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Article

Supporting the Design and Development of Solar Cooling Integrated Façades: A Framework of Decisions, Information, and Stakeholder Involvement

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Abstract

Given the global challenges arising from climate change, relevant, promising methods to expedite the energy transition are essential. The integration of solar cooling technologies into façades represents an important option. Potential benefits of applying solar cooling technologies include conserving primary and conventional electricity sources, lowering peak energy demand to achieve cost savings, and offering environmental benefits. This study aimed to support the design team and stakeholders involved at the design and development stages with a framework that supports developing solar cooling integrated façades. This study adopted a participatory research methodology to identify, outline, and validate key decisions, information, and stakeholders supporting product design and development. The key study findings revealed that the integration of solar cooling technologies into façades should be considered at the conception stage, where the client, climate designer, building physicists, building service consultants, and architects were identified as key participants who should be involved in the decision-making process. The most critical information identified for supporting design decisions includes technology costs, performance and efficiency, cooling demand, and construction characteristics of the thermal envelope.

Keywords: renewable energy; global climate change; sustainable energy preservation; energy transition; air conditioning; envelope; collaborative design

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1. Introduction

Given the global challenges arising from climate change, relevant, promising methods to expedite the energy transition are essential [1–4]. The integration of solar cooling technologies into façades represents an important option, especially given the expected increase in cooling demand within the built environment population [5]. This is due to the fact that building façades can have a huge number of surfaces exposed to solar radiation, which can be used to harvest solar energy to drive cooling equipment. Additionally, the potential benefits of applying solar cooling technologies include conserving primary and conventional electricity sources, lowering peak energy demand to achieve cost savings, and offering environmental benefits [6].

Solar cooling technologies, which emerged in the 1970s, utilize solar energy to produce either conditioned air or chilled water [7]. These systems harness solar energy in two primary ways: by generating hot water through solar thermal collectors (STCs) or by producing electricity via photovoltaic (PV) panels [8]. Consequently, this gives rise to two fundamental methods for achieving a cooling effect from solar energy: thermally driven systems and electrically driven systems [7–12] (Figure 1). In thermally driven systems, solar thermal energy is employed either to power the generators of sorption cooling systems or to be converted into mechanical energy, which is subsequently used to produce cooling effects [8]. Various types of solar thermal collectors are available on the market, with the flat-plate collector, the evacuated tube collector, and the parabolic trough collector representing the primary categories [10]. In addition to solar collectors, thermal energy storage (TES) can be employed to enhance cooling systems by improving their operational efficiency, as it can incorporate phase change materials (PCMs) to mitigate diurnal temperature fluctuations [13,14]. For electrically driven systems, solar energy is primarily harnessed through photovoltaic (PV) systems, which convert solar radiation into electricity to power cooling processes via conventional methods, such as vapor compression chillers or thermoelectric systems [8]. An example of such systems is the solar electric chiller, which consists of PV panels, batteries, inverters, and electrically driven refrigeration components. Notably, the refrigeration process in these systems is typically based on vapor compression cycles [12]. Regarding thermoelectric technologies, these generators are composed of thermocouples that produce relatively low thermoelectric voltage but can generate high electric currents. This configuration offers the advantage of operating at lower heat source temperatures, which is beneficial for converting solar energy into electricity. Similarly, a thermoelectric refrigerator consists of thermocouples made from semiconducting thermoelements, through which the current generated by the thermoelectric generator flows [8].

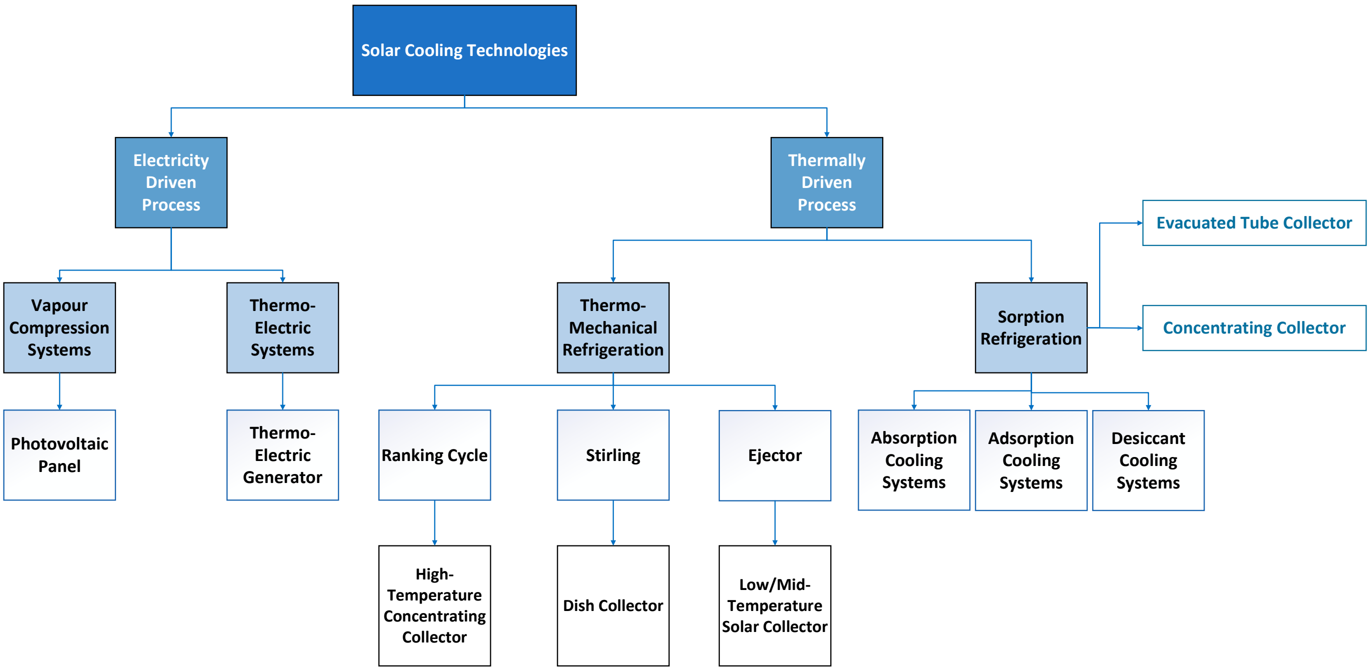

Figure 1. Solar cooling technologies (reproduced from (Alsagri et al. [11]).

Various studies have investigated the integration of solar cooling technologies into façades, including integrating the technologies into passively designed façades for application in hot climates [15,16]. Among the various technologies, electrically driven solar cooling technologies that incorporate PV panels and vapor compression chillers have been identified as a relevant option due to several factors, including their lower costs and ease of assembly [17]. Although there have been developments in the technological advancement of solar cooling systems, their integration into façades in real projects has been limited [18,19]. Enabling their application should involve a collaborative product design, as it represents a group decision-making process involving multiple criteria, in which diverse viewpoints are brought together to develop a shared solution among stakeholders. This approach incorporates a broader range of perspectives than any individual could offer alone, as each stakeholder contributes their unique viewpoint [20]. Accordingly, identifying a relevant design team and matrix of responsibilities, as well as managing relationships among diverse stakeholder groups, is becoming increasingly vital during the preplanning, design, and construction phases [21]. However, understanding the most effective ways to manage diverse stakeholders remains a crucial area for further investigation as involving a larger number of stakeholders in the design process may result in procedural complexity, as the team requires effective coordination and management [22,23]. Hence, investigating the management of diverse stakeholders requires participatory approaches that engage relevant expertise and provide a systematic process of stakeholder involvement and multi-actor participatory decision-making [24–26]. Therefore, this study aims to support the effective management of the diverse stakeholders involved in the design and development stages of solar cooling integrated façades. This study outlines key decisions to be made by relevant stakeholders, recognizing that the decision-making environment in architecture, engineering, and construction (AEC) sector is strongly influenced by social and business factors, which often rival or even outweigh technical considerations [27].

To achieve this, this study involved several steps. First, it identified and outlined key design decisions, the information required to support them, and the relevant stakeholders involved in the design and development of solar cooling integrated façades, based on desk research. Subsequently, a pre-workshop survey was distributed to relevant stakeholders, and a workshop was conducted to evaluate and further elaborate on the identified design decisions, information needs, and stakeholders. Following this, the design decisions and related aspects were refined based on the workshop outcomes. Finally, these design and development aspects and stages were validated through a design experience survey.

Section 2 outlines the research approach and methods used to build, evaluate, refine, and validate the framework. Then, Section 3 presents the findings from all steps involved in identifying, outlining, evaluating, elaborating on, refining, and validating decisions, information, and stakeholders. After that, the findings are discussed in Section 4. Finally, Section 5 offers conclusions and recommendations for future research.

2. Research Approach and Methods

This study adopted a participatory research methodology to identify, outline, evaluate, elaborate on, refine, and validate key decisions, information, and stakeholders supporting the design and development of solar cooling integrated façades. This includes a workshop that engages relevant stakeholders and enables them to have a higher level of involvement in developing design solutions [28–32]. Figure 2 presents the study research approach and methods, which are explained in the following sections.

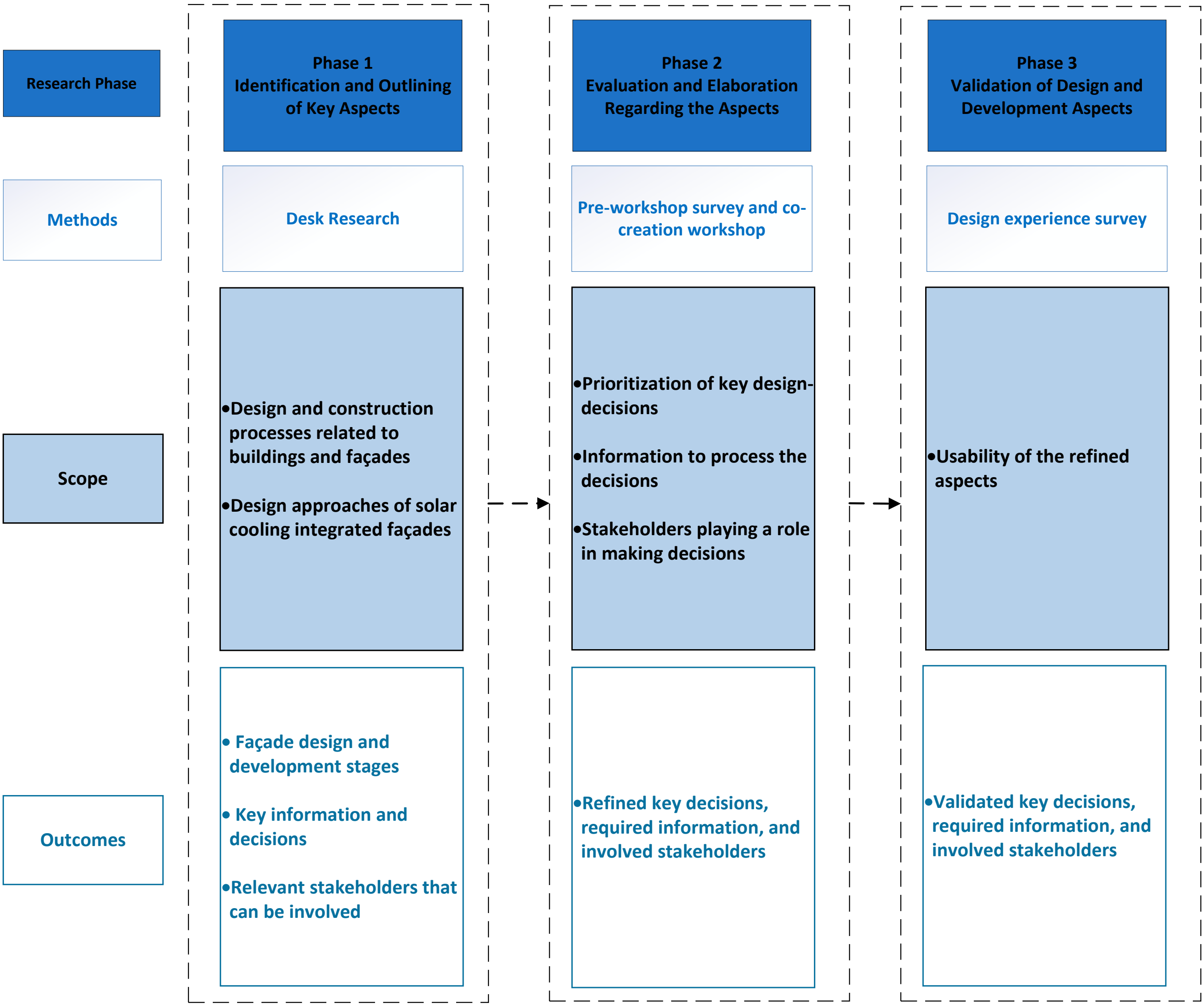

Figure 2. Research approach and methods of this study.

