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Towards designing and evaluating solar cooling integrated façades in office buildings

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Abstract

The present research proposes a framework to design and evaluate façade products integrating solar cooling technologies (SCTs), applied in an office building in a Southern Europe region. The building comprises various types of façade elements, such as opaque walls, glazed curtain walls, overhangs, and balconies. Key regulatory measures were implemented considering national energy saving regulations. The results represent annual energy consumption (kWh/m^2/year) and the average daily cooling demand in Summer Design Week (kWh/day) of the simulated base model. This energy consumption lies within range of a previously simulated generic office and the average annual energy consumption of office blocks. Potential scenarios for integrating SCTs were outlined and evaluated using the solar fraction (SF) as an indication to measure the potential performance of the system based on nominal efficiencies, providing an initial reference of its ability to meet cooling demands, an essential step in early design stages. Scenarios per configuration related to double-effect chillers with evacuated tubes collectors and water-cooled vapor compression chiller and photovoltaic (PV) panels were the only one having an SF value of 1 or more, meaning that they can be able to handle the required cooling demand. Future steps should consider a second level of technical evaluation of scenarios having SF values of 1 or more, which should involve aspects related to how to physically integrate the technology, considering compactness and space usability and also maintenance requirements, among other relevant criteria.

Keywords: Semi-arid climate, thermal envelope, solar fraction, PV panels

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 (Enteria and Sawachi, 2020; Sahin and Ayyildiz, 2020; Santamouris, 2016). Accordingly, 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 (Santamouris, 2016). Consequently, supporting the use 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. Therefore, the façade integration of solar active cooling technologies can have an important role in minimizing the use of conventional cooling systems since façades are usually highly exposed to solar radiation. Hence, solar energy can be harvested through the façade in order to drive cooling systems (Prieto et al., 2017).

The integration of solar active technologies in facades can be defined as “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” (Hamida et al., 2023c). It should be noted that providing design approaches to professionals who lack the experience with such technologies can have a vital role in enabling the widespread application (Saini and Weiss, 2023). Hence,

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this study presents initial findings of an ongoing research aiming to propose a framework supporting designers at early stages to design and evaluate façade products integrating solar cooling technologies to meet the cooling demand of a particular building. The framework proposition is based on a “research through design” methodology considering the development of design alternatives and their evaluation with respect to relevant design criteria.

The framework focuses on designing and evaluating such façade products for office buildings located in Southern European climates. The Spanish context has been selected with a focus on Madrid as a case study, which had as a cold semi-arid climate according to Koppen Geiger classification (Del Ama Gonzalo et al., 2023). 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 (Inspain News, 2023). Furthermore, Spain 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. Madrid accounted total of €471 million (65% of total office investment) (Cushman & Wakefield, 2023). In addition, Madrid city had the greatest share (40%) of European business and professional services which can have a direct relation with office demand (Savills Commercial Research, 2023).

2. Research Methods

To propose a framework for designing and evaluating SCIFs, this study is based on a “research through design” strategy. Therefore, the adopted strategy for the proposed framework is based on gathering and organizing relevant information needed to design and evaluate solar cooling integrated facades considering the definition of (Hamida et al., 2023c).

2.1. Key Design Stages

The aim of the research is to support designers at early key design stages to design a suitable product able to meet the cooling demand. This is due to the fact that having proper design can avoid many issues as well as ensure proper assembly and operation (Hamida et al., 2023a, 2023b). There are various ways and categorizations of design and construction stages that are available in the literature, including RIBA workplan for all disciplines on the construction industry (RIBA, 2020), integrated design and construction processes for new building construction and renovation projects identified by (Oliveira and Melhado, 2011), key phases associated with zero-energy residential building renovation (Prieto et al., 2023), and the façade design and construction processes associated with the curtain wall industry that were identified by (Klein, 2013). Hence, it is essential to have key identified design stages that can be used for proposing the framework through the case study. A total of four stages have been identified, namely (i) conception and strategic definition, (ii) preparation and briefing, (iii) façade technological selection, and (iv) architectural design. This paper presents results related to the conception and strategic definition as well as part of the preparation and briefing, as indicated throughout the paper.

