cooling system components	• Low periodic maintenance complexity, low cleaning complexity of solar collection devices, and low accessibility complexity
Level B (Acceptable): 0.75	• Rooftops only, relatively compact solar collection devices, relatively simple structural support requirements to install components, • Façade only, moderate compactness of solar collection devices, and simple structural support requirements to install components, or • Both rooftops and façade, compact sizes of solar collection devices, and extremely simple structural support requirements to install components	• Only rooftops, low use of hydraulic components among the cooling system components, and no use of hydraulic components through the façade	• Some periodic maintenance complexity, low cleaning complexity of solar collection devices, and low accessibility complexity, or • Low periodic maintenance complexity, low cleaning complexity of solar collection devices, and some accessibility complexity
Level C (Somehow acceptable): 0.50	• Both rooftops and façade, relatively compact collection devices, and relatively simple structural support requirements to install components, or • Rooftops only, bulky sizes of solar collection devices, and more structural support requirements to install components	• Only façades, low use of hydraulic components among the cooling system components, and Use of hydraulic components through the façade	• Some periodic maintenance complexity, some cleaning complexity of solar collection devices, and low accessibility complexity, or • Low periodic maintenance complexity, some cleaning complexity of solar collection devices, and some accessibility complexity
Level D (Difficult to be acceptable): 0.00	•Facades only or both rooftops and façade, bulky sizes of solar collection devices, more structural support requirements to install components	•Rooftops and façades, high use of hydraulic components among the cooling system components, and use of hydraulic components through the façade	•Some periodic maintenance complexity, some cleaning complexity of solar collection devices, and some accessibility complexity
Notes	•Compact, moderate compact, relatively compact, and bulky sizes of solar collection are assumed to be corresponding to panel thinness $<$50 mm, 50 mm $\leq$ panel thinness $<$100 mm, 100 mm $\leq$ panel thinness $<$150 mm, and panel thinness $\geq$150 mm, respectively •Extremely simple, simple, relatively simple, and more structural support requirements are assumed to be corresponding to weight density $<$10 kg/m^2, 10 kg/m^2$\leq$ weight density $<$20 kg/m^2, 20 kg/m^2$\leq$ weight density $<$30 kg/m^2, and 30 kg/m^2 $\geq$ weight density	–	•Low periodic maintenance complexity correspond to low system care requirements and no corrosive materials •Some periodic maintenance complexity correspond to some preventive maintenance requirements and some corrosive materials. •Low accessibility complexity corresponds to Rooftops only •Some accessibility complexity correspond to both rooftops and façades or façades only

$$SF = SCOOL_{out} / COOL_{req} \quad \text{(eq. 1)}$$

$$SCOOL_{out} = SOL_{input} \times SOL_{arry} \times COP_{solarsys} \times COP_{coolsys} \times \left[1 - \sum Loss\right] \quad \text{(eq. 2)}$$

The following points describe the parameters associated with equations (1) and (2).

- $COOL_{req}$: Average daily cooling demand (kWh/day) in summer design week of a particular indoor environment. It is calculated using of dynamic energy simulation software, namely DesignBuilder 7.0.2.006.
- SOL_{input}: The average daily solar radiation availability (kWh/m^2/day) on a particular location/orientation considering the month of summer design week. It is calculated using dynamic energy simulation software, namely the System Advisor Model (SAM) 2023.12.17.
- SOL_{arry}: Designed area for collection (m^2), which is obtained from calculating the amount of the installed units of PV or STC.
- $COP_{solarsys}$: Efficiency of the applied solar collection system, that can be either PV panels or solar thermal collectors (STCs), which is obtained from published technical reports/case studies
- $COP_{coolsys}$: Coefficient of performance of the cooling technology, which is obtained from published technical reports/case studies
- $\sum$Loss: Sum of estimated percentages of energy losses at multiple stages, including solar energy collection, energy conversion, cooling generation, distribution, and storage, which is obtained from published technical reports/case studies
- $SCOOL_{out}$: Cooling effect delivered by the selected technology to a specific indoor environment, represents heat removed by cooling technology (kWh/day), which is calculated by applying equation (2).
- SF: Solar fraction of the designed façade system), which is calculated by applying equation (1). Having an SF value of 100 % and more indicates that the system can be able to handle the required cooling demand

2.3.1.2. How to integrate the technology and operating it?. Considering identified scenarios having SF values of 1 or more, it is essential to involve a second level of technical evaluation of these scenarios. Such evaluation should include aspects related to how to integrate the technology and operate it. This phase considers the following set of design criteria (Table 2).

- *Compactness and Space Usability:* The compactness and space usability aims to assess the amount of used area and space by solar cooling components, mainly solar collection devices, and also the feasibility to integrate the system in façade modules. Depending on the applied components of components, the amount of space may vary. Key aspects covered within this criterions are related to the bulkiness of products, namely amount of used area and space by solar collection devices and their compactness. It also include structural support requirements based on the wight density.
- *Assembly and Connections:* The assembly and connections of components aims to assess the complexity of connection of components, physical integration, and the nature of working principle of applied components. Hence, key aspects covered within this criterion include the use of hydraulic components based on pipe lengths and their amounts and the number of connections.
- *Maintenance Requirements:* The maintenance requirements aimed to assess aspects related to maintenance complexity, which included working materials and periodic maintenance, complexity of product cleaning, as well as complexity of product accessibility.

Measuring the three aforementioned criteria can be a challenging task as there are available feature related to these criteria lack measurable numbers. Having a measurement tool facilitating transforming such key features into quantifiable measures represent a key step to enable the evaluation of scenarios [51,53,57]. A four-scale qualitative scoring and rating technique was adopted to evaluate design scenarios in order to providing a simplified tool for designers to deal with complexity while enabling objective evaluation (Table 3).

2.3.2. Economic criteria

The application of renewable energy technologies on buildings requires assessing their economic feasibility in order to estimate the cost-effectiveness and worthiness of investments. There can be various parameters that can influence such assessment [19]. Furthermore, there are different techniques, which have been adopted to assess renewable energy projects economically [58]. Therefore, two main indicators were adopted to evaluate the economic feasibility, namely the life cycle costs (LCC) and the LCOE [48,58,59]. LCC cover the system life costs, which include the investment as well as the operation and maintenance (O&M) costs. Cost estimation in building design varies in accuracy and level of detail depending on the design stage. As the design progresses, cost estimates become more detailed and precise. Initial estimates rely on general assumptions and historical data, whereas later estimates incorporate specific project details. Different classifications of cost estimates have been established. For instance, some frameworks define five classes, ranging from the least detailed (order-of-magnitude estimate) to the most detailed (detailed estimate). These classifications include the feasibility estimate, which assesses project viability and compares alternatives. Such a class has an accuracy range of −30 % to +50 % [60]. As this study aimed to map the process of designing and evaluating solar cooling integrated façades to provide a comparative assessment of early feasibility across different scenarios and technologies, the assessment of LCC costs was based on the feasibility estimate.