2.1. Identification and Outlining of Key Aspects

Desk research was conducted to identify and outline key decisions, the required information to support them, and relevant stakeholders that might be involved in the design and development of solar cooling integrated façades. Desktop research involves the use of existing data collected by others. It is a time-efficient and cost-effective method, as it relies on readily available information rather than generating new data [33]. It entails reviewing published reports, academic articles, studies, and other publicly accessible sources to gather relevant insights and support informed decision-making [34]. Accordingly, the topics include design and construction processes, key stakeholders involved in the façade design and construction stages, and the design approaches to solar cooling integrated façades [17,35–38]. The identification of key aspects involved synthesizing the desk research findings by considering the following main points:

- Stages and processes related to the design and development of solar cooling integrated façades.
- Key inputs, requirements or considerations, decisions, and outcomes associated with different stages.
- Relevant stakeholders that might be involved the design and development.

The desk research focused on understanding how integrated design and construction processes are applied in sustainable building projects. The Royal Institute of British Architects (RIBA) Plan of Work [38] provided a structured overview of project stages across disciplines, while Oliveira and Melhado [37] highlighted coordination challenges in both new builds and retrofits. To address energy efficiency in housing, Prieto et al. [36] outlined critical phases for zero-energy renovations. Insights into façade workflows were drawn from Klein [35], particularly regarding the curtain wall industry, and Hamida et al. [17] contributed strategies for integrating solar cooling into façade design. These sources together informed a cross-disciplinary view of how design intentions are translated into sustainable construction outcomes. Hence, to identify and outline key aspects, this study considered five stages, as indicated in Figure 3. While these stages may not follow a strictly linear sequence due to the iterative nature of the design process, which often relies on continuous feedback [39], this structured approach facilitates the systematic organization of information within the framework.

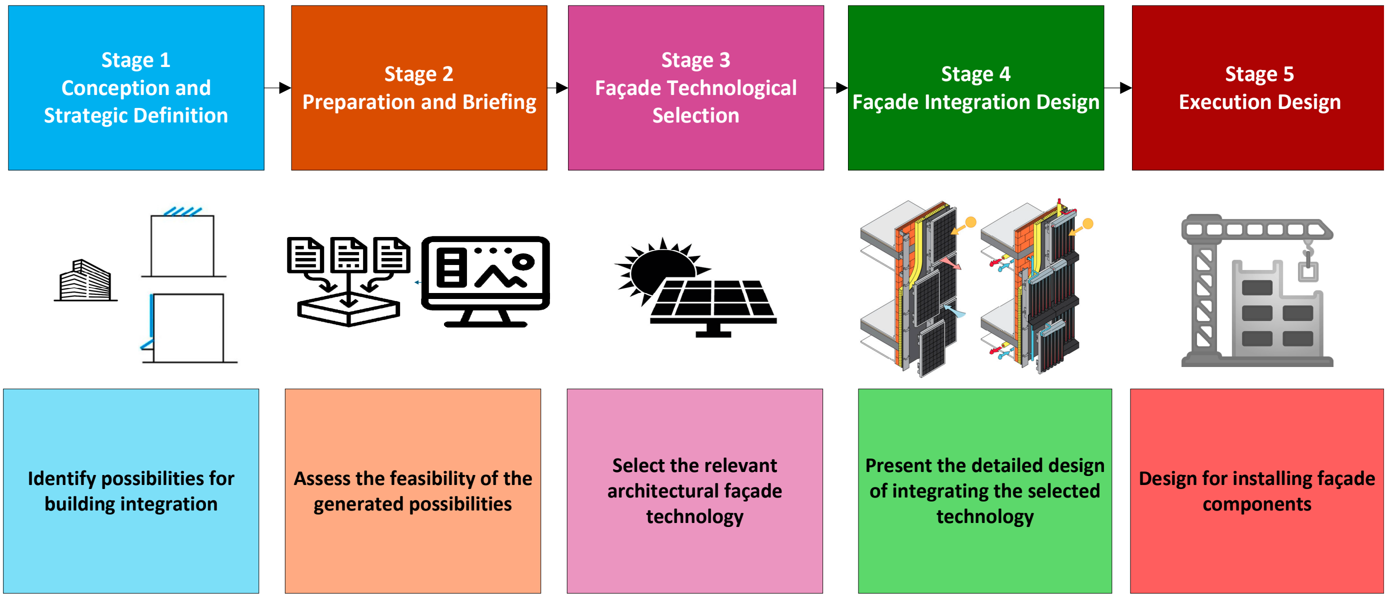

Figure 3. Research design and development stages.

When determining the main stakeholders involved in the design and development stages and their roles and responsibilities, various ways of categorizing these stakeholders have been used, depending on the context [35,37,38]. Hence, to facilitate identifying and outlining key aspects, it was essential to synthesize such variation through involving a relevant categorization. Accordingly, this study involved the following categorization of the main stakeholders involved in design and development stages:

- Client Team: Owner, investor, and/or real estate/property developer.
- Design Team: Design coordinator, architectural designer, façade designer, and/or consultant (Mechanical, Electrical, and Plumbing (MEP), building physics, or façade consulting).
- Construction Team: Contractor, subcontractor, supplier/manufacturer, and/or façade builder/assembler.

2.2. Evaluation and Elaboration Regarding the Key Aspects

To evaluate, elaborate on, and refine the identified and outlined aspects, this phase involved distributing an online pre-workshop questionnaire as well as designing and moderating a workshop.

2.2.1. Pre-Workshop Survey

Identifying and outlining key aspects involved designing, testing, and distributing an online pre-workshop questionnaire survey for identified relevant stakeholders. The survey was distributed using Microsoft Forms [40], and it was intended to identify the potential involvement of different stakeholders. The questions covered two parts related to each of the design and development stages (Figure 3). First, participants were given a multiple-choice list of roles that can be taken on at each stage and were asked to select the ones they could play. They were also given the option to write in roles they thought were not listed. Second, participants were given a multiple-choice list of stakeholders they could interact with. They were also given the option to write in stakeholders they thought were not listed.

As this study focuses on addressing key aspects related to the design and development of façade products integrating solar cooling technologies, the selection of representatives from the design and construction teams required the adoption of a relevant sampling technique—specifically, a purposive, non-probabilistic approach [41,42]. Such a sampling technique continues to be an effective method for obtaining detailed, context-specific data, especially in qualitative and mixed-methods research. By strategically targeting particular characteristics within a population, it enables researchers to gather detailed and contextually meaningful data [43]. Accordingly, to ensure the presence of relevant representatives from the key stakeholder, the selection criteria for participants were as follows:

- Main Criteria: Participants should have a technical background in architecture, building physics, engineering (civil, mechanical, or electrical), or another relevant field.
- Sub-Criteria: To ensure a well-rounded perspective, participants should meet at least one of the following conditions:
    1. Experience in the European façade design and construction industry, including design, production, or assembly.
    2. Involvement in projects related to the application or façade integration of solar or solar cooling technologies in buildings, such as photovoltaics (PV), solar thermal collectors (STCs), or solar cooling technologies (electrically or thermally driven).

The survey was tested with two practitioners working as architects prior to its distribution. The pilot study resulted in improving the questions as well as improving the questionnaire structure. Appendix B shows a sample of the main questions related to stage.

2.2.2. Workshop Design and Moderation

This phase involved designing a guide for the virtual co-creation workshop that was designed to include the contents, slides, and also activities facilitating the framework evaluation. Workshops tend to be as follows [44]:

- Focus group research, which involves gathering a group of participants to focus on a certain topic of group discussion.
- Action research that includes research, which can lead to social actions.
- Action learning that considers the beliefs of participants, who can develop solutions without requiring experts and lectures.
- Participatory design that involves multiple stakeholders in research with a broad perspective.

Taking into account that workshops tend to be centered on focus group research, the design of the workshop guide covered the key elements related to the focus group discussion protocol. The elements included a welcome and introduction round, research background, interactive session and activities, reflection, and conclusion and closing [45,46]. As the outlined aspects represent a form of a previously designed artifact, the reflection part was intended to allow participants to evaluate and improve such an artifact through the workshop [47]. Based on the developed protocol, a pilot study was conducted twice with researchers and experts in the field of façade design and engineering to ensure the clarity and feasibility of the workshop. Appendix C shows the virtual workshop guide, including the slides and activities to be carried out using MS Teams and MS Whiteboard. While electrically driven solar cooling technologies that incorporate PV panels and vapor compression chillers have been identified as a promising option, the workshop guide was designed to provide a holistic perspective on different design solutions. The purpose of including such examples (Table A6) was to highlight that the development of solar technologies is a continuous process, with performance, dimensions, operating principles, and costs likely to evolve over time. Furthermore, this approach was intended to facilitate an effective and comprehensive discussion regarding the organization of design decisions, the information required, and stakeholder involvement. The evaluation of the outlined aspects was carried out in the interactive session as well as the reflection parts through the following process:

1. Participants in the interactive session were given a hypothetical office building case, where they were asked to think and plan together and perform the different tasks, namely identifying, organizing, and prioritizing key design decisions, determining required information to process the decisions, and identifying main stakeholders playing a role in making decisions. The hypothetical case was based on an office building case and its outcomes [17,48].
2. Participants, in the reflection part, were asked to identify any parts related to the outlined aspects that were not addressed (Appendix C).

Consequently, the workshop was moderated virtually using the Microsoft Teams platform and Microsoft Whiteboard [49,50], which were provided by the research institution. The moderation involved a video recording, as well as the observation and documentation of interactions and outcomes among participating stakeholders.

2.2.3. Refinement of Identified and Outlined Aspects

The refinement of identified and outlined aspects involved reporting, analyzing, interpreting, and synthesizing the outcomes. As the workshop involved evaluating previously introduced aspects, the analysis phase included relevant methods, such as referring to observations and notes, the video recording and its transcription, and group discussions [47]. Hence, the aspects were refined based on the outcomes obtained from the workshop, which included contextualizing them at a deeper level.

2.3. Validation of Design and Development Aspects

Taking into account that the workshop represents a verification step for elaborating on the integration of key aspects, a validation step was conducted to test the feasibility and usability of the refined aspects in practice, considering a design experience task [51]. To facilitate this validation, a design experience survey was used. The survey was developed using Microsoft Forms [40] and was intended to be completed by the main stakeholders involved in the design and development of SCIFs. To facilitate such validation, participants were asked to give their opinion on key design decisions, required information to process the decisions, and stakeholders involved in making decisions. An office building project case was given with relevant information about the project, which was the hypothetical case used in the co-creation workshop [17,48]. After that, the following considerations related to key decisions, required information, and involved stakeholders were included to validate the identified and outlined aspects:

- Determining at which stage the integration of solar cooling technologies (or other solar technologies) into the façade can be considered.

- Identifying the two key stakeholders who should be involved in making the decision to integrate solar cooling technologies (or other solar technologies).
- Identifying the key information required to determine the possibilities for envelope integration (rooftops, façades, or both), as well as a suitable solar cooling technology (thermally driven or electrically driven).
- Investigating the priority of key decisions included in the refined aspects.
- Investigating the priority of the following relevant design criteria, namely assembly and connections, compactness and space usability, product performance and efficiency, and maintenance requirements [17].
- Determining key financial factors that should be considered when evaluating different design solutions.

Finally, participants were asked to reflect on the case, considering the following key points:

- Assessing the willingness of participants to adopt solar cooling technologies in an office building context, based on the presented information.
- Investigating how the information shared throughout the design and development process of solar cooling integrated façades influenced or supported the participants' decision-making.
- Determining key struggles faced by participants when making decisions.
- Identifying potential gaps in information or support experienced during the design exercises.

The validation instrument was tested with a practitioner working as an architect as well as two experts in the field of building engineering prior to its distribution. Appendix D shows sample components of the validation instrument (MS Forms). To facilitate the distribution and collection of relevant responses, flyers containing a QR code linking to the validation instruments were distributed at an international event, namely the Future Façade conference, in the Netherlands in May 2025. The event brought together professionals involved in façade design and engineering from across Europe. The participants were selected using purposive sampling, taking into account the criteria and sub-criteria outlined for participant selection (Section 2.2.1), in order to gather detailed and contextually meaningful data.

3. Results

This section presents the study findings. Section 3.1 presents the findings related to identifying and outlining the key aspects based on desk research. Section 3.2 shows the outcomes of evaluating, elaborating on, and refining the key aspects through the pre-workshop survey as well as the moderated workshop. Finally, Section 3.3 provides the validation results obtained from the design experience survey.

3.1. Identifing and Outlining Key Aspects

The desk research findings were synthesized through considering main stages, processes, inputs, requirements or considerations, decisions, outcomes, and also main stakeholders involved in the design stages. Starting with processes related to the design and development of building façades, from the first four publications we analyzed (Table A1) [35–38], it was obvious that there are different ways to categorize design stages depending on the context. Furthermore, Hamida et al. [17] categorized the design phases of solar cooling integrated façades into four main stages, namely conception and strategic definition, preparation and briefing, façade technological selection, and façade integration design. This categorization was adopted to develop design guidelines for solar cooling integrated façades. The guidelines included processes, inputs, requirements or considerations, decisions, and outcomes within these four stages. Although the guidelines were developed to support the process of designing and evaluating façades integrating solar cooling technologies, they do not take into account the development of these products in further executive stages.