2.1.1. Conception and Strategic Definition

The key outcomes of this stage include the establishment of possibilities related to integrating solar cooling technologies into the façade by taking into account different requirements and considerations, namely legal prerequisites as well as the building requirements. The legal prerequisites consider national guidelines related to energy savings. The building requirements consider that the definitions of solar active cooling integrated façades include having a self-sufficient solar renewable electric and/or thermal energy needed to generate cooling effect in a particular indoor environment (Hamida et al., 2023c). To obtain possibilities of façade integration as a main outcome of the conception and strategic definition phase, a set of three steps should be followed:

- Establishment of reference building model: The establishment of the reference building requires detailed descriptions of different aspects, such as geometry, location, occupancy profile, set-point temperatures. Such reference building can be considered as a benchmark for investigating different scenarios (Ochs et al., 2020). Accordingly, it was essential to identify constant and variable parameters to define the basis of the reference model (Ferrari and Zanotto, 2016). Therefore, key inputs should include the project characteristics (building size and location). Hence, main tools considered were data collection and market survey, which involved identifying the two main aspects needed to establish the base model. The first one includes assumptions of constant parameters which are climate contexts, internal heat loads (occupancy schedule and density based on the number of people per square meter), heating, cooling, and air-conditioning (HVAC), and air infiltration. The second one includes construction characteristics of the thermal envelope elements according to national energy saving guidelines.

- Assessment of energy performance of reference model: Considering the established base model, assessing its performance was carried through performing different sets of dynamic energy simulations using DesignBuilder 7.0.2.006, which is a graphical interface software of EnergyPlus. Such sets of simulations aim to assess the energy and cooling demands and compare the building energy performance with relevant data, and determine and select the suitable building base model. Energy simulations considered all thermal zones to assess the building energy performance at four different orientations, which included orienting the building main entrance to the North (N), South (S), East (E), and West (W) directions.

- Identification of possibilities for façade integration: The identification of such possibilities took into account relevant technologies to be involved in the process of generating and evaluating scenarios with respect to different criteria. The possibilities for integrating technologies into the façade are identified based on determination of key configurations of selected technologies and establishment of matrix of possibilities for integrating technologies into the façade.

2.1.2. Preparation and Briefing

This phase aimed to assess the technical and economic feasibility of the generated possibilities, and to determine functional requirements. This study provides the initial findings related to the pre-feasibility technical evaluation of different scenarios, which is based on assessing the product performance and efficiency and the ability to meet user cooling requirements. Considering that the definitions of solar active cooling integrated façades indicated by (Hamida et al., 2023c), it is essential to have a particular indicator that takes into account different aspects. These aspects include the delivered solar renewable electric and/or thermal energy, the generated cooling effect in a particular indoor environment, and the cooling demand in such environment. One of the commonly used measurements considering such aspects while enable evaluating the technical feasibility of product applicability is based on calculating the Solar Fraction (SF) (Noaman et al., 2022; Prieto et al., 2018a). Two main parameters are divided, namely cooling effect delivered by the selected technology and cooling demand of a particular indoor environment as shown in equation 1. Equation 2 and table 1 indicate 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.

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

$$SCOOL_{out} = SOL_{input} \times SOL_{arry} \times COP_{solarsys} \times COP_{coolsys} \quad \text{(eq. 2)}$$

2.2. Solar Cooling Technologies

This study aimed to involve relevant options for both of solar electrically-driven and thermally- driven technologies, which are involved in the process of generating and evaluating scenarios with respect to design criteria. 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 (Hamida et al., 2023a). For thermally-driven technologies, solar absorption cooling was identified to be a relevant option as it is a mature technology and has a high growth rate compared to other thermally-driven systems (Alsagri et al., 2020). In addition, 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 (Alahmer and Ajib, 2020). Furthermore, solar absorption cooling technologies were found to have relevant technical feasibility at different climate contexts (Prieto et al., 2018a, 2018b).

Tab. 1: Assessment of pre-technical feasibility (Noaman et al., 2022; Prieto et al., 2018a)