Since a solar cooling system can consist of various elements and components, estimating investment and maintenance costs at the early feasibility stage can be challenging. To reduce complexities in the early design stages, this study focuses on estimating the investment and maintenance costs of cooling generation components, namely solar collection devices (SCDs) and chillers. These components have been identified as accounting for 47 %–61 % of investment costs, corresponding to small-to medium-capacity systems, respectively [61]. Furthermore, the cost of the auxiliary and mounting structure of SCDs were assumed to be the same regardless the variations of tilt angles. Although the LCC can be presented in different forms, such as Present Worth (PW) or Annual Worth (AW), this study focuses on presenting it in AW. Hence, the life cycle cost in annual worth (LCC_{AW}) (Table 2) was adopted, as it facilitates estimating the LCOE. Regarding the LCOE, its main concept involves the identification of the unit cost of energy overt the technology/project life through dividing all related to the energy system by the energy output from that system [58]. As the scope focuses on the comparison among scenarios and configurations related to renewable solar cooling systems, the main indicator is based on the levelized cost of cooling (LCOC) [49,62,63]. Hence, LCOC is estimated by dividing the life time costs of the system (in a form of annual equal amounts) by the annual solar renewable energy produced by the selected technology. For the sake of simplicity, the estimated LCOC focused on the annual energy produced for cooling during summer season only (Table 2). Equations (3)–(8) indicate the assessment of all parameters needed to estimate the LCC and LCOC.

$$I = I_{SCD} + I_{chiller} \qquad \text{(eq. 3)}$$

$$A_{LP} = I \times \left[\frac{r \times (1+r)^N}{(1+r)^N - 1}\right] \qquad \text{(eq. 4)}$$

$$A_{O\&M} = (\%\ of\ I) \times \left[\frac{r \times (1+r)^N}{(1+r)^N - 1}\right] \qquad \text{(eq. 5)}$$

$$LCC_{AW} = A_{LP} + A_{O\&M} \qquad \text{(eq. 6)}$$

$$ESCOOL_{out} = ESOL_{input} \times SOL_{arry} \times COP_{solarsys} \times COP_{coolsys} \times \left[1 - \sum Loss\right] \qquad \text{(eq. 7)}$$

$$LCOC = \frac{LCC_{AW}}{ESCOOL_{out}} \qquad \text{(eq. 8)}$$

The following points describe the parameters associated with equations (3) and (8).

- I: Investment cost (€) that includes solar collection devices and their auxiliaries (I_{SCD}) and also chillers ($I_{chiller}$). It is calculated by using equation (3), and also referring to the cost estimation models for chiller, collector, and auxiliary costs published in technical reports/previous studies [49,61,64–66].
- A_{LP}: Annual loan payment (€/year), which is calculated using equation (4).
- $A_{O\&M}$: Annual operation and maintenance cost (€/year). It is calculated by using equation (5), and also referring to the cost estimation models for chiller, collector, and auxiliary costs published in technical reports/previous studies.
- N: System life span, which is assumed to be 20 for all scenarios [49].
- *r*: The interest rate, which is assumed to be 6 % [64].
- LCC_{AW}: Life cycle cost (€/year) of the system in a form of annual equal amounts, annual worth (AW), which is calculated by using equation 6
- $ESOL_{input}$ Plane array irradiance ($kWh/m^2/year_{summer}$) available on a particular location/orientation considering whole summer as the time frame. It is calculated using of dynamic energy simulation software, namely SAM 2023.12.17.
- $\sum$Loss: Sum of estimated percentage of energy losses at multiple stages, including solar energy collection, energy conversion, cooling generation, distribution, and storage, which is obtained from published technical reports/case studies
- $ESCOOL_{out}$: Annual solar renewable energy produced by the selected technology (kWh/year), focusing on whole summer as the time frame. It is calculated using equation (7).
- LCOC: Levelized cost of cooling (€/kWh/year), which is calculated using equation (8).

2.3.3. Techn-economic feasibility

Taking into account of the involvement of various design criteria and different alternatives, the selection of the architectural façade technology can be challenging as every criterion has its own indicator and measurement. In order to facilitate the selection processes, this step involves representing the performance of all scenarios having SF equal to or more than 1.0, with respect to all criteria. The representation is carried out using radar chart graphical method. The charts are constructed according to the scores of the scenario with respect to design criteria based on the following points.

- The score of product performance and efficiency and the ability to meet user cooling requirements and represents the SF of the scenario which is equal to or more than 1.
- The scores of compactness and space usability, assembly and connections, and maintenance requirements correspond to the score for the assigned level for a particular scenario. The scores can have a value of 1.0, 0.75, 0.5, or 0.0 for levels A, B, C, or D, respectively.

- The scores of LCC_{AW} and LCOC are obtained by mapping the domains of the values of LCC_{AW} and LCOC linearly in curves. The curves have a score of 1.0 for the lowest LCC_{AW} and LCOC, while a score of 0.0 for the highest LCC_{AW} and LCOC. Hence, scores of LCC_{AW} and LCOC for a scenario (n) can be obtained by applying equations (9) and (10), respectively. Constructing such curve facilitates transforming the costs into a unitless indicators, such as the ones obtained from the SF and the assigned levels.

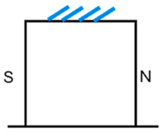
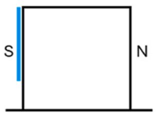
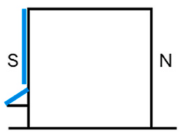
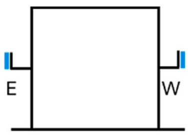
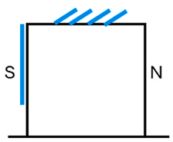
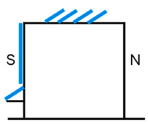
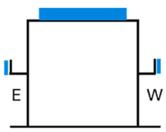
$$Score\ LCC_{AWn} = 1 - \left[\frac{LCC_{AWn} - Lowest\ LCC_{AW}}{Highest\ LCC_{AW} - Lowest\ LCC_{AW}}\right] \quad \text{(eq. 9)}$$

$$Score\ LCOC_{n} = 1 - \left[\frac{LCOC_{n} - Lowest\ LCOC}{Highest\ LCOC - Lowest\ LCOC}\right] \quad \text{(eq. 10)}$$

2.4. Development of key design strategies

This step involves the development of key strategies guiding the design and evaluation of solar cooling integrated façades in office buildings through synthesizing the outcomes of the case study steps and key decisions. This synthesisation is carried out through relating the following key items systematically into the key four design stages; (1) key steps/processes carried out within each phase to achieve its outcomes, (2) key required information and inputs required to carry out each step, (3) key decisions that were taken within each phase which had an influence on sequential streps, (4) the outcomes obtain from the processes, and (5) main tools and means

Table 4
Identified possibilities for façade integration.

Envelop Possibilities	Scenarios Per Configuration and Key Design Features	Graphical Representation
A. Rooftops only	A.I. Installing solar collection devices on rooftops with a particular tilt angel (30°) and orientation (S), and different use factors (0.15, 0.25, 0.40, 0.50, and 0.60)	
B. Façade only	B.I. Only vertical attachment of solar collection devices along the external layer of the opaque façades(Backside of the building-opposite to the main entrance)	
	B.II. Same as B.I with additional overhangs on the top of windows of the first floor eating rooms for installing the collector at different tilt angles (60°, 30°, and 0°)	
	B.III. Same as B.II with additional vertical attachment of solar collection devices along the external layer of balcony rails and roofs	
C. Rooftops & Façades	C.I. Combination of A.I and B.I	
	C.II. Combination of A.I and B.II	
	C.III. Combination of A.I and B.III	

adopted to carry out steps/processes within each phase.

3. Case study results

This section aims to present the results of designing and evaluating solar cooling integrated facades based on the approach and methods (section 2). The following subsections indicate findings of the systematic design and evaluation of solar cooling integrated facades considering four key design stages (Section 2.2).

3.1. Conception and strategic definition

Obtaining the possibilities for façade integration required an establishment of reference building model, assessment of building performance of reference model, and identification of possibilities for façade integration. The establishment of the reference model involved considering relevant regulatory requirements and also data collection and market survey. The aspects include construction characteristics of the thermal envelop elements (Table A.1) and the assumptions of constant parameters for the base case (Table A.2). Consequently, the performance of the established model was assessed through performing dynamic energy simulations using DesignBuilder 7.0.2.006. The simulations comprised different orientations of the building main entrance (Table A.3). The results of the simulated base model revealed considering all orientations ranged between 227.02 and 230.96 [kWh/m^2/year] for orienting the building main entrance to the North and South, respectively. Considering the simulated hypothetical large office case by Ref. [39] at different European climates considering Spanish energy savings requirements, the annual energy consumption in Madrid was estimated to be between 192.2 and 242.23 [kWh/m^2] which corresponds to pre and post COVID-19 conditions, respectively. This indicates that the building energy consumption lies within range of the simulated case. Consequently, orienting the building main entrance has been selected as the building base case for generating and evaluating the scenarios as it tends to have lowest building energy use intensity and cooling demand intensity. Such model has the opaque façade on the south side as well as shaded balconies are on the Ease and west sides.