3.2. Evaluated and Refined Aspects

3.2.1. Distributed Pre-Workshop Survey

For the pre-workshop survey, invitations were sent to more than fifteen professionals to attend the workshop, a total of six professionals accepted the invitation and completed the online survey. Figures A2–A7 show participants' profiles in terms of their educational and technical background, professional experiences in the building industry, and years of professional experience. Accordingly, key decisions, the required information to support them, and the relevant stakeholders who might be involved were identified and outlined based on the conducted desk research and distributed survey. Regarding stakeholders, it is evident that almost all stakeholders were identified as being potentially involved in all stages, with variations in the number of responses. However, it is clear that stakeholders belonging to the design team are more involved in Stage 1, while they are less involved in Stage 5, where the construction team can play a more prominent role.

3.2.2. Moderated Workshop

A two-hour workshop was organized on 28 February 2025. Of the six participants who completed the pre-workshop survey, four attended the workshop. Three represented the design team, while one represented the construction team. The outcomes revealed that the identification of decisions revolves around key aspects that can be categorized into demand-related factors, architectural integration, practical considerations, and system characteristics, as summarized below:

- Energy Demand and Optimization:
  - Designing buildings to reduce energy demand.
  - Focusing on passive design strategies, particularly for cooling.
  - Integrating the system with passive measures to optimize efficiency.
  - Understanding overall cooling demand and how it affects system feasibility.
- Architectural and Building Typology Considerations:
  - Understanding how the system is integrated with building typology.
  - Identifying architectural elements like daylight, orientation, and overall façade design.
  - Considering the importance of façade design in combining functionality with aesthetic and performance goals.
- Practical Considerations and System Characteristics:
  - Taking into account access to maintenance and maintenance requirements.
  - Considering the ease of installation: plug-and-play, prefabricated, or industrialized solutions.
  - Understanding life expectancy and durability: reliability and proven solutions for large investments.
  - Involving factors related to weather resistance.
  - Determining the type of technology used and components of the system (e.g., storage, evaporation).
  - Practical aspects such as size, weight, and fire safety.

These key aspects were linked to different stages. Based on the workshop outcomes, the key aspects were refined. This refinement involved further contextualizing the aspects.

Accordingly, Tables 1–3 as well as Figure 4 present the refined aspects. In addition to the main outcomes of the workshop, this section also summarizes other essential outcomes from the workshop, which relate to the following:

- *Consideration of installation aspects from the early design phase:* The construction team, primarily the contractor, emphasized the necessity of planning the installation process from the beginning. Considerations should extend beyond cost to include auxiliary elements and required labor. Construction companies can typically work with a client's pre-existing building design. This can include the considerations of prefabricated or plug-and-play solutions, which can reduce on-site construction time and simplify installation. Hence, the decision to implement prefabrication depends entirely on client approval.
- *The relationship between building design and product design:* Building design tends to follow a sequential process, beginning with large-scale considerations, prior to selecting specific components. Product design adopts a different methodology, wherein standardized systems are developed and subsequently adapted to various buildings. Taking into account the considerations of prefabrication and standardization, it was pointed out that developing a product tailored to a single building is not commercially viable. Accordingly, a successful modular solar cooling façade system should be adaptable across various building types to ensure market feasibility.
- *Client influence:* The design team emphasized that designers, owners, and constructors have differing perspectives on façade solutions, with cost being a primary concern for designers. Clients often assess façades based on cost per square meter, which can make it challenging to justify innovative solutions. Furthermore, clients generally fall into two categories: investors, who prioritize cost per square meter and are less inclined to adopt new technologies, and owners, who maintain the building and are more open to innovation due to long-term payback considerations. When the owner and investor are the same entity, there is greater flexibility to implement energy-efficient systems. To secure client approval, factors such as life cycle cost analysis, payback periods, and maintenance requirements should be considered from the project's outset.
- *Collaboration:* The conventional construction process involves clients setting a budget, designers proposing solutions, and contractors bidding for the lowest cost. Such a cost-driven approach can be challenging when it comes to the adoption of innovative façade technologies. Hence, it was pointed out that a more effective alternative could involve a collaborative approach in which the client, designer, and builder engage from the outset, optimizing processes despite potential increases in initial costs. Successful implementation requires collaboration among an innovative client, architect, and supplier.
- *Responsibility:* The lack of clear responsibility among stakeholders represents a major challenge in adopting innovative façade systems. While client support is essential, conflicts can often arise when suppliers do not assume responsibility for installation. For instance, architects in some countries are required to sign off on projects and are held accountable for design decisions, making their involvement crucial. However, architects may lack the technical expertise needed for integrating and installing innovative solutions. Hence, having a clearly accountable party represents an essential factor for the successful integration of innovative façade systems. It was therefore pointed out that a potential solution could include involving suppliers in supervising installation to ensure expertise is maintained throughout the process.

Table 1. Refined identified and outlined roles and tasks considered at each stage.

Stage				
(1) Conception and Strategic Definition	**(2) Preparation and Briefing**	**(3) Façade Technological Selection**	**(4) Façade Integration Design**	**(5) Execution Design**
Determination of project objectives and criteria	Assessment of pre-technical feasibility by determining available envelope possibilities meeting cooling demand	Review how much space is available within the façade	Determination of characteristics of key elements	Identifying potential missing elements in tendering documents
Definition of basic requirements for façades	Evaluation of how the technology can be integrated and operated considering component weights and structural impact	Summarization of techno-economic feasibilities	Identification of means of connections according to the standards	Spatial coordination of architectural and engineering information
Determination of functional requirements of façades	Integration of building and energy solutions	Selection of architectural façade technology and agreement on products	Demonstration of detailed design	Analysis of installation process considering auxiliary elements to avoid conflicts with other activities
Assessment of energy performance and cooling demand	Assessment of economic viability	-	Check on details and available spaces in the envelope	Approval of final design, production, and assembly design
Determination of relevant measures to optimize energy performance	Assurance of the fire safety of materials	-	Review of maintenance requirements	Planning and scheduling the project while ensuring no disruptions or interventions
Determination of relevant solar cooling technologies	-	-	-	Detailed cost estimate
Identification of available envelope possibilities for building integration: rooftops and/or façades	-	-	-	Check alternatives
Preliminary analysis of the sequence of activities on-site	-	-	-	-
Data collection that takes into account the costs versus benefits, such as payback period and amortization	-	-	-	-

Table 2. Revised identified and outlined key design decisions.

Stage				
(1) Conception and Strategic Definition	**(2) Preparation and Briefing**	**(3) Façade Technological Selection**	**(4) Façade Integration Design**	**(5) Execution Design**
Determine relevant measures to optimize building design	Determine available envelope possibilities meeting cooling demand	Determine the scenario with the highest scores with respect to design	Determine the relevant types of systems for implementing modular, prefabricated, industrialized, or plug-and-play solutions	Approve the final design
Select an optimized and appropriate building design with reduced energy consumption and cooling demand	Determine potential additional requirements in terms of structural support and reinforcements, including costs	Select relevant architectural façade technology	Determine means of connections according to the standards	Order all necessary components
Determine configurations of cooling generation, distribution, and delivery components	-	Identify components that can be prefabricated as modules off-site	-	Determine installation techniques for the façade system and identify the required construction equipment
Identify available envelope possibilities for technological integration, considering building orientation and architectural elements	-	-	-	Approve the order of activities to ensure no disruptions or interventions
Identify opportunities to implement modular, prefabricated, industrialized, or plug-and-play solutions	-	-	-	Identify a company that provides guarantees and has sufficient expertise to carry out the installation

Table 3. Adjusted identified and outlined information required to support decision-making processes.

Stage				
(1) Conception and Strategic Definition	**(2) Preparation and Briefing**	**(3) Façade Technological Selection**	**(4) Façade Integration Design**	**(5) Execution Design**
Technical and economic design criteria and performance requirements	Technical and economic design criteria and performance requirements	Regulatory requirements (structural safety, fire resistance, and thermal performance)	Relevant safety requirements and standards	Façade composition and constriction details
Regulatory requirements	Costs of technologies	CE marking for existing products	Façade composition and constriction details	Building drawings
Building use profile	Regulatory requirements (fire safety)	Detailed cost calculation data	Main elements of the solar cooling technology (storage, evaporation, electrical driven heat pump)	Tendering documents

Table 3. *Cont.*

Stage				
(1) Conception and Strategic Definition	**(2) Preparation and Briefing**	**(3) Façade Technological Selection**	**(4) Façade Integration Design**	**(5) Execution Design**
Building drawings	Building required cooling demand	Technical and economic design criteria and performance requirements	Sizes of components	Warranties
Weather, geographic, and urban data	Performances and efficiencies of technologies	Summary of techno-economic feasibilities	Maintenance accessibility requirements	Construction activities
Construction characteristics of the envelope	Working materials of technologies	-	-	Information about installation
Relevant solar cooling technologies	Weights of components	-	-	-
Performances and efficiencies of technologies	-	-	-	-
Working materials of technologies	-	-	-	-
Costs of technologies	-	-	-	-
Technology maintenance requirements	-	-	-	-

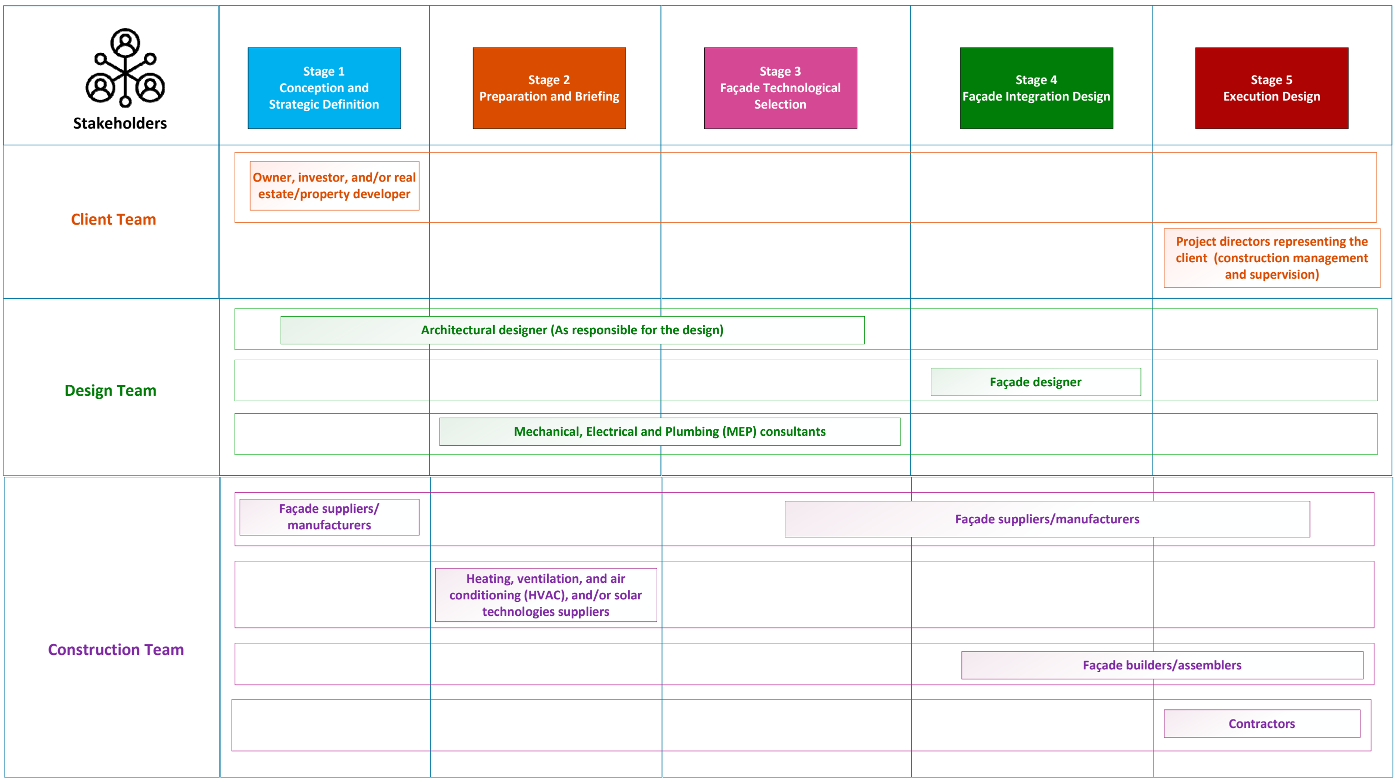

Figure 4. Modified list of identified and outlined stakeholders involved in decision-making.

3.3. Validation Results

A total of twenty-seven responses were collected, as summarized in Figures A11–A14. The following section summarizes the outcomes of the validation survey in order to understand to what extent the refined framework can support the design and development process of SCIFs.