Item	Parameter						SF
	$COOL_{req}$	SOL_{input}	SOL_{arry}	$COP_{solarsys}$	$COP_{coolsys}$	$SCOOL_{out}$	
Description	Average daily cooling demand in summer design week of a particular indoor environment	The average daily solar radiation availability on a particular location/orientation considering the month of summer design week.	Designed area for collection	Efficiency of the applied solar collection system, that can be either PV panels or solar thermal collectors (STCs)	Coefficient of performance of the cooling technology	Cooling effect delivered by the selected technology to a specific indoor environment, represents heat removed by cooling technology	Solar fraction of the designed façade system
Unit	kWh/day	kWh/m²/day	m²	Unitless	Unitless	kWh/day	Unitless
Assessment Method	Use of dynamic energy simulation software, such as DesignBuilder 7.0.2.006	Use of dynamic energy simulation techniques, such as the System Advisor Model (SAM) 2023.12.17 software	Calculation of the amount of the installed units of PV or STC	Published technical reports/case studies	Published technical reports/case studies	By using eq. 2	By using eq. 1
Notes	Having an SF value of 100% and more indicates that the system can be able to handle the required cooling demand						

2.3. Standards and Regulations

It is crucial to include key aspects in the decision-making process for integrating technologies into building façades. According to (Prieto et al., 2017), the design and development of solar cooling integrated façades are only worth pursuing when all other passive measures are unable to meet indoor requirements. Accordingly, the study aims to reduce cooling demand using relevant guidelines as a first step. Hence, his study considers the Spanish energy saving regulations to optimize the building design by implementing necessary passive measures to lower energy demand (CTE, 2022a). Although some researchers used the Passive House Standard, (Borrallo-jiménez et al., 2022) indicated that applying the Passive House standard could not provide competitive benefits related to improving the building energy performance when it is compared to the local Spanish regulations. It should be noted that the efficiency improvement of the European building sector has been identified to be addressed by two main instruments, namely the Energy Performance of Building Directives (EPBD) and also the Energy Efficiency Directives (EED) (de Arriba Segurado, 2021). The Spanish Technical Building Code, El Código Técnico de la Edificación (CTE), contributes to transporting such directives into the legal system by modifying the Basic Document, Documento Básico (DB-HE) (CTE, 2022b). Such document provides rules and procedures allowing basic energy saving requirements to be met.

2.4. Building Case

The consideration of a typical building case in a particulier context contribute to demonstrating the framework applicability from practical point of view. Taking into account that the building industry is fragmented with various construction materials and systems, (Ebbert, 2010) sorted various office façade typologies in Western Europe systematically in a matrix in order to have an insight into the functions of different façade types so that various façade refurbishment strategies can be developed and applied. However, 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. This makes the consideration of a particular façade typology can be a challenging task since every project is unique. Accordingly, proposing the framework by considering 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. Hence, the selected building case in a generic office 5-story building. Each floor has a hight of 4.2 m. The ground floor has its own layout in terms of sizes and numbers of thermal zones and spaces functions, such as office areas and storerooms, while first and second floors have similar layouts. The third, fourth, and fifth floors have similar layouts. The key characteristics of this building are that they take into account the common features of newly constructed office buildings in major European cities (Costanzo and Donn, 2017). Majority of the external walls consist of glazed units attached to a concrete structure, although the backside of the building are opaque walls. The building presents flat concrete roof surfaces that are bitumised. Table 2 and Figure 1 provide an overview of the selected building case for framework proposition.

Tab. 2: Overview of the selected building case for framework proposition

Item	Description	Values
Altitude	Altitude with respect to sea level	655 m
Ground floor area	Ground has its own same layout	2695.68 m^2
First/second floor area	First and second floors have same layout and sizes	2851.2 m^2
Third/Fourth/fifth floor area	Third, fourth and fifth floors have same layout and sizes	1866.24 m^2
Gross floor area	Sum of all floor areas	13996.8 m^2
Floor height	All floors have an equal hight	4.2 m
Window-to-Wall Ratio (WWR)	Proportion of exterior glazed walls	55%