The possibilities for integrating relevant solar electrically-driven and thermally-driven technologies into the façades were identified through determining key configurations of selected technologies and identifying possibilities for façade integration. The generation of suitable products that integrate solar absorption cooling technologies into façades can have various forms (Table A.4) [18, 53]. Considering the fact that the small-scale integration of such technologies into façades still remains large due to the variations in the sizes of system components, the partial integration of solar absorption technologies into building façades tends to be an appropriate path for outlining the possibilities [53]. The identification of possibilities focused on water-air heat exchanger cooling delivery components, namely fan-coil units. A total of three main configurations related to the components of cooling generation were considered, namely single-effect (SE) absorption chillers with flat-plate collectors (FPCs), SE absorption chillers with evacuated tubes collectors (ETCs), and double-effect (DE) absorption chillers with ETCs. Moving to electrically-driven systems, the use of PV for cooling through coupling it with conventional HVAC system was considered to be the base to generate the scenarios. The cooling generation device included the use of water-cooled vapor-compression chiller (VCC), whereas Variable Air Volume (VAV) terminal box was considered for the distribution [39]. Regarding the solar collection device used for energy conversion, Polycrystalline panels were considered [67,68].

Based on the determined configurations, façade integration possibilities were identified by analyzing project characteristics and building drawings. The process explored three installation approaches: rooftop only, façades only, and a combination of both, enabling effective scenario evaluation. As indicated in Table 4, various installation types and numbers of installed units depend on the building characteristics. To estimate SOL_{arry}, three groups were established, ranging from minimal to maximum spaces and surface utilization.

- Rooftops-only group (A): This represents the starting point and the lowest utilized area. It considers the use of flat roofs only, keeping the façades of the base model unchanged.
- Façades-only group (B): This focuses on installing solar collection devices on the upper façade surfaces of the base model, such as opaque façades, without utilizing flat roofs.
- Rooftops and façades group (C): This represents the final group, utilizing the largest area by combining both rooftops and façades.

3.2. Preparation and briefing

The following sections presents the findings of assessing the feasibility of the of the generated possibilities in Table 4 through applying the multi-stepped evaluation methodology (Fig. 2 and Table 2).

3.2.1. Assessed technical criteria

The assessment of technical feasibility had two main parts aiming at identifying relevant types of technologies and components as well as investigating how technologies can be integrated and operated.

The identification of relevant types of technologies and components was based on assessing the product performance and efficiency considering SF as an indicator. Scenarios having an SF value 1 or more were considered for investigating how technologies can be integrated and operated. To calculate the SF values (Equations (1) and (2)), $COOL_{req}$ was based on the selected base model which is having an orientation of the building main entrance to the North (Table A.3). The solar energy input to the façade system was assessed by estimating the average daily solar radiation availability on a particular location/orientation (SOL_{input}) (kWh/m^2/day) considering the month of summer design week of Madrid, July (Figure B.1). Such assessment was performed using the simulation tool of System Advisor Model (SAM) 2023.12.17 software and EnergyPlus weather file (Madrid 082210 (IWEC)). Regarding the SOL_{arry}, the amounts and areas of installed units of solar collection devices were estimated in m^2 based on the identified possibilities (Table 4). The values of $COP_{solarsys}$ and $COPc_{oolsys}$ were obtained from published technical reports or case studies (Table 5). Regarding the $\sum$Loss of electrically driven technologies, solar panels lose efficiency as temperatures rise, with crystalline silicon panels losing about 0.3 %–0.5 % per °C above 25 °C. At 60 °C, this can lead to a 10–15 % reduction in power output. Additional losses occur in inverters (around 3 %) and wiring (typically 2 %, but reducible to 1 % with optimized design) [69–71]. Consequently, the $\sum$Loss of water-cooled VCC and PV panels was assumed to be 14 %. For thermally driven technologies, determining energy loss percentages in solar absorption cooling systems is challenging due to variations in design, components, and operation. While exact figures for cooling distribution and thermal energy storage (TES) losses are not universally defined, studies provide useful insights.

- Cooling Distribution Losses: Heat loss from storage tanks and piping is a major concern, emphasizing the need for proper insulation and system design [56].
- TES Losses: The solar collector accounts for up to 70 % of total losses, while the generator and absorber contribute 6–14 %. Although the study examines entropy generation in system components, it highlights the importance of optimizing TES to improve overall efficiency [72].

As this study aimed to map the process of designing and evaluating solar cooling-integrated façades to provide a comparative assessment of early feasibility across different scenarios, the loss of thermally driven technologies was also assumed to be 14 %. Therefore, $SCOOL_{out}$ and SF values for all scenarios were assessed. Figs. 3–5 summarize the SF values for all scenarios, including losses, while Figure B.2 summarizes the SF values for all scenarios related to envelope possibilities (A), excluding losses. While previous studies have used a simplified equation to assess the SF—considering only losses in components related to cooling generation while neglecting losses associated with storage and distribution—it is clear that the SF value can be significantly affected by the inclusion or exclusion of these losses. Accordingly, based on the results of assessing the SF (including losses) for different envelope configurations across various scenarios, the following possibilities were considered for investigating how to integrate and operate the technologies, as they have SF values greater than 1.

- DE absorption chillers with ETCs: Rooftops & Façade (Groups C.I, C.II and C.III)
- Water-cooled VCC and PV panels: Rooftops & Façade (Only Group C.III)

Consequently, the matrix of the assessing how technologies can be integrated and operated (Table 3) was applied on the aforementioned identified relevant types of technologies and components. The information were collected from relevant literature as well as available product specifications. Tables A.5 to A.6 show results of applying the matrix while considering collected relevant information [9,53,68,73].

3.2.2. Assessed economic criteria

The economic feasibility of scenarios with an SF equal to or greater than one was assessed using equations (3)–(8) to evaluate the LCC_{AW} and LCOC. The analysis covered the two groups of configurations that met the required SF value (Section 3.2.1). The values related to the I_{SCD}, $I_{chiller}$, $O\&M_{SCD}$, and $O\&M_{chiller}$, were obtained from published in technical reports/previous studies as well as market survey (Table A.7). Figure B.3 shows the $ESOL_{input}$ obtained from SAM 2023.12.17 software. Accordingly, Fig. 6 summarizes the results of assessing LCC_{AW} and LCOC for all scenarios having SF equal to or more than 1. The lowest and highest LCC_{AW} were associated with the water-cooled VCC and PV panels (C.III: rooftops & façades with a rooftop use factor of 0.6) and DE absorption chillers with ETCs (C.III: rooftops & façades with a rooftop use factor of 0.60 and overhangs), accounting for €52,838.36 and €115,877.24 per year, respectively. However, when considering the LCOC, the lowest and highest values were associated with the water-cooled VCC and PV panels (C.III: rooftops & façades with a rooftop use factor of 0.60 and overhangs with a tilt angle of 0°) and DE absorption chillers with ETCs (C.III: rooftops & façades with a rooftop use factor of 0.4 and overhangs with a tilt angle of 60°), accounting for €0.0589 and €0.1076 per kWh per year (summer), respectively.

3.3. Façade Technological Selection

The selection of the relevant architectural façade technology involved summarising the techno-economic feasibility (Section 2.3.3).

Table 5
Key information required to investigate the type of technology and products [9,12,39,61,74].