3.3.1. Key Stakeholders

The outcomes revealed that the majority of respondents believed that the integration of solar cooling technologies into façades should be considered at the conception stage. At this stage, the following stakeholders were identified as key participants who should be involved in the decision-making process for façade integration (Figures 5 and 6):

1. Project client—including the owner, investor, and/or real estate/property developer.
2. Design team professionals:
    - Design professionals in the fields of climate design, building physics, and building services, which can be further divided into:
        - Climate design experts and building physics consultants, who are responsible for optimizing the building design and reducing energy demand through passive measures.
        - Building service experts, including HVAC and MEP consultants, who ensure that the building's energy demands are met using active systems.
    - Architectural designers, who are responsible for the overall building design.

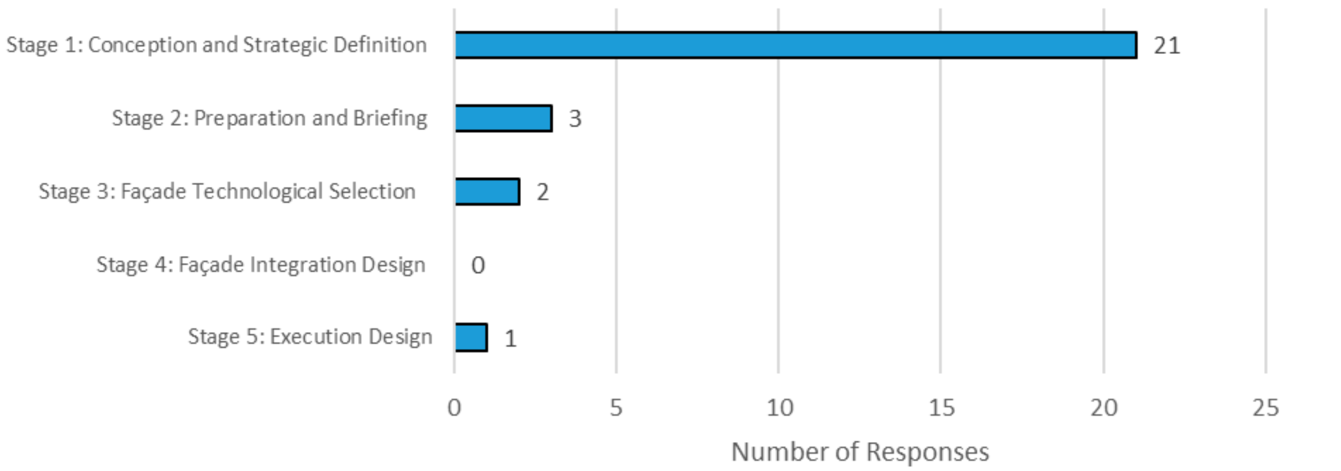

Figure 5. The relevant stage at which the integration of solar cooling technologies (or other solar technologies) into façades should be considered.

Compared to the refined framework (Figure 4), it is clear that similarities exist regarding the involvement of the owner, investor, and/or real estate/property developer, as well as the architectural designer, as main stakeholders. This may be due to the fact that clients tend to set the project budget, whereas architectural designers play a key role by being responsible for the design. On the other hand, differences arise regarding the involvement of façade suppliers/manufacturers in the refined framework (Figure 4) and climate design, building physics, and building service consultants in the validation results (Figure 6). This is due to the fact that every project is unique, and the involvement of additional stakeholders, such as suppliers, depends on the context and nature of the project. Although these additional stakeholders can play a key role in developing design solutions, convincing the client in the early stages about techno-economic feasibility requires support from climate designers, building physicists, and building service consultants. Therefore, collaboration among façade suppliers/manufacturers, building physics consultants, technology providers, and builders can take place at later stages—after clients have been convinced to support the effective integration of advanced technologies, reduce inefficiencies, and lower long-term costs, as indicated in Section 3.2.2.

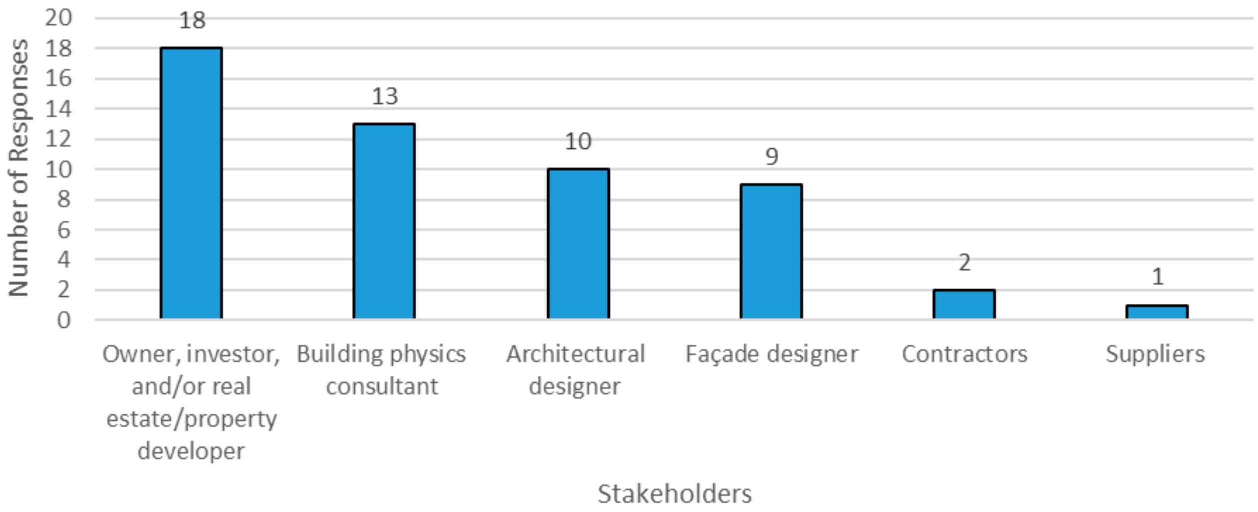

Figure 6. Key stakeholders identified to be involved in making the decision to integrate solar cooling technologies (or other solar technologies).

3.3.2. Key Information and Design Decisions

The validation survey revealed that the key information required to support decisions regarding envelope integration possibilities depends on various data sources (Figure 7). However, the most critical information identified for supporting design decisions includes technology costs, performance and efficiency, cooling demand, and construction characteristics of the thermal envelope. These findings complement the results presented in Section 3.3.1 and can be summarized as follows:

- The performance and efficiency of technologies, along with cooling demand, must be assessed by the design professionals in the fields of climate design, building physics, and building services to ensure that the proposed design solutions meet the cooling requirements (Figures 8 and 9).
- The construction characteristics of the thermal envelope are essential for evaluating design options against relevant criteria, such as compactness and space usability, assembly and connections, and maintenance requirements (Figure 9). Addressing these aspects requires collaboration among architectural and façade designers, manufacturers, and suppliers.
- Technology costs must be considered to assess economic feasibility and return on investment, as the project budget is a key financial constraint influencing the evaluation of design solutions from the client's perspective (Figure 10).

Overall, the prioritization of design decision as well as criteria (Figures 8 and 9) tend to be consistent with the refined aspects (Table 1), as the aspects indicated the following order of roles and tasks:

- Assessment of pre-technical feasibility by determining available envelope possibilities meeting cooling demand
- Evaluation of how the technology can be integrated and operated considering component weights and structural impact
- Analysis of installation process considering auxiliary elements, avoiding conflicts.

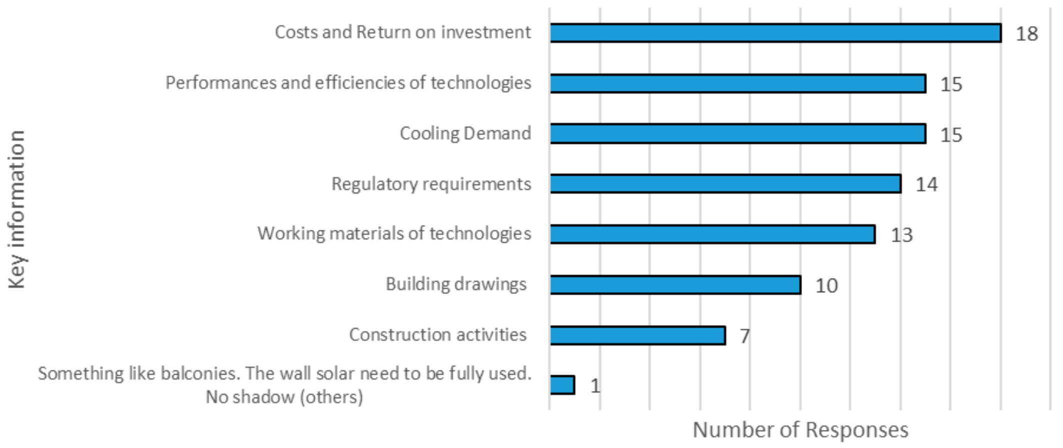

Figure 7. Key information required to support decisions on envelope integration possibilities (rooftops/façades).

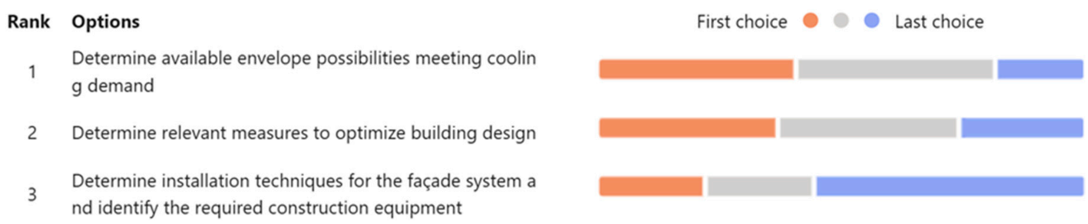

Figure 8. Prioritization of design decisions.

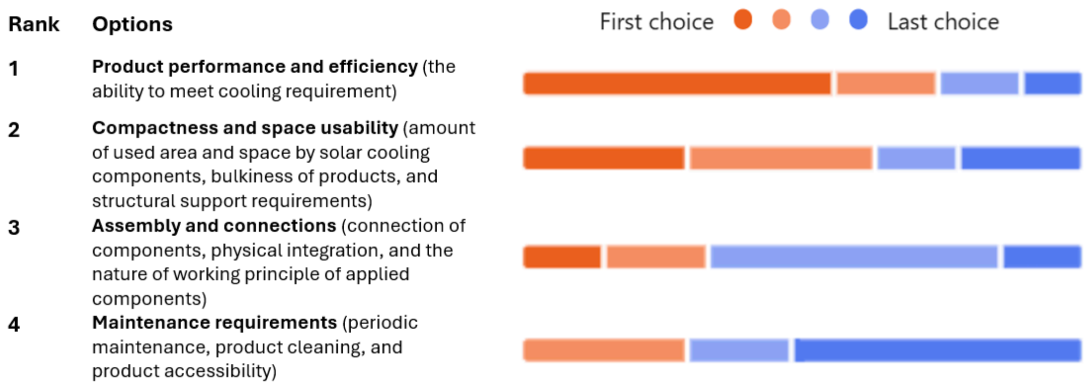

Figure 9. Prioritization of design criteria.

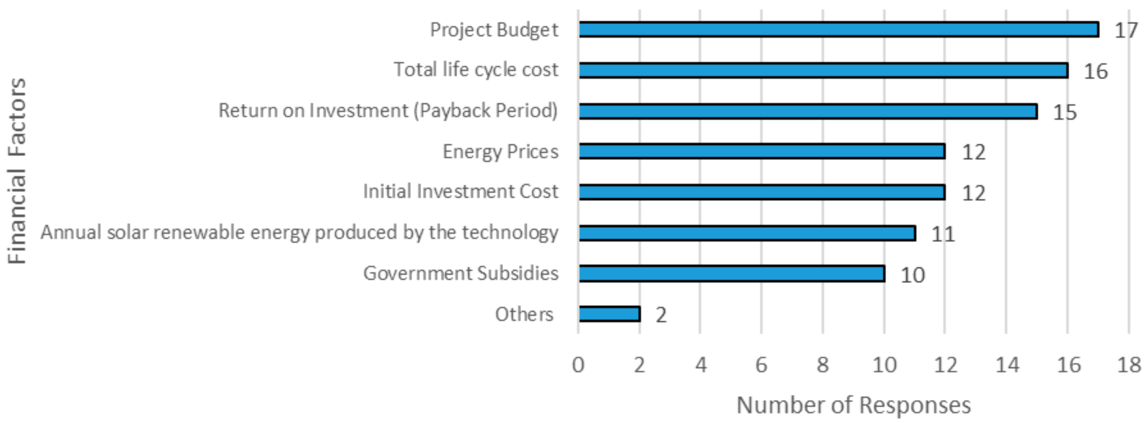

Figure 10. Financial factors to be considered to evaluate the design solutions.

Finally, among the various factors influencing the selection of a design solution (Figure 10), efficiency and life cycle costs were perceived as playing a crucial role in the decision-making process.