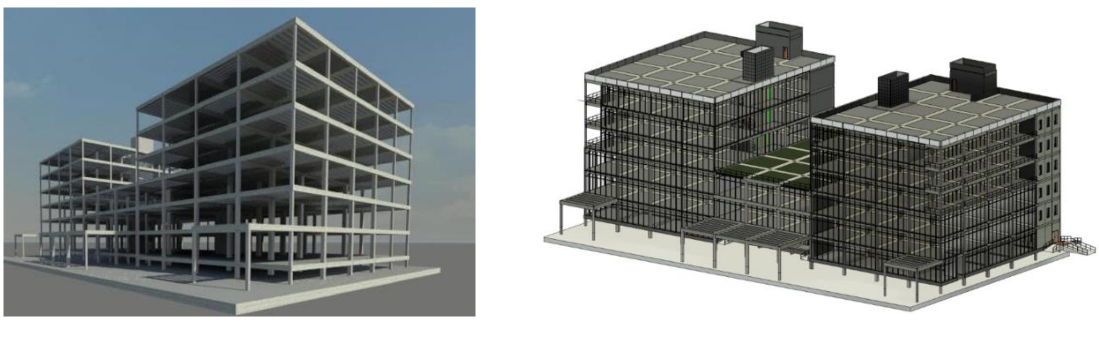


Fig. 1: Selected building case

3. Results

This section presents the findings of the conception and strategic definition phase (sections 3.1) as well as part of the preparation and briefing phase (sections 3.1). Hence, section 3.1 provides the results of the established reference model, and also identified possibilities for façade integration. On the other hand, section 3.2 shows findings of assessing the technical feasibility of generated possibilities based on the SF values.

3.1. Conception and Strategic Definition

As indicated in section 2.1.1, the key outcomes of this stage include the establishment of possibilities to integrate solar technologies into the façade by taking into account different requirements, legal and building prerequisites and specifications. The legal requirements in this study were considered based on Spanish guidelines related to energy savings (CTE, 2022a). Table 3 shows the building and façade characteristics, including Window-to-Wall ratio (WWR), of the reference model when considering different orientation of the building main entrance.

Tab. 3: WWR and thermal zones of simulated base case scenarios

Item		**Orientation of the Building Main Entrance**			
		N	**S**	**E**	**W**
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 has its own layout	15 zones			
Number of thermal zones in the 1st /2nd floor area	First and second floors have the same layout	14 zones			
Number of thermal zones in the 3rd/4th /5th floor area	Third, fourth and fifth floors have the same layout	10 zones			
Total Number of thermal zones	Sum of all zones	73 zones			
Spaces functions		Generic office areas, storerooms, toilets, dining rooms, and light plant rooms			

Figure 2 shows simulation outcomes that include the annual building energy use intensity while Figure 3 indicates the building average daily cooling demand in summer design week of (COOLreq) (kWh/day). 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. These values were compared with other values in literature to have an initial validation of simulated reference base case. Considering the simulated office case by (Cortiços and Duarte, 2022) 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]. Considering this range of energy consumption, the building energy consumption simulated base case lies within this range.

According to simulation outcomes, it is shown that the orientation of the main entrance to the north, where opaque façade on the south side as well as shaded balconies are on the Ease and west sides, resulted in the lowest building energy use intensity and cooling demand intensity in both of yearly and summer design week time periods. On the other hand, orienting the building main entrance to the north had the highest energy and cooling demand. Hence, orienting the building main entrance has been selected as the building base case for generating and evaluating the scenarios.

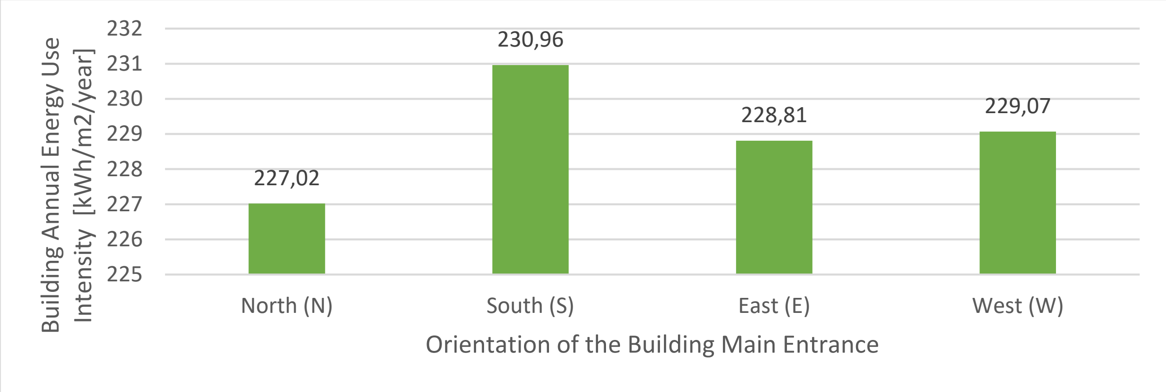


Fig. 2: Building annual energy use intensity according to the orientation of the building main entrance