Item	Thermally-Driven Technology			Electrically-Driven Technology
	SE absorption chillers with FPCs	SE absorption chillers with ETCs	DE absorption chillers with ETCs	Water-cooled VCC and PV panels
$COP_{coolsys}$	0.7	0.7	1.2	2.6
$COP_{solarsys}$	0.6	0.65	0.65	0.22
SOL_{input} **SOL_{array}**	Depending on the scenarios per configuration and key design features			

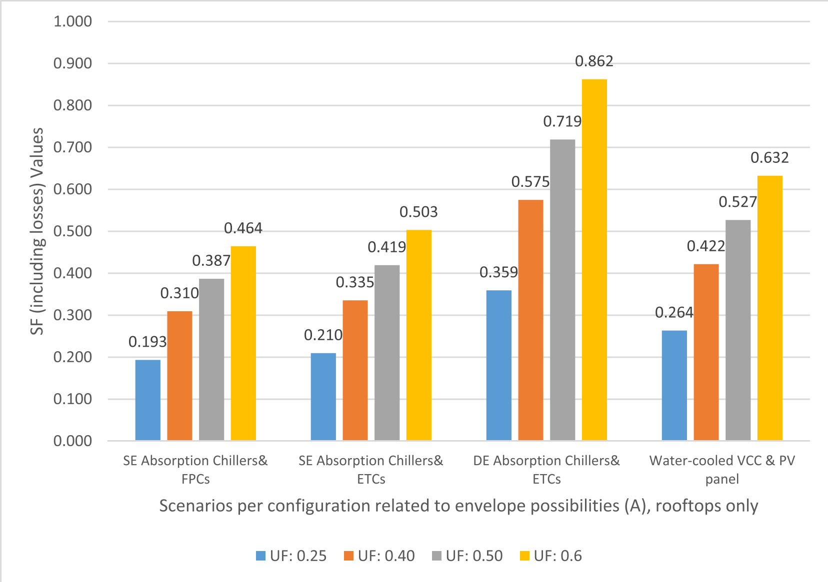


Fig. 3. SF values (including losses) for scenarios related to envelope possibilities (A), rooftops only.

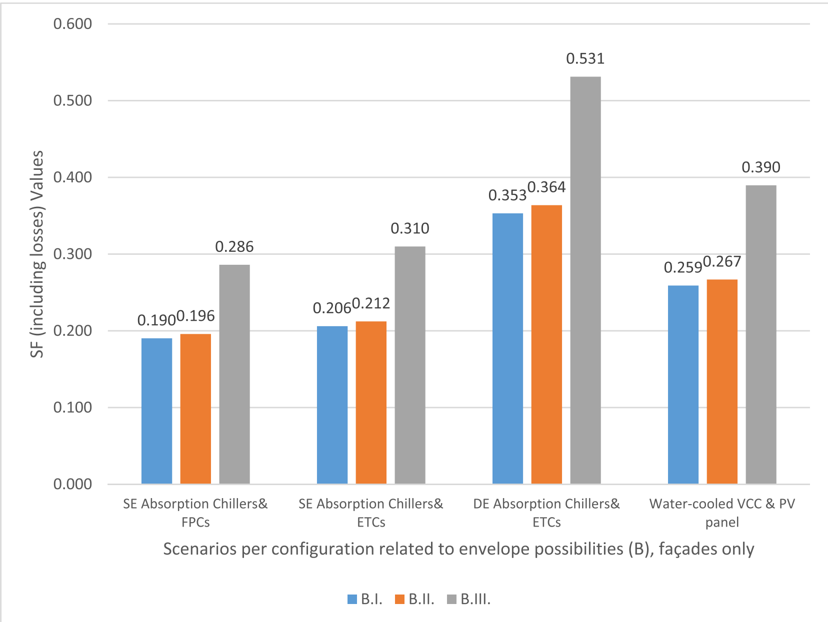


Fig. 4. SF values (including losses) for scenarios related to envelop possibilities (B), façades only.

Given the large number of radar charts generated, representative charts for each group of configurations were selected, as follows (Fig. 7).

- DE absorption chillers with ETCs:
  - o C.I: Rooftops & Façade with a rooftop use factor of 0.50 – Sum of scores: 2.020
  - o C.I: Rooftops & Façade with a rooftop use factor of 0.60 – Sum of scores: 2.204
  - o C.II: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs with a tilt angle of 0° – Sum of scores: 2.216
  - o C.III: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs with a tilt angle of 0° – Sum of scores: 2.157
- Water-cooled VCC and PV panels (C.III: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs with a tilt angle of 0°) – Sum of scores: 5.397

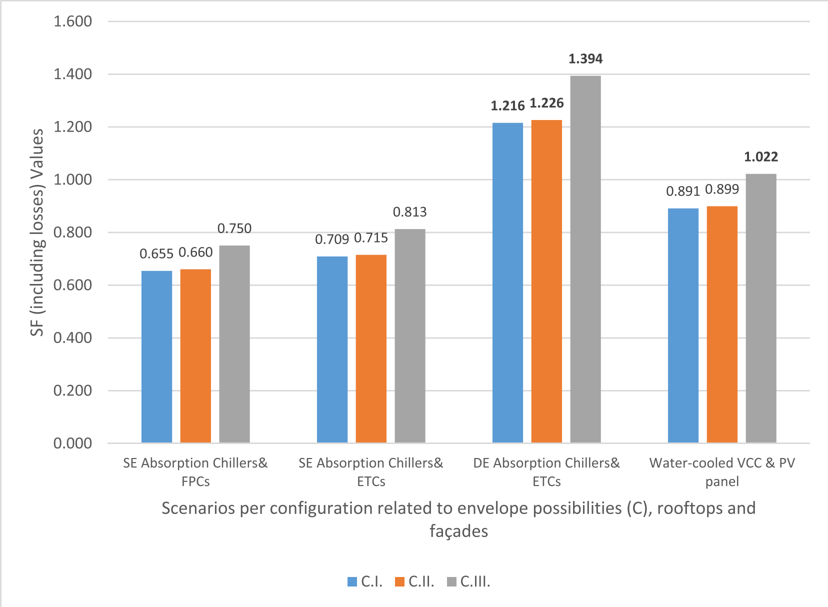


Fig. 5. SF values (including losses) for scenarios related to envelop possibilities (C), rooftops and façades.

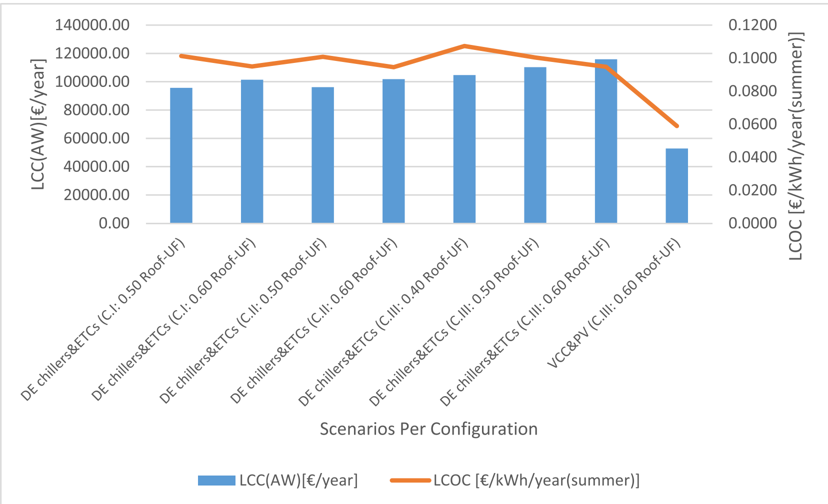


Fig. 6. Cost-effectiveness based on LCC_{AW} and LCOC for scenarios involving Double-Effect (DE) absorption chillers with Evacuated Tube Collectors (ETCs) (thermally driven) and water-cooled VCC and PV panels (electrically-driven), considering those with Solar Fraction (SF) values of 1 or higher.

Having analysed the radar charts and the total scores (Fig. 7), the most suitable option was the water-cooled VCC and PV panels (Rooftops & Façade). In contrast, DE absorption chillers with ETCs (Rooftops & Façade) appear to be the least suitable option, despite having the highest SF values. Based on these findings, the selected configuration was the water-cooled VCC and PV panels (C.III: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs).