3.3.3. Respondents' Willingness Toward Technological Integration

The reflection section of the validation survey indicated that 37% of respondents were willing to integrate solar cooling technologies into the office building, while the remaining 63% were unsure. This uncertainty may be attributed to the fact that more than half of the respondents perceived the information provided throughout the design and development process as moderately supportive of key phases, but not comprehensive. Limited knowledge of the technologies, along with the lack of detailed cost information—particularly regarding return on investment and comparisons with conventional systems—were identified as critical information gaps (Figures 11 and 12).

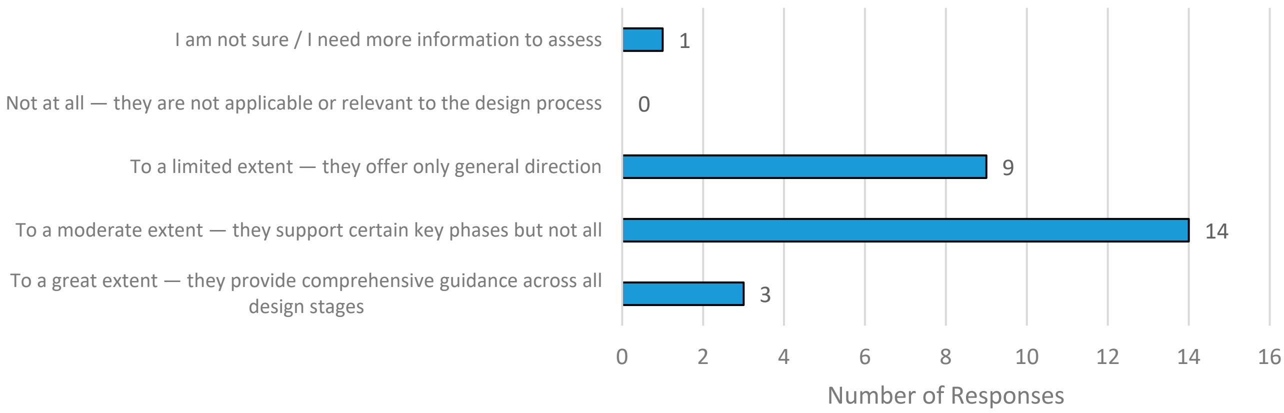

Figure 11. Participants' perspectives on the information provided throughout the design and development process.

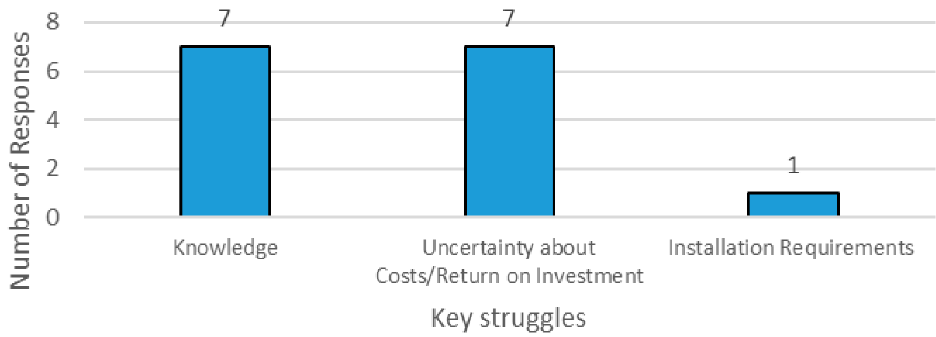

Figure 12. Key struggles faced by participants when making decisions.

4. Discussion

This section discusses the outcomes of this study (Section 4.1) and draws lessons learned for framework application (Section 4.2).

4.1. Product Design and Development Framework

This study aimed at identifying, outlining, and validating key decisions, information, and stakeholders supporting the design and development of solar cooling integrated façades. This study adopted a participatory research methodology engaging relevant stakeholders. The outcomes revealed that the integration of solar cooling technologies (or other solar technologies) into façades should be considered at the conception stage, where the owner, investor, and/or real estate/property developer, climate designers, building physicists, building service consultants, and architectural designers were identified as key participants who should be involved in the decision-making process for façade integration. Furthermore, the key information required to support decisions regarding envelope integration possibilities and the selection of suitable solar cooling technologies for developing design solutions depends on various data sources. The most critical information identified for supporting design decisions includes technology costs, performance and efficiency, cooling demand, and construction characteristics of the thermal envelope.

The framework validation indicated that the prioritization of design decision as well as criteria tend to be consistent with the refined framework. Furthermore, the validation findings indicated that 37% of respondents were willing to integrate solar cooling technologies into the assigned design case, while the remaining 63% were unsure. This uncertainty may be attributed to the fact that more than half of the respondents perceived the information and integrated aspects provided throughout the design and development process as moderately supportive of key phases, but not comprehensive. Limited knowledge of the technologies, along with the lack of detailed cost information—particularly regarding return on investment and comparisons with conventional systems—were identified as critical information gaps. Hence, the validation revealed that the presented aspects and the associated design experience case focused on providing a comparative context for designing and evaluating different scenarios and technologies, considering relevant pieces of information, including LCC and LCOC. However, since convincing the client by assessing pre-technical feasibility represents a key step, information related to return on investment was found to be essential. Although the determination of project objectives and criteria in Stage 1 (Table 1) can vary from one project to another, as every project is unique, clients often assess façades based on return on investment/payback periods (Section 3.2.2).

4.2. Lessons Learned for Framework Application

Based on the validation outcomes and the aspects considered, the application of the framework should be tailored to address the bottlenecks associated with limited knowledge of the technologies and the lack of detailed cost information, through the following considerations:

- Convincing the client by assessing pre-technical feasibility represents a key step. This involves evaluating product performance and efficiency and its ability to meet cooling requirements and roughly estimating the return on investment for various conceptual designs. This may require collaboration among the following stakeholders:
    - The client, who defines the project goals, objectives, and budget constraints.
    - Architectural designers, who are responsible for the overall project design.
    - Climate designers, building physicists, and building service consultants, who support optimizing the building design and reducing energy demand through passive strategies, as well as ensuring the building's energy needs are met using active systems.
- Assessing compactness and space usability, including the area occupied by solar cooling components, product bulkiness, and structural support requirements. This may require collaboration among the following stakeholders:
    - Architectural designers, who are responsible for the overall project design.
    - Climate designers, building physicists, and building services consultants, who provide input on feasible design solutions.
    - Façade designers, who are tasked with translating conceptual designs into more detailed solutions.
    - Façade suppliers/manufacturers and technology providers, who offer information related to product compactness and space requirements.

- Evaluating requirements for the assembly, connections, and maintenance of products, including component integration, working principles, periodic maintenance, product cleaning, and accessibility. This may require collaboration among the following stakeholders:
    - Architectural designers, who are responsible for the overall project design.
    - Façade designers, who transform detailed designs into executable solutions.
    - Façade suppliers/manufacturers and technology providers, who provide information on installation requirements and maintenance considerations, such as working materials, accessibility, and cleaning.
    - Façade assemblers/builders, who contribute expertise related to façade component installation, prefabrication opportunities, and execution design to ensure the project can be effectively implemented.

As managing relationships among diverse stakeholder groups becomes increasingly vital during the preplanning, design, and construction phases, the aforementioned considerations can help facilitate stakeholder management and mitigate procedural complexities by supporting effective team coordination and management.

Finally, the proposed framework may require adaptation to accommodate other contexts. This is due to the fact that this study was conducted with a focus on the European context—in terms of the participants involved, as well as the developed workshop guide and validation survey—and was based on a single case study in Madrid, Spain. Consequently, the following points provide guidelines for potential adaptations when applying the framework in other contexts:

- Analyzing the local market structure and stakeholders involved, as the building industry can vary depending on the context, including the distribution of roles, local practices, and cultural factors.
- Understanding the local climate conditions and comfort requirements, such as those in humid temperate climates, as these factors can influence the technical feasibility of solar cooling technologies.
- Considering local regulatory requirements related to the aesthetics of specific building typologies and neighborhoods, as these factors can influence the integration of new technologies into the building envelope.
- Complying with local safety requirements, including structural and fire-related regulations, which may involve ensuring the use of available local and certified products.

5. Conclusions

Given the global challenges arising from climate change, relevant, promising methods to expedite the energy transition are essential. Hence, the integration of solar cooling technologies into façades represents an important option, especially given the expected increase in cooling demand within the built environment population. This is due to the fact that building façades can have a huge number of surfaces exposed to solar radiation, which can be used to harvest solar energy to drive cooling equipment. Although there have been developments in the technological level of solar cooling systems, their integration into façades in real projects has been limited due to various challenges. This study aimed to support the design team and stakeholders involved at the design and development stages with a framework that supports developing solar cooling integrated façades. The framework is intended to integrate key decisions, information, and stakeholders supporting the design and development of solar cooling integrated façades. This study involved several steps. First, it identified and outlined key design decisions, the information required to support them, and the relevant stakeholders involved in the design and development of solar cooling integrated façades, based on desk research. Subsequently, a pre-workshop survey was distributed to relevant stakeholders, and a workshop was conducted to evaluate and further elaborate on the identified design decisions, information needs, and stakeholders. Following this, the design decisions and related aspects were refined based on the workshop outcomes. Finally, these design and development aspects and stages were validated through a design experience survey. The key study findings revealed the following:

- The integration of solar cooling technologies (or other solar technologies) into façades should be considered at the conception stage, where the owner, investor, and/or real estate/property developer and climate designers, building physicists, building service consultants, and architectural designers were identified as key participants who should be involved in the decision-making process for façade integration.
- The key information required to support decisions regarding envelope integration possibilities and the selection of suitable solar cooling technologies for developing design solutions depends on various data sources. The most critical information identified for supporting design decisions includes technology costs, performance and efficiency, cooling demand, and construction characteristics of the thermal envelope.
- The framework validation indicated that the prioritization of design decision as well as criteria tend to be consistent with the refined framework.
- The validation findings indicated that respondents who were unsure about integrating solar cooling technologies into the assigned design case tended to attribute their uncertainty to bottlenecks related to limited knowledge of the technologies and a lack of detailed cost information. These issues can be mitigated through collaboration among various experts during different design stages.

Based on these findings, future work should address the development of prefabricated façade products that incorporate a degree of standardization while maintaining flexibility for various applications. Furthermore, investigating relevant business models with clearly defined roles and responsibilities can enhance collaboration among stakeholders. This would help facilitate information exchange and address bottlenecks related to limited knowledge and differing perspectives on façade solutions among designers, owners, and constructors.

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Institutional Review Board Statement: This study was approved by the Human Research Ethics Committee (HREC) at Delft University of Technology on 7 February 2025. The research team obtained informed consent from all participants involved in the study. The authors adhered to the committee's regulations, including those concerning the tools used for data collection.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting these research findings are openly available in 4TU.ResearchData at this link: https://doi.org/10.4121/aa369b1c-6d92-4048-ad53-95b6f1cc8b30.

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Conflicts of Interest: The authors declare no conflicts of interest.

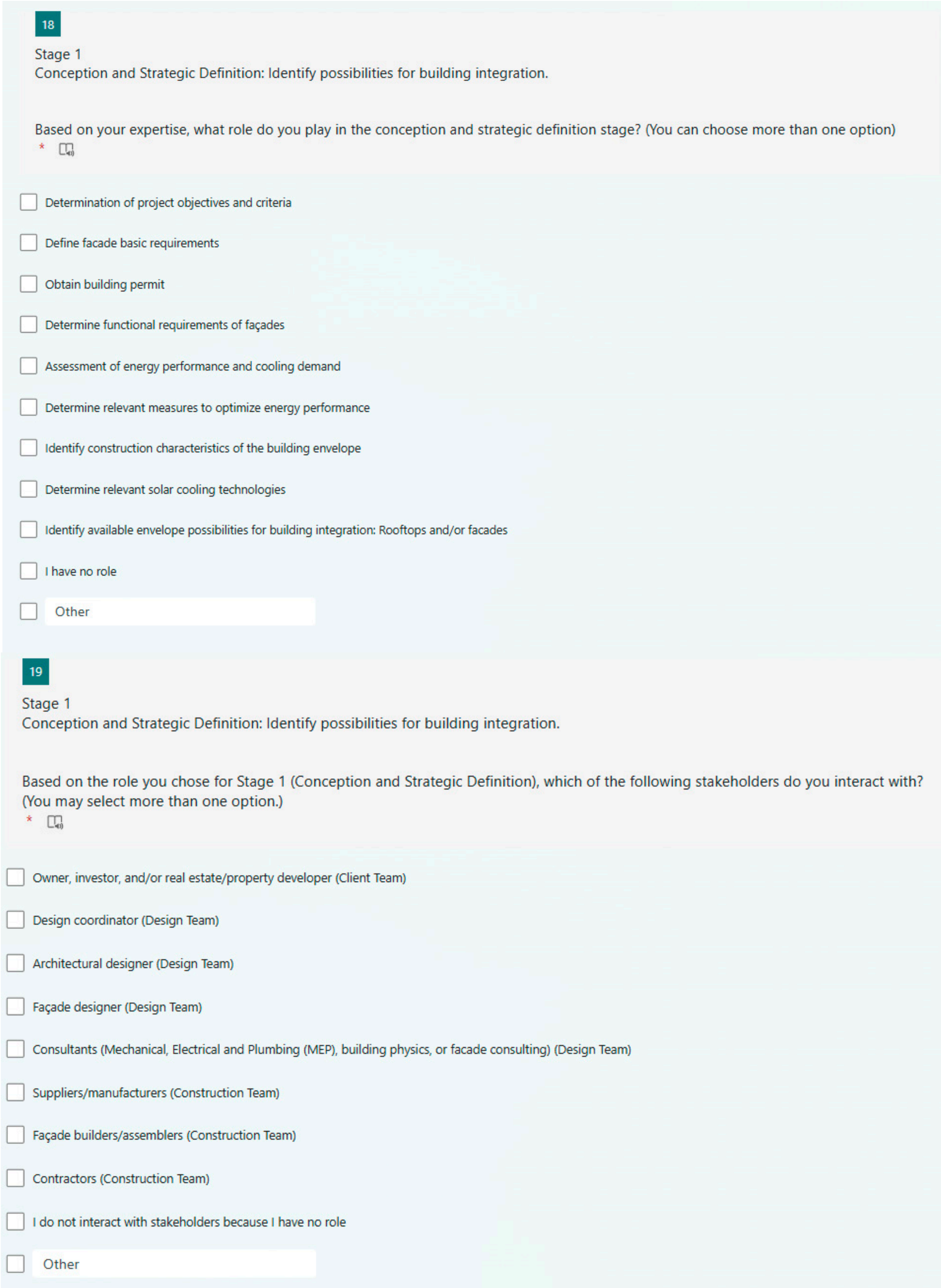
Appendix A. Desk Research and Analyzed Relevant Publications

Table A1. Summary of analyzed relevant publications.