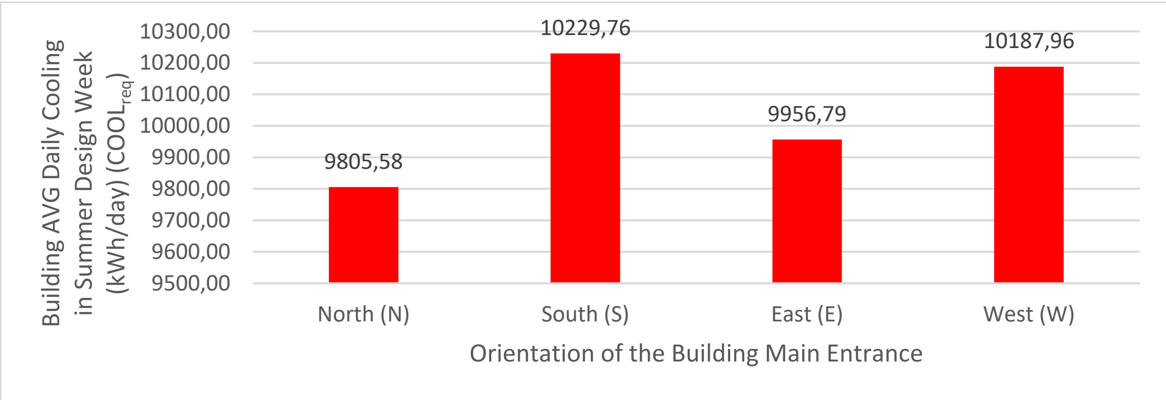
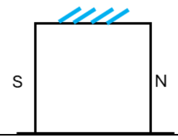
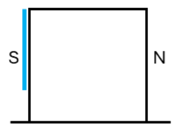
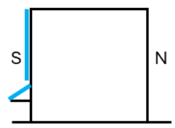


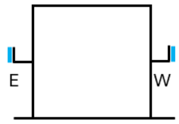
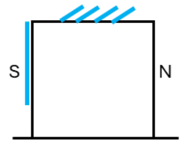
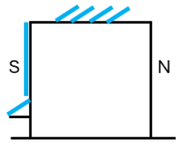
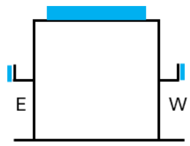
Fig. 3: Building average daily cooling demand in Summer Design Week (COOLreq) according to the orientation of the building main entrance

Based on the selected reference model, the identification of such possibilities took into account relevant technologies to be involved in the process of generating and evaluating scenarios with respect to different criteria, namely SF in the present paper. The generation of scenarios was based on the establishment of matrix of possibilities for integrating both technologies into the façade, which facilitated estimating SOL_{arry} (Table 5). It also considered different configurations of solar cooling technologies, which facilitate determining the $COP_{solarsys}$ $COP_{coolsys}$ of components related to both technologies (Table 5) (Alahmer and Ajib, 2020; Ayou and Coronas, 2020; Cortiços and Duarte, 2022; Mugnier et al., 2017; Prieto et al., 2018a).

Tab. 4: Matrix of possibilities for integrating both technologies into the façade

Envelope 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 (0.25, 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 window of the first floor dining rooms for installing the collector at different tilt angles (60°, 30°, and 0°)	

Tab. 4: Matrix of possibilities for integrating both technologies into the façade (cont.)

Envelope Possibilities	Scenarios Per Configuration and Key Design Features	Graphical Representation
B. Façade only	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 & Façade	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	

Tab. 5: Key information required to generate scenarios

Item	Thermally Driven Technology			Electrically Driven Technology
	Single-effect (SE) absorption chillers and flat-plate collectors (FPCs)	Single-effect (SE) absorption chillers and evacuated tubes collectors (ETCs)	Double-effect (DE) absorption chillers and evacuated tubes collectors (ETCs)	Water-cooled vapor compression chiller (VCC) and PV panel
$COP_{coolsys}$	0.70	0.70	1.20	2.60
$COP_{solarsys}$	0.60	0.65	0.65	0.22

3.2. Preparation and Briefing

This phase aimed to assess the technical feasibility of the generated possibilities in Table 4, to determine the technical feasible scenarios having an SF value 1 or more. To assess such feasibility, two key steps were considered, namely assessing of solar energy input to the system and then assessing the SF value of each scenario considering Table 2.