3.4. Façade Integration Design

The detailed design for integrating the selected technology involved determining the characteristics of key elements considering relevant reference standards for component connections. Given that the selected technology was water-cooled VCC and PV panels (C. III: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs), the detailed design focused on this system while also providing a comparison to the competing technology, DE absorption chillers with ETCs. Therefore, the characteristics of key elements were identified using graphic design software, with a focus on key components related to the selected architectural façade technology to

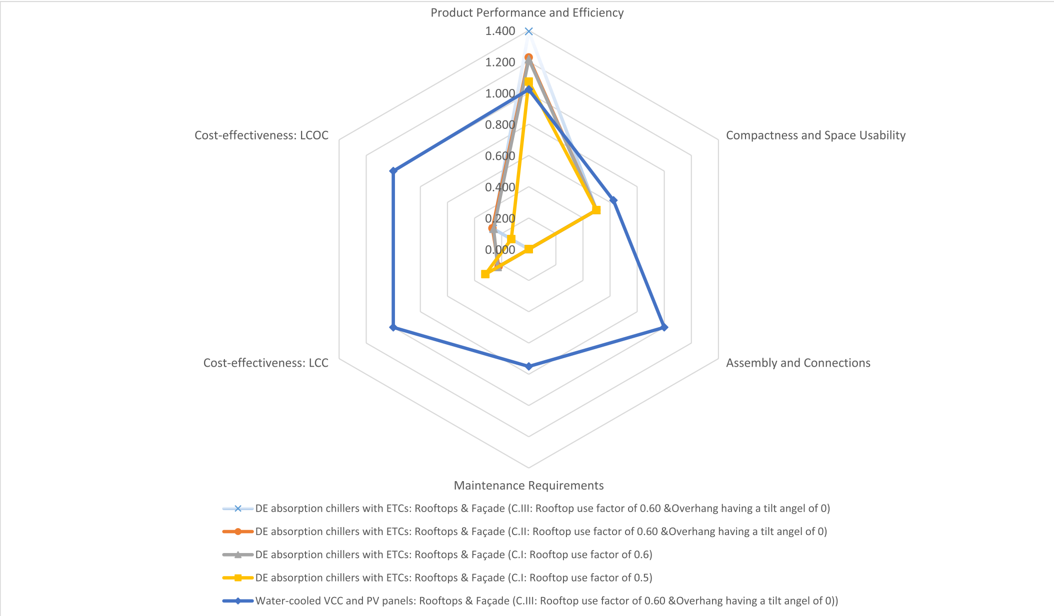


Fig. 7. Summarised techno-economic feasibility.

conceptualise their features. These key elements pertained to façade components, as rooftops are among the most common and widespread applications of PV panels. Consequently, the graphic design covered façade elements, specifically the vertical installation of PV panels on the opaque façade along the building's backside. The detailed design was demonstrated by representing façade components, connections, and element dimensions to provide construction details that translate design intent into technical representations. To ensure compliance with relevant reference standards, EAD 090062-01-0404 ("Kits for external wall cladding mechanically fixed") was adopted. Additionally, to facilitate various aspects related to installation, maintenance, and disassembly, cladding kits family G was chosen as the connection method in accordance with the standard. The main element connections consisted of cladding element, cladding fixing, subframe, substrate, anchor, thermal insulation, and others (air Cavity, water proofing, internal cladding layer of gypsum curry and base plaster). Hence, Fig. 8 provides information and demonstrates the detailed design of the selected technology—water-cooled VCC and PV panels—while at the same time presenting comparisons with the competing technology, DE absorption chillers with ETCs. The purpose of including ETCs is to highlight some of the complexities involved in this option

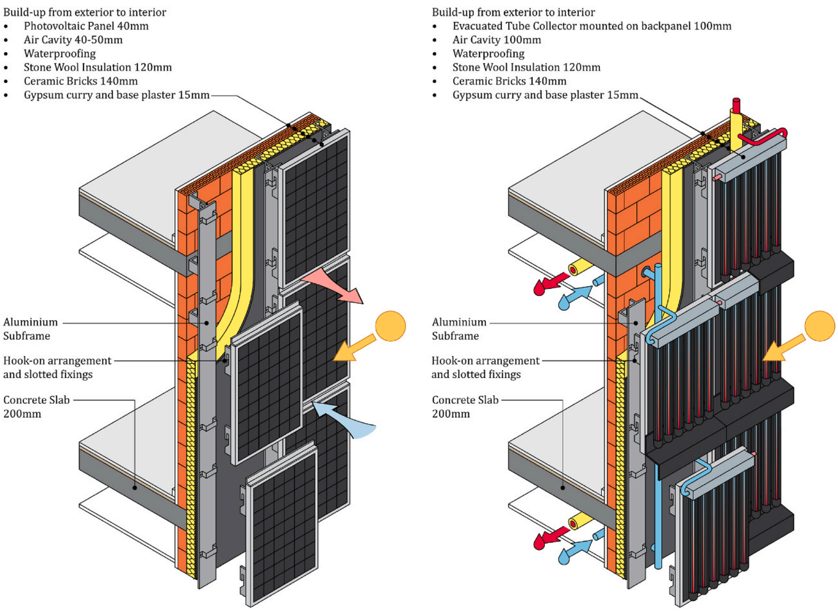


Fig. 8. Demonstration of a detailed design of the PV façade (left side) and the ETC façade (right side).

compared to PV panels.

4. Key façade design and evaluation strategies

This case study maps the process of designing and evaluating solar cooling integrated façades at early project stages, highlighting key lessons to guide design strategies. These strategies equip the early-stage project team with essential knowledge for informed decisions. Based on Section 3, this section develops key strategies by synthesizing case study outcomes, linking steps, inputs, decisions, outputs, and tools to design stages (Section 2.4). Table 6 summarizes the resulting façade design and evaluation strategies.

5. Discussion

This section aims to discuss the main outcomes from the case study (section 5.1) and the developed key design strategies (section 5.2).

5.1. Case study outcomes

The research scope focused on designing building façades considering a standalone building envelope systems using and/or controlling solar radiation to deliver self-sufficient solar renewable electric and/or thermal energy needed to generate cooling effect in a particular indoor environment. Therefore, the harvested solar energy by solar collection devices are used for cooling purposes. The case study mapped the process of designing and evaluating solar cooling integrated façades, comparing different scenarios. Unlike previous studies that assessed technical feasibility without accounting for energy losses, this study incorporated product performance, efficiency, and energy losses, which influenced SF values and design decisions. Water-cooled VCC and PV panels (rooftops & façades) were found to be the most suitable configurations due to their compactness, ease of assembly, maintenance, and lower costs compared to thermally driven options. While electrically driven technologies proved more feasible for façade integration, thermally driven systems showed competitive performance but scored lower in maintenance and cost-effectiveness. Key challenges for thermally driven technologies include material improvements to reduce maintenance and technological advancements in solar collectors to simplify cleaning. Subsidies could improve their economic feasibility by reducing investment costs.

The proposed multi-step techno-economic assessment method supports decision-making by systematically evaluating different scenarios. However, its results should be considered case-specific due to various factors such as.

- *Project and building characteristics:* Every project is unique, as each building has its own size, energy load profile, architectural design, and construction characteristics. Consequently, design outcomes vary from one project to another due to differences in energy and cooling demands.
- *Climate context and geographic location:* The availability of solar radiation varies from one location to another, influenced by factors such as shading from the surrounding environment. This, in turn, affects cooling demand, the required number of solar cooling devices (SCDs), and the system's energy input.
- *Status of technological development:* The development of solar technologies is an ongoing process, meaning that performance, sizes, working principles, and costs can change over time. As a result, the outcomes of techno-economic assessments are time-dependent.
- *Stakeholders involved and prioritization of techno-economic requirements and design criteria:* The case study outcomes, such as generated radar charts, were based on an equal prioritization of technical and economic criteria. However, since every project is unique, stakeholders—such as investors—may have different priorities, which can influence the selection of the most suitable option.

Cost estimations in this study were based on feasibility estimates from sources like the IEA, market surveys, and literature. Future research should refine these assessments for later design stages by incorporating localized cost data, practical estimations for real-world projects, and detailed analyses of long-term operations, including maintenance, equipment replacement, and performance degradation. This is because design stages are not linear in many cases, as the nature of the design process depends on regular feedback Additionally, integrating environmental impact assessments, such as embodied energy and life cycle analysis (LCA), would further enhance the evaluation of solar cooling technologies.