Reference		Stages	Stakeholders
[38]	RIBA workplan for all disciplines in the construction industry	0. Strategic definition 1. Preparation and briefing 2. Concept design 3. Spatial coordination 4. Technical design 5. Manufacturing and construction 6. Handover 7. Use	• Client team • Design team
[37]	Integrated design and construction processes for new building construction	1. Building conception 2. Design 3. Construction preparation 4. Façade construction/assembly 5. Construction delivery and facilities management	• Project owner • Architectural designer • Design coordinator • Façade designer • Suppliers/façade assemblers • Contractor
[37]	Integrated design and construction processes for renovation projects	1. Conception 2. Design	• Project owner • Design coordinator • Architectural designer • Façade designer
[36]	Key phases associated with zero-energy residential building renovation	1. Pre-project 2. Concept design 3. Final design 4. Execution and handover 5. Post-construction	• Client team • Design team • Consultants • Construction team • Subcontractors • Facility management team
[35]	Façade design and construction processes associated with the curtain wall industry	1. System design 2. Pre-design/development 3. Architectural design 4. Execution design 5. Production 6. Assembly 7. Use (building operation) 8. End of life	• System supplier/developer • Investors/developers • Architects • Consultants • Façade builder • Facility management team • User
[17]	Design strategies guiding the design and evaluation of solar cooling integrated façades	1. Conception and strategic definition 2. Preparation and briefing 3. Façade technological selection 4. Façade integration design	-

Appendix B. Pre-Workshop Survey Form (MS Forms) and Results

Appendix B.1. Sample Questions from the Pre-Workshop Survey



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Stage 1
Conception and Strategic Definition: Identify possibilities for building integration.

Based on your expertise, what role do you play in the conception and strategic definition stage? (You can choose more than one option) *

- [ ] Determination of project objectives and criteria
- [ ] Define facade basic requirements
- [ ] Obtain building permit
- [ ] Determine functional requirements of façades
- [ ] Assessment of energy performance and cooling demand
- [ ] Determine relevant measures to optimize energy performance
- [ ] Identify construction characteristics of the building envelope
- [ ] Determine relevant solar cooling technologies
- [ ] Identify available envelope possibilities for building integration: Rooftops and/or facades
- [ ] I have no role
- [ ] Other

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Stage 1
Conception and Strategic Definition: Identify possibilities for building integration.

Based on the role you chose for Stage 1 (Conception and Strategic Definition), which of the following stakeholders do you interact with? (You may select more than one option.) *

- [ ] Owner, investor, and/or real estate/property developer (Client Team)
- [ ] Design coordinator (Design Team)
- [ ] Architectural designer (Design Team)
- [ ] Façade designer (Design Team)
- [ ] Consultants (Mechanical, Electrical and Plumbing (MEP), building physics, or facade consulting) (Design Team)
- [ ] Suppliers/manufacturers (Construction Team)
- [ ] Façade builders/assemblers (Construction Team)
- [ ] Contractors (Construction Team)
- [ ] I do not interact with stakeholders because I have no role
- [ ] Other

Figure A1. Sample of the main questions related to Stage 1.

Appendix B.2. Participants' Profiles

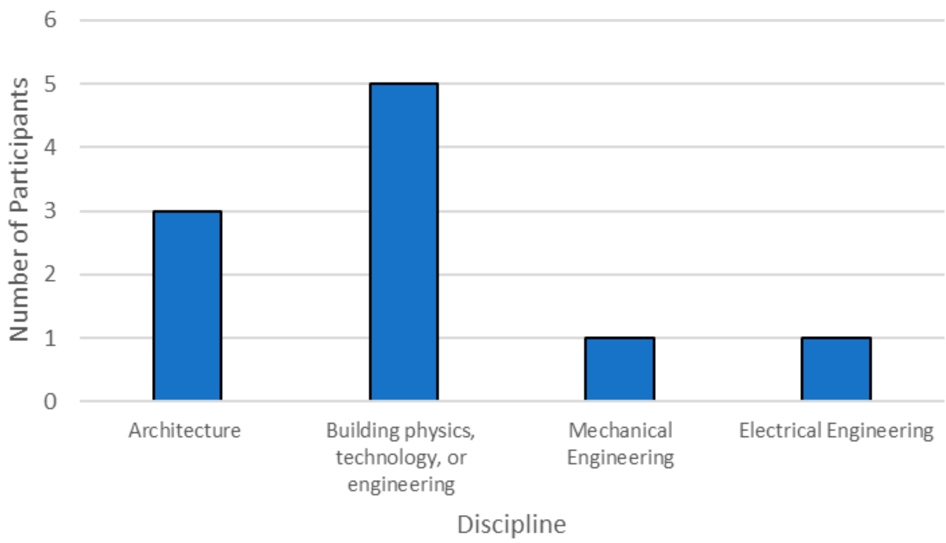


Figure A2. Main educational and technical background.

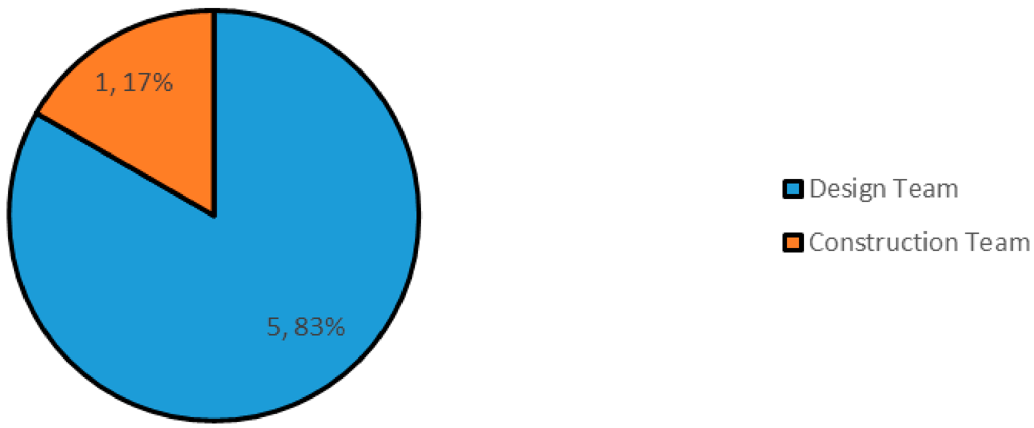


Figure A3. Field of professional experience in the building industry.

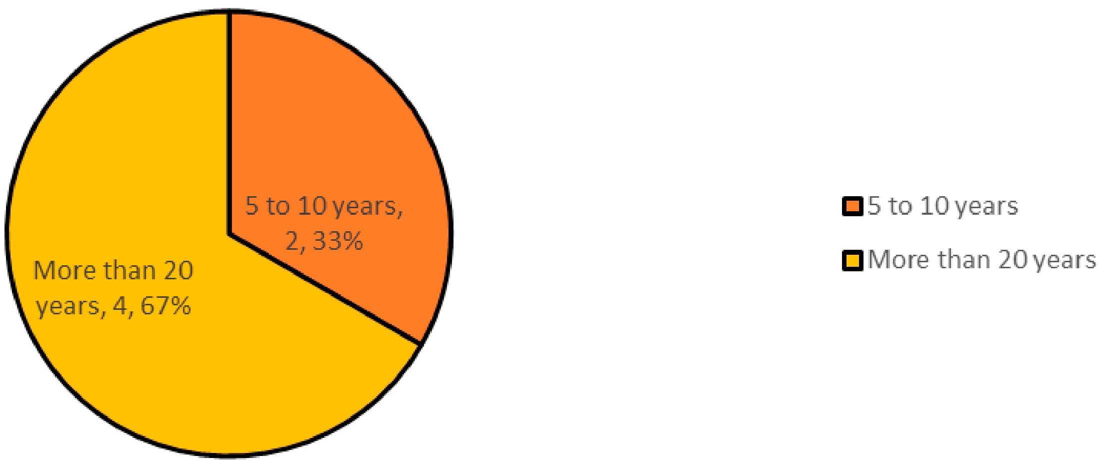


Figure A4. Years of professional experience.

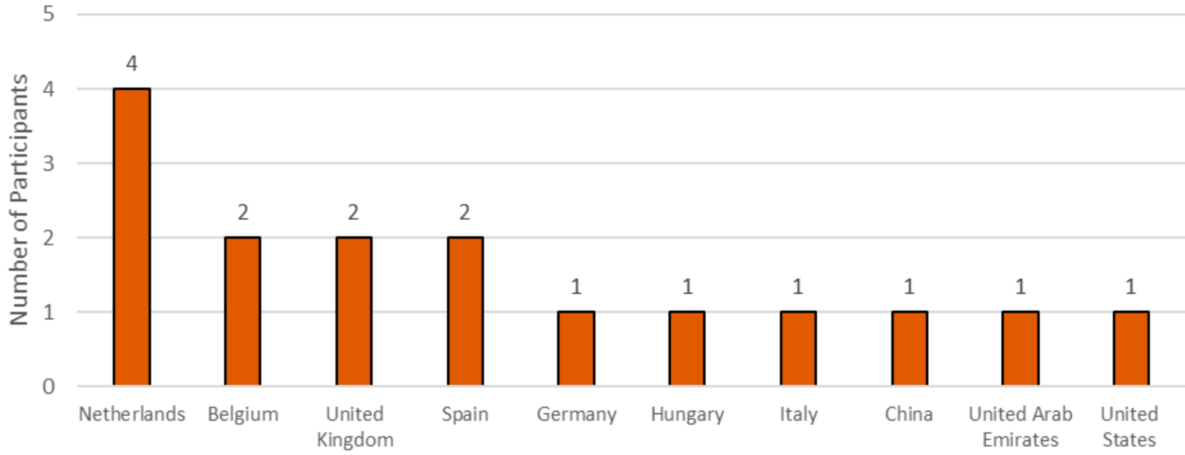


Figure A5. Countries where most of the project participants had worked.

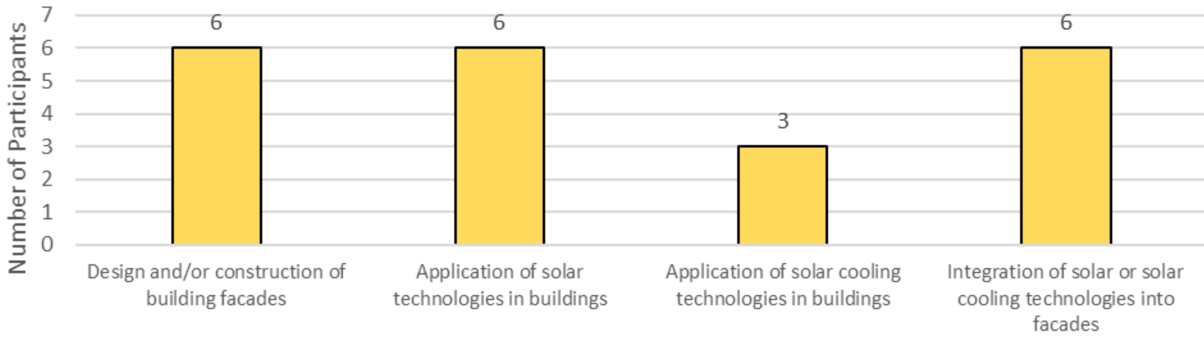


Figure A6. Involvement of participants in different types of projects.