3.2.1. Assessment of Solar Energy Input to the Façade System

This step aimed at assessing solar energy input to the façade system through considering different physical positioning of the solar collection devices in the building envelope, such as rooftops, vertical facades or overhangs. The assessment was carried out 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. Such assessment was performed using the simulation tool of System Advisor Model (SAM) 2023.12.17 software and the EnergyPlus weather file of Madrid, which is the same file used on DesignBuilder 7.0.2.006 software. Figure 4 provides the daily average solar irradiation of 90º, 60º, 30º, and 0º tilted plane, respectively, for the summer design month of Madrid.

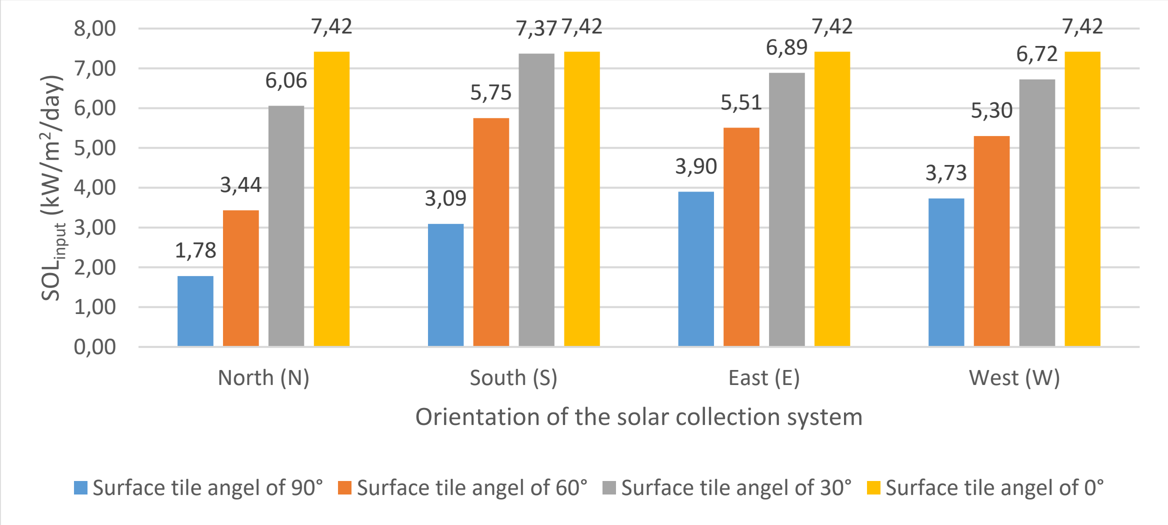


Fig. 4: SOL_{input} at different orientations of the solar collection system considering the month of summer design week

3.2.2. Assess the Product Technical Feasibility based on the SF

Considering key parameters required to assess the SF (Table 1), assessed SOL_{array} of solar collection devices of different scenarios (Table 4), efficiencies considered for different components of technologies ($COP_{solarsys}$ and $COPc_{oolsys}$) (Table 5), and assessed solar energy input to the façade system (Figure 4), the SF values for all scenarios were assessed. The results of assessing the SF values of the three main envelope possibilities, namely rooftops only (A), facades only (B), and also rooftops & façade (C) are shown in Figures 5, 6 and 7, respectively. As mentioned in Table 2, having an SF value of 100% and more indicates that the system can be able to handle the required cooling demand. Hence, it is shown that some of the scenarios per configuration related to DE absorption chillers and ETCs (thermally driven) and water-cooled VCC and PV panel (electrically driven) were the only one having an SF value of 1 or more. Furthermore, only DE absorption chillers and ETCs were able to meet the cooling requirements by considering only rooftops installations. However, none of all configurations were able to meet the cooling requirements using façade installations only, such as opaque, overhang, and balconies installations.