5.2. Developed design strategies

Analysis of the developed strategies (Table 6) shows that the first two stages—conception and strategic definition as well as preparation and briefing—contained most steps, inputs, decisions, and outcomes. Early-stage processes significantly impact later phases, such as construction characteristics in detailed design. This is due to the need for thorough early investigations, including regulatory measures, passive strategies, and project requirements. Although the case study focuses on Madrid, these strategies can assist design teams working in similar semi-arid or Southern European climates. However, local technical evaluations should incorporate region-specific weather data, regulations, and energy saving requirements, as building envelope criteria vary by location. Since each project is unique, aspects of the developed strategies depend on project-specific factors, including size, stakeholder priorities, and investor goals. For instances, determining optimization measures and selecting an appropriate model in the first stage depend on project objectives.

Table 6
Key façade design and evaluation strategies.

Stage	Key processes/steps	Key required information and inputs	Key decisions	Key Outcomes	Tools and means to obtain the outcomes
Conception and Strategic Definition	• Establishment and assessment of the reference model	• Regulatory requirements • Project characteristics/building drawings/building use profile • Weather, geographic and urban data	• Determine relevant measures to optimize building design • Select building optimized and suitable model	• Construction characteristics of the envelope • Building required cooling demand of the optimized and suitable model	• Data collection and market survey • Energy simulation
	• Identification of possibilities for façade integration	• Construction characteristics of the envelope of the optimized suitable model • Relevant solar cooling technologies	• Determine configurations of cooling generation, distribution, and delivery components • Identify available envelope possibilities for technological integration based on the selected model and relevant solar cooling technologies	• Possibilities for façade integration	
Preparation and Briefing	• Investigation of the type of technology and components	• Building requirements in terms of cooling demand • Performances and efficiencies of technologies • Technical design criteria and performance requirements	• Determine available envelope possibilities meeting cooling demand	• Assessed product performance and efficiency of generated possibilities meeting cooling demand	• Data collection and market survey • Energy simulation • Cost estimation
	• Evaluation of how the technology can be integrated and operated	• Sizes, wights, working materials, and maintenance requirements • Technical design criteria and performance requirements	–	• Evaluated technological potentials for building integration	
	•Assessment of economic viability	•Cost of technologies •Economic design criteria and requirements	–	•Cost-effectiveness of possibilities meeting cooling demand	•Data collection and market survey •Energy simulation •Cost estimation
Façade Technological Selection	•Summarisation of techno-economic feasibilities	•Assessed techno-economic feasibility of the generated possibilities •Design criteria and techno-economic requirements	–	•Summary of techno-economic feasibilities	•Data visualization •Multi-criteria analysis
	•Selection of architectural façade technology	•Summary of techno-economic feasibilities	•Determine the scenario having highest scores with respect to design criteria and selected relevant architectural façade technology	•Relevant architectural façade technology	
Façade Integration Design	•Determination of characteristics of key elements •Demonstration of detailed design	•Selected relevant architectural façade technology •Relevant safety requirements and standards	– •Determine means of connections according to the standards	•Features of main elements of the selected technology •Façade composition and constriction details	•Graphic and detailed design

While this study focused on orientation and cooling demand, real-world projects may prioritize different parameters. The same applies to selecting solar cooling technologies, which should be assessed based on project-specific needs. Finally, considering the aforementioned aspects of the developed strategies, it is essential for the design team to account for the project's nature and the stakeholders involved to tailor strategies accordingly. Nonetheless, these guidelines provide a crucial foundation that can be expanded upon in future research by contextualizing them based on project-specific factors, including stakeholder involvement. Contextualization contributes to extending these strategies to later project stages, such as executive design, production, installation, and operational use. Expanding these strategies into a comprehensive framework that considers these additional stages may require relevant research methodologies, such as action research approaches, where different stakeholders—such as façade builders—are actively involved.

6. Conclusion

Designing façades with solar cooling technologies presents challenges, requiring designers to consider technical, financial, and process-related aspects. These complexities arise from the multidisciplinary nature of the field and its connection to various social and technical domains. This study developed early-stage design strategies to guide the integration of solar cooling technologies into building façades, aiming to support their widespread application in the construction industry. A design-based research approach was used, focusing on Madrid as a case study. The selected building featured diverse façade elements, and key national energy regulations were applied. Various solar cooling integration scenarios were assessed using techno-economic criteria, incorporating both qualitative and quantitative indicators. Water-cooled vapor-compression chillers (VCC) and photovoltaic (PV) panels were found to be more suitable for the case study compared to thermally-driven technologies.

The research mapped the early-stage design and evaluation process, identifying critical design decisions. The first two stages—conception & strategic definition and preparation and briefing—were found to involve the highest number of decisions, with early-stage outcomes significantly influencing later phases. The study highlights the importance of considering regulatory measures, passive strategies, and project requirements from the outset. The developed strategies provide a structured methodology to help designers navigate the complexities of integrating solar cooling technologies, particularly those with limited experience. These guidelines can be further refined through future research by involving stakeholders such as construction team and exploring additional considerations, including.

- Technical and operational interfaces covering components, elements, and systems.
- Interfaces related to façade use and maintenance, including cleaning equipment, inspection accessibility, and real-time monitoring systems.
- Detailed estimations for real-world projects and accurate evaluation of economic viability, considering a detailed analysis of long-term operations, such as performance degradation of components and repair costs.
- Identification of potential design team, matrix of responsibilities, and procurement strategies.
- Installation techniques of the facade system and spatial coordination of architectural and engineering information.

Future studies should expand the strategies to different building typologies (residential, administrative, industrial) and assess variations in thermal capacity and glazing. Exploring advanced technologies such as bifacial solar panels, photovoltaic-thermal (PVT) collectors, and desiccant cooling systems in various climates could further enhance the applicability and impact of the developed strategies.

CRediT authorship contribution statement

Hamza Hamida: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alejandro Prieto:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Lourdes Beneito:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Thaleia Konstantinou:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Ulrich Knaack:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Case Study Tables

Table A.1
Construction characteristics of the thermal envelop elements according to local energy saving guidelines in Spain

Construction element	Requirements			Considered materials and system to meet requirements			
	Value		Reference	System	Description	Reference	Value
Opaque façade enclosure (External walls and columns)	Thermal transmittance of external walls (U-value)	0.27 [W/m^{2}K	DB-HE (HE 1) [37,39]	Ventilated Façade using Stone Wool Insulation	Multi-layered opaque external walls that can prevent heat entrance into buildings and maintain a comfortable temperature in summer	[75,76]	U-Value = 0.263 [W/m^{2}K]
Glazing (Openings)	Thermal transmittance of glass and frame assembly as well as windows (U-value)	1.6 [W/m^{2}K]	DB-HE (HE 1) [37,39]	Doble-glazing low-emissive	Double glazing of a thickness of 6 mm. An interior air chamber of 16 mm.	[77,78]	U-Value = 1.353 [W/m^{2}K]
	Solar Heat Gain Coefficient of glazing	0.58	[39]				SHGC = 0.396
					Polyvinyl Chloride (PVC) Window Frame		U-value = 2.2 [W/m^{2}K]
Roofs (Top slab)	Thermal transmittance of roofs (U-value)	0.22 [W/m^{2}K]	DB-HE (HE 1) [37,39]	Cast concrete slab	Bitumen sheet, cement mortar, expanded polystyrene insulation (EPS), cast concrete slab, air cavity and gypsum plasterboard	[77]	U-value = 0.211 [W/m^{2}K]
External floors (Floor in contact with outside air)	Thermal transmittance of slabs (floors in contact with outside air) (U-value)	0.27 [W/m^{2}K]	DB-HE (HE 1) [37,39]	Cast concrete slab	Stoneware tiles, cement mortar, expanded polystyrene insulation (EPS), cast concrete slab, air cavity, and gypsum plastered board	–	U-value = 0.240 [W/m^{2}K]
GF Slabs (floors in contact with ground)	Thermal transmittance of slabs (floors in contact with ground) (U-value)	0.48 [W/m^{2}K]	DB-HE (HE 1) [37,39]	Cast concrete slab	Stoneware tiles, cement mortar, Cast concrete slab, expanded polystyrene insulation (EPS), water proof membrane, and sand and gravel	[77]	U-value = 0.301 [W/m^{2}K]