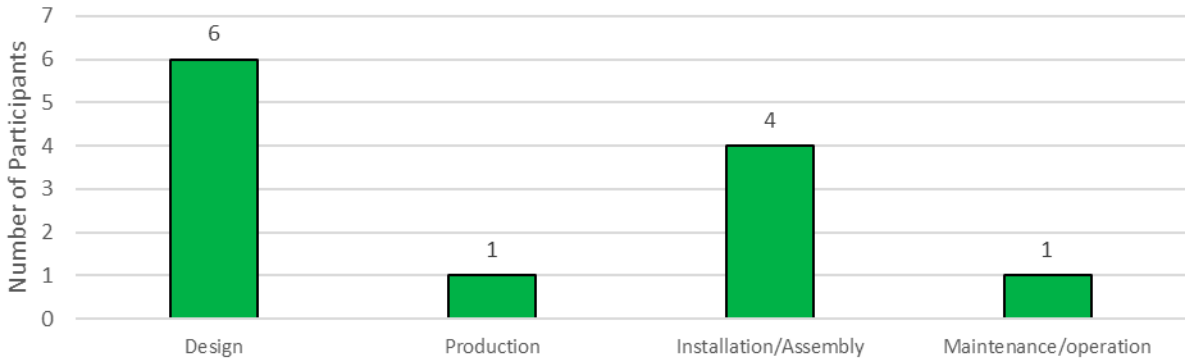


Figure A7. Phases in which participants were involved during the design or construction of building façades.

Appendix C. Virtual Workshop Guide Protocol (MS Teams and MS Whiteboard)

1. *Welcome and introduction round (PowerPoint Slides):*
    - Presenting the workshop agenda and time schedule.
    - Presenting the research group and team members involved in the study.
    - Letting participants introduce themselves to the group, including their technical background and practical experience.
    - Introduction to the research project.
    - Explaining the role of participants during the workshop.
2. *Research background (PowerPoint Slides):*
    - A short presentation about the research background, including providing an overview of previous findings as well as relevant definitions.

3. *Interactive session and activities (PowerPoint Slides and MS Whiteboard):*
   - Describing the moderation principles and rules related to the behavior of participants and expectations. This included the set-up and tools that participants could use during the virtual workshop, which include the main tools of Microsoft Teams and Microsoft Whiteboard
   - Overview hypothetical building case and activities [17].

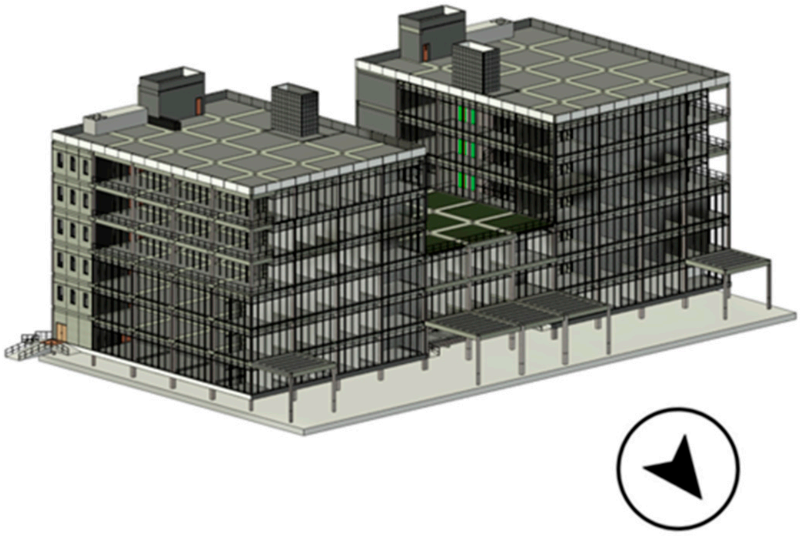


Figure A8. Overview of hypothetical building case.

Table A2. Overview of the selected building case.

Item	Description	Values
Function	Office building (5 story building)	-
Project	New construction	-
Location	Madrid, Spain	-
Spaces functions	Generic office areas, storerooms, toilets, eating/drinking areas, and light plant rooms	-
Ground floor area	Ground has its own same layout	2695.68 m^2
Window-to-wall ratio (WWR)	Proportion of exterior glazed walls	55%

Table A3. Construction characteristics of the thermal envelope elements according to local energy-saving guidelines in Spain.

Construction Element	Considered Materials and System to Meet Requirements	Values
Opaque façade	Ventilated façade: multi-layered opaque external walls	U-value = 0.263 [W/m^2 K]
Glazing (openings)	double-glazed, low emissions	U-value = 1.35 [W/m^2 K]
Roofs (top slab)	Cast concrete slab	U-value = 0.21 [W/m^2 K]
GF slabs (floors in contact with ground)	Cast concrete slab	U-value = 0.30 [W/m^2 K]

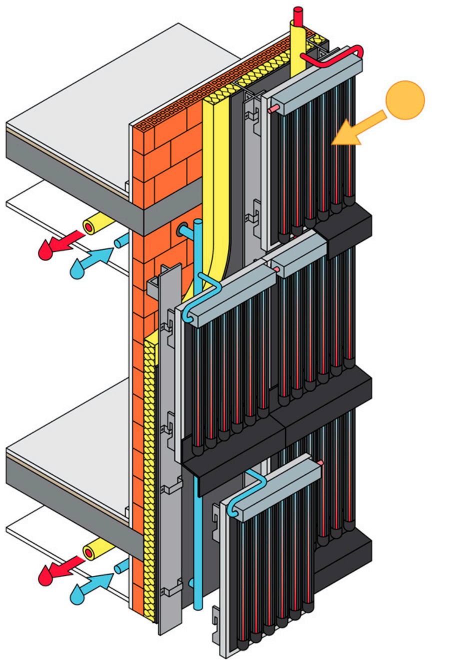
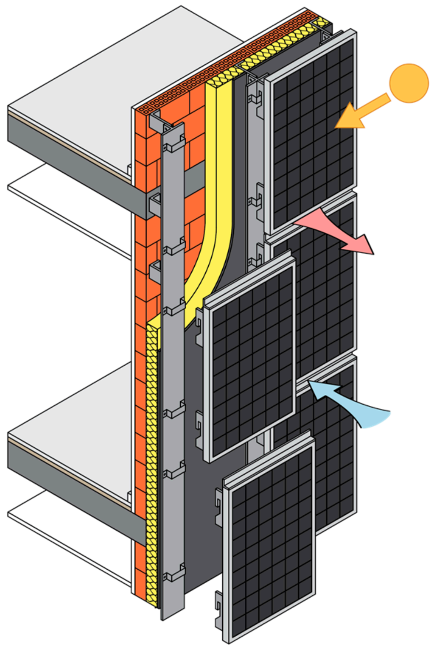
Table A4. Energy performance of the building.

Item	Value
Building's annual energy use intensity	227.02 [kWh/m^2/year]
Building's annual cooling demand intensity	53.61 [kWh/m^2/year]
Building's average daily cooling demand in summer design week	9805.58 [kWh/day]

Table A5. Contracting method and type of building ownership.

Item	Type
Project client	The client is a private owner investor
	The client has the freedom to determine which other stakeholders are involved in the project
Building ownership and use	A single company owns the whole building
	The owner is the building user

Table A6. Example of solar cooling technology design solutions.

	Design Solutions	
Category	Thermally driven	Electrically driven
Options	Evacuated tube solar thermal collectors and absorption chillers	Photovoltaic (PV) panels and water-cooled vapor compression chillers
Demonstration		

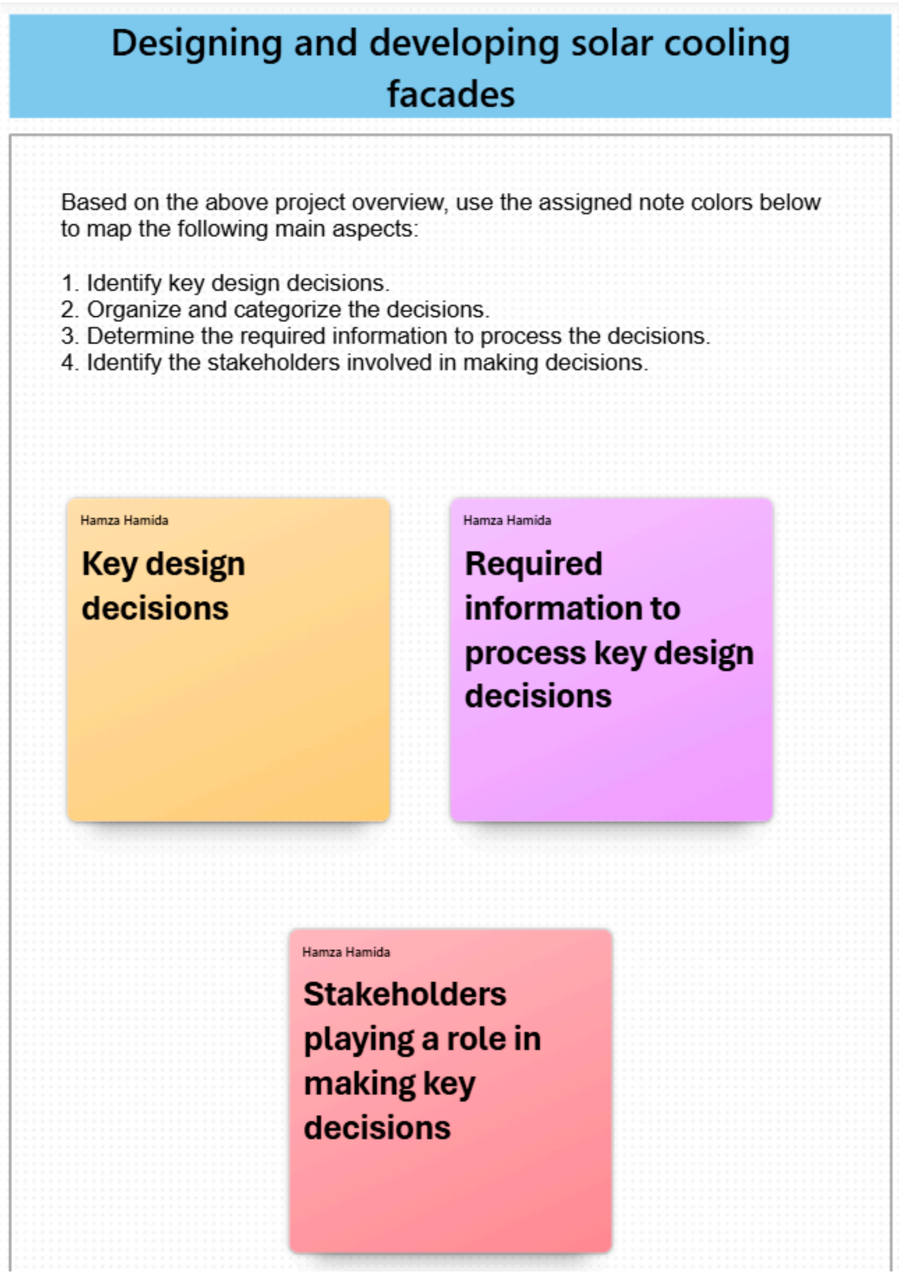


Figure A9. Assigned note colors.

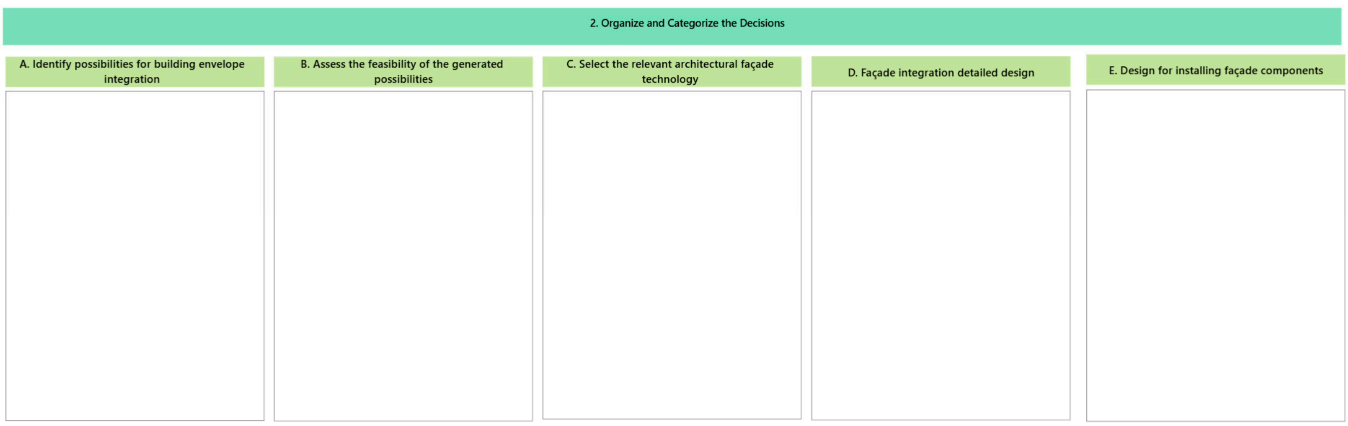


Figure A10. Main canvas.