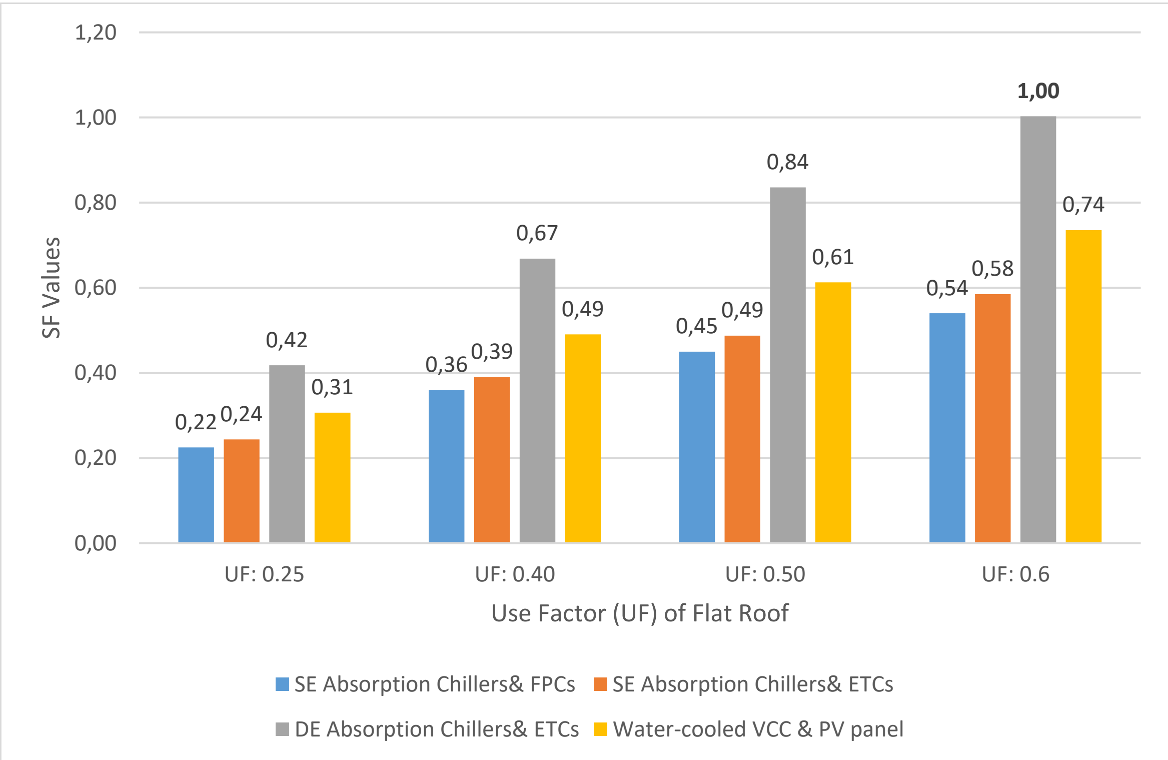


Fig. 5: Results of assessing the product technical feasibility for rooftops only (A) based on the SF

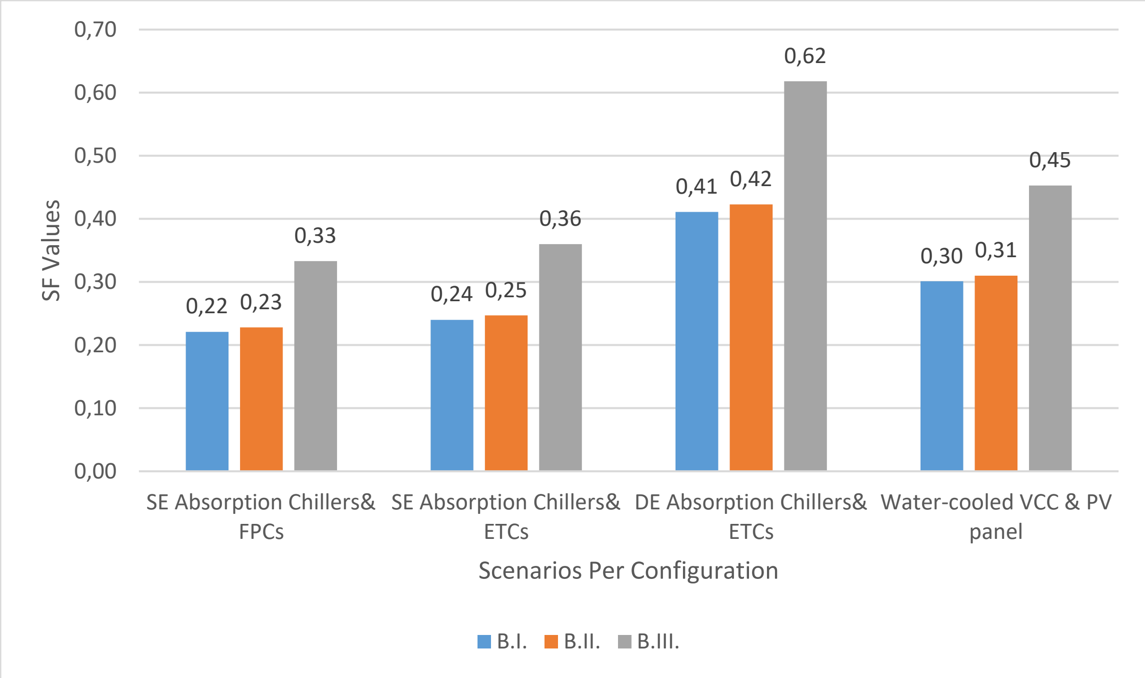


Fig. 6: Results of assessing the product technical feasibility for façades only (B) based on the SF