Table A.2
Assumptions of constant parameters considering Spanish code and relevant references (Base Case)

Parameter			Description	Considerations and Values	Reference
Climate Context			Madrid: Köppen-Geiger climate classification: BSk - a cold semi-arid climate	EnergyPlus weather file (Madrid 082210 (IWEC))	[79]
Internal Heat Loads	Appliances		Plug and equipment's power density	18.04 W/m^2 Schedule: Monday to Friday from 9:00 to 19:00	[39]
	Lighting	Average illumination	Average illumination in the horizontal plane	600 lux	[37]
		Power	Power of the installed lighting	10 W/m^2 Schedule: Monday to Friday from 9:00 to 19:00	[37,80]
	Occupancy	Number of occupants	Number of people per square meter (m^2)	0.13 people/m^2	[80]
		Occupancy hours	The period at which the building is occupied and operated	Overall occupancy schedule: Monday to Friday from 9:00 to 19:00, except Dining and drinking areas which have an occupancy schedule: Monday to Friday from 13:30 to 15:30	[81,82]
		Holidays	Labour holidays in the Community of Madrid in 2024 that include 12 days	January 1st, January 6th, March 28th, March 29th, May 1st, May 2nd, July 25th, August 15th, October 12th, November 1st, December 6th, and December 25th	[83]
Heating, Cooling, and Air Conditioning (HVAC) - Variable Air Volume (VAV)	Heating (Gas-fired boiler)	Set-point	Schedule: Monday to Friday from 9:00 to 19:00	20 °C	[39]
		Set-back	Use end use default: Heating demand	17 °C	
		Efficiency	Efficiency of the boiler, heating system seasonal CoP	0.9	
	Cooling	Set-point	Schedule: Monday to Friday from 9:00 to 19:00	25 °C	[39]

(continued on next page)

Table A.2 (*continued*)

Parameter			Description	Considerations and Values	Reference
		Set-back	Use end use default: Cooling demand	27 °C	
		Efficiency	Efficiency of the chiller, cooling system seasonal CoP	2.6	[37,39]
	Mechanical Ventilation	Fresh air (person)	Outdoor air rate (person)	2.5 l/s Schedule: Monday to Friday from 9:00 to 19:00	[38,39]
		Fresh air (area)	Outdoor air (area m^2)	0.43 l/s Schedule: Monday to Friday from 9:00 to 19:00	[39]
Air infiltration			Air Change Units	0.15 ACH	[36]

Table A.3
Simulation outcomes as well as the key features associated with different orientations

Item		Orientation of the Building Main Entrance			
		N	S	E	W
Building annual energy use intensity [kWh/m^2/year]		227.02	230.96	228.81	229.07
Building annual cooling demand intensity [kWh/m^2/year]		53.61	57.54	55.41	55.66
Building average daily cooling demand in Summer Design Week (COOLreq) [kWh/day]		9805.58	10229.76	9956.79	10187.96
WWR	Total	0.55	0.55	0.55	0.55
	North	0.84	0.01	0.71	0.71
	South	0.01	0.84	0.71	0.71
	East	0.71	0.71	0.84	0.01
	West	0.71	0.71	0.01	0.84
Number of thermal zones in the ground floor	Ground have its own layout	15 zones			
Number of thermal zones in the 1st/2nd floor area	First and second floors have same layout	14 zones			
Number of thermal zones in the 3rd/4th/5th floor area	Third, fourth and fifth floors have same layout	10 zones			
Total Number of thermal zones	Sum of all zones	73 zones			
Spaces functions		Generic office areas, store rooms, toilets, eating/drinking areas, and light plant rooms			

Table A.4
Framework of technical possibilities of integrating solar absorption cooling technologies into facades [18,53].

Functions									Potential façade integration path
(1) Cooling Generation				(2) Cooling Distribution		(3) Cooling Delivery			
Energy converter		Cooling Generator		Components - Transport and Driver	Transfer medium	Delivery Components	Delivery medium	Delivery technologies	
Energy conversion components	Energy conversion technology	Cooling Generation components	Cooling principles and working materials						
Solar thermal collectors: • Glazed flat plate • Evacuated tubes	Water-based collectors	Absorption heat pumps: • Singl-effect chiller • Double-effect chiller	Sorption Cooling: • Lithium-Bromide/water • Lithium-Chloride/water	Air ducts fans	Air-based transfer	Diffusers	Air cooling	Air-air exchanger	Modular plug and play
				Hydronic system pumps	Water-based heat transfer	Embedded pipes Mounted pipes Capillary tubes	Surface cooling	Water-based radiant cooling	Partial façade integration
						Fan-coil units or induction units	Air cooling	Water-air heat exchanger	

Table A.5
Evaluation of compactness and space usability, assembly and connections, and maintenance requirements for DE absorption chillers with ETCs (Rooftops & Façades) [9,53,73].

C_n	Aspects Considered	Relevant information related to the aspects	Level (Status): Score
Compactness and Space Usability	• Amount of used area and space by solar collection devices and their compactness • Structural support requirements based on the wight density (Kg/m2)	Rooftops & Façades Thickness = 100 mm: Relatively compact collection devices (100 mm ≤ Panel thinness <150 mm) 24–24.7 kg/m2: Relatively simple structural support requirements to install components (20 kg/m2≤ weight density <30 kg/m2)	**Level C (Somehow acceptable)**
Assembly and Connections	• Use of hydraulic components based on pipe lengths and their amounts • Number of connections	• Rooftops and façades • High use of hydraulic components among the cooling system components	**Level D (Difficult to be acceptable)**

(*continued on next page*)

Table A.5 (*continued*)

C_n	Aspects Considered	Relevant information related to the aspects	Level (Status): Score
Maintenance Requirements	• Working materials and periodic maintenance	• Use of hydraulic components through the façade • Some periodic maintenance complexity: ○ Some preventive maintenance requirements: Preventive maintenance required for pumps and heat exchangers, required a twice shutdown every year for diluting lithium bromide solution, and required replacement of absorbent every 5 years ○ Some corrosive materials	**Level D (Difficult to be acceptable)**
	• Complexity of product cleaning	• Some cleaning complexity of solar collection devices: Medium cleaning complexity	
	• Complexity of product accessibility	• Some accessibility complexity: Both rooftops and façades or façades only	

Table A.6
Evaluation of compactness and space usability, assembly and connections, and maintenance requirements for water-cooled VCC and PV panels (Rooftops & Façades) [9,68].

C_n	Aspects Considered	Relevant information related to the aspects	Level (Status): Score
Compactness and Space Usability	• Amount of used area and space by solar collection devices and their compactness • Structural support requirements based on the wight density (Kg/m2)	Rooftops & Façades Thickness = 34 mm: Compact sizes of solar collection devices (Panel thinness <50 mm) 10.89 kg/m^2: Simple structural support requirements to install components (10Kg/m2≤ weight density <20 kg/m2)	Somewhere between Level B (Acceptable): 0.75 and Level C (Somehow acceptable): 0.50 **Final Score: Average B-C**
Assembly and Connections	• Use of hydraulic components based on pipe lengths and their amounts • Number of connections	○ No use of hydraulic components among the cooling system components	**Level A (Extremely acceptable)**
Maintenance Requirements	• Working materials and periodic maintenance	• Low periodic maintenance complexity: ○ Low system care requirements ○ No corrosive materials	**Level B (Acceptable)**
	• Complexity of product cleaning	• Low cleaning complexity of solar collection devices	
	• Complexity of product accessibility	• Some accessibility complexity: Both rooftops and façades or façades only	

Table A.7
Key information required to investigate cost-effectiveness [48,49,61,64–66,84–88]