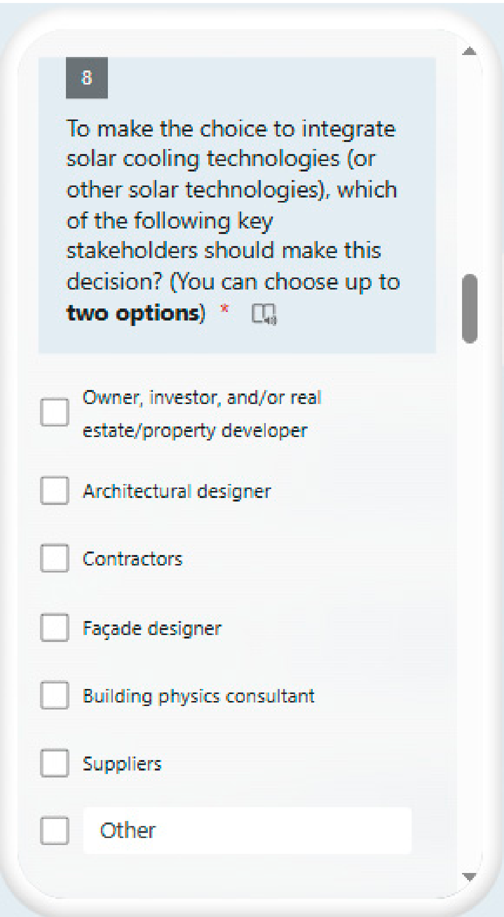
4. *Reflection (MS Whiteboard):*
   - Are there any key aspects that we have not covered?
   - Were there any parts of my framework that were not addressed?
   - Which parts did you find difficult to decide on, and why?
   - To what extent do the integrated decisions, information and stakeholders support the design and development of solar cooling integrated façades? (Consider both drivers and concerns.).
5. *Conclusion:*
   - Summarization of key points and themes and reflecting on their thoughts, obtaining some perspectives regarding future developments.

Appendix D. Validation Instrument (MS Forms) and Results

Appendix D.1. Sample Questions from the Validation Instrument

Table A7. Sample components of the framework validation instrument.

MS Forms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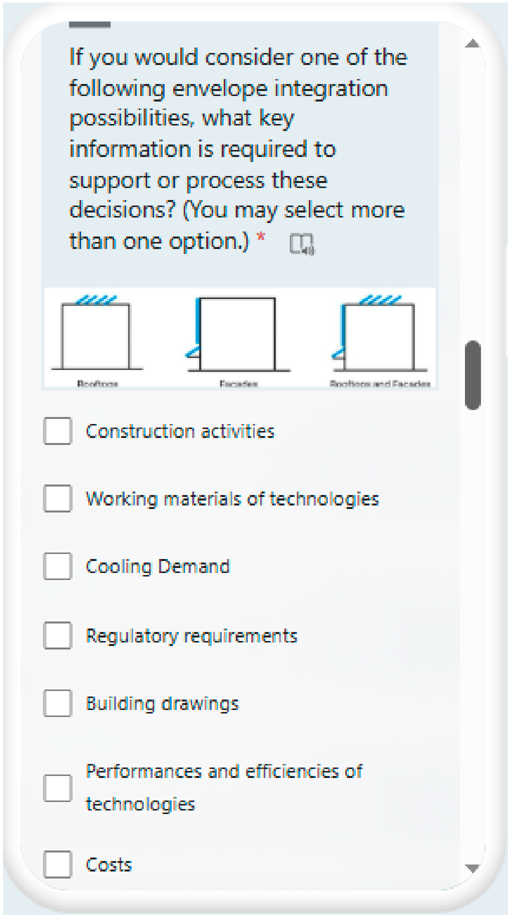
To make the choice to integrate solar cooling technologies (or other solar technologies), which of the following key stakeholders should make this decision? (You can choose up to **two options**) *

- Owner, investor, and/or real estate/property developer
- Architectural designer
- Contractors
- Façade designer
- Building physics consultant
- Suppliers
- Other


If you would consider one of the following envelope integration possibilities, what key information is required to support or process these decisions? (You may select more than one option.) *

- Construction activities
- Working materials of technologies
- Cooling Demand
- Regulatory requirements
- Building drawings
- Performances and efficiencies of technologies
- Costs

Appendix D.2. Respondents' Profiles

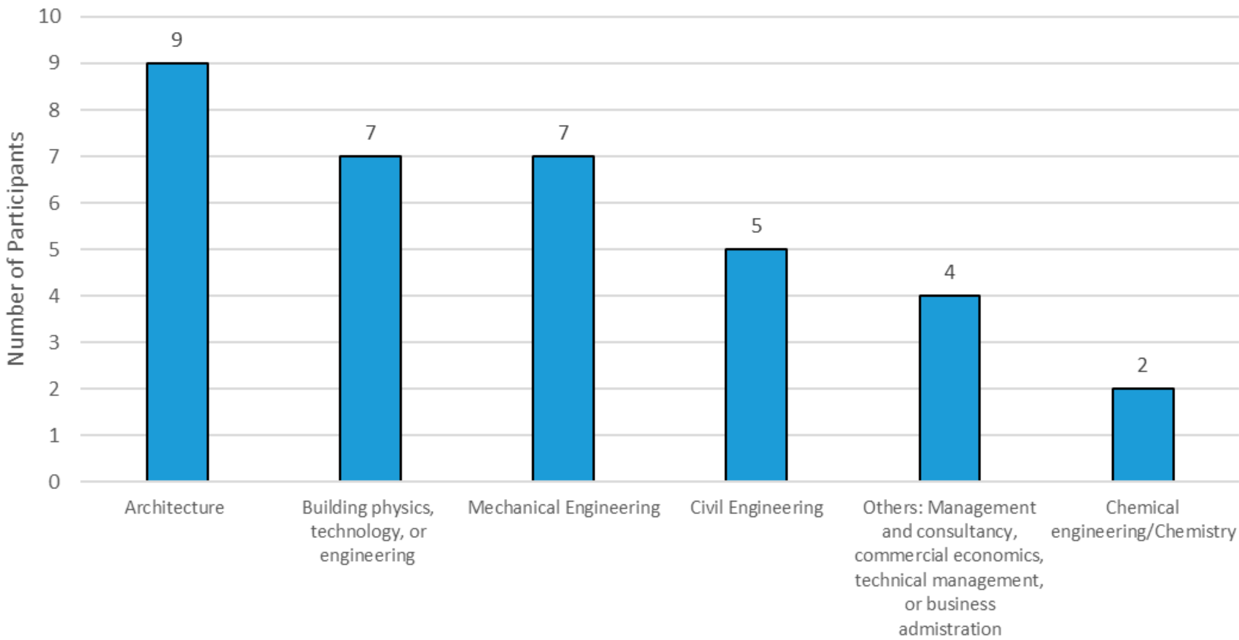


Figure A11. Main educational and technical background.

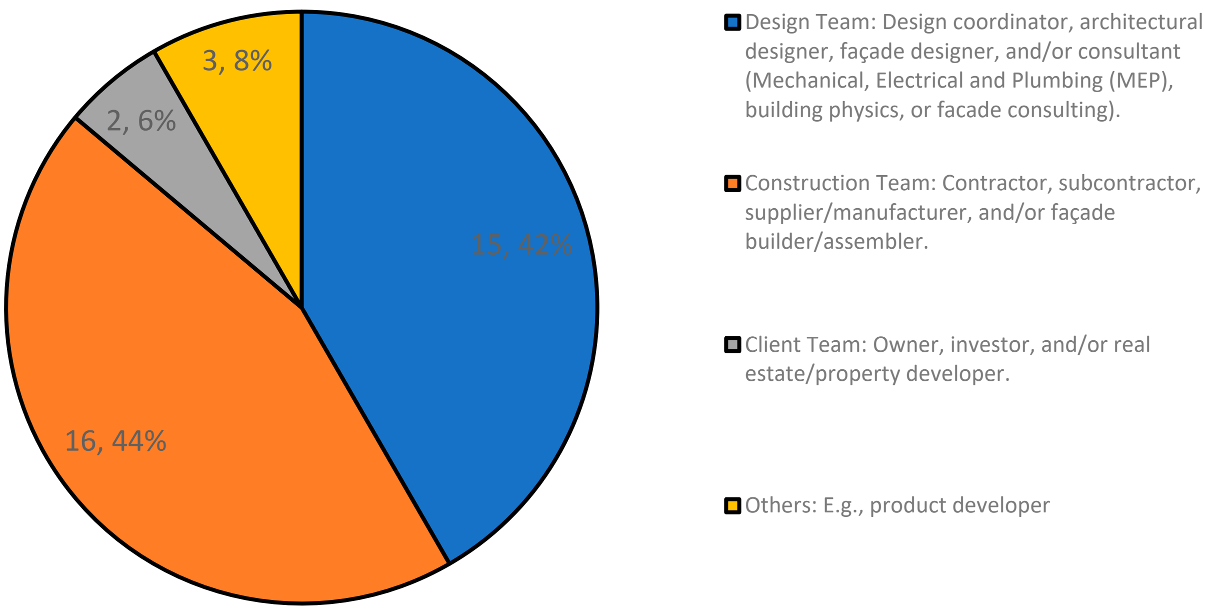


Figure A12. Respondents' fields of professional experience in the building industry.

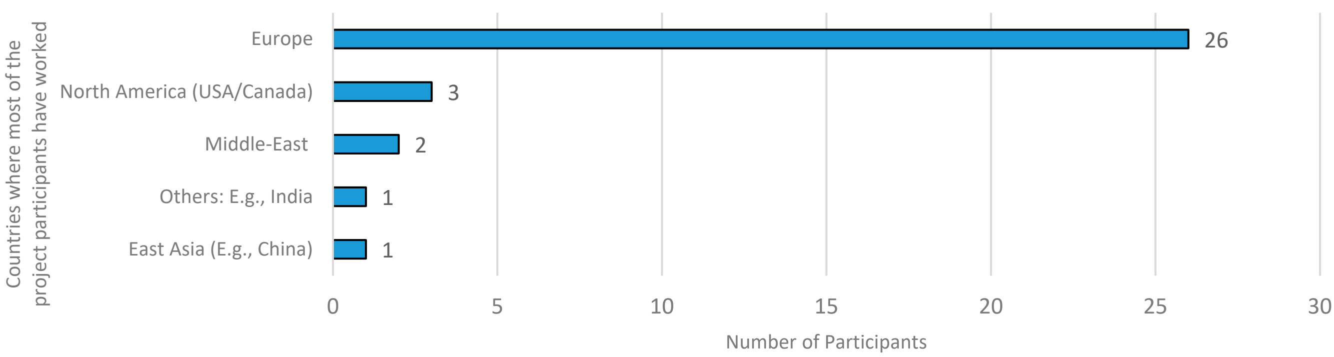


Figure A13. Countries where most of the project respondents have worked.

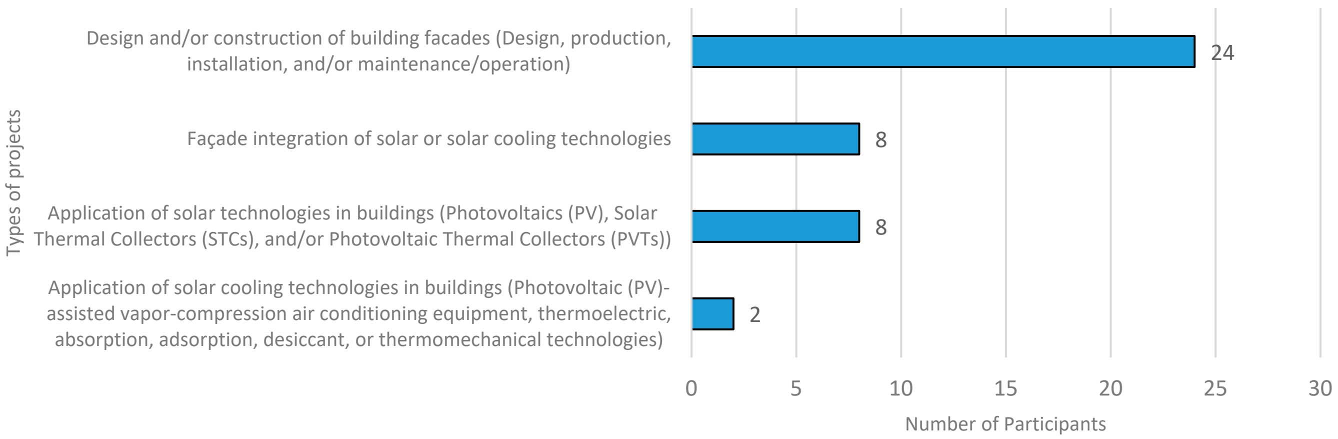


Figure A14. Types of projects respondents worked on.

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