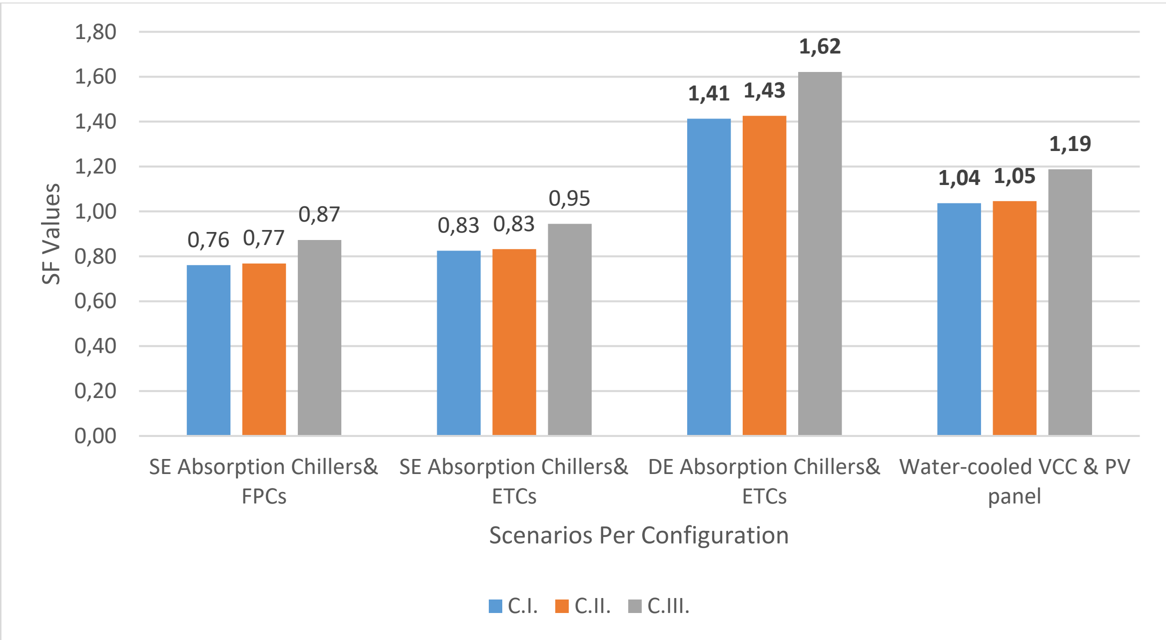


Fig. 7: Results of assessing the product technical feasibility for rooftops and façades (C) based on the SF

4. Conclusion

The present research aims to propose a framework to guide the architectural integration of solar cooling technologies (SCTs) in an office building with various façade types, located in Southern Europe. Key regulatory measures were implemented considering national energy saving guidelines. The results represent annual energy consumption (kWh/m^2/year) and the average daily cooling demand in Summer Design Week (kWh/day) of the simulated base model. This energy consumption lies within range of a previously simulated generic office and the average annual energy consumption of office blocks. Potential scenarios for integrating SCTs were outlined and evaluated using the SF as an indication to measure the product performance and efficiency and its ability to meet cooling demand represent as essential step during early design stages. 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. Such step helps the decision regarding what type of technology and components could be selected for a second level of technical evaluation. Scenarios per configuration related to double-effect chillers with evacuated tubes collectors (thermally driven) and water-cooled vapor compression chiller and PV panel (electrically driven) were the only one having an SF value of 1 or more. Future steps should consider a second level of technical evaluation of scenarios having SF values of 1 or more involving aspects related to how to integrate the technology, which may consider the compactness and space usability, assemble and connections, and maintenance requirements. Once this second level is carried out, economic feasibility aspects can be considered to evaluate and compare pre-defined potential scenarios at a higher level of detail.

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