Item		Thermally-Driven Technology	Electrically-Driven Technology
		DE absorption chillers with ETCs	Water-cooled VCC and PV panels
Investment cost (I)	I_{SCD}	• **Specific cost of ETCs [€/m^2] = 760.59*(ETCs area in m^2)$^{-0.135}$** Based on the collector area in m^2 the scenario has, the aforementioned equation gives the estimated specific costs of ETCs [€/m^2] taking into account the economy of scales **Investment cost of ETCs = Specific cost of ETCs [€/m^2] * Size of collectors (m^2)**	• Electricity generation of common PV solar panels = 400 W_p/m^2 • Typical price of a standard module crystalline silicon = 0.22 €/Wp • Specific cost of PV panels = (Electricity generation of common PV solar panels)*(Typical price of a standard module crystalline silicon) = 88 €/m^2 • **Investment cost PV panels = Specific cost of PV panels [€/m^2] *Size of PV panels (m^2)**
		• **Specific cost of ETCs auxiliaries [€/m^2] = 5500*(ETCs area in m^2)$^{-0.696}$** Based on the collector area in m^2 the scenario has, the aforementioned equation gives the estimated specific costs of ETCs auxiliaries [€/m^2] taking into account the economy of scales **Investment cost of ETCs auxiliaries = Specific cost of ETCs auxiliaries [€/m^2] *Size of collectors (m^2)**	• Electricity generation of common PV solar panels = 400 W_p/m^2 • Typical price solar mounting system = AVG (0.0263, 0.0279, 0.022, 0.0201) = 0.0241 €/Wp • Specific cost of solar mounting system = (Electricity generation of common PV solar panels)*(Typical price of solar mounting system) = 9.64 €/m^2 • **Investment cost of solar mounting system = Specific cost of solar mounting system [€/m^2] *Size of PV panels (m^2)**
	$I_{chiller}$	• **Specific cost of DE absorption chillers [€/kW_c] = 4300*(nominal capacity in kW)$^{-0.46}$** Based on the chiller nominal capacity in kW the scenario has, the aforementioned equation gives the estimated specific costs of SE absorption chillers [€/kW_c] taking into account the economy of scales • **Investment cost of DE absorption chillers = Specific cost of DE absorption chillers [€/kW_c] *Size chiller (kW)**	**Specific cost of Water-cooled VCC [€/kW_c] = 6543*(nominal capacity in kW)$^{-0.534}$** Based on the chiller nominal capacity in kW the scenario has, the aforementioned equation gives the estimated specific costs of SE absorption chillers [€/kW_c] taking into account the economy of scales • **Investment cost of Water-cooled VCC = Specific cost of Water-cooled VCC [€/kW_c] *Size chiller (kW)**

(*continued on next page*)

Table A.7 (*continued*)

Item		Thermally-Driven Technology	Electrically-Driven Technology
		DE absorption chillers with ETCs	Water-cooled VCC and PV panels
O&M Costs	**O&M$_{SCD}$**	• **O&M cost of ETCs = 1.5 % of Investment cost of ETCs** • **O&M cost of ETCs auxiliaries = 2.5 % of Investment cost of ETCs auxiliaries**	• **O&M cost of PV panels = 1.0 % of Investment cost of PV panels and solar mounting system**
	O&M$_{chiller}$	• **O&M cost of DE absorption chillers = 3.0 % of Investment cost of DE absorption chillers**	• **O&M cost of Water-cooled VCC = 3.0 % of Investment cost of Water-cooled VCC**

Appendix B. Case Study Figures

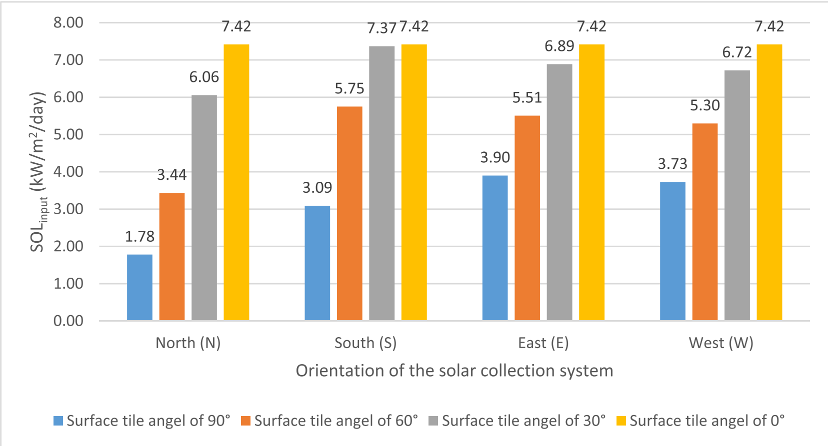

Fig. B.1. Daily average solar irradiance SOLinput at different orientations of the solar collection system considering the month of summer design week

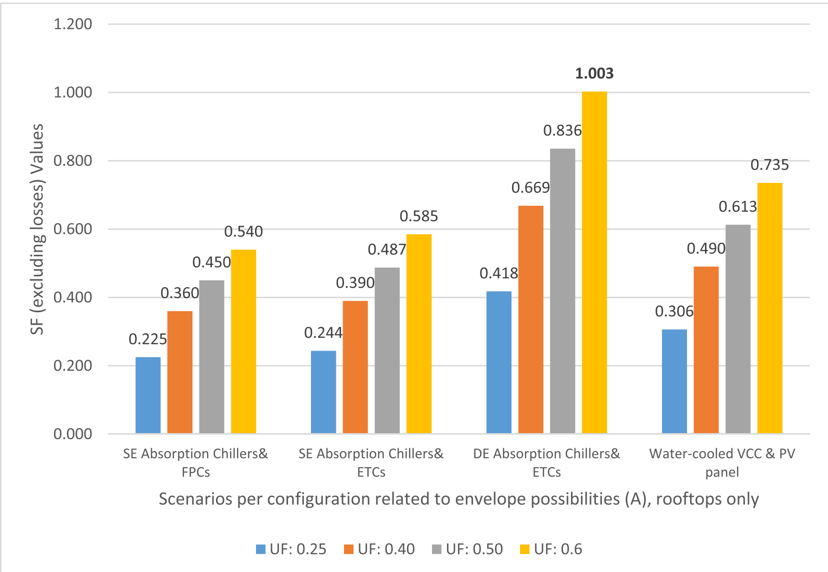

Fig. B.2. SF values (excluding losses) for scenarios related to envelope possibilities (A), rooftops only.

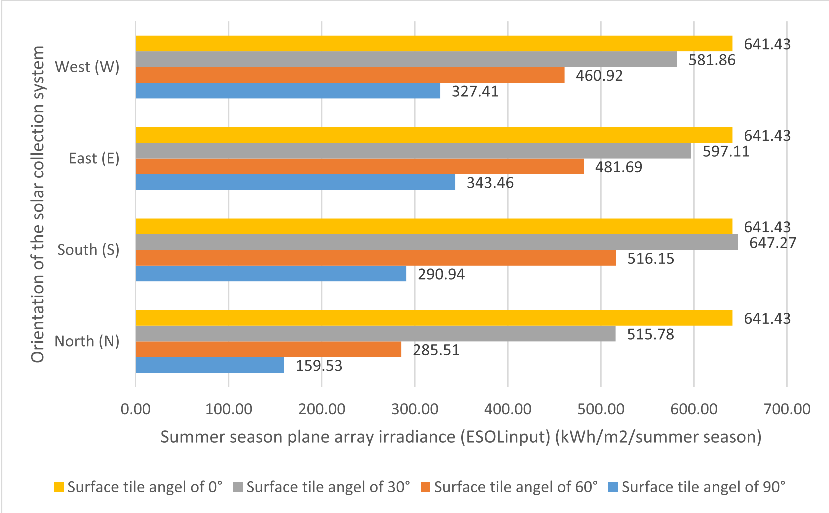

Fig. B.3. Plane array irradiance available on a particular location/orientation considering whole summer as the time frame $ESOL_{input}$

Data availability

The data supporting this research findings is openly available at this link: https://doi.org/10.4121/ce64c708-8347-4eb3-9d9c-91a2d5e0c96d.